The value of understanding feedbacks from ecosystem functions to species for managing ecosystems

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Ecological systems are made up of complex and often unknown interactions and feedbacks. Uncovering these interactions and feedbacks among species, ecosystem functions, and ecosystem services is challenging, costly, and time-consuming. Here, we ask: for which ecosystem features does resolving the uncertainty about the feedbacks from ecosystem function to species improve management outcomes? We develop a dynamic value of information analysis for risk-neutral and risk-prone managers on motif ecosystems and explore the influence of five ecological features. We find that learning the feedbacks from ecosystem function to species does not improve management outcomes for maximising biodiversity, yet learning which species benefit from an ecosystem function improves management outcomes for ecosystem services by up to 25% for risk-neutral managers and 231% for risk-prone managers. Our general approach provides useful guidance for managers and researchers on when learning feedbacks from ecosystem function to species can improve management outcomes for multiple conservation objectives.
Ecosystems are experiencing dramatic degradation worldwide, making optimal management a pressing topic for both science and practice given limited resources for conservation. At the simplest level, ecosystems are a tangled web of plants and animals connected by feeding links, but further interactions exist between species, ecosystem function, and the services they provide. Ecosystem functions not only contribute to the production of ecosystem services (e.g., nutrient cycling that supports soil fertility and boosts crop production) but also support the survival of species in an ecosystem. We refer to this critical support that ecosystem functions provide for species survival as ‘ecosystem function-species feedbacks.’ Ecosystem function-species feedbacks have been observed in numerous empirical studies yet rarely considered for guiding ecosystem management. For instance, coral reefs provide nutrient cycling functions that can support both fisheries species (i.e., an ecosystem service) and shark populations (i.e., biodiversity). Similarly, pollination functions provided by birds and insects are critical to both crop productions and native plants within the community. Consequently, species extinctions that degrade ecosystem functions can reduce the quantity or quality of ecosystem services while also threatening the survival of other species in the community that benefit from ecosystem function-species feedbacks. In our above examples, reduced nutrient cycling function could threaten both the service provision (i.e., coral reef-dependent fisheries) and biodiversity (i.e., shark populations). Similarly, decreased pollination from local pollinator extirpations could affect crop production and pollinator-dependent native plants.

Learning about these feedback links from ecosystem function to species could be important to inform decisions on species management priority to maximise biodiversity or ecosystem services. However, to the best of our knowledge, consideration of how this information may impact species management priorities is non-existent.

In the past few decades, a growing suite of research on ecological interactions and networks has considered feedbacks between ecosystem functions and species. Those feedbacks have been represented as non-trophic links between species, such as mutualistic interactions that facilitate biodiversity maintenance. The majority of this work, however, focuses on the stability of food webs to perturbations, rather than the management of these systems in light of the feedbacks between ecosystem functions and species. Other studies investigating ecosystem function—species relationship using bio-economic models have focused on specific communities, such as mangrove-fishery ecosystems, pollinator-plant communities, or forests, for ecosystem service management. Yet those studies are restricted to two or three species where the exact ecosystem function—species relationships are assumed to be known, which is rarely the case. The smaller set of studies that consider and model the potential importance of feedbacks for management do not quantify the benefits of collecting this information for management outcomes. For instance, fishery management studies have acknowledged that ecosystem functions benefit both ecosystem services and endangered species’ recovery. However, these studies perform scenario-based analysis that do not assess whether collecting information on feedbacks from ecosystem functions to species improve biodiversity or ecosystem services outcomes.

In practice, collecting information about feedbacks, i.e., the set and strength of links from an ecosystem function to different species in the food web, is challenging, costly, and time-consuming. However, knowing this information could potentially greatly improve management outcomes. Because ecosystem functions support both service provision and species survival in ecosystems, such information about these links could improve management by aiding the identification of win–win management strategies for maximising biodiversity and ecosystem services benefits. Yet, determining whether collecting feedback information will improve species management outcomes and under what ecological conditions remains an open question.

We develop an approach to evaluate when resolving uncertainty about feedbacks from ecosystem function to species will improve management outcomes for maximising biodiversity and ecosystem services benefits. We combine value of information analysis—an approach for quantifying how much management outcomes could be improved if a decision-maker could resolve uncertainties, and stochastic dynamic programming—an optimisation approach that has been widely applied on sequential decision-making problems. To model the complex ecosystem dynamics we use four species motifs, which are common species interaction sub-structures identified from large empirical food webs. Motifs have served as a convenient tool for studying system stability and evolution and have been utilised to compute management priorities for threatened and pest species, and disease networks. To evaluate the feedbacks with ecosystem network models, we connect each motif with one major function that contributes to a key ecosystem service in the system. Using this model we investigate how different ecological features, such as the motif, the feedback strength and the trophic level of the species providing the ecosystem function, drive the management benefit of this information. We estimate the value of having the feedback information using the relative Expected Value of Perfect Information (EVPI), which is obtained by dividing the absolute EVPI by the total number of species or the total value of the ecosystem services depending on the management objective and steps of calculating EVPI in Supplementary Fig. 1. We also calculate the relative EVPI for varied management costs and managers’ risk preferences. Our analyses show that learning the feedback information from ecosystem function to species does not improve management outcomes for biodiversity objective, but could improve management outcomes for ecosystem services by up to 231% for risk-prone managers. To illustrate the value of our work to real-world situations, we also apply our approach to an empirical salt marsh ecosystem in Carpinteria Salt Marsh Reserve, CA, USA from Hechinger et al. and find consistent results with our theoretical findings.

Results

The value of feedback information depends on the management objective. We assess the management benefits of reducing uncertainty for network motifs with different ecological features (see Table 1) under our two different objectives: maximising ecosystem services and species richness. We found that the value of obtaining full knowledge of the feedback links from ecosystem function to species depends on the management objective. Under the management objective of maximising species richness, the relative EVPI is close to zero for all ecological features tested (Fig. 2a). This result suggests that learning this feedback information does not improve the ability to maximise the number of species extant.

Under the management objective of maximising ecosystem services, the relative EVPI varies substantially, ranging from 0 to 25% (Fig. 2b). When species’ baseline probabilities of survival ($p^0$), feedback strength ($\alpha$), and predation strength ($b$) are small, there is no benefit from knowing the feedback information: applying an optimal strategy with and without knowing the feedback information provides similar ecosystem services outcomes. In contrast, for ecosystem networks with high baseline survival probabilities ($p^0$), high feedback strengths ($\alpha$), and high
Among the five ecological features studied, the trophic level of species providing the ecosystem function influenced the value of relative EVPI the most, followed by the species baseline probability of survival ($p_0^j$), network motif, the predation strength ($b$), and the feedback strength ($\alpha$) (see Supplementary Table 1 equal cost conclusion). Although the highest relative EVPI occurs for the omnivory motif (trophic level = 4, $p_0^j = 0.8, \alpha = 0.8, b = 0.9$), managers must also consider the influence of other ecological features. For example, the relative EVPI drops from 25% to 0.02% of improvement of ecosystem service values when comparing the top predator providing the ecosystem function (trophic level = 4, EVPI = 25%) versus the secondary consumer providing the ecosystem function (trophic level = 3, EVPI = 0.02%), holding the other parameters constant (Figs. 2b and 3c, d).

The decision tree analysis provides additional insights into the influence of the ecological features on the relative EVPI (Supplementary Fig. 2a). Generally, high relative EVPI (>6%) occurs for omnivory or intraguild competition motifs where higher trophic level species generate the ecosystem function (Supplementary Fig. 2a). In contrast, there is little value to investigate the feedback information when the ecosystem

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**Table 1** The five ecological features defining an ecosystem configuration in our model

| Ecological features          | Value tested | Explanation                                                                 |
|-----------------------------|--------------|-----------------------------------------------------------------------------|
| Motif                       | 1,2,3,4      | The network motif of species interactions (1 = linear, 2 = apparent competition, 3 = omnivory, 4 = intraguild competition) (see Fig. 1). |
| Trophic level               | 1,2,3,4      | The trophic level of the species providing an ecosystem function. The value 1 to 4 represents bottom to top trophic levels (see Fig. 1). |
| Feedback strength ($\alpha$) | 0.1–0.8 by 0.1 | The feedback strength represents how much ecosystem function goes back to support species’ survival. |
| Baseline survival probability ($p_0^j$) | 0.1–0.9 by 0.1 | The baseline survival probability for species $j$ at the initial time step (see Methods). |
| Predation strength ($b$)    | 0.1–0.9 by 0.1 | The predation strength between two species in the motif network. |

We simulated all possible combinations of the features’ values, leading to 10,368 theoretical ecosystems. These ecosystems were used to calculate the Expected Value of Perfect Information (EVPI) under a biodiversity objective and an ecosystem services objective (see Methods).
function originates from species at the bottom trophic level, because informed and uninformed strategies have similar management outcomes (Fig. 3a).

Management cost has little influence on the value of feedback information. We also investigated the influence of management costs on our results. We found that when assuming that higher trophic level species are more expensive to manage, our general conclusions were mostly consistent, with slightly different ordering of which ecological features ranked as important (Supplementary Table 1; Supplementary Figs. 2–4). The trophic level of the species providing the ecosystem function remained the most influential ecological feature for EVPI, while the feedback strength (α) became the second important feature, instead of the feature with the lowest EVPI (Supplementary Table 1). The decision tree visualization further shows that, with increased management cost, the highest relative EVPI only occurs when top predator performs the ecosystem function with a high feedback strength (α > 0.75) and high baseline survival probability (p^0 > 0.65) (Supplementary Fig. 2). Overall, we also found that higher
management costs of higher trophic level species resulted in higher relative EVPI values for ecosystem services objective (maximum relative EVPI = 72%, Supplementary Fig. 3).

Salt marsh case study. In the salt marsh ecosystem, we identify four motifs (linear, apparent competition, omnivory, and intra-quad competition) between functional groups from Hechinger et al.36 with major ecosystem functions (shoreline stabilization, water filtration, and biomass production for fisheries) provided from different trophic levels (mainly bottom and top trophic levels)34. For each, we calculate the relative EVPI (see Supplementary Fig. 1 for main steps). We then compare the findings from the empirical case study with our theoretical results to assess if and when feedback information alters optimal management strategies for biodiversity and ecosystem services.

Results from the salt marsh case study are consistent with our theoretical findings. First, when management objective is maximising biodiversity, the relative EVPIs for all motifs and trophic levels are close to zero. Second, for all four motifs identified from the salt marsh ecosystem, when the ecosystem function is provided by the bottom trophic level (i.e., vascular plants stabilizing the shoreline), the relative EVPIs are close to zero compared to ecosystem function provided by higher trophic levels (bivalves, or fish functional groups) (Fig. 4).

Risk preferences of managers influence the value of feedback information. The EVPI is an expected value and therefore reflects a risk-neutral decision-maker (indifferent to risk when making decisions)49. Decision-makers can also exhibit risk-averse (avoid risk) or risk-prone (seek risk for a higher payoff) preferences and as such we also use the minimax regret criterion30, which represents the maximum outcome improvement that could be reached if the feedback information is available (Minimal expected regret and min-max regret approaches in the Supplementary Methods)51. For the biodiversity objective, the maximum regret remains small (from 0.04% to 0.34%, Supplementary Fig. 5a). For the ecosystem service objective, collecting more data could lead to, at best, a maximum regret of 231% ecosystem service improvement compared to no data is collected prior to deciding (Supplementary Fig. 5b). This large improvement in management outcomes occurs in the omnivory motif when the ecosystem function is provided by the top predator (Supplementary Fig. 6a). In this case, uninformed strategies prioritise protecting the basal species while the informed strategies prioritise protecting higher trophic level species (Supplementary Fig. 6c). This difference occurs because one assumes equal probabilities of every possible feedback structures when no information about the true ecosystem function-species feedback structure is available. Therefore, in absence of additional information, protecting the basal species is optimal, to support higher trophic levels for functions and services (Supplementary Fig. 6).

Although we observed that ecological features that have high EVPI have high values of the maximum regret (Fig. 2b, d), these two values do not peak for the same ecological features. For instance, the ecosystem configuration with the highest relative EVPI (omnivory motif, top predator providing the ecosystem function, 80% of function going back to species, 0.8 baseline probability of survival, and 0.9 predation strength, EVPI = 25%, maximum regret = 170%) was not the ecosystem configuration with the highest maximum regret (omnivory motif, with a top predator providing the ecosystem function, 80% of function going back to species, 0.9 baseline probability of survival, and 0.9 predation strength, maximum regret = 231%, EVPI = 24%).

Together, the EVPI and maximum regret information provide decision-makers with a richer understanding of the value of reducing uncertainty under different ecosystem structures.

Discussion

Ecosystem functions not only underpin ecosystem service provision but also provide critical support for species survival. We provide a study investigating the value of knowing part of the ecosystem network structure—the feedbacks from ecosystem function to species—for improving biodiversity or ecosystem services management outcomes. Collecting feedback information
Crabs
Crustaceans

Table 1: Functional groups providing ecosystem function are listed in each row. Values indicate the maximum relative EVPI for a specific species providing the ecosystem function. EVPI values range from 0% to 5.87%. The provisional link from the functional group to ecosystem function is given in brackets under each EVPI value.

| Motifs | Trophic levels of functional groups providing ecosystem function |
|--------|---------------------------------------------------------------|
| Fish   | 1 = Linear (vascular plants → shoreline stabilization)         |
| Crustaceans | 2 = Apparent competition (vascular plants → shoreline stabilization) |
| Bivalves | 3 = Omnivory (algal → water filtration)                       |
| Vascular plants | 4 = Intraguild competition (fish → biomass production for fishery) |

1. First consumer (2 = Apparent competition)

- 2.12% (bivalves → water filtration)

2. Second consumer (3 = Omnivory)

- 0% (algal → water filtration)

3. Top predator (4 = Intraguild competition)

- 0% (fish → biomass production for fishery)

4.46% (fish → biomass production for fishery)

25.44% (fish → biomass production for fishery)

17.44% (fish → biomass production for fishery)

Fig. 4 The relative Expected Value of Perfect Information (EVPI) for the salt marsh case study. Four motifs with corresponding ecosystem functions are identified from salt marsh ecosystem in California based on Xiao et al.34 and Hechinger et al.46. Motifs are listed in columns, and the trophic levels of the functional groups providing ecosystem function are listed in each row. Values indicate the maximum relative EVPI for a specific motif in the column and a specific trophic level in the row. The provisional link from the functional group to ecosystem function is given in brackets under each EVPI value.

is challenging and time consuming, so it is important to find out whether and how much management outcomes could be improved when feedback information is available.

Our results show that knowing the feedback information results in little improvement in biodiversity outcomes yet potentially large improvements for ecosystem services (up to a 25%, Fig. 2). For ecosystem management targeting biodiversity conservation, strategies under perfect information and no information about feedbacks tend to protect the same species: information does not improve the management strategy (Supplementary Fig. 7). In contrast, for management targeting ecosystem services, strategies can be improved by reducing the uncertainty about the ecosystem function-species feedback structure, yet the extent of improvement greatly depends on the particular ecological features (Fig. 3).

Among the five ecological features investigated, the trophic level of the species providing the ecosystem function had the largest impact on EVPI, followed by the baseline probability of survival, the motif structure, the predation strength between species and finally the proportion of ecosystem function going back to biodiversity (Supplementary Table 1). This result has direct implication for managers: by identifying that basal species provides the ecosystem function, decision makers could forgo disentangling complex ecosystem function-species feedbacks for the purpose of improving management decisions, as knowledge of these feedbacks will not improve management outcomes (Fig. 3). The salt marsh case study further supports this result—when basal species (i.e., vascular plants or algae) provide ecosystem functions, such as shoreline stabilization or water filtration, understanding which species or functional groups benefit from the ecosystem function will have little influence on optimal management strategies and outcomes for sequestered carbon or clean water (Fig. 4). By showing that knowledge of the trophic level of the species providing the ecosystem function improve management outcomes substantially, our study complements the existing literature that have shown that species trophic levels are an important factor for food web stability52–55 and for potential trade-offs when managing for biodiversity and ecosystem services34.

For management targeting an ecosystem service objective, we identified the ecosystem configuration with the highest relative EVPI (Fig. 2). For the omnivory motif where the top predator performs the ecosystem function, having information about the feedback links from the ecosystem function to species could improve management outcomes by up to 25%—higher than any other motif tested (Figs 2 and 3). These results are consistent with the salt marsh case study when algae, snails, burrowing shrimps, and fish form the omnivory motif with fish providing the ecosystem function (Fig. 4). In this case, the feedbacks could be indirect positive effects of fish biomass on lower trophic levels56, or no feedbacks at all in the ecosystem network (subplot (a) in Supplementary Fig. 8 and Supplementary Discussion). These results, from our theoretical framework and the case study, prompt important questions for future work, including: how common are these ecosystem structures in nature, and what services are most likely to be produced by such a network structure?

A decision-maker’s risk preferences can influence species protection priorities in conservation57–59. Here, we consider both risk preferences and structural uncertainty over ecosystem network to analyse the value of learning the information on feedbacks between ecosystem function and species. We observe that ecosystems with high relative EVPI do not necessarily show high maximum regret for management improvement. A risk-neutral manager would choose to investigate the feedback structures for the ecosystem with the highest expected value, while a risk-prone manager would prefer to learn in another ecosystem with the highest maximum regret.

To gain general mechanistic insights, we considered the stylised system where (1) the network was small (four-nodes motifs) with one ecosystem function and one service provided, (2) learning information about feedbacks had no cost, (3) only
trophic interactions were known, and (4) following species losses, no rewiring of the interaction networks was possible. Future work could relax these assumptions. For example, our approach could account for other types of interactions (e.g., parasitism or symbiosis) and larger ecosystem networks with multiple interactions between species and ecosystem functions.65,66 Incorporating multiple ecosystem functions will require careful consideration of the management objective due to the increased complexity of interactions between species and functions—should one focus on maximising one particular ecosystem service or ecosystem service bundles67. In our optimisation model, we assumed each species contributes to the biodiversity reward function equally, however, managers may assign higher biodiversity reward for protecting specific species (iconic, umbrella, or keystone species), which might lead to a higher EVPI for a biodiversity objective. In contrast, for the ecosystem services objective, we assumed no substitutability between species in the delivery of services. However, in many terrestrial ecosystems, ecosystem functions show resilience because several species can perform the same ecosystem function.61 In this case, a lower EVPI might be expected for ecosystem services objective. In particular, for an ecosystem where all components of the system provide the same ecosystem function (e.g., multiple plant species can provide habitat for birds and pollinators), future work could investigate the value of information for not only which species benefit from the ecosystem function (the location of the feedback links) but also on the relative importance of those links because of the potential for interspecies competition, complementarity and substitutability.61

We assumed equal management cost for each species; however, management cost for species in higher trophic levels of the food web could be higher, because these species could experience higher extinction rates, requiring more costly interventions to maintain their populations (62 but see63 for a counter example), or require protection of more area due to their larger ranges.64 For completion, we also analysed the influence of increased management cost for species in higher trophic levels and found similar results (Supplementary Table 1). Practically, ecosystem manager would also have to consider whether feedback information from ecosystem function to species could be easily collected—in other words, is this uncertainty reducible, and is reducing it cost-effective? Information about feedbacks between ecosystem functions and species could be difficult to detect from the ecosystem dynamics and the field data. Quantifying if and how much a species benefits from or depends on particular functions of the system is even more challenging.65,66 For biodiversity objective, managers would not choose to reduce the feedback uncertainty no matter the cost of collecting the information, because there is little biodiversity outcome improvement with feedback information (relative EVPI close to zero). However, for ecosystem services objective, managers may need to explicitly consider the ecological features of the ecosystem and balance the costs of acquiring information with the management returns from having that information. Further research on case studies which examine the cost of monitoring and field work would complement our recommendations.67

Both the production of ecosystem services and the protection of nature are key aims for ecosystem management. The tangled web of connections and feedbacks within ecosystems clearly complicate management decisions for both aims. Knowing when additional information about these connections is warranted helps inform more effective decisions that can protect species and the services on which society relies. Our study provides an approach, combining network theory and optimisation techniques, to assess the importance of learning about the connections in ecosystems with feedbacks between ecosystem function and species prior to making costly decisions. By quantifying the value of information about feedbacks information, in terms of improved outcomes for biodiversity conservation and ecosystem services for numerous ecosystem configurations, we provide a scaffold for scientists and managers to discern the circumstances in which learning this information would be most promising, and thus help take a further step towards better ecosystem management for species and ecosystem services around the world.

Methods
Overview. To determine whether collecting data on feedback information results in management improvement, we use network motifs (i.e., network subgraphs) between species and ecosystem functions (ecosystem service) to determine the value of resolving this uncertainty. Then, we investigate how EVPI changes across five ecological features: different motifs, trophic level of the function, feedback strengths (a), baseline probability of survival (p(b)), and predation strength (b). In addition, we compare the ecological features of the maximum EVPI, also called the ‘expected regret’, with those features of the ‘maximum regret’ that a manager could have when the feedback information is not available (‘Minimal expected regret and min-max regret approaches’ in the Supplementary Methods).

Network motifs. We consider network motifs with four nodes connected to one ecosystem function and one species (Fig. 1). A node represents a species, and its position in the motif represents the species trophic level from low (basal species) to high (top predator). We assume that species’ feeding relationships and the provisioning links from species to ecosystem function and services are known, but we have uncertainty over the different possible combinations of species that benefit from the ecosystem function. In other words, the ecosystem function could benefit either one, two, three, or all species in the motif, resulting in 16 possible structures per motif (Supplementary Fig. 8). We assume that, for a fixed amount of a function provided by species, there is a trade-off between its provision for services and feedback for biodiversity. For example, the more freshwater is taken out of a stream for irrigation purpose, the less water is left to support biodiversity in that ecosystem.69 We also assume that for the amount of ecosystem function going back, species will consume these feedbacks equally.

The dynamics and management problem of our ecosystem networks are modelled as Markov Decision Processes (MDPs), see below subsection ‘Ecological dynamics and transition probabilities’ and ‘Using Markov Decision Processes to model species dynamics and protection actions effects’ in the Supplementary Methods). Building on previous work by Xiao et al., we have added the interactions between species and ecosystem functions, and top-down effects (i.e. the probability of survival of a species depends on predators and prey neighbours, see ‘Using Markov Decision Processes to model species dynamics and protection actions effects’ in the Supplementary Methods). Management actions. We assume that managers can protect one species at each time step, with the same management cost for each species (we run further analysis with increased management cost as the trophic level of the species increases, Supplementary Table 1). We define a strategy δ as a function that prescribes which species to protect for a given ecosystem state (defined by the set of species extant in the ecosystem). The strategy is applied in the initial ecosystem state, at the next time step some species become extinct while other remain extant. The strategy then is applied to this new ecosystem state, and so on. The sequential application of the strategy defines a sequence of species to protect.

An optimal strategy is defined as a strategy that yields the maximum level of the ecosystem outcome (see ‘Value function and optimal strategy’ in the Supplementary Methods). Here, we consider two definitions of the outcome: the discounted sum of expected number of extant species across all possible states in the system, and the discounted sum of expected amount of ecosystem service provided by the system (measured in US dollars).

Ecosystem dynamics and transition probabilities. The ecosystem dynamics are captured in the transition probability matrix in MDP. Let P be the transition probability matrix representing the dynamics of the system from time step t to time step t + 1. P(x(t+1)|x(t), p(j), a, b, f, M) represents the conditional probability of the ecosystem transitioning from state x(t) to x(t+1) given action a is implemented at time t. We assume that species j could be present (x_{jt} = 1) or absent (x_{jt} = 0) at each time step. This transition probability is also conditional on the baseline probability of survival of species j p(b), the feedback strength a (the percentage of the ecosystem function going back to a species), the predation strength b, the feedback structure/
and the food web matrix $M$ representing the prey-predator interactions of the system. To model this transition probability, we assume that, knowing the state at time $t$, $x_t$, the state of species $j$ at time $t + 1$ is independent of the state of the other species at time $t + 1$. So we can define the transition probability $P(x_{t+1} | x_t, a_t, b_t, f_t, M)$ as

$$P(x_{t+1} | x_t, a_t, b_t, f_t, M) = P(x_{t+1} | x_t, a_t, b_t, f_t, M)$$

Survival probability of a species will increase with the number of extant prey $N_{prey}(j, x_t)$ and ecosystem function available $E_f(x_t, f_t)$, and will decrease with the number of extant predators $N_{predator}(j, x_t, f_t)$. We assume that $N_{prey}(j, x_t, f_t)$, $N_{predator}(j, x_t, f_t)$, and $N_{predator}(j, x_t, f_t)$ are maximum at the initial time step where all species are present (i.e. $x_t = x_0 = [1,1,1,1]$). Formally, we defined the transition probability when species $j$ is not under protection ($a się$) as the product of four terms:

$$P(x_{t+1} | x_t) = p_{j_{t+1}} = \frac{N_{prey}(j, x_t)}{N_{prey}(j, x_t + 1)} \times \frac{N_{predator}(j, x_t, f_t)}{N_{predator}(j, x_t, f_t + 1)} \times \left(1 - \frac{1}{N_{predator}(j, x_t, f_t)}\right)$$

In this way, under the most favourable condition where species $j$ has no predator, no prey loss and receive maximum level of ecosystem function, the above equation reduces to its baseline probability of survival $p_{j_{t+1}}$. However, species $j$ survival probability will decrease when at least one of the following three events happen: prey loss, predator presence, or insufficient functional support (see ‘Using Markov Decision Processes to model species dynamics and protection actions effects’ in the Supplementary Methods).

Calculating the Expected Value of Perfect Information (EVPI). The value of Information can be determined by calculating the Expected Value of Perfect Information (EVPI)34,35. The EVPI is an indicator of how much additional information from the ecosystem function to species ($\delta = \max_i V_i(x_0, f)$) and the food web matrix $M$ representing the prey-predator interactions of our empirical salt marsh ecosystem that provides ecosystem functions and services, based on Xiao et al.34 and Hechinger et al.35. The salt marsh food web consists of 12 functional groups with four types of ecosystem functions34, including carbon sequestration (i.e., provided by vascular plants), water filtration (e.g., provided by bivalves), shoreline stabilization (e.g., provided by vascular plants), and biomass production for fisheries (i.e., provided by upper trophic levels) (Supplementary Fig. 10). From that food web, we identified four motifs—linear, apparent competition, omnivory, and intraguild competition with corresponding ecosystem functions (Fig. 4, ‘Salt marsh case study’ in the Supplementary Methods). We use the approach from Xiao et al.34 to calculate the baseline survival probabilities for each functional group (represented as a node in the motif). As there is no empirical data on the feedback strength and predation strength, we simulate a wide range of values for the feedback strength (between 0.1 and 0.9 by 0.01 intervals) and predation strength $b$ (between 0.1 and 0.9 by 0.01 intervals). We calculate the relative EVPI for each motif and trophic level if that trophic level is associated with ecosystem function provision (see Supplementary Fig. 1 for details). We then calculate the maximum value across different values in $p_f$, $b$ and $\delta$ for each motif and trophic levels from this salt marsh network. 

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
All data to support the conclusions in this paper are available in the main text or the supplemental materials.

Code availability
All simulations were conducted in Matlab and R. The source code to reproduce our results for equal management cost is available at https://doi.org/10.6084/m9.figshare.7120909.v135. And the source code to reproduce our results for increased management cost is available at https://doi.org/10.6084/m9.figshare.6668087.v136.

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