Journal for Nature Conservation 68 (2022) 126218

Contents lists available at ScienceDirect

Journal for Nature Conservation

journal homepage: www.elsevier.com/locate/jnc

Local scale prioritization of cost-efficient protection within the National Park Thy

Camilla Langkilde-Lauesen [a], Niels Strange [a,*], Kerrie A. Wilson [b]

[a] Department of Food and Resource Economics & Center for Macroecology, Evolution and Climate, University of Copenhagen, Rolighedsvej 23, 1958 Copenhagen, Denmark
[b] Institute for Future Environments, Queensland University of Technology, GPO Box 2434, Brisbane QLD 4001, Australia

ARTICLE INFO

Keywords:
Conservation planning
Local planning
Spatial prioritisation
MARXAN

ABSTRACT

This study applied MARXAN to identify cost-efficient areas for biodiversity protection, within the Thy National Park in Denmark. Public authorities have requested a more systematic approach to managing public land, which identifies cost-effective solutions and potential trade-offs between economic cost and biodiversity benefits. The aim of this study was to support the local management staff in setting conservation targets and prioritizing their management efforts. This was addressed through the creation of two primary scenarios: i) applying uniform conservation targets to all biodiversity features, and ii) heterogeneous targets addressing various degrees of conservation importance. Four sub-scenarios were established for each primary scenario to investigate the implications of various conservation targets on conservation cost. Local data on red-listed species and habitat types were used to assess biodiversity benefits. Detailed cost estimates of required conservation actions were included. The results indicated that scenarios with uniform conservation targets provided more flexible networks of protected areas but contributed less to target achievement and a smaller share of selected planning units overlapped with current protected areas. Applying heterogeneous targets based on threat status resulted in a higher degree of target achievement and compactness, but provided less flexible networks. However, these networks may be more suitable for efficient management due to a higher level of clustering and spatial overlap with threatened species distributions.

1. Introduction

In the past century, non-sustainable use of natural resources has resulted in a substantial loss of biodiversity (Newbold et al. 2016; Johnson et al. 2017). Anthropogenic pressures such as habitat loss, pollution, and invasive species have led to a degradation of diverse natural systems worldwide. The current global rate of species extinction is likely to be the largest in recent evolutionary history (Ceballos et al. 2015) and in Denmark a recent assessment found between 2007 and 2018 the conservation status has declined for 33% of the terrestrial habitats and 57% of evaluated Annex 4 species are in unfavourable conservation status (Fredshavn et al. 2019).Through international initiatives, such as the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) established in 2012, the United Nations Convention on Biological Diversity and the European Union (EU) Biodiversity Strategy, Denmark is obliged to protect and conserve its natural values including biological diversity. Despite Denmark quickly ratified the Convention on Biodiversity in 1992 the lack of sufficient financial support and implementation of command and control mechanisms has led to international criticism (OECD 1999). As a response, in 1999 the Danish Government appointed the so-called Wilhjelm Committee which prepared a report forming the basis for the Government's action plan for biodiversity and nature conservation (Wilhjelm Committee 2001). The Committee recommended that Denmark should adopt an adaptive, systematic and cost-effective approach to conservation. One of the main recommendations was the need for establishing large and coherent nature conservation areas. The Danish Government suggested seven areas to develop a Danish model for national parks. The pilot project phase was run in 2005 and based on a bottom-up participatory approach. In 2008 five national parks were established to enhance biodiversity and landscape values.

Despite this response, agriculture (including aquaculture and intensive livestock farming), urbanisation and increased infrastructure development continued to exert negative impacts on nature and

* Corresponding author.
E-mail address: nst@ifro.ku.dk (N. Strange).

https://doi.org/10.1016/j.jnc.2022.126218
Received 23 September 2020; Received in revised form 20 May 2022; Accepted 7 June 2022
Available online 11 June 2022

biodiversity in Denmark (OECD 2010). Main challenges included lack of presence/absence data, lack of national conservation targets and plans to achieve UN and EU conservation targets, lack of biodiversity indicators, and insufficient monitoring system on biodiversity (Rahbek et al. 2012).

The case of the current study, Thy National Park, was established in 2007 and one of the first national parks in Denmark. The majority of the area, approximately 75%, is publicly owned and privately-owned land is split between a large number of landowners. Management responsibilities are delegated to the Danish Nature Agency and Danish Ministry of Food and the Environment. The majority of funding for conservation come from Thy National Park and Danish Nature Agency. It is mandatory that each national park management authority in Denmark develops a plan for operation and management every five years. The Board of Directors of Thy National Park drafts a national park plan, which includes descriptions of conservation actions, and sends the plan for public hearing. The final plan is approved by the Board and implemented by the Secretariat. Implementation is based on voluntary agreements and collaborations between private and public stakeholders and landowners. The plan is not legally binding for landowners. It is rather expressing the objectives and priorities of the Board.

However, in a recent review prepared by the Danish Public Accounts Committee (2016) on the performance of the national parks it was concluded that management practices lacked clear and measurable objectives as well a systematic approach to prioritize conservation efforts. The objectives should be more specific and action plans should suggest how, where, and when to prioritize conservation areas within Thy National Park. It requires collecting and utilizing biodiversity data within the national parks for preparing systematic conservation plans if they should meet this critique of lack of effectiveness in management. Lack of knowledge and competences within Thy National Park Secretariat and The Danish Nature Agency are mentioned as the main reason for not developing systematic conservation plans.

The process of systematically selecting and prioritizing new areas for biodiversity conservation has been the focus of conservationists, practitioners and decision-makers for two decades (Margules and Pressey 2000). Internationally, several prioritization strategies and decision support tools have been developed to improve the cost-efficiency in making conservation decisions. Scholars suggest that "good" conservation reserve design tools relate to how well they minimize the impacts of uncertainty on decisions (Moilanen et al. 2009; Regan et al. 2009). Further, reserve design tools should be realistic in the sense that they make use of sufficiently rich information on conservation cost and budgets. Ignoring this may lead to inefficiency and underachievement (Knight et al. 2013; Mills et al. 2013) (Petersen et al. 2016). The results of the spatial prioritization tool should be addressing relevant and clearly defined planning objectives. The results should additionally be suitable for implementation and on the ground conservation planning and ideally they address the spatial composition of the network of protected areas, if targets are met or not (i.e. over- or underrepresentation), and how flexible the suggested solutions are (Watts et al. 2009). Stakeholder acceptance of the conservation layout can be crucial for successful implementation of conservation plans (Ruiz-Frau et al. 2015). This has been noted during e.g. the rezoning plan for the Great Barrier Reef Marine Park (Fernandes et al. 2005), the implementation of the Marine Life Protection Act in California (Gleason et al. 2010), as well as planning of marine fishery management in Northern Ireland (Yates and Schoeman 2013). These studies document the importance of aligning the spatial prioritization tool with the objectives and policy context to facilitate any uptake of a decision support tool in conservation policy (Gibson et al. 2017). Furthermore, stakeholders often provide valuable input that improves the overall quality of the planning process and outcome.

The purpose of the study was to assist the local Thy National Park in making conservation priorities and allowing them to compare the cost-efficient solutions with their annual budgets. This study evaluated a portfolio of possible conservation network solutions to inform the Secretariat (the management authority) of Thy National Park about the most cost-efficient networks for biodiversity protection. The aim was to clarify where management efforts should be placed geographically, and specifically the size of a conservation area needed for all threatened species and habitat types to be represented adequately at different levels of protection and the cost of the resulting conservation network. This was addressed through two primary scenarios with different target levels for protection of various threatened species and nature types. The first scenario identified the most cost-efficient networks for biodiversity protection in Thy National Park when all species and habitat types were uniformly targeted whereas the second scenario was tailored to select targets based on the threat status of species and nature types. Each primary scenario entailed four sub-scenarios developed to investigate how weighting the importance of different features according to pre-set objectives affects site selection and allocation of funds. The cost-efficient networks were compared to the current designations of protected areas. This study also contributed to the literature demonstrating an application of the spatial prioritization tool MARXAN to resolve a real on the ground conservation problem. Application of such a tool for on ground conservation planning required detailed data reflecting the heterogeneity in management actions and cost. This study incorporated a broad spectrum of taxonomic species groups and information about threat status of individual species and habitat types.

2. Materials and methods

2.1. Study area

Thy National Park is situated in Northwest Jutland, Denmark, and covers approximately 24 400 ha (244 km2), of this approximately 8 000 ha is covered by dune plantations and 12 900 ha are open nature landscapes. In the park, several low nutrient wetlands are situated as well as lakes and coastal limestone cliffs (nationalparkthy.dk). It was established in 2007 as the first Danish National Park. The area was selected because of its large connected areas of internationally threatened habitat type, North Atlantic dune heath lands, as well as the local involvement and support. The national park is hosting large shares of Denmark's threatened and endangered species within species groups: vascular plants(13%), butterflies (31%), birds (4%) and mammals (27%) (National Park Thy Foundation, 2016). Beside high nature values, Thy has an interesting cultural history that can be traced in the landscape of burial monuments, coasts, dunes, protective dune plantations from 18th century to reduce sand erosion, heath lands and lakes. There are also smaller areas with agricultural land-use within the boundaries of the National Park. The National Park contains both nationally (58%) and internationally (53%) Natura 2000 protected areas. Approximately 14% of the area is classified as being in unfavourable conservation status, and threatened species and habitat types are lost. This is mainly caused by invasive species, re-growth of tree species in open land habitat types, nutrient deposition, and destruction of natural hydrology (e.g. caused by ditches and drainage) (National Park Thy Foundation, 2016).

2.2. Land use types

The land uses and public and private ownership in Thy National Park are presented in Fig. 1. About 35% of the study area is covered by forest and of this approximately 91% is owned by the state. Polygon data on land use types consisted of data on private forest, state owned forest and open land habitat types. Data was obtained from Ejrnæs et al. (2014), The Danish Nature Agency in Thy (2015) and Schumacher & Nord-Larsen (2014). Agricultural lands and smaller areas with intensive land use and low conservation values were excluded from conservation prioritization analysis. Approximately 9,000 ha of the National Park is covered by open habitat types, primarily heath land, coastal dunes, grassland, salt marsh and meadows and coastal dunes.. Most of the

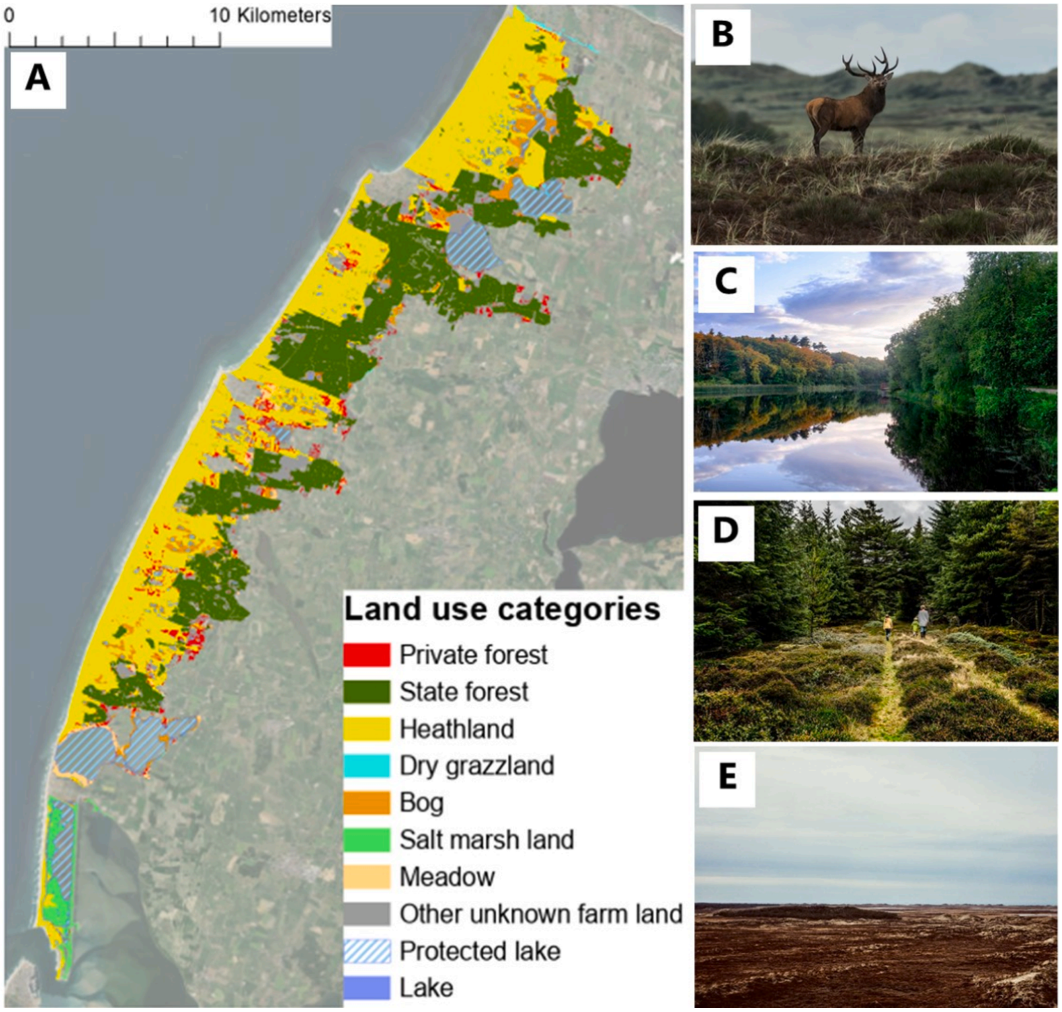

Fig. 1. Thy National Park holds a range of land uses (A, source: Levin et al. (2017)), large populations of reed deer (*Cervus elaphus*) (B, photo: Susanne Worm), protected lakes (C, photo: Kristian Amby), private and public plantations (D, photo: Mette Johnsen), and large areas of heathland (E, photo: Andreas Houmann).

threatened species are located on nutrient poor soils.

2.3. Species data

The local species distribution data is based on occurrence data and habitats from the Danish National Biodiversity Map (Ejrnæs et al. 2014). Spatial polygon layers for 90 species within the National Park with conservation status are either CR (critically endangered, 7% of species), EN (endangered, 28%), VU (vulnerable, 36%) or NT (near threatened, 29%) according to the Danish Red List (Wind and Pihl 2004). The main species groups in the data set are fungi belonging to the Basidiomycota phylum (30 species), followed by vascular plants (24 species) and insects (20 species) including butterflies and hoverflies among others. The remaining species include five Ascomycota and eleven birds. There are a number of important taxonomic groups which are not a part of the dataset, such as mosses, lichens and other types of invertebrates such as spiders. The selected species are considered the most relevant ones for setting conservation targets and making conservation priorities for threatened species within Thy National Park.

2.4. Conservation actions

Conservation actions are suggested to promote and improve conditions of the individual habitat types within the case study area. The conservation actions targeted two main types of areas: open land habitat types and forests. An increasing number of studies have shown that a large part of forest biodiversity depend on old trees, deadwood and coarse woody debris (Müller et al. 2007; Lassauce et al. 2011). The chosen conservation actions in forest is based on passive setting aside forest areas (Halme et al. 2013) and include an immediate stop of harvesting or thinning, and drainage in broad-leaved forests, allowing for conversion of commercial production forests into unmanaged forests with natural hydrology. The aim is to restore the natural hydrology in the landscape by removing or clutching existing ditches and drainage systems. This implementation follows the general governmental recommendations for restoring forest biodiversity (Danish Ministry of Food and Environment 2016). This recommendation rests on unmanaged forests will increase the continuity of the forest cover and gradually increase the amount of dead wood, as well as variation and dynamics with respect to tree species, age structure and density. Harvesting can be allowed in smaller areas adjacent to coniferous plantation forest to provide open habitat types within the forest to further increase the habitat diversity. These areas are left for natural succession and, if needed, future maintenance to prevent the invasion by shrubs and trees.

Species in open land habitat areas are mainly threatened by eutrophication from air-born nitrogen, re-growth of scrubs and trees in habitats which light-depending species depend on, and invasion of non-native species (e.g. Pinus *mugo*, Pinus *contorta*, Prunus *serotina*, Rosa *rugosa*) which displace the native vegetation. The conservation actions in open habitat type areas include grazing and harvest of hay to export nutrients from the sensitive areas and reduce competition from scrubs and fast-growing plants. Manual and machine assisted removal of vegetation is applied if needed to prevent invasion by shrubs and trees and non-native species.

2.5. Conservation cost

The conservation cost estimates are based on the recommendations of the National Park Secretariat and the Danish Nature Agency. The estimated costs are divided into two categories:

1) Direct management costs related to implementation of conservation actions. These are annual costs associated with management of the existing open land habitat types as described above;

2) Estimates of the opportunity costs of conservation when setting forest aside into perpetuity. Costs are calculated as an annual expected economic loss of foregone timber production, measured as loss of annual land rent.

Planning unit size is set at 1 ha which is close to the management size of state forest parcels. The estimated cost of each planning unit is estimated as the annual cost per hectare depending on the habitat types within the planning unit.. This is to obtain estimates and final costs of the reserve networks which are comparable to the actual and budgeted management costs in Thy National Park. For all open habitat types including heath land, bog, grassland, lake, meadow and salt marsh, estimates for conservation cost were obtained from management and accounting staff at Thy National Park Secretariat and Danish Nature Agency, and from analysis of accounting data (Table 1). The estimates include the net income from renting the areas (e.g., for grazing) and costs such as manual /machine operations cost, salary (incl. pension and social costs), and general administrative costs. The cost of open land habitat management was calculated as an area weighted average based on the habitat condition and management requirements for each nature type. For example, maintenance of parts of the heathland that are in a good condition can be achieved at relatively low cost. In other parts, overgrown with larger trees (e.g. Pinus *mugo* or Pinus *contorta*) management will be more intensive and expensive. On average, management costs were highest for grassland, due to the rough terrain often requiring manual maintenance. The cheapest sites to manage were bog and salt marsh. The conservation cost does not include subsidies from the EU or the Danish Government.

The opportunity cost of lost timber production from setting aside forest areas were based on site specific information about tree species, yield class, age in the state owner forest areas, and timber prices (Danish Forest Owners Association 2015). The site class was estimated for each site using information on species, height and age of all state-owned forest stand in the National Park. Appropriate rotation ages were determined using Weiser-percentage estimations (Klemperer 2003). This detailed information allowed for relative precise estimation of the opportunity cost of setting aside the forest area immediately and prohibiting timber extraction (lost expectation value) at high spatial resolution. For the privately owned forests we were able to obtain data for the species composition, but not the age and yield class composition. Hence we applied the average values of conifers (250 DKK/ha/yr), broadleaf (364 DKK/ha/yr) and mixed forests (304 DKK/ha/yr) in the state owned forests as proxies for the opportunity cost of privately owned forests (Fig. 1, panel B). The private forests account only for a minor share of the forest area (9%).

Table 1
Conservation cost distributed on open habitat types (1 EURO = 7.47 DKK).

	Poor condition Cost (DKK/ha/yr)	Average condition Cost (DKK/ha/yr)	Good condition Cost (DKK/ha/yr)	Best condition Cost (DKK/ha/yr)	Area weighted Average Cost (DKK/ha/yr)
Heath land	1 333	375	100	17	358
Lakes	1 000	400	100	0	278
Meadow	667	250	100	0	253
Bog	333	125	40	0	121
Grassland	1 000	500	100	17	569
Salt Marsh	667	250	100	0	250

2.6. Scenarios and conservation targets

To investigate the effects of target levels on the spatial configuration and cost of the final conservation reserve networks for Thy National Park, the appropriate range of targets was identified using guidelines provided in Svancara et al. (2005). They identify the typical range of average targets for biodiversity features used in policy driven approaches between 10.3 and 15.7 % of the area in a country or a region. In evidence-driven approaches the average target range is 26.1–34.6% of the spatial distribution of the biodiversity feature, when targets were based on thresholds (percentage of suitable habitat) at which habitat fragmentation or loss had damaging effect on the specific features, or 33.9–49.3% when targets were based on conservation assessments of the overall conservation area needs in conservation planning. Based on this information, two main scenarios A and B were formulated as:

Scenario A: All biodiversity features were equally protected in the final reserve network. This was implemented by applying uniform targets to all features. Four sub-scenarios with increasing targets were developed, A1 (10%), A2 (23%), A3 (37%), and A4 (50%).

Scenario B: Biodiversity features are prioritized within each scenario (B1-B4). Targets increase from B1 to B4 and from near threatened to critically endangered (Table 2). Targets of habitat types varied with assumed threat status. Target levels of the most threatened nature type heathland, grassland, lake, salt marsh were set similar to critical endangered species. Target levels of meadows were between vulnerable and endangered. Target levels of forest were set at levels of near threatened species.

2.7. Spatial optimization

We applied MARXAN (Ball et al. 2009) to find the most optimal solutions to target achievements.

MARXAN is globally one of the most widely used spatial prioritization tools for conservation planning (marxan.net). The first version was developed more than twenty years ago (Ball and Possingham 2000). It provides conservation network solutions, which minimise the total cost of the conservation network, while aiming at achieving a set of conservation targets. MARXAN allows for examining the overall flexibility of conservation network resulting from the optimisation. It has also been integrated with tools such as Zonae Cogito that further facilitates exploration of alternative solutions (Segan et al. 2011). Game et al. (2011) applied MARXAN to guide national conservation priority

Table 2
Targets in scenarios B1-B4 in percent of localities where species and habitats occur, based on data from Danish National Biodiversity Map (Ejrnæs et al. 2014).Targets of threatened species were set according to IUCN threat categories in the Danish red list. Targets of habitat types varied with assumed threat status.

Scenario name	B1	B2	B3	B4
Target interval (%)	2.5–25%	5–50%	7.5–75%	10–100%
Threatened species				
Critically endangered	25	50	75	100
Endangered	17.5	35	52.5	70
Vulnerable	10	20	30	40
Near threatened	2.5	5	7.5	10
Habitat types designated according to Danish Nature Protection Act §3 and as Natura 2000 areas (European Environment Agency, 2021)				
Heathland, grassland, lake, salt marsh	25	50	75	100
Meadow	13.75	27.5	41.25	55
Forest	2.5	5	7.5	10

strategies under climate change and uncertainty about impacts. Care must also be taken to incorporate the most appropriate cost into spatial prioritization analyses (Evans et al. 2015). This may require that the decision framework and conservation cost is tied to a local scale. A limited number of studies have applied MARXAN at local scale. Levin et al. (2013) used MARXAN with Zones to spatially allocate vegetation types at least cost within a 4.5 km2 privately-owned nature park in Israel. Lin (2014) used spatial prioritization at 0.5 km2 scale to identify protected areas based on estimated species distributions and landscape suitability. Although both studies demonstrate the potential of applying spatial prioritization tools at local scale, neither includes stakeholders nor other types of information important for implementation (e.g. economic cost data).

MARXAN applies a boundary length modifier (BLM) to encourage clustering and compactness of the reserve network solutions. It also includes a species penalty factor (SPF) which penalizes solutions when

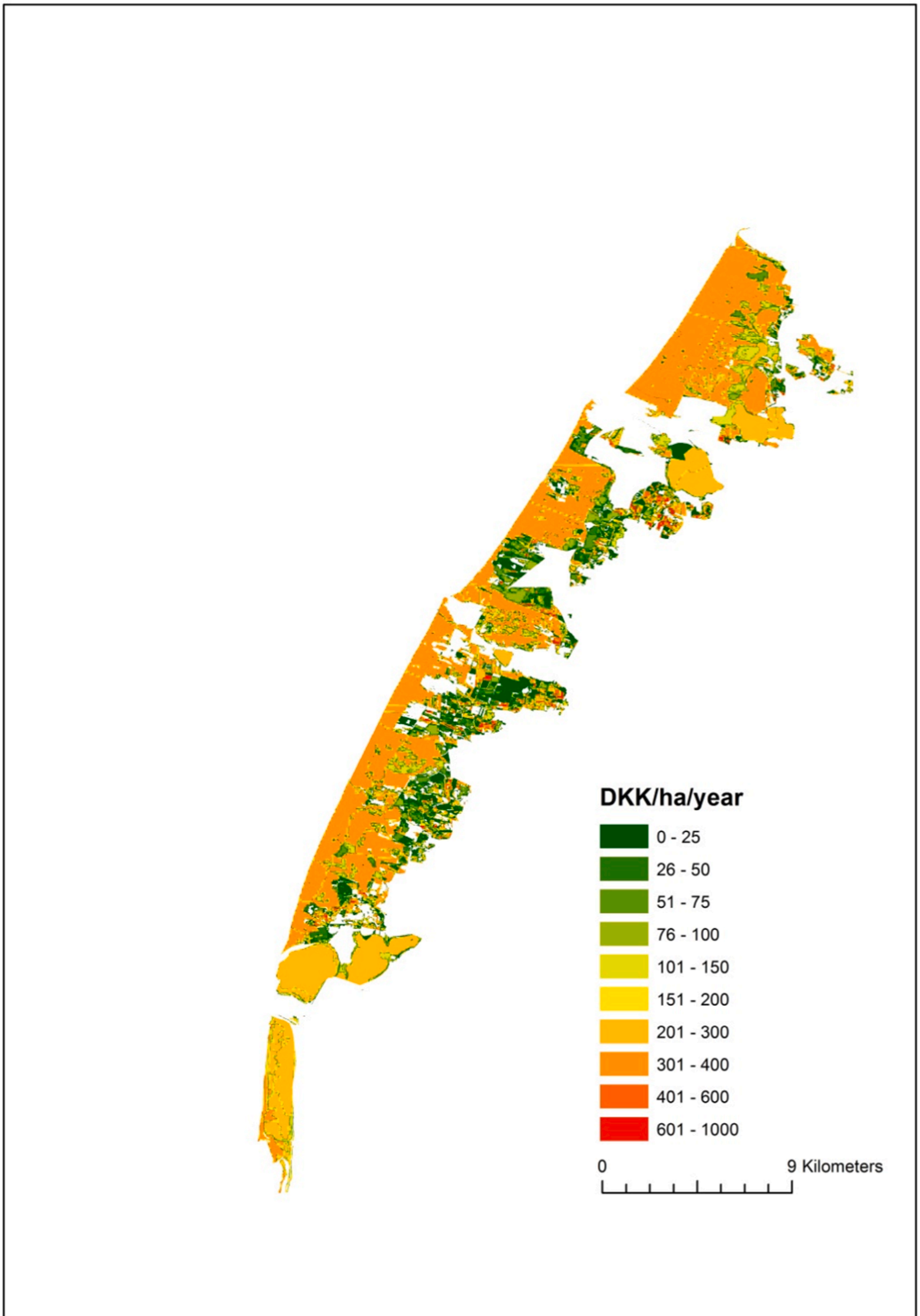

Fig. 2. The distribution of annual conservation costs (DKK ha^{-1} yr^{-1}) in Thy National Park.

species targets are not met. The objective is to minimize the sum of total cost of the conservation network and the penalized boundary length and penalized unmet species targets. The species penalty factor and boundary length modifier were calibrated before each scenario following the procedure of Fischer et al. (2010). A weighting method (Fischer and Church 2005) was applied to systematically explore multi-objective trade-offs in optimization to identify a BLM where both boundary and cost were minimized.

After optimizing all scenarios, the best and summed solution was visualized using the "Capture a Conservation Solution" tool in NatureServe Vista (2015). The resulting possible cost-efficient network for biodiversity protection were evaluated according to how compact they were (perimeter to area ratio), how well targets had been achieved (penalties for less than 100% target achievement, missing values = number of features for which targets where not achieved) and whether and how much they were overachieved (overrepresented distribution area compared to set targets). Additionally, the distribution of land use type and species in the best solutions were investigated visually and quantitatively to determine the effect of different target ranges and priorities on the network. The best solution for each scenario was defined as the solution where conservation targets were achieved at a minimum cost.

The overall flexibility of the networks in terms of the selection frequencies for each planning unit for each scenario were examined and compared to the current protected areas to evaluate similarities and differences. Additionally, individual areas which may be particular important for cost-effective biodiversity conservation under the given constraints and with the available input data, were identified by summing selection frequencies across scenarios and visualizing sites which had been selected in more than 50% of the total MARXAN runs for each main scenario A and B, respectively. Planning units which were selected more than 50% of the runs were considered high-priority conservation areas. These area networks were also compared to the current protected area networks in terms of spatial overlap.

3. Results

3.1. Spatial distribution of conservation cost

Based on land use types within the 100*100 m grid net and estimated opportunity cost of forest and open habitat types a cost layer was estimated (Fig. 2). In more than half of the planning units the cost of conservation actions amounted to more than 300 DKK/ha/yr, with the most expensive planning units located in the east part of the National Park, in stands consisting primarily of Sitka spruce, Oak and Beech with an opportunity cost of 500–1000 DKK/ha/yr. The areas with the lowest opportunity costs (0–100 DKK/ha/yr) were generally areas dominated by *Pinus mugo* in the west part of the forested areas in the study area.

3.2. Target achievement, compactness and budget

To evaluate the efficiency of each of the eight scenarios and to identify the most cost-effective networks in Thy National Park, each scenario was evaluated based on the perimeter/area ratio, cost, penalties, missing values and overrepresentation for the best solutions. The summed solutions for each scenario were evaluated to assess the overall flexibility of the networks. Overall, the best solution (target achieved at minimum cost) for each scenario shows as expected that an increase in conservation targets and thereby the level of protection, leads to an increase in the total area, boundary length of the reserve system, number of planning units and the total cost of the reserve network (Table 3). Conversely, the perimeter/area ratio decreases with increasing target levels. The networks tend to be more fragmented at low target levels, particularly in the scenarios with uniform targets where all biodiversity features are equally protected. The higher the targets the more clustered are the networks (Fig. 3).

In scenarios with uniform targets, the proportion of the National Park prioritized for conservation range from approximately 9% of the case area in scenario A1 to 46 % in scenario A4. When targets are varied according to the conservation status of the features, 16% of the National Park is prioritized in scenario B1 and 48% in scenario B4. Thus the total area included in the final reserve network in each scenario is comparable between scenarios with uniform- and variable targets, but the B scenarios have a higher cost of conservation (Table 3). Scenario A4 is the most compact of the A scenarios and A1 the least despite them having the same BLM. The boundary length in A4 is approximately 3 times as large as in scenario A1 (results included) and the area 5 times as large. This results in a smaller perimeter/area ratio and a more compact system with increasing target level.

When features are prioritized according to their conservation status, the stepwise increase in cost, boundary length, perimeter/area ratio and area change when targets are changed from 7.5 to 75% (B3) to 10–100% (B4) (Table 3). The total cost of the network and corresponding area increases marginally from B3 to B4, 0.02% and 0.1% respectively. In both scenarios conservation targets are fully achieved, but in B3 it is within a more compact network, which is reflected in the perimeter to area ratio. The number of planning units in B4 is only slightly higher than B3 and 84% of the area is overlapping. Thus, B3 achieves the most compact protected area networks of the scenarios with variable target levels.

Since we calibrate the species penalty factor (SPF) for all scenarios the number of features, where targets are not met, are expected to be zero. However, for scenario A1, targets for two features are not adequately met and the penalty for missing targets is subsequently highest for this scenario. For scenarios A2-4 targets were most adequately achieved in scenario A3 with a penalty of 8.6. For all scenarios with variable targets the penalty was zero except for scenario B2, and all targets were achieved within the 99% pre-set level of minimum target achievement. We estimated the overrepresentation as the area covered of red-listed species and conservation features beyond the targeted distribution, and found habitat types are generally not significantly overrepresented (Supplementary Information Figure S1).

3.3. Spatial distribution of cost

In terms of total cost of conservation and area included in the final

Table 3
Results for the best run in scenarios A1-A4 and B1–B4 (BLM = Boundary Length Modifier, SPF = Species Penalty Factor).

Scenario	Target range (%)	BLM	SPF	Area (ha)	Penalty	Perimeter/ area ratio (km/ha)	Open land habitat cost (DKK/yr)	Forest cost (DKK/yr)	Total Cost (DKK/yr)
A1	10	0.1767	10	2 092	391.8	0.375406	411 615	46 465	458 080
A2	23	0.1	20	4 881	31.3	0.317715	967 706	132 952	1 100 658
A3	37	0.0634	25	7 936	8.6	0.264993	1 576 170	296 065	1 872 235
A4	50	0.17665	33	10 803	109.2	0.203431	2 148 274	513 943	2 662 217
B1	2.5–25	0.0245	25	3 813	0	0.351701	1 040 703	55 698	1 096 421
B2	0.5–50	0.018	15	7 514	18.9	0.245241	2 110 274	104 565	2 214 839
B3	7.5–75	0.06	13	11 288	0	0.141184	3 176 535	170 506	3 347 041
B4	10–100	0.0331	15	11 300	0	0.145149	3 179 190	16 863	3 347 822

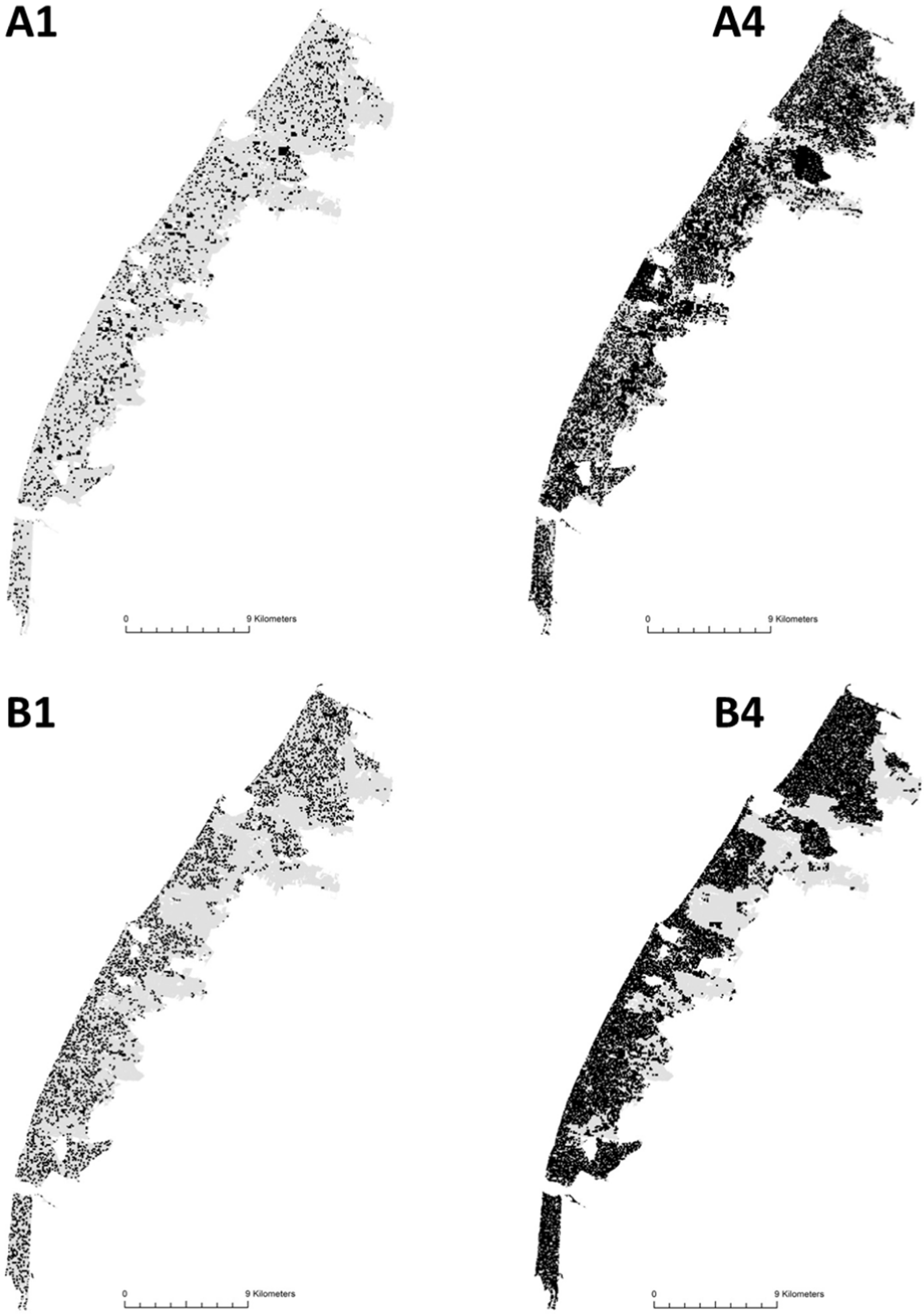

Fig. 3. Best solutions for scenarios A1, A4, B1, and B4. Black areas are the most frequently selected areas.

reserve networks, both increased with increasing target levels for all land use types (Table 3). More area has been selected in open habitat types than in forested areas and subsequently the total cost of the planning units selected in open habitat types was higher than in forested areas. For scenarios A1-A4, the ratio between areas of open habitat types to forest was somewhat consistent with increasing target level. In scenarios B1-B4, where target levels on forest were lower than open habitat types, this ratio was much larger. Across all scenarios, heath land covers the biggest part of the protected area network, followed by forest growing on nutrient poor soils. Its management constitutes the largest expense in the reserve network in all scenarios ranging from 60 % to 66 % of the total cost of the best solutions (Table 3).

Currently, the state forest area in Thy National Park is 3 times higher than the private (National Park Thy Foundation, 2016). We would generally expect that the share of state forests is significantly higher than the share of private forests, but it is found the shares represented in the solution depend on whether targets are uniform or heterogeneous (Table 4). The share of state forest in the network is slightly higher than

Table 4
Percentage of private and state forest included in the network from each scenario (%).

Scenario	A1	A2	A3	A4	B1	B2	B3	B4
Private forest	5.7	15.4	22.2	37.1	14.6	25.3	39.0	38.1
State forest	7.9	18.6	31.7	43.8	3.8	6.6	9.7	9.5

the share of private forest if uniform targets (A1-A4) are applied. On the hand, when targets are heterogeneous (B1-B4) the share of private forest included are 3–4 times larger than the proportion of state forest. One reason may be that the private forest is more frequently than state forest located next to or in smaller patches in the open landscape (Fig. 1A). Since the target for forest include both private and state forest Marxan will minimize its cost function by selecting the planning units in the network, which both meet the area target for forest and decrease the overall boundary length of the network. This is more likely to be achieved in B1-B4 (than A scenarios) by selecting private forest sites located next to open habitat areas which are required for target achievement.

3.4. Conservation network compared to the current protected areas

Scenario A4 and B4 were generally the best performing scenarios in terms of achieving targets for conservation features, flexibility and the compactness of the networks. The level of average overrepresentation was relatively high for both scenarios but within the range of overrepresentation for A and B scenarios respectively. Fig. 4 compares scenario A4 and B4 to the current protected areas in Thy National Park.

The proportion of sites prioritized for conservation which overlap with the current protected areas and untouched forest were larger (78% of planning units) in scenario B4 compared to scenario A4 (51% of planning units)(Fig. 4). Most of this area consists of open habitat types, predominantly heath land. The spatial distribution pattern of prioritized sites in B4 reflects high targets for open habitat types. The areas not overlapping with the current protected areas constitute 306 ha and the main land use type is forest where 265 ha are owned by the state and 0.41 ha are owned by private landholders. When all biodiversity features are equally protected, sites prioritized for conservation were more evenly distributed across the case area than in scenario B4. A total of 1,905 ha were located outside the currently protected areas in A4. As in scenario B4, forest was the primary prioritized land use type not included in the current protected areas. Comparing scenario A4 and B4 with the current protected areas, the most cost-efficient network with variable targets was spatially congruent with the current protected areas.

4. Discussion

The overall aim of the current study was to provide decision support to Thy National Park to achieve more cost-effective conservation outcomes. This was achieved in two ways. Firstly, by comparing the most cost-efficient conservation networks if all biodiversity features are uniformly targeted or if targeted according to threat status of species and habitat types. Secondly, by comparing the identified cost-efficient

Fig. 4. Overlap between the best solution (light green) and current protected areas (dark green) for scenarios A4 and B4. The black pixels are part of the best solution but located outside the protected areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

networks to the current designation of protected areas.

4.1. Conservation cost and budget

Resources to protect conservation areas in Thy National Park, are limited and there is a need to reallocate them efficiently. Prioritizations should therefore seek to account for spatial heterogeneity in the costs of conservation (Armsworth 2014). This study obtained spatially explicit data on conservation needs at 100 by 100 m spatial resolution. The Danish Nature Agency which manages the main part of the National Park is annually spending 2.8 million DKK on conservation in Thy National Park (Danish Nature Agency 2017). In addition, Thy National Park receives approximately 1.7 million DKK per year from the Danish state to support nature conservation actions. This study estimated cost of conservation range from 458 080 DKK/yr for the least expensive network (A1), to 3 347 822 DKK/yr (B4) for the most expensive network. This indicates that the total cost of B4 is within the annual conservation budget of the Danish Nature Agency and Thy National Park, which may increase the feasibility of the conservation plan. Moreover, the detailed geographic identification of conservation areas supports Thy National Park and The Danish Nature Agency in allocating conservation action and budgets in a much more systematic way than previously. More specifically, the selected planning units may guide the management on where to implement conservation projects.

4.2. Setting appropriate targets for conservation planning

In this project different target levels and target ranges were applied to examine the effect of the targets on the reserve network configuration. One of the main challenges using target-based conservation software such as MARXAN is the question of how much is enough? Ideally information on the habitat requirements for each species should be incorporated, but such information is rarely available and in most cases it would take too long to obtain.

Proponents argue that it is a useful way to provide planners with flexible options for reserve networks and that the results can provide a constructive input to the decision- and negotiation process with various stakeholders (Cowling et al. 2003; Levin et al. 2015). Often policy based targets such as 10–12 % are applied, but may be inadequate (Svancara et al. 2005). Evidence-based targets are almost three times higher than policy-based targets, which indicate a gap between ecologically feasible and politically feasible targets (Carwardine et al. 2009; Svancara et al. 2005). It has been suggested that a sensitivity analysis of target ranges may facilitate the exploration of consequences of ecological and politically feasible targets (Levin et al. 2015). It may give decision makers an idea about the impact of different targets levels on the solutions. Furthermore, setting explicit targets and applying systematic conservation approaches may address the critique Thy National Park has received from Danish Public Accounts Committee (2016).

The implementation of conservation action on privately owned land depends on voluntary agreements, collaboration between private and public stakeholders and landowners. Investigating the distribution of area on land use types in the different scenarios reveal certain selection patterns between private and state forest. We found the area of state forest is largest in both A and B scenarios and the selected area increases for both private and state forest with increasing targets. The proportion of the total amount of private forest selected in scenarios with uniform targets is smaller than the proportion of state forest. Interestingly, in the scenarios with variable targets the pattern is opposite and the proportion of private forest which is included in the final networks is higher than for state forests. The reason may be that private forests are generally located in proximity to the open landscapes and smaller patches are situated within the heath land. Since the target for forest aims at both private and state forest MARXAN tends to select the planning units with private forest in scenario B1-B4 to decrease the overall boundary length of the system by selecting forest sites that are close to other areas required for target achievement. Thus, the analysis is clearly driven by the high prioritized targets. Thy National Park may target their agreements towards segments of private forest owners who may be more willing to engage in conservation agreements Nielsen et al. (2017).

4.3. Flexibility, irreplaceability and selection frequencies

One feature of MARXAN is its capacity to generate solutions and provide inspiration and support decisions within the current planning regime, being able to modify the resulting network according to stakeholder input or legislative limitations are key for the solutions feasibility with regards to implementation (Ban et al. 2013; Kukkala and Moilanen 2013; Levin et al. 2015). If MARXAN would generate a large variation in solutions it would provide flexibility for decision makers to consider a range of other factors, such as stakeholder involvement or socioeconomics, which are difficult to include in the optimization problem formulation (Levin et al. 2015). It is generally found that flexibility decreases with increasing targets and flexibility of the A scenarios are lower than the B scenarios. The lowest flexibility is estimated for scenario A4. The reason is that the uniform target scenarios generally have high target requirements for the biodiversity features compared to the B scenarios. If 50% of the distribution of a biodiversity feature is required for target achievement, A4, the options to replace a planning units are fewer and the network is thus less flexible than a scenario with target variation between 10 and 100%, (B4) (Kukkala and Moilanen 2013). However, using selection frequencies above a certain thresholds as an expression of irreplaceability of planning units is questioned (Ardron et al. 2008). A high degree of certainty of the quality of the chosen surrogates for representing biodiversity would be required in order to interpret selection frequencies as irreplaceability (Fischer et al. 2010) and the selection frequencies should be based on a MARXAN output with 100% feasible solution for each run. The summed selection frequency is only applied to provide a measure of the flexibility of the best solutions of the scenarios and not the irreplaceability of individual planning units. Delays or lack of interest from private landowners in making conservation agreements, unforeseen budget cuts (Strange et al. 2006) or costs (Robillard and Kerr 2017), or other implementation challenges may require Thy National Park would need to deviate from the optimal conservation plan. Mapping and visual exploration of flexibility could help them in designing alternative priorities without losing the benefits of making systematic decisions.

5. Concluding remarks

This study presents an application of MARXAN to assisting Thy National Park Secretariat in making systematic conservation decisions and stimulated a discussion on how to translate conservation objectives into a set of quantitative targets for biodiversity features. Further it allowed Thy National Park to explore a range of spatial configurations of alternative networks, which may serve as useful input in the planning process. In a follow-up interview with staff in Thy National Park Secretariat it was highlighted that the resulting maps of conservation priorities provide important inputs for the discussion of where they could achieve the highest conservation benefits compared to costs. They also emphasized the steps in systematic conservation planning are supporting the discussion of future spatial priorities of conservation efforts. Since fundraising is important for Thy National Park, this data driven process may also strengthen the quality of conservation project applications and increase the attraction of external funding for such projects.

This study demonstrates that in order to translate conservation goals and objectives into conservation actions, science and practice should be coupled to obtain sustainable and efficient outcomes. The collaboration between Thy National Park and scientists revealed that such an integrated approach could support a planning process by incorporating realistic information on cost and stakeholder preferences/experiences in setting targets. Such collaborations may establish knowledge coproduction and stimulate dialogue and built capacity for future implementation of conservation projects.

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.

Acknowledgements

The authors thank the Danish National Research Foundation (grant no. DNRF96) for supporting the research at the Center for Macroecology, Evolution and Climate.

References

Ardron JA, Possingham HP, Klein CJ (2008) Marxan Good Practices Handbook Editors. Pacific Marine Analysis and Research Association.

Armsworth, P. R. (2014). Inclusion of costs in conservation planning depends on limited datasets and hopeful assumptions. *Ann N Y Acad Sci, 1322*, 61–76. https://doi.org/10.1111/nyas.12455

Ball I, Possingham H (2000) Marxan v1. 8.2: Marine reserve design using spatially explicit annealing. A Manual Prepared for The Great Barrier Reef Marine Park Authority. University of Queensland, Australia.

Ball, I. R., Possingham, H. P., & Watts, M. E. (2009). *Marxan and relatives: Software for spatial conservation prioritisation*. Oxford, UK: Oxford University Press.

Ban, N. C., Mills, M., Tam, J., et al. (2013). A social-ecological approach to conservation planning: Embedding social considerations. *Front. Ecol. Environ., 11*, 194–202.

Carwardine, J., Klein, C. J., Wilson, K. A., Pressey, R. L., & Possingham, H. P. (2009). Hitting the target and missing the point: Target-based conservation planning in context. *Conservation Letters, 2*, 4–11. https://doi.org/10.1111/j.1755-263X.2008.00042.x

Ceballos, G., Ehrlich, P. R., Barnosky, A. D., et al. (2015). Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Sci Adv, 1*.

Cowling, R., Pressey, R., Rouget, M., & Lombard, A. (2003). A conservation plan for a global biodiversity hotspot—the Cape Floristic Region, South Africa. *Biol Conserv, 112*, 191–216. https://doi.org/10.1016/S0006-3207(02)00425-1

Danish Forest Owners Association (2015) Annual price statistics.

Danish Ministry of Food and Environment (2016) Agreement on the Nature Package. 19.

Danish Nature Agency (2017) Annual accounting report 2016. Ministry of Environment and Food, The Danish Nature Agency, Randbøl.

Danish Public Accounts Committee (2016) Beretning om etablering af nationalparkerne i Danmark [Review of the establishment of national parks in Denmark].

Ejrnæs R, Petersen AH, Bladt J, et al (2014) Biodiversitetskort for Danmark [Biodiversity map of Denmark]. Videnskabelig rapport fra DCE - Nationalt Center for Miljø og Energi nr 112, Aarhus.

European Environment Agency. (2021). *The Natura 2000 protected areas network*. https://www.eea.europa.eu/themes/biodiversity/natura-2000.

Evans, M. C., Tulloch, A. I. T., Law, E. A., et al. (2015). Clear consideration of costs, condition and conservation benefits yields better planning outcomes. *Biol Conserv, 191*, 716–727. https://doi.org/10.1016/j.biocon.2015.08.023

Fernandes, L., Day, J., Lewis, A., et al. (2005). Establishing representative no-take areas in the great barrier reef: Large-scale implementation of theory on marine protected areas. *Conserv Biol, 19*, 1733–1744.

Fischer DT, Alidina HM, Steinback C, et al (2010) Ensuring robust analysis. In: Possingham HP, Ardron JA, Klein CJ (eds) Marxan Good Practice Handbook 2. Pacific Marine Analysis and Research Association, Victoria, BC, Canada, 165 pp.

Fischer, D. T., & Church, R. L. (2005). The SITES reserve selection system: A critical review. *Environ. Model. Assess., 10*, 215–228.

Fredshavn, J., Nygaard, B., Ejrnæs, R., et al. (2019). Bevaringsstatus for naturtyper og arter – 2019. *Habitatdirektivets Artikel*, 17-rapportering.

Game, E. T., Lipsett-Moore, G., Saxon, E., et al. (2011). Incorporating climate change adaptation into national conservation assessments. *Glob Chang Biol, 17*, 3150–3160. https://doi.org/10.1111/j.1365-2486.2011.02457.x

Gibson, F. L., Rogers, A. A., Smith, A. D. M., et al. (2017). Factors influencing the use of decision support tools in the development and design of conservation policy. *Environ Sci Policy, 70*, 1–8. https://doi.org/10.1016/j.envsci.2017.01.002

Gleason, M., McCreary, S., Miller-Henson, M., et al. (2010). Science-based and stakeholder-driven marine protected area network planning: A successful case study from north central California. *Ocean Coast Manag, 53*, 52–68. https://doi.org/10.1016/J.OCECOAMAN.2009.12.001

Halme, P., Allen, K. A., Auniņš, A., et al. (2013). Challenges of ecological restoration: Lessons from forests in northern Europe. *Biol Conserv, 167*, 248–256. https://doi.org/10.1016/j.biocon.2013.08.029

Johnson, C. N., Balmford, A., Brook, B. W., et al. (2017). Biodiversity losses and conservation responses in the Anthropocene. *Science, (80-*.

Klemperer, W. D. (2003). *Forest economics and finance*. McGraw-Hill.

Knight AT, Rodrigues ASL, Strange N, et al (2013) Defining effective solutions to conservation planning problems. In: Macdonald DW, Willis KJ (eds) Key Topics in Conservation Biology 2. John Wiley & Sons, pp 362–383.

Kukkala, A. S., & Moilanen, A. (2013). Core concepts of spatial prioritisation in systematic conservation planning. *Biol Rev, 88*, 443–464.

Lassauce, A., Paillet, Y., Jactel, H., & Bouget, C. (2011). Deadwood as a surrogate for forest biodiversity: Meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. *Ecol Indic, 11*, 1027–1039.

Levin, N., Mazor, T., Brokovich, E., et al. (2015). Sensitivity analysis of conservation targets in systematic conservation planning. *Ecol Appl, 25*, 1997–2010.

Levin, N., Watson, J. E. M., Joseph, L. N., et al. (2013). A framework for systematic conservation planning and management of Mediterranean landscapes. *Biol Conserv, 158*, 371–383. https://doi.org/10.1016/j.biocon.2012.08.032

Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature, 405*, 243–253.

Mills, M., Pressey, R. L., Ban, N. C., et al. (2013). Understanding characteristics that define the feasibility of conservation actions in a common pool marine resource governance system. *Conserv Lett n/a-n/a*. https://doi.org/10.1111/conl.12025

Moilanen, A., Wilson, K. A., & Possingham, H. P. (2009). *Spatial conservation prioritisation: Quantitative methods and computational tools*. Oxford, UK: Oxford University Press.

Müller, J., Hothorn, T., & Pretzsch, H. (2007). Long-term effects of logging intensity on structures, birds, saproxylic beetles and wood-inhabiting fungi in stands of European beech Fagus sylvatica L. *For Ecol Manage, 242*, 297–305. https://doi.org/10.1016/j.foreco.2007.01.046

National Park Thy Foundation (2016) National Park Plan Thy 2016-2022. Hurup.

NatureServe Vista (2015) NatureServe Vista: decision support for better planning.

Newbold, T., Hudson, L. N., Arnell, A. P., et al. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science, (80-*.

Nielsen, A. S. E., Strange, N., Bruun, H. H., & Jacobsen, J. B. (2017). Effects of preference heterogeneity among landowners on spatial conservation prioritization. *Conserv Biol, 31*, 675–685. https://doi.org/10.1111/cobi.12887

OECD (1999) OECD environmental performance review Denmark.

OECD (2010) OECD environmental performance review Denmark.

Petersen, A. H., Strange, N., Anthon, S., et al. (2016). Conserving what, where and how? Cost-efficient measures to conserve biodiversity in Denmark. *J Nat Conserv, 29*, 33–44. https://doi.org/10.1016/j.jnc.2015.10.004

Rahbek C, Agger P, Bruun HH, et al (2012) Danmarks biodiversitets fremtid – de væsentligste udfordringer og højest prioriterede virkemidler. In: Meltofte H (ed) Danmarks natur frem mod 2020 – om at stoppe tabet af biologisk mangfoldighed (Denmark's nature in 2020 - stopping biodiversity loss). The Green Contact Working group, Copenhagen, Denmark, pp 101–112.

Regan HM, Ensbey MJ, Burgman MA (2009) Spatial conservation prioritization - quantitative methods and computational tools. In: Moilanen A, Wilson KA, Possingham HP (eds). Oxford University Press, Oxford, UK, pp 145–157.

Robillard, C. M., & Kerr, J. T. (2017). Assessing the shelf life of cost-efficient conservation plans for species at risk across gradients of agricultural land use. *Conserv Biol, 31*, 837–847. https://doi.org/10.1111/cobi.12886

Ruiz-Frau, A., Possingham, H. P., Edwards-Jones, G., et al. (2015). A multidisciplinary approach in the design of marine protected areas: Integration of science and stakeholder based methods. *Ocean Coast Manag, 103*, 86–93. https://doi.org/10.1016/j.ocecoaman.2014.11.012

Schumacher, J., & Nord-Larsen, T. (2014). Wall-to-wall tree type classification using airborne lidar data and CIR images. *Int J Remote Sens, 35*, 3057–3073.

Segan, D. B., Game, E. T., Watts, M. E., et al. (2011). An interoperable decision support tool for conservation planning. *Environ Model Softw, 26*, 1434–1441. https://doi.org/10.1016/j.envsoft.2011.08.002

Strange, N., Thorsen, B. J., & Bladt, J. (2006). Optimal reserve selection in a dynamic world. *Biol Conserv, 131*, 33–41. https://doi.org/10.1016/j.biocon.2006.02.002

Svancara, L. K., Brannon, J. R., Scott, M., et al. (2005). Policy-driven versus Evidence-based Conservation: A Review of Political Targets and Biological Needs. *Bioscience, 55*, 989–995.

Watts, M. E., Ball, I. R., Stewart, R. S., et al. (2009). Marxan with Zones: Software for optimal conservation based land- and sea-use zoning. *Environ Model Softw, 24*, 1513–1521. https://doi.org/10.1016/j.envsoft.2009.06.005

Wilhjelm Committee (2001) En rig natur i et rigt samfund [A rich nature in a rich society]. Copenhagen, Denmark.

Wind P, Pihl S (2004) The Danish Red List. The National Environmental Research Institute, Aarhus University, Denmark.

Yates, K. L., & Schoeman, D. S. (2013). Spatial Access Priority Mapping (SAPM) with Fishers: A Quantitative GIS Method for Participatory Planning. *PLoS One, 8*, Article e68424. https://doi.org/10.1371/journal.pone.0068424