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Review article

Population and habitat assessments for conservation: Comparing national strategies for Canadian boreal caribou and Norwegian wild reindeer

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ABSTRACT

Habitat loss and fragmentation are major threats to biodiversity. While essential, demographic data alone may be insufficient to rapidly detect habitat-driven population declines and identify efficient management actions. This study explores how conservation strategies can use and integrate demographic and environmental information to detect, monitor and counter population declines. By comparing two extensive conservation strategies for Rangifer tarandus in Canada and Norway, we draw key insights for more comprehensive and actionable strategies. Conservation strategies often use multicriteria approaches combining population and habitat metrics, but seldom succeed in formally integrating these through a causal understanding of habitat-population relationships. The Canadian strategy probabilistically assesses the viability of boreal caribou populations both through direct population modeling, and by statistically linking habitat disturbance to recruitment - thus indirectly capturing habitat-mediated changes in predator-prey dynamics and their consequences on caribou vital rates. The Norwegian strategy develops an expert-based approach to score the quality of wild reindeer populations by combining assessments of habitat quality, connectivity, demography, genetics and health. While the Norwegian assessment is more locally anchored and explores a wider range of drivers, the Canadian one is more targeted and provides a statistical conversion rate between habitat and population metrics. Both assessments serve as a basis for follow-up management actions. This study highlights the need to intensify research to quantify cumulative anthropogenic impacts on the loss of

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functionally connected habitat, and their consequences on population viability. This would enable early-warning systems for assessing population declines, and help shape more targeted prevention, mitigation and restoration actions.

1. Introduction

Biodiversity is declining rapidly due to the cumulative effects of climate and anthropogenic landscape changes (IPBES, 2019; Keck et al., 2025). Land use and infrastructure development are increasingly causing habitat loss, degradation and fragmentation, among the major threats to terrestrial biodiversity worldwide (Foley et al., 2005; Maxwell et al., 2016). Given rapid ongoing global changes, accurately quantifying biodiversity loss has become critical to support effective conservation strategies (Hoffmann et al., 2010; Pimm et al., 2014). Assessing the current state of populations, predicting their future, and identifying threats to their persistence is essential to national and international conservation regulations and policies, including the Kunming-Montreal Global Biodiversity Framework, which supports the achievement of the Sustainable Development Goals through specific conservation goals and targets (Hughes et al., 2023; United Nations, 2022).

Because species declines are linked to anthropogenic pressures and increasingly involve habitat-driven mechanisms (Keck et al., 2025), conservation strategies tend to incorporate habitat condition as a means to achieve demographic objectives, such as population viability. For instance, the IUCN Red List of Threatened Species uses criteria related not only to population size, trend and structure, but also to the geographic extent and quality of habitat (IUCN, 2022). However, the approaches and the extent to which population and habitat information are integrated into holistic assessments can vary considerably. In this paper, we aim to gain insights into how conservation strategies use and integrate demographic and environmental information. Specifically, we present and compare the two largest, long-term conservation efforts for *Rangifer*, in Canada and Norway, to explore perspectives on how to achieve more comprehensive and actionable conservation strategies and guide decision-making.

1.1. Population assessment in conservation strategies

Population assessment is central to conservation strategies, as a primary means of monitoring population performance, tracking changes in demographic trends and estimating future viability (Head et al., 2013; Maxwell and Jennings, 2005; Southwell et al., 2017). The assessment can range from basic population estimates (e.g., presence-absence, population density, relative abundance; McComb et al., 2018), to monitoring of demographic parameters (e.g., sex ratio, breeding success, survival; Belder et al., 2019; Clout et al., 2002; Josserand et al., 2017) and non-demographic factors (e.g., health, genetics, metapopulation dynamics; Catlin et al., 2016; Desforges et al., 2018; Weeks et al., 2017), up to detailed population modeling. Common approaches include direct (e.g., total counts, distance sampling, mark-recapture, catch-per-unit-effort) and indirect (e.g., eDNA, browsing index, camera trapping, acoustic monitoring) monitoring methods (see Buckland et al., 2023; ENETWILD, 2020; McComb et al., 2018 for reviews), and may involve citizen science data (Gallagher et al., 2024), traditional and local ecological knowledge (Ahmad et al., 2021; Charnley et al., 2007; Sheppard et al., 2024; Tomaselli et al., 2018). Population viability analysis (PVA) is often used to probabilistically estimate future population conditions and assess extinction risk (Boyce, 1992; Morris and Doak, 2002), with modeling approaches varying depending on available data and the focal species' ecology (Akçakaya and Sjögren-Gulve, 2000). However, as a data-intensive procedure, PVA is most commonly applied to rare or declining species where extensive demographic data are available (Reed et al., 2002) – for instance, the Northern spotted owl (Dunk et al., 2019) or the Asian tiger (Linkie et al., 2006).

Threatened species can be challenging to monitor – e.g., when they are rare, elusive, or live in remote, inaccessible habitats – leading to poor conservation status assessments (Likens and Lindenmayer, 2018) or even extinction without prior documentation (i.e., "crypto" or "dark extinction"; Boehm and Cronk, 2021). In many cases, demographic data are limited to specific areas or seasons of higher leverage or significance. To address these gaps, researchers often integrate additional sources of information – such as habitat metrics, citizen science, traditional and local ecological knowledge, and other forms of expert knowledge (e.g., in marine turtles – Girard et al., 2022; Arctic tern – Henri et al., 2020; polar bear – Rode et al., 2024; Atlantic salmon – Thorstad et al., 2017; orangutans – Utami-Atmoko et al., 2017). Expert knowledge is particularly key to contextualizing empirical data and engaging local stakeholders in conservation strategies (Camino et al., 2020; Peacock et al., 2020; Stern and Humphries, 2022). However, demographic information alone may be insufficient to effectively monitor and, most importantly, counter population declines when habitat-driven mechanisms are involved (Fitzgerald et al., 2021; Wolf et al., 2015).

1.2. The central role of habitat in conservation strategies

Habitat – i.e., the availability and connectivity of suitable biotic and abiotic conditions – influences individual distribution and fitness, survival and recruitment, ultimately scaling up to affect population dynamics (DeCesare et al., 2014; Fahrig, 2003; Pulliam, 2000; Sandford et al., 2017). Many ecological processes essential to population viability – such as migration, dispersal and gene flow – are shaped by habitat patterns (Fletcher et al., 2016; Hanski and Ovaskainen, 2000; Matthiopoulos et al., 2015). The importance of connected, suitable habitat for species survival, recovery, and long-term persistence is reflected in key conservation policies and regulations, including the Habitat Directive (Directive 92/43/EEC, 1992) and the Environmental Impact Assessment Directive in Europe (Directive 2014/52/EU, 2014), the Endangered Species Act in the US (1973), the Environmental Protection and Biodiversity

Conservation Act in Australia (1999), and the Species at Risk Act in Canada (2002). As such, habitat assessment represents a valuable complement to demographic information for monitoring and countering population declines.

Various approaches exist to assess habitat condition – from heuristic assessments to data-driven and analytical approaches. Habitat suitability can be assessed directly through measurements of key landscape attributes to which the focal species might respond (e.g., vegetation types, topography, anthropogenic disturbance), or estimated from distribution (e.g., presence-absence, density), individual condition (e.g., physical or physiological traits), population performance (e.g., reproduction, survival, growth) or behavior (e.g., foraging rate) data (see Camaclang et al., 2015; Johnson, 2007; McComb et al., 2018 for reviews). Common methods, such as species distribution models (Elith and Leathwick, 2009; Guisan and Zimmermann, 2000) and resource selection functions (Boyce and McDonald, 1999; Manly et al., 2002), use habitat use or selection patters to estimate spatial variation in occupancy likelihood as a function of environmental attributes (Aarts et al., 2012), representing the species' realized niche or suitable habitat (Hirzel and Le Lay, 2008). However, these methods involve several assumptions (Avgar et al., 2020; Boyce et al., 2016; Northrup et al., 2021) and might be misleading with respect to habitat suitability and subsequent demographic outcomes (Aldridge and Boyce, 2007; McLoughlin et al., 2010; Van Dyck, 2012). Data on habitat-specific individual fitness or population performance is key to understanding carrying capacity, but is typically very difficult to obtain, especially over large geographic ranges. Thus, the results of common habitat selection approaches, without direct links to fitness, should be interpreted with caution (Gaillard et al., 2010). Expert knowledge can enhance available data and support analytical approaches (e.g., Leblond et al., 2014; Tendeng et al., 2016) or provide a basis for identifying suitable habitat (e.g., Drew and Collazo, 2012; Pédarros et al., 2020; Stern and Humphries, 2022).

Connectivity – i.e., the degree to which the landscape facilitates or impedes movement among resources (Taylor et al., 1993) – represents a critical, multiscale aspect of habitat condition, that can influence population viability (Fletcher et al., 2016; Rudnick et al., 2012). While movements enable access to habitat (Soberón and Peterson, 2005; Van Moorter et al., 2016), movement barriers can severely reduce the amount of suitable habitat available (Matthiopoulos et al., 2020) and fragment populations into smaller, more vulnerable subunits (Panzacchi et al., 2013, 2016). Failure to account for accessibility and movement constraints can lead to severe overestimations of habitat availability and use (Barve et al., 2011; Dorber et al., 2023; Matthiopoulos, 2003). Consequently, recent approaches, such as (integrated) step selection functions (Avgar et al., 2016; Fortin et al., 2005; Thurfjell et al., 2014) or landscape genetics (Broquet et al., 2006; Shafer et al., 2012), explicitly model movement of individuals or genes to improve estimates of functionally connected habitat (Van Moorter et al., 2023a).

1.3. Conservation strategies for *Rangifer*

Arctic and subarctic regions have undergone rapid expansion of human infrastructure over the past 50 years, primarily driven by industrial development and tourism (UNEP, 2001). These changes have caused habitat loss and fragmentation, which triggered significant losses of biodiversity and ecosystem services (Johnson et al., 2010). *Rangifer tarandus* ("reindeer" in Eurasia and "caribou" in North America) is a key species in northern ecosystems, well adapted to arctic, subarctic, tundra, boreal and mountainous regions of Northern Europe, Siberia, and North America. In 2016, *Rangifer* was globally listed as Vulnerable by the IUCN based on a 40 % decline in total population size over three generations (Gunn, 2016). Although specific threats differ greatly among populations, the species is globally vulnerable to barriers and anthropogenic disturbance (Vors and Boyce, 2009) because of its broad spatial requirements and long migrations (Joly et al., 2019).

1.3.1. Boreal caribou in Canada

Anthropogenic disturbance can operate through multiple pathways, producing varying effects across *Rangifer* populations. In Canada, boreal caribou (i.e., the boreal population of woodland caribou, *Rangifer t. caribou*) typically inhabit mature coniferous forests and peatland complexes, where they occur at low densities and spatially separate from predators and alternative preys (Bowman et al., 2010; Rettie and Messier, 2000). Large areas of continuous, undisturbed habitat provide refugia from predation and enable caribou to cope with naturally dynamic environments shaped by recurring disturbances, such as wildfires. Hence, caribou are highly sensitive to human activities (EC, 2012; Festa-Bianchet et al., 2011). In addition to direct habitat loss and fragmentation, human activities – primarily industrial forestry, mining and hydrocarbon exploitation – lead to the replacement of mature forests with early successional stages, which are more productive and attractive to moose and deer, thereby increasing predator abundance (Latham et al., 2011; Schaefer, 2003; Vors et al., 2007; Wittmer et al., 2005). This habitat-mediated apparent competition (Holt, 1977; Serrouya et al., 2019) leads to increased predation rates on caribou, further exacerbated by the presence of linear infrastructures (e.g., roads, pipelines, seismic lines) that facilitate predator movements into caribou habitat (DeMars and Boutin, 2018; Dickie et al., 2017; Newton et al., 2017). As a result, most of the 51 local populations (hereafter subpopulations) of boreal caribou are at imminent risk of extirpation (ECCC, 2017), with predation as their proximate cause of decline (Festa-Bianchet et al., 2011; Frenette et al., 2020; McLoughlin et al., 2003). Current population estimates are incomplete due to difficulties in counting animals over vast and dense forest areas, but suggest that only ca. 33 000 boreal caribou remain (EC, 2012). The population is currently classified as Threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC; COSEWIC, 2014), and is listed under Canada's Species at Risk Act (SARA; SARA, 2002).

1.3.2. Wild reindeer in Norway

Norway hosts the last remaining European population of wild mountain reindeer (*Rangifer t. tarandus*, hereafter wild reindeer). It is divided into 24 subpopulations typically delimited by fjords or valleys with roads, urban areas, tourism and industrial activities. Most of them are closely monitored thanks to the smaller and more accessible habitats compared to Canada, the ease to count reindeer in open mountain and alpine landscapes, and the availability of millions of GPS positions. The population counts around 22 000 animals and is mainly regulated through hunting, to prevent overgrazing of available forage resources in a system with few natural predators (villrein.no; Strand et al., 2012). The recent outbreak of Chronic Wasting Disease (CWD) has led to significant density reductions due to the eradication of a large subpopulation (> 2 000 animals) and increased hunting quotas in some areas (Mysterud et al., 2024; Mysterud and Rolandsen, 2018). For the majority of the subpopulations, however, habitat loss and fragmentation – mainly from transport infrastructures, tourism, second-home development, and renewable energy production – currently represent the major threat (Panzacchi et al., 2015, 2016). Due to habitat loss and fragmentation, the previously panmictic wild reindeer populations are now divided in 24 isolated units and virtually all ancient migrations have been lost (Panzacchi et al., 2013). As a result, wild reindeer are at risk from a combination of stress, forage resource limitation, genetic isolation and increased vulnerability to stochastic events, threatening their long-term viability (Gundersen et al., 2022; Rolandsen et al., 2022, 2023). In 2021, the CWD-related reductions in population size have led wild reindeer to be classified as Near Threatened on the national red list (Eldegard et al., 2021).

1.4. *Comparing conservation strategies for Rangifer: aim and objectives*

In an effort to halt the decline of this species, Canada (EC, 2011) and Norway (Kvalitetsnorm for villrein, 2020; Mysterud et al., 2025) have independently developed government-led conservation strategies to assess and manage boreal caribou and wild reindeer populations and their habitat. These two large-scale and long-term conservation efforts were developed for the same species in different socio-ecological contexts. Both are grounded in extensive data, knowledge and research providing mechanistic understanding of the factors driving population declines. Hence, examining how these countries have addressed similar challenges offers a unique opportunity to gain insights into the applications of population and habitat assessments in conservation strategies.

In this paper, we aim to (1) examine how conservation strategies implement and integrate population and habitat assessments, focusing on the two *Rangifer* case studies, and (2) discuss challenges, perspectives and implications for future conservation strategies. We first systematically compare how population and habitat conditions are assessed and integrated in the two *Rangifer* strategies. Then, we examine the main differences and similarities of both conservation efforts, and synthesize key insights and heuristic principles for integrating habitat and population assessments. Finally, we discuss how and why this integration can be crucial in providing an early-warning system to detect and monitor habitat-driven population declines, and in identifying the most efficient management measures to counter these declines.

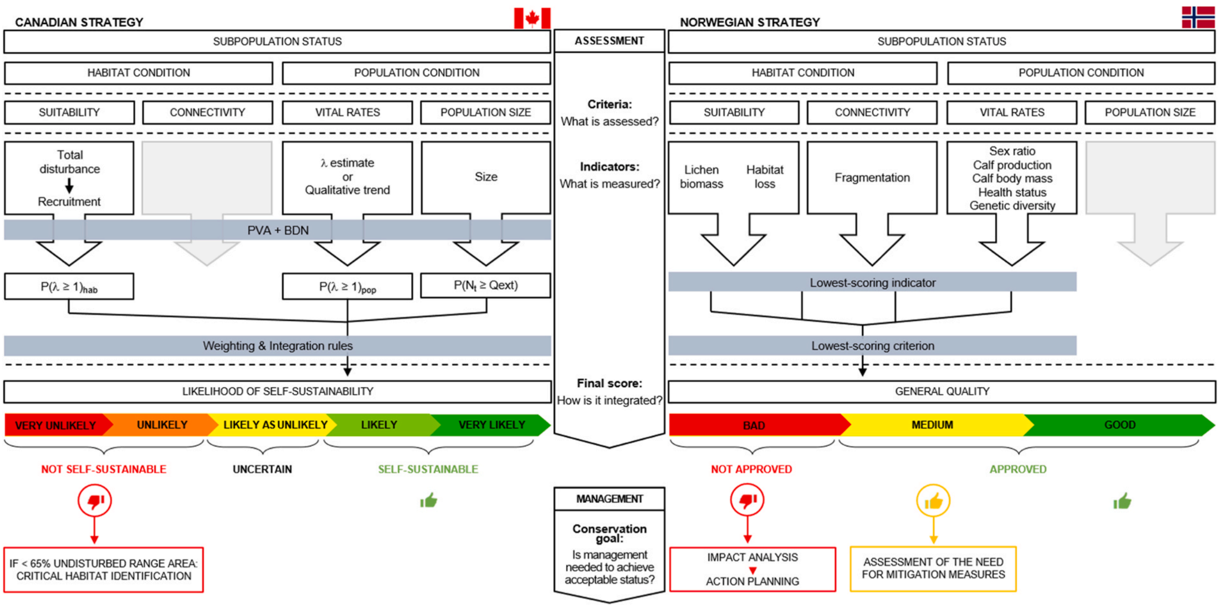

Fig. 1. Description of the Canadian Critical Habitat Framework (Canadian Strategy, CS) for boreal caribou and the Norwegian Quality Standard (Norwegian Strategy, NS) for wild reindeer in the general framework. Subpopulation status is assessed along population and habitat conditions. Both population and habitat assessments rely on criteria quantified by indicators measured within each subpopulation, then integrated into a final score. The final score reflects either the likelihood of self-sustainability of the subpopulation, in the CS, or its general quality, in the NS. This assessment triggers management measures if the conservation goal is not met. In the CS, ranges with < 65 % undisturbed habitat benefit from critical habitat identification, while the NS provides for impact analysis and action planning to identify causes of a Bad score and management levers to raise it to Medium or Good. Medium-scoring subpopulations are approved, but the NS nevertheless advises assessing the need for mitigation measures. Suitability, connectivity, vital rates, and population size here represent assessment criteria and not ecological components named after them, thus allowing for a linear representation. Each indicator was listed under the unique criterion it reports on in the CS and the NS, for sake of readability, but may provide information relevant to several criteria. Grey empty boxes indicate criteria that are not explicitly addressed with a dedicated indicator.

2. Material and methods

Conservation strategies rely on both the assessment and the management of populations, species, communities, up to whole ecosystems (Gerber and González-Suárez, 2010). In their conservation strategies for *Rangifer*, both Canada and Norway use population and habitat assessments to evaluate the status of subpopulations against a conservation goal. This goal sets requirements and specifies limits for what is an acceptable status. The detection of an unacceptable status, inconsistent with the conservation goal, flags the need for management measures (Fig. 1). This paper primarily focuses on the assessment phase of each strategy, which applies to subpopulations (i.e., a group of individuals spatially distinct from other groups and whose demography is influenced by similar factors) within their geographical area of occupation – referred to as the range.

2.1. The Canadian critical habitat framework for boreal caribou

As part of the national recovery strategy under the SARA, the Canadian Critical Habitat Framework (EC, 2011; hereafter the Canadian Strategy, CS) aims at conserving or recovering self-sustaining subpopulations of boreal caribou throughout their current distribution in Canada. A self-sustaining subpopulation is defined as one that (1) demonstrates a stable size or positive average trend over the short term ($\leq$ 20 years), and (2) has a sufficient size to withstand stochastic events and persist over the long term ($\geq$ 50 years), without active management (EC, 2011).

The CS assesses self-sustainability using three probabilistic indicators (Fig. 1). Two are derived from population condition, while the third one is based on habitat condition. Critical habitat for boreal caribou self-sustainability is defined primarily by low predator densities, minimizing the proximate dominant cause of decline. The CS operationalizes this definition by assessing habitat condition via the total amount of range disturbance (Fig. 1), as a proxy for predation. Total disturbance is an aggregated measure of the non-overlapping but cumulative extent of buffered anthropogenic disturbances and unbuffered wildfires ($\leq$ 40 years), expressed as the percentage of disturbed range area. Anthropogenic disturbances are visually identified from Landsat imagery and buffered by 500 m (see buffer analysis pp. 22–23 in EC, 2011; Appendix S1 in Johnson et al., 2020) to account for their ecological effects (i.e., zone of influence) and spatial configuration. Fire data are collected from jurisdictional agencies, Parks Canada and the Canadian National Fire Database for the last 40 years. Based on the negative, empirical relationship between the percent total disturbance and variation in calf recruitment in boreal caribou (i.e., the disturbance-recruitment relationship; pp. 23–25 in EC, 2011), the habitat metric of total disturbance is converted into a demographic metric of estimated recruitment (i.e., calves/100 adult females) for each subpopulation. It is then combined with the national average for adult female survival to derive annual population growth (λ) and parametrize a habitat-based demographic model (p. 29 in EC, 2011). Unlike data on habitat condition, which were available for and standardized across ranges, demographic data reported by jurisdictions varied from no data to population size, qualitative trend (positive, stable or increasing) and sometimes quantitative λ estimates. Population condition is assessed through current population size and trend (Fig. 1), based on the best available demographic data for each subpopulation, used to parametrize a population-based demographic model.

This information is then used in a two-part analytical framework (pp. 26–29 in EC, 2011) combining a non-spatial PVA – using a generic ensemble model to create a large database of simulated demographic projections – and probabilistic decision-analysis tools (Bayesian Decision Networks, BDN) – which use the database to estimate the three indicators in each local population (Fig. 1). First, (1) the probability for population size to exceed the quasi-extinction threshold over 50 years ($P(N_t \geq Qext)$) is estimated based on current population size, when available, assuming stable population trend. It considers the extirpation risk from stochastic events, as an increased threat in very small subpopulations. In addition, the probability of having a stable or growing population over 20 years is estimated twice, (2) once based on population condition (i.e., reported λ or population trend; $P(\lambda \geq 1)_{pop}$), and (3) once based on habitat condition (i.e., estimated λ from total disturbance; $P(\lambda \geq 1)_{hab}$). Both indicators of population growth are averaged over all possible population sizes to reflect variability in expected results based on observable population sizes at a national level.

The three probabilities are then discretized into likelihood statements based on probability intervals, weighted and integrated through a set of decision rules (pp. 32–35 in EC, 2011) to assess the likelihood of self-sustainability of the subpopulation. This final assessment score is conditional on the uncertainty associated with available demographic data, the consistency among the three indicators, potential biases (e.g., due to predator control) and the precautionary principle (i.e., more weight attributed to the indicator associated with the lowest likelihood). Ultimately, each subpopulation is assigned a score for its likelihood of self-sustainability on a five-level scale ranging from Very Unlikely to Very Likely (Fig. 1). The conservation goal requires a Likely to Very Likely self-sustainability score. Then, this score can guide management either towards the maintenance or improvement of the subpopulation status based on a 65 % threshold established later in the CS. This corresponds to the minimum amount of undisturbed habitat necessary to achieve a self-sustaining subpopulation with a minimum probability of 60 %. In parallel with the assessment of population viability, the CS summarizes caribou habitat use patterns by ecozone. These results are intended to guide the identification, protection and restoration of critical habitat in subpopulations with $<$ 65 % undisturbed habitat (Fig. 1).

2.2. The Norwegian environmental quality standard for wild reindeer

In response to its international responsibility for conserving Europe's last wild mountain reindeer population, and as part of its national conservation strategy for this species, the Norwegian Government has adopted the Environmental Quality Standard for wild reindeer (Kvalitetsnorm for villrein, 2020; hereafter the Norwegian Strategy, NS). The NS assesses the quality of each subpopulation based on its population condition, grazing resources and human impact on its habitat (Kjørstad et al., 2017).

Assessment of population condition relies on three demographic indicators, namely the effective sex ratio (i.e., number of males $\geq$ 3 years old/number of females $\geq$ 1 year old), calf production (i.e., number of calves/100 adult females and yearlings of both sexes) and the average calf body mass (carcass weight) in autumn (Fig. 1). These indicators are estimated annually for each subpopulation using data from aerial surveys, field counts and hunting statistics. They are regarded as proxies for a set of factors contributing to recruitment, and ultimately, population growth: the likelihood and timing of fertilization, birth rate and early calf survival, and calf winter survival, respectively. In addition, health status (i.e., the presence of notifiable diseases, currently focused on CWD) and genetic diversity (i.e., the percentage of lost genetic variation over four years) are also monitored as factors that may influence vital rates on the short or long term (Fig. 1; Hansen et al., 2024; Kvalnes et al., 2024).

Grazing resources assessment focuses on lichen biomass (Fig. 1) as a key but slow-growing winter forage in wild reindeer, prone to overgrazing and likely to limit the carrying capacity of reindeer habitat. Lichen biomass (g/m^2) is estimated within each subpopulation from remote sensing data combined with a machine-learning model and supplemented by field surveys for ground truthing (Erlandsson et al., 2022).

Human impact on reindeer habitat is assessed in terms of habitat loss and fragmentation as two major threats to wild reindeer in Norway (Fig. 1). The NS uses expert assessment of changes in reindeer presence over the last 10 years compared to the past 50 years, as a proxy of human impact. The degree and extent of these changes are assessed only in focal areas – i.e., areas of perceived socio-ecological conflicts between wild reindeer conservation and human activities within a range – reflecting the practical limits of expert-based assessments, which require a smaller spatial extent. Habitat loss is assessed in focal areas within the seasonal habitats of the subpopulation – i.e., areas associated with the main ecological seasons in wild reindeer, namely the summer pastures, winter pastures and calving areas. It is measured as the percentage of habitat affected by medium to severe reduction in reindeer presence within focal areas, presumably due to avoidance of anthropogenic disturbance, as compared to the entire area of seasonal habitats. Fragmentation is assessed through a similar procedure within focal areas on major migration routes connecting seasonal habitats. It is based on changes in reindeer crossing frequency or crossing speed, presumably due to anthropogenic barriers. See Appendix A for details on data and assessment procedures.

The NS uses a three-level scoring system to describe the subpopulation as of Good, Medium or Bad quality (Fig. 1). Previous indicators are scored on this three-level scale based on specific intervals of values established by experts in Kjørstad et al. (2017), except for health status scoring either Good or Bad depending on the presence/absence of CWD. The scores for the sex ratio, calf production and calf body mass are based on the five-year average and are additionally raised or lowered by one level, respectively, in the event of a significant positive or negative trend over ten years. Then, the lowest-scoring indicator within each category determines the score for population condition, grazing resources and human impact on habitat. For instance, a Good genetic diversity and health status, Medium calf production and body mass, and Bad sex ratio will result in a Bad score for population condition. The same principle applies when these three categories are integrated into a final quality score. The conservation goal requires each subpopulation to have a minimum quality of Medium, otherwise, management measures must be initiated (Fig. 1). Note that, insufficient information for any of the above parameters results in an Uncertain score, which is not factored in the final quality score but is an important signal to acquire the necessary data until the next assessment. In the management phase, subpopulations that do not meet the conservation goal benefit from an expert-based procedure aimed at synthesizing (1) the main causes of concern and (2) targeted mitigation measures to improve their status (Fig. 1).

2.3. A common framework

In order to compare these two strategies, we developed a general framework providing a common format and consistent vocabulary for their description (Fig. 1). This involved slight modifications in the terminology and formatting of the two original works (EC, 2011 and Kjørstad et al., 2017), including minor simplifications. This general framework describes the assessment of the subpopulation status along two components – population and habitat conditions – based on different criteria. Criteria for habitat assessment are (1) suitability – i.e., biotic and abiotic conditions influencing fitness, including food resources, predators, competitors, pathogens, etc., and (2) connectivity – providing access to these conditions. (3) Habitat disturbance can influence both criteria with distinct effects. Criteria for population assessment are (4) population size and (5) vital rates – encompassing predictive (i.e., potentially influencing vital rates; e.g., sex ratio, diseases, genetics; Carlsson et al., 2018; Frankham et al., 2014; Spielman et al., 2004) and retrospective (i.e., resulting from vital rates; e.g., λ, population trend) indicators. Indicators are the measures taken within each subpopulation to quantify each criterion. They represent the assumed main limiting factors based on available data in each system and therefore vary between the two strategies. Population and habitat indicators are ultimately integrated into a final score reflecting the subpopulation status relative to the conservation goal specific for each system.

3. Results

Although independently developed in different contexts (see 1.3.1 and 1.3.2) both *Rangifer* strategies have similar conservation objectives to maintain or recover viable subpopulations. Both evaluate the status of these subpopulations by combining population and habitat assessments. However, the CS and the NS differ in their implementation and integration of these assessments. Here, we discuss how differences in ecological context (i.e., habitat-mediated apparent competition vs. risk of forage limitation) and management objectives (i.e., self-sustaining vs. harvested subpopulations) led to differences in criteria, indicators and integration of the indicators into a final score (Table 1) between the two strategies.

The first striking difference is the emphasis placed on the different criteria, which we believe is due to differences in ecological and management contexts. In Norway, the NS does not explicitly estimate population size, which is mainly determined by management decision using hunting quotas and may thus be considered a biased criterion of population condition in wild reindeer (Strand et al., 2012). Habitat loss and fragmentation limit reindeer access to suitable habitat and increase the risk for forage depletion, so that a much larger population size is not desirable for many of these subpopulations (Rolandsen et al., 2022, 2023). Consequently, the NS emphasizes lichen biomass and habitat loss as important factors limiting habitat suitability in wild reindeer, and explicitly assesses connectivity based on reindeer movement patterns (Kjørstad et al., 2017). In contrast, the CS focuses on indicators of population size, trend and habitat disturbance – known to be correlated with changes in predator–prey dynamics and declines in caribou vital rates (Johnson et al., 2020). Population size is incorporated to flag the risk of extirpation from stochastic events for small subpopulations (EC, 2011). Total disturbance serves as an indirect indicator of predation risk, which is the dominant limiting factor to habitat suitability and proximate driver of caribou decline. Regarding connectivity, there was limited evidence supporting the use of a specific fragmentation indicator beyond the effects already captured by total disturbance (EC, 2011).

Overall, the NS uses a larger set of indicators, covering a broader range of factors that may influence population viability and potential management levers. For instance, population assessment includes health and genetic indicators in addition to purely demographic ones, as possible predictive indicators of reindeer vital rates on the short or long term (Hansen et al., 2024; Kvalnes et al., 2024). Habitat assessment monitors reindeer use of seasonal habitats and migration routes, as key ecological requirements in this wide-ranging and highly mobile species (Kjørstad et al., 2017). These factors are less relevant in boreal caribou and are thus less prominent in the CS (EC, 2011), which uses fewer but highly targeted indicators. Instead, the CS primarily focuses on habitat disturbance as an indirect way to capture the mechanistic relationship between changes in predator–prey dynamics and declines in caribou vital rates (Johnson et al., 2020). Furthermore, differences in the number and type of population indicators likely reflect different monitoring intensities and data availabilities. While Norwegian subpopulations are relatively accessible – enabling close and standardized monitoring – demographic data reported for boreal caribou are more variable and often incomplete due to challenges in accurately counting animals across vast and dense forest areas.

A further difference relates to the integration of population and habitat indicators into a final score and the information captured by this score. The Norwegian final score ultimately is determined by the lowest-scoring indicator among all criteria, all indicators being equally weighted. This implies that the most severe symptom of risk determines the final score. Uncertainty is assessed with respect to some indicators in the NS and addressed through qualitative discussions of the final score (Kjørstad et al., 2017). However, it is not propagated upon the integration of the indicators and is therefore confounded, rather than explicitly represented, in the final score. The CS demonstrates a rigorous approach by assigning weights to its indicators and integrating them through decision rules, ensuring that uncertainty and precautionary principles are explicitly incorporated into the final assessment (see 2.1). Uncertainty related to

Table 1
Systematic comparison of the Canadian Critical Habitat Framework (Canadian Strategy, CS) for boreal caribou and the Norwegian Quality Standard (Norwegian Strategy, NS) for wild reindeer. The first block compares indicators used in the CS (column 2) and the NS (column 3) to quantify each criterion (column 1) of population assessment. The second block makes the same comparison for habitat assessment. The third block compares the integration of population and habitat indicators between the CS and the NS, based on the type of indicators integrated, the approach used for integration of the indicators into a final score, the propagation of uncertainty upon the integration, and the information provided by the final score. An X indicates that a criterion is not explicitly addressed with a dedicated indicator.

POPULATION	CANADIAN STRATEGY	NORWEGIAN STRATEGY
Vital rates	Uses estimates of λ or qualitative trend as retrospective indicators of vital rates. Availability of demographic data varies among the subpopulations.	Uses demographic, health, and genetic metrics as predictive indicators of vital rates. Demographic, health and genetic monitoring is standardized across all subpopulations.
Population size	Uses reported population size. Availability of demographic data varies among the subpopulations.	X
HABITAT	**CANADIAN STRATEGY**	**NORWEGIAN STRATEGY**
Suitability	Uses remote sensing to measure the aggregated extent of anthropogenic and wildfire disturbances as a percentage of range area, then translated into recruitment. The assessment covers the entire subpopulation's range.	Uses remote sensing to measure lichen biomass. Uses expert assessment of changes in reindeer habitat use over 50 years. The assessment is limited to focal areas within the subpopulation's range and is conducted on a seasonal basis.
Connectivity	X	Uses expert assessment of changes in reindeer movements over 50 years. The assessment is limited to focal areas within the subpopulation's range and is conducted on a seasonal basis.
FINAL SCORE	**CANADIAN STRATEGY**	**NORWEGIAN STRATEGY**
Indicators	Derives demographic probabilities from a PVA-BDN framework and discretizes them into likelihood statements using probability intervals.	Discretizes quantitative measures into quality scores using expert-based intervals of values for each indicator. Quality scores are also influenced by trends in some indicators.
Integration	Assigns weights and uses decision rules to integrate the indicators based on the quality of available demographic data, consistency among the indicators, potential biases, and the precautionary principle.	Assigns equal weight to all indicators and uses the lowest-scoring indicator to determine the final score.
Uncertainty	Propagates uncertainty when integrating the indicators. Uncertainty is explicitly represented in the final score.	Assesses uncertainty for some indicators through qualitative discussions of the final score but does not propagate it when integrating the indicators. Uncertainty is not explicitly represented in the final score.
Final score	The subpopulation status is assessed as its likelihood of self-sustainability.	The subpopulation status is assessed as its general quality.

variability in reported demographic data types and consistency among indicators is thus propagated and reflected in the final score, based on probability intervals (pp. 32–35 in EC, 2011). The final score reports on subpopulation status as the likelihood of self-sustainability, in the CS, whereas it is a summary measure of the subpopulation's general quality in the NS. This reflects different perspectives on population viability linked to different management objectives: the CS aims at preventing imminent risks of extirpation for boreal caribou subpopulations, while expert-based interval thresholds used in the NS seem to target not only viable, but also well-performing and productive subpopulations, able to support different ecosystem services including hunting (Kaltenbron et al., 2017; Kjørstad et al., 2017).

4. Discussion

4.1. Strengths, challenges and perspectives

Population declines are often influenced by multiple threats (Bonebrake et al., 2019), which conservation strategies aim to address comprehensively. However, in practice, conservation strategies are tailored to specific challenges and constraints of the focal system. As illustrated by the comparison of the Canadian and Norwegian case studies, conservation strategies are shaped first and foremost by context and prior knowledge, and no universal approach can be recommended for assessing population viability. Both strategies were built on in-depth understanding of the factors driving caribou and reindeer declines, resulting in a statistically grounded, predation-focused strategy in Canada, where this threat plays a major role, and in a broader, expert-based approach in Norway, including multiple threats. Note that, in Norway, CWD and loss of genetic variation were not considered significant threats to wild reindeer until very recently (Hansen et al., 2024; Mysterud et al., 2024) – highlighting that currently insignificant threats may become significant in the future. This is particularly true in the context of climate change (DeMars et al., 2023), which neither the CS nor the NS currently address. Therefore, conservation strategies must balance the efficiency of targeting current dominant threats with the flexibility to address emerging ones (Tilman et al., 2017).

Conservation strategies are often challenged by the scarcity of data available to assessing population viability (Fitzgerald et al., 2021). In Canada, since λ estimates were missing for about 40 % of the subpopulations, the CS largely relies on habitat assessment, for which data are available for and standardized across all ranges, to monitor boreal caribou status and track its changes over time (ECCC, 2017, 2020). This allowed building a targeted and strong analytical framework leading to a probabilistic assessment of population viability, explicitly reporting associated uncertainty. As a complement to population viability assessment, the CS also links vital rates to habitat condition to inform management decisions, and probabilistically establishes the 65 % threshold as the minimum amount of undisturbed habitat necessary to achieve self-sustaining caribou subpopulations (corresponding to a minimum probability of 60 %; EC, 2011; EC, 2012). The need to protect and restore critical habitat in caribou ranges with < 65 % undisturbed habitat was then highlighted as the primary management measure in the subsequent Recovery Strategy (EC, 2012). Yet, this management threshold still carries a considerable risk (around 40 %) of not achieving the self-sustainability goal, may significantly vary between subpopulations due to model uncertainty and is likely to increase with climate change (EC, 2011; EC, 2012). For instance, while it may provide a reasonable benchmark for supporting caribou viability in landscapes dominated by anthropogenic disturbance, the 65 % threshold is less suitable for addressing the dynamic and large-scale nature of wildfire disturbance (Johnson et al., 2020). Additional demographic monitoring will be key to better characterizing the effects of disturbances and assessing the relevance of the 65 % management threshold across boreal caribou subpopulations, and to guiding its adjustment under changing habitat condition (ECCC, 2020; Johnson et al., 2020).

On the contrary, in Norway, wild reindeer management is strongly rooted locally, and thus the NS was initiated as a participatory process guided by expert knowledge and integrating various types of data and information (Kjørstad et al., 2017). The NS illustrates the value of expert elicitation for assessing factors associated with population declines, and stresses the importance of involving local stakeholders in conservation strategies (Camino et al., 2020; Gundersen et al., 2022). At the same time, it illustrates some limitations of expert-based approaches. For instance, habitat loss and fragmentation were assessed, for feasibility, only within focal areas identified based on socio-ecological conflicts – introducing potential biases – and thresholds for habitat condition relied on expert judgements, which may be difficult to update or replicate in future iterations (Panzacchi et al., 2022a; Rolandsen et al., 2022). In parallel, the Norwegian authorities also supported analytical research and requested a performance comparison of analytical models vs. expert-based assessment (Panzacchi et al., 2022a,b; Van Moorter et al., 2023b,c), based on which it has been suggested to integrate more quantitative approaches in future iterations of the NS (Mysterud et al., 2025, Rolandsen et al., 2022, 2023). Current modeling approaches enable a quantitative, integrated assessment of habitat loss and fragmentation in wild reindeer (Van Moorter et al., 2022; 2023a) and provide spatially explicit, continuous, and high-resolution maps (see Lelotte, 2021; Panzacchi et al., 2022a,b; Van Moorter et al., 2023b). These models are also used to guide the identification of efficient mitigation measures through scenario analyses (Dorber et al., 2023; Niebuhr et al., 2023; Panzacchi et al., 2024).

Research in recent decades has stressed the importance of assessing habitat fragmentation, in conjunction with habitat loss (Chase et al., 2020; Correa Ayram et al., 2016; Fletcher et al., 2016; Seaborn et al., 2020; Van Moorter et al., 2021). Failure to do so risks significantly underestimating human impact on wildlife habitats and populations (e.g., Dorber et al., 2023; Iwamura et al., 2013; Kuipers et al., 2021). Although increasingly emphasized in conservation strategies (Keeley et al., 2021; Laur, 2021; Rudnick et al., 2012), functional connectivity often remains poorly addressed, despite its critical role in establishing effective movement corridors (Fletcher et al., 2016). The NS stands out for its attempt to address functional connectivity based on reindeer movement patterns – although not currently assessed through analytical approaches – as fragmentation is a major threat to wild reindeer in Norway. In Canada, fragmentation is considered a minor concern for boreal caribou at the subpopulation level compared to the amount of undisturbed habitat, and its relevance is limited to highly disturbed landscapes (EC, 2012). As such, little evidence supported the use of specific fragmentation metrics within the CS (EC, 2011), which therefore only indirectly captures structural barrier effects through its total disturbance indicator. Recent network-based developments, such as the "equivalent connected habitat" (ECH; Saura et al., 2011; Van Moorter et al., 2022) and "habitat functionality" metrics (Van Moorter, et al., 2023a), point towards the simultaneous assessment of habitat loss and fragmentation by focusing on accessible and suitable habitat (hereafter functionally connected habitat). It resulted in cutting-edge studies performing simulations to forecast the consequences of specific human activities on the loss of functionally connected habitat (e.g., Dorber et al., 2023; Panzacchi et al., 2024).

While these approaches offer the opportunity to translate the effect of barriers to movement (i.e., fragmentation) into lost access to suitable habitat – or units of habitat loss – ultimately inferring the impact of specific human activities on individual fitness and population performance remains challenging. In practice, population and habitat assessments originate from different scientific disciplines (see 1.1 and 1.2). Habitat is assessed in spatial units (e.g., km^2 of suitable habitat, km^2 ECH, likelihood of occupancy), while populations are commonly measured in demographic units (e.g., number of individuals, offsprings per female). The lack of formal link and shared measurement units makes it challenging to integrate habitat and population assessments. In the CS, estimates of total range disturbance (% range area, i.e., spatial units) are converted into estimates of recruitment (calves/100 adult females, i.e., demographic units) based on an empirical disturbance-recruitment relationship (see 2.1). This conversion thus translates a habitat indicator into demographic units, making it easier to integrate with population indicators and enabling to link habitat to conservation goals such as population viability. Although this correlative relationship masks a series of mechanisms linking habitat disturbance to changes in caribou vital rates, it synthesizes decades of research highlighting these mechanisms into a simple and intuitive framework for integrating habitat and population assessments. It also offers better ecological grounding as well as uncertainty propagation, which represent major strengths compared to "worst-case scenario" approaches used in the NS and the COSEWIC assessments, for instance, which prioritize the most severe symptoms of risk and may result in more conservative and threshold-sensitive evaluations. While similar relationships between cumulative disturbances and both recruitment and survival have been tested in boreal caribou (Fortin et al., 2017; Rudolph et al., 2017), functional, quantitative links between habitat and demography remain challenging to establish (Matthiopoulos et al., 2015).

Despite this central challenge, conservation strategies should remain flexible to address emerging threats, such as climate change, which is expected to amplify currently marginal threats. For instance, in Canada, the climate-driven northward expansion of apparent competitors (e.g., moose, white-tailed deer) will likely increase habitat loss, predation, and disease risk for boreal caribou (Arifin et al.,

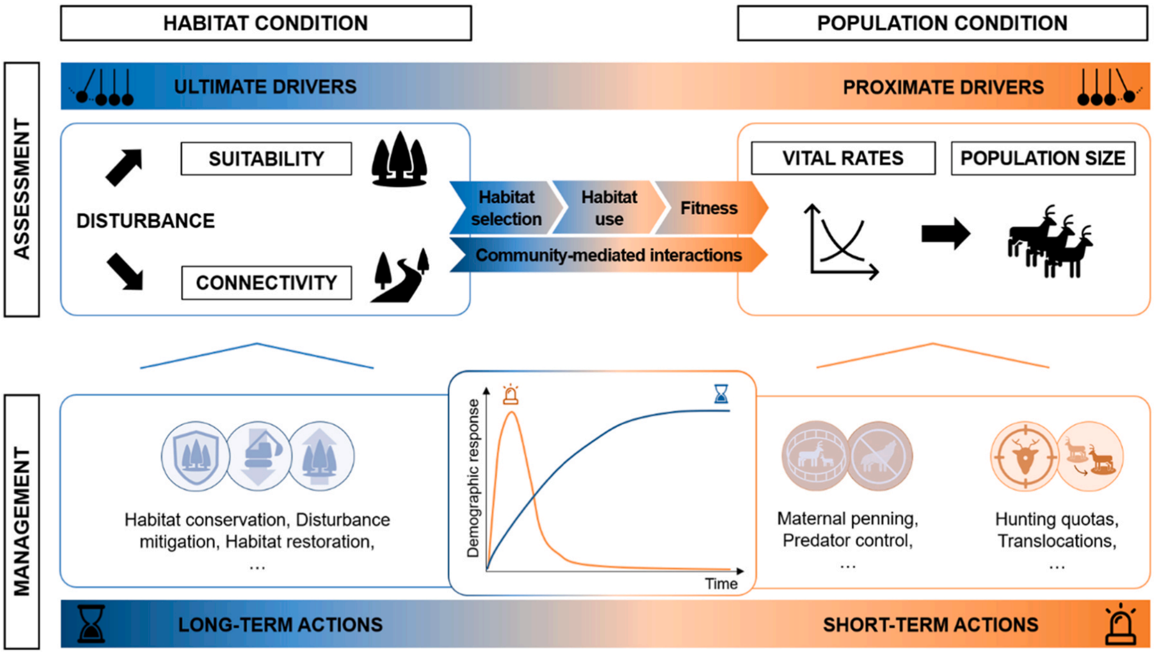

Fig. 2. Conceptual diagram illustrating the interplay between population and habitat conditions as proximate and ultimate drivers of population viability in the context of habitat-driven population declines. Habitat condition is characterized by the suitability and connectivity of biotic and abiotic conditions, and by disturbances constraining them. These determine habitat selection and use, in turn influencing individual fitness, vital rates, and ultimately, population size. Habitat condition can also influence demography through community-mediated interactions. Population condition depends on vital rates, which can be influenced by underlying habitat condition and, in turn, directly influence population size. The assessment of population condition reflects current demographic performance, and may lag behind changes in habitat condition. Thus, the assessment of habitat condition can help predicting future demographic trends. Management can target vital rates or population size via short-term actions, triggering rapid but transient demographic responses, or habitat condition via long-term actions, leading to delayed but more sustainable demographic responses (see examples in the figure).

2020; Barber et al., 2018; Dawe et al., 2014; Kennedy-Slaney et al., 2018; Pickles et al., 2013). In addition, food limitation may become more significant due to weather events and changing resource availability (DeMars et al., 2021; Schmelzer et al., 2020). Similar impacts are expected for wild reindeer, for instance due to increased frequency of icing caused by rain-on-snow events, which are anticipated to increasingly reduce access to resources during winter (Hansen et al., 2011; Mallory et al., 2018). As such, climate change challenges conservation strategies and may require shifts in management practices beyond traditional habitat conservation and restoration approaches (DeMars et al., 2023; Groves et al., 2012; Heller and Zavaleta, 2009).

4.2. *Ultimate and proximate drivers of population viability*

Habitat loss, degradation and fragmentation are among the main causes of species endangerment and biodiversity loss worldwide (Keck et al., 2025; Maxwell et al., 2016). In this context, habitat disturbance has an indirect but foundational influence on population performance, size and viability (Fig. 2). By modifying the availability and connectivity of suitable biotic and abiotic conditions, disturbance sources affect movement choices, habitat selection and use, with consequences on individual fitness, vital rates, and ultimately population size (e.g., DeCesare et al., 2014; Johnson et al., 2020; Matthiopoulos et al., 2015). Habitat disturbance can also influence populations through community-mediated interactions, such as apparent competition (Frenette et al., 2020) and trophic cascades (Geary et al., 2018). Vital rates, on the other hand, directly influence population size by driving population dynamics towards growth or decline, but are themselves influenced by underlying habitat condition. Hereafter, we refer to habitat suitability and connectivity as "ultimate drivers" of population viability, and to vital rates as "proximate drivers" (Fig. 2).

Population assessment is essential to measure population performance, viability, and progress against conservation and management goals. However, demographic data in isolation are often insufficient to monitor ultimate drivers and underlying mechanisms causing observed population trends, and may therefore have limited ability to predict future demographic trajectories and suggest actions upon them (Fitzgerald et al., 2021; Wolf et al., 2015). A main reason is that there may be significant time lags between changes in habitat condition and the detection of deteriorating population condition (Lira et al., 2019; Maxwell and Jennings, 2005; Tilman et al., 1994; Vors et al., 2007). Habitat assessment can offer a broader perspective on the limiting factors affecting population performance, support more accurate viability projections, provide early warnings of population decline, and guide effective management actions (Larson et al., 2004; Matthiopoulos et al., 2019). Moreover, it enables using tools such as remote sensing or habitat modeling to estimate or predict population condition in areas where demographic monitoring is unfeasible or highly unreliable (e.g., Rode et al., 2024), or under scenarios of land use or climate change (e.g., Dorber et al., 2023).

From a management perspective, spatially explicit information on habitat condition is crucial to inform and guide species conservation. Recent network-based developments in habitat modeling make it possible to use scenario analyses to identify the most significant mitigation, restoration and offset actions, as well as to identify the most sensitive areas, corridors and bottle-necks to be prioritized for protection or restoration (Dorber et al., 2023; Kivimäki et al., 2024; Van Moorter et al., 2023a). While management actions can be implemented both at the population and habitat level, their effect on population viability may differ significantly. The main differences lie in the timing and duration of measurable demographic responses (Fig. 2). Population-oriented actions target either vital rates (e.g., predator control, maternal penning) or population size (e.g., translocations, hunting quotas), and are typically effective in the short term. Their focus on proximate drivers triggers a rapid but transient demographic response, requiring recurrent interventions (Johnson et al., 2022; Lamb et al., 2024). By contrast, achieving self-sustaining and resilient populations in the long term requires addressing the ultimate drivers of population decline (Chambers et al., 2019; Johnson et al., 2022) – namely, for habitat-driven declines, it requires habitat-oriented actions (e.g., habitat conservation, restoration, disturbance mitigation) aimed at restoring or protecting functional landscape attributes and ecological processes that support population viability. However, habitat-oriented actions can have longer response times, be costly and trigger conflicts with competing socio-economic interests on the landscape (Gundersen et al., 2022; Hebblewhite, 2017), which should ideally be addressed through both participatory approaches and robust science-based evidence (Stern and Humphries, 2022). These actions alone may therefore not always be feasible or fail in addressing imminent risks of extirpation, and short-term, population-oriented actions may be needed as temporary "buy-time" measures until habitat recovery overcomes the consequences of its degradation (García-Antón and Traba, 2021; Schrott et al., 2005; Serrouya et al., 2019).

5. Conclusion

Population viability and species persistence are intrinsically linked to the availability of functionally connected habitat. While essential, demographic data alone are often insufficient to anticipate or rapidly detect habitat-driven population declines, as they may lag behind changes in habitat condition. These data may also fail in identifying sustainable management actions targeting ultimate causes of population decline – i.e., habitat condition. On the other hand, focusing solely on habitat condition may overlook key mechanisms that influence demographic processes. Thus, integrating population and habitat assessments is crucial for developing more comprehensive and actionable conservation strategies and supporting informed decision-making, particularly given the significant threat that habitat loss and fragmentation pose to biodiversity worldwide.

Rigorous research aimed at understanding the mechanisms driving population decline is fundamental for targeting relevant, context-specific criteria for population and habitat assessments. Their integration can then be operationalized in various ways, from functional, quantitative relationships that establish conversion rates between habitat and population metrics, as seen in the CS, to simpler, expert-based combinations of indices, as seen in the NS. Despite long-standing efforts and promising recent developments to integrate habitat and population studies, there is still a need to formally quantify the contribution of each anthropogenic activity to the loss of functionally connected habitat and, in turn, to individual fitness and population performance. This would enable more precise, early-warning systems for assessing population declines, and help shape more targeted prevention, mitigation and restoration actions. Ultimately, understanding how anthropogenic disturbances – both individually and cumulatively – affect population viability and species persistence is crucial for reversing the biodiversity crisis and guiding conservation strategies.

Ethics

Not applicable: This manuscript does not include human or animal research.

CRediT authorship contribution statement

Lelotte Lucie: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Panzacchi Manuela:** Writing – review & editing. **Johnson Cheryl A:** Writing – review & editing. **Mysterud Atle:** Writing – review & editing. **Hansen Brage B:** Writing – review & editing. **Niebuhr Bernardo Brandão:** Writing – review & editing. **Boyce Mark S:** Writing – review & editing. **Stien Audun:** Writing – review & editing. **Merrill Evelyn H:** Writing – review & editing. **Rolandsen Christer M:** Writing – review & editing. **Tveraa Torkild:** Writing – review & editing. **Gundersen Vegard:** Writing – review & editing. **Van Moorter Bram:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

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

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APPENDIX A. Assessment procedure for human impact on wild reindeer habitat as part of the Norwegian Environmental Quality Standard for Wild Reindeer (adapted from Panzacchi et al., 2022a)

Appendix A provides a detailed description of the assessment procedure for human impact on wild reindeer habitat used in the Environmental Quality Standard for Wild Reindeer (Kvalitetsnorm for villrein, 2020; hereafter the Norwegian Strategy, NS). The NS assesses the general quality of wild reindeer subpopulations in Norway based on population condition, grazing resources and human impact on habitat. Population condition and grazing resources are directly assessed from quantitative monitoring of relevant parameters measured within each subpopulation (Fig. A.1). Human impact on habitat, meanwhile, is assessed according to a more complex, expert-based procedure developed by Kjørstad et al. (2017). Hereafter, we refer to the latter assessment part as NSS3 and describe the related assessment procedure in more detail.

NSS3 aims at identifying areas where anthropogenic disturbance on reindeer habitat exceeds the acceptable level and where mitigation measures are to be considered. Human impact on reindeer habitat is assessed in two parts, namely: changes in reindeer habitat use (i.e., habitat loss; NSS3A) and changes in connectivity (i.e., fragmentation; NSS3B). NSS3A targets reindeer seasonal habitats – i.e., areas associated with the main ecological seasons in wild reindeer, namely the summer pastures, winter pastures and calving areas. NSS3B targets major migration routes for these three seasons. Both parts are operationalized using similar procedures, as described below.

Data

NSS3 is based on expert assessment of different types of data and information sources. Since direct correlations between the presence of infrastructure or human activities and disturbance effects on wild reindeer are challenging to establish, NSS3 uses reindeer presence as a proxy to calculate human impact on habitat.

A major effort has been made over many years in several areas to collect both reindeer positions (GPS tagging) and local knowledge (interviews, workshops) about reindeer habitat use, through interviews with local nature managers, hunters, and other mountain people. In addition, NSS3 uses reindeer observations from monitoring diaries and database of observations ("sett-rein"), and cultural history data (i.e., information related to ancient trapping facilities – e.g., bow positions, animal burials, mass trapping sites), where such data are available (see Kjørstad et al., 2017).

The assessment procedure for NSS3 focuses on observed and assumed reduction in wild reindeer presence in an area as a proxy of human-induced reduction in habitat condition, and does not rely on any measurement of habitat characteristics. While NSS3 is not assessed directly from data on infrastructure development or human activities, such knowledge is part of the expert-based assessment.

Methods

The above information was assessed and synthesized by local experts for each subpopulation's range (hereafter wild reindeer area) to form the input basis for the assessment of NSS3A and NSS3B. As a crucial step, seasonal habitats, migration routes, and focal areas were mapped within each wild reindeer area (Fig. A.2). Summer, winter and calving habitats, and migration routes connecting them through seasonal movement, were first mapped for each subpopulation. Then, focal areas were identified within both seasonal habitats (focal areas NSS3A) and migration routes (focal areas NSS3B), and delineated as polygons based on conservation challenges and societal conflicts. A focal area is thus defined as a part of a wild reindeer area where challenges for wild reindeer conservation arise from conflicts with human activities.

Focal areas make the basis for the assessment of NSS3A and NSS3B. It is important to note that the rest of the wild reindeer area (i.e., outside the focal areas) is assumed to be of good enough quality, and still functional for wild reindeer, so that changes are assessed only within the focal areas. Technically, NSS3 assumes that the level of disturbance outside the focal areas is so low that one cannot detect any significant changes in reindeer presence (i.e., < 50 % reduction in habitat use). The delineation of focal areas is based on a holistic assessment of landscape features/topography, the area's original function for wild reindeer and the disturbance sources.

Assessment procedure for NSS3A: changes in habitat use

i. Focus is directed on focal areas NSS3A (i.e., within seasonal habitats).

ii. Within each focal area, it is assessed how much current reindeer habitat use (over the last 10 years) has decreased compared to the past 50 years. Use reduction by reindeer is characterized either as severe (> 90 %), medium (50 – 90 %), or small (< 50 %).

iii. The total extent (in km^2) of focal areas where reindeer habitat use has severely (> 90 %) decreased, presumably due to avoidance of anthropogenic disturbance over the past 50 years, is calculated and it is then assessed whether this sum represents a small (< 10 %), medium (10 – 20 %) or large (> 20 %) proportion of the entire area of summer pastures, winter pastures and calving areas within the wild reindeer area.

iv. The same procedure is repeated for the total extent (in km^2) of focal areas impacted by medium (50 – 90 %) use reduction.

v. The assessments of severe and medium changes in reindeer habitat use are combined, and the lowest score of the two determines the NSS3A score – either Good, Medium or Bad – for each wild reindeer area (Fig. A.3).

Note that the procedure is conducted independently for each seasonal habitat type. NSS3A is thus assessed three times, with the lowest seasonal score determining the overall NSS3A score for the wild reindeer area (Fig. A.3). For example, if the seasonal scores for summer pastures, winter pastures and calving areas are respectively Good, Medium and Bad, the lowest score of the calving areas will determine the overall NSS3A score as Bad. The overall NSS3A score describes the availability of seasonal habitats for wild reindeer throughout the year – depending on the degree and the extent of avoidance of anthropogenic disturbance.

Assessment procedure for NSS3B: changes in connectivity

i. Focus is directed on focal areas NSS3B (i.e., within major migration routes).

ii. Within each focal area, it is assessed how much current reindeer use of migration routes (over the last 10 years) has decreased compared to the past 50 years. (2a) First, it is assessed whether there has been a severe (> 90 %), medium (50 – 90 %), or small (< 50 %) decrease in reindeer crossing frequency or increase in reindeer crossing speed on these migration routes, compared to what happened in historical migrations. (2b) The total area (in km^2) reindeer lost access to, due to reduced migration opportunities over the past 50 years, is calculated. This area is considered the zone of influence.

iii. The total extent (in km^2) of focal areas where reindeer use of migration routes has severely (> 90 %) decreased, presumably due to anthropogenic barriers, is calculated and summed with the total size (in km^2) of the zone of influence. It is then assessed whether this sum represents a small (< 10 %), medium (10 – 20 %) or large (> 20 %) proportion of the entire extent of the migration routes within the wild reindeer area.

iv. The same procedure is repeated for the total extent (in km^2) of focal areas impacted by medium (50 – 90 %) reduction in migration opportunities.

v. The assessments of severe and medium changes in migration opportunities are combined, and the lowest score of the two determines the NSS3B score – either Good, Medium or Bad – for each wild reindeer area (Fig. A.3).

Note that the procedure is conducted independently for each seasonal habitat type – i.e., for migration routes to summer, winter and calving habitats. NSS3B is thus assessed three times, with the lowest seasonal score determining the overall NSS3B score for the wild reindeer area (Fig. A.3). The NSS3B score describes the accessibility of seasonal habitats for wild reindeer throughout the year – depending on the degree and the extent of changes in migration opportunities due to anthropogenic barriers.

Overall assessment: the NSS3 score

The lowest score between NSS3A and NSS3B determines the NSS3 score for the entire wild reindeer area, which describes wild reindeer overall habitat condition under human impact – either as Good, Medium or Bad (Fig. A.3).

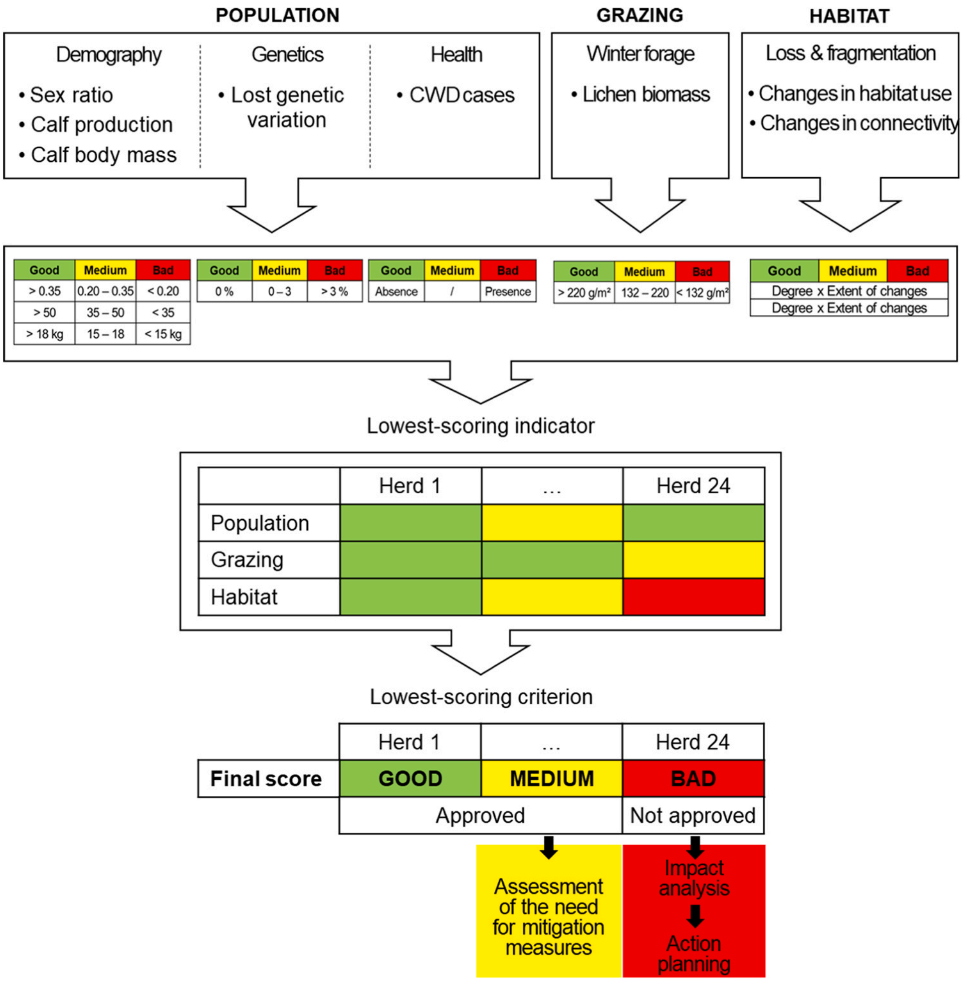

Fig. A.1. Graphical depiction of the workflow for the Norwegian Quality Standard for wild reindeer (adapted from Kjørstad et al., 2017).

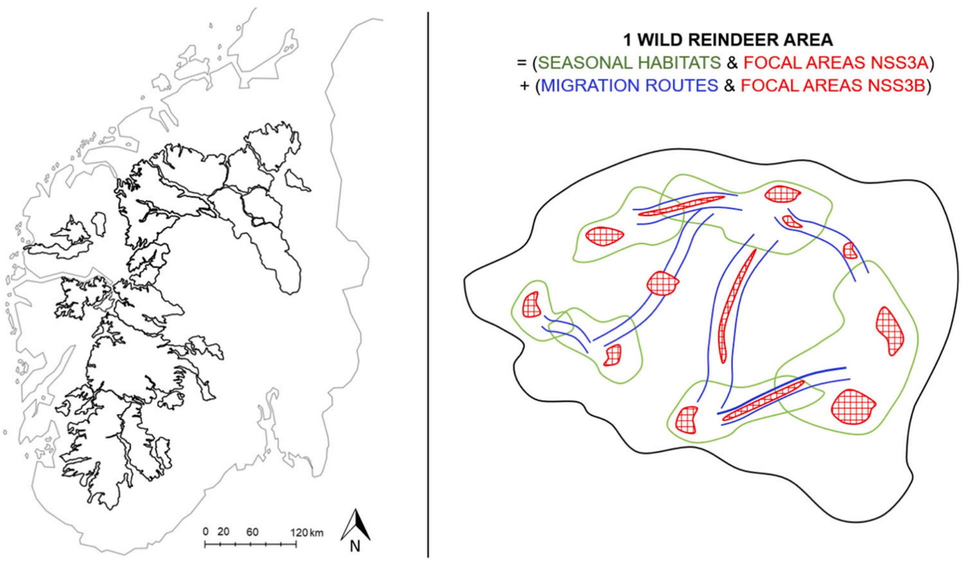

Fig. A.2. Spatial hierarchy between seasonal habitats, migration routes and focal areas within a subpopulation's range or wild reindeer area. The left part of the figure shows the location of the 24 wild reindeer areas in southern Norway. The right part of the figure focuses on a fictive wild reindeer area (black) to illustrate the spatial hierarchy between seasonal habitats (green), migration routes (blue) and focal areas (red). Focal areas are delineated within the seasonal habitats (focal areas NSS3A) and the migration routes (focal areas NSS3B) inside each wild reindeer area.

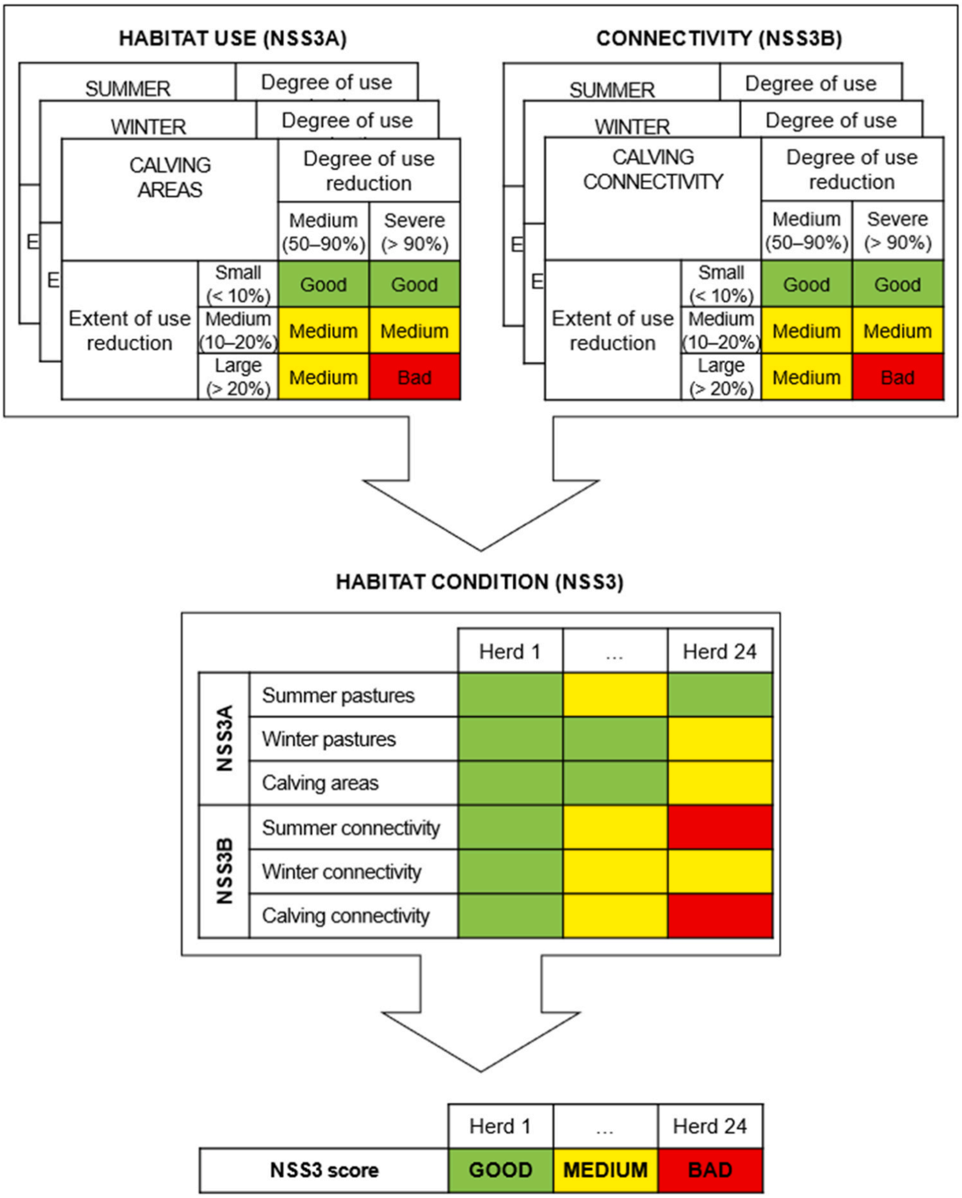

Fig. A.3. Graphical depiction of the workflow for the assessment of wild reindeer habitat condition and human impact (NSS3), as part of the Norwegian Quality Standard for wild reindeer (Norwegian Strategy, NS). NSS3 assessment is based on the degree and the extent of changes in wild reindeer habitat use (NSS3A) and connectivity (NSS3B). NSS3A assessment focuses on reindeer seasonal habitats – i.e., summer pastures, winter pastures and calving areas. NSS3B assessment focuses on major migration routes for these three seasons. (adapted from Kjørstad et al., 2017).

Data availability

No data was used for the research described in the article.

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