Understanding the socio-ecological system (SES) of Arctic Reindeer husbandry

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Abstract: Arctic reindeer husbandry is a socio-ecological system (SES) of vital regional significance that is naturally connected to the cultural heritage, spiritual identity, and food security of Indigenous peoples throughout the Circumpolar North. This review integrates the multifaceted challenges and adaptive strategies of this complex adaptive system (CAS), which is increasingly exposed to accelerating environmental and socio-economic changes. Climate change, such as enhanced rain-on-snow events, ground-icing, shrubification, and phenological changes, has immediate impacts on pasture quality and accessibility, compromising reindeer health and herd sustainability. These ecological stresses are compounded by anthropogenically driven stressors, such as widespread land-use fragmentation by industrial mining, forestry, and infrastructure expansion, which break up migratory routes and reduce grazing areas. This socio-ecological system (SES) resilience is inherently linked to active Indigenous and Local Knowledge (ILK) systems that inform adaptive husbandry tactics, seasonal mobility, and collective choice-making. However, governance frameworks frequently produce policy mismatches, and economic stress and youth out-migration jeopardize intergenerational knowledge transfer. This analysis emphasizes that Arctic reindeer husbandry, in the long term, depends on adaptive co-management systems that guarantee Indigenous land rights, incorporate ILK and scientific research formally through knowledge co-production, and apply cumulative impact assessments. Ensuring a 'safe operating space' for herders by prioritizing inclusive, multi-level governance is essential for developing strong and sustainable pastoral communities in the rapidly changing Arctic.

Keywords: socio-ecological system; Arctic; reindeer husbandry; Indigenous and Local Knowledge; climate change adaptation;

1. Introduction

Arctic reindeer herding is a socio-ecological system (SES) of global importance that is highly enmeshed with Indigenous cultural heritage, spiritual identity, and nutritional requirements in the vast Circumpolar North region (Eira et al., 2008; Horstkotte et al., 2022; Oskal et al., 2023; Tonkopeeva et al., 2022). Covering extensive areas in Northern Europe (Fennoscandia), Russia, and North America, this ancient practice employs approximately 100,000 herders and approximately 2.5 million semi-domesticated reindeer, including Sámi reindeer husbandry, which represents about one-third of the world total (Eira et al., 2008). Reindeer pastoralism is typified by its complex dependence on Indigenous knowledge systems built over generations, which control husbandry methods, seasonal migration routes, and adaptive practices for managing extreme environmental variability (Eira et al., 2008; Johnsen et al., 2022; Oskal et al., 2023). This enables the sustainable use and management of northern terrestrial ecosystems, testifying to the long-standing relationship between human societies and the Arctic environment (Eira et al., 2008; Pásková, 2018). It is the base of Indigenous cultures, with particular worldviews, language, and rituals that account for world cultural diversity (Delfino, 2024; Johnson and Mbah, 2024; Oskal et al., 2023).

The Arctic, which is warming at over twice the rate of the global average, is subject to unprecedented rates of environmental change, which pose major risks to the stability and functionality of such reindeer husbandry SES (Fohringer et al., 2021; Horstkotte et al., 2022; Lopez et al., 2018; Pape and Löffler, 2012; Tonkopeeva et al., 2022). Climate change is exemplified by irregular weather conditions, changes in tundra vegetation patterns, and an amplified number of freeze-thaw occurrences (Fohringer et al., 2021; Laptander et al., 2023; Ocobock et al., 2022; Pape and Löffler, 2012). These climatic changes have direct effects on reindeer pastures, rendering necessary forage resources such as lichen less available due to increased snow depth, ice cover, or changed vegetation structure, hence threatening traditional grazing grounds (Harnesk, 2022; Laptander et al., 2023; Ocobock et al., 2022). For example, warmer winters and increased icing events have direct effects on reindeer herder occupational safety, health, and well-being in areas such as northern Finland (Ocobock et al., 2022). Hydrological cycle shifts and substantial declines in ice-bearing permafrost and glaciers have resulted in enhanced open water, which may block conventional migration corridors and hinder access to pastures, as experienced by Nenets reindeer pastoralists in the Russian north (Amstislavski et al., 2013). In addition to climate effects, land-use conflicts between extractive

activities, such as massive mining and other industrial activities, enhance pressure by splitting up landscapes and diminishing available pasturelands, making resilience a challenge in these systems (Fohringer et al., 2021; Pape and Löffler, 2012).

Reindeer herding is an example of a complex adaptive system (CAS) (Levin, 1998), where ecological and social elements engage dynamically and are therefore very sensitive to rapid change (Tyler et al., 2007; Talukder et al., 2023). The vulnerability of SES stretches far beyond ecological disturbances to cover socio-economic and cultural effects on Indigenous peoples (Brännlund and Axelsson, 2011; Loginov et al., 2020; Tonkopeeva et al., 2022). The capacity of Indigenous societies to adjust is determined by the interplay of socioeconomic forces, institutional structures, and historical contexts (Brännlund and Axelsson, 2011; Chimi et al., 2023). For instance, changes in reindeer husbandry in the Nenets Autonomous Okrug demonstrate how globalization, urbanization, and market reforms require changes in Arctic economic systems to affect traditional ways of life and social structures (Romanenko & Bogdanova, 2023). These persistent issues emphasize the imperative to learn about the complex responses and feedback processes within such systems in response to changes in the environment (Wei et al., 2021).

Given the multifaceted challenges and critical significance of reindeer husbandry to the Indigenous peoples of the Arctic, a review is crucial for informing effective policy and management measures (Favretto and Stringer, 2024; Tonkopeeva et al., 2022). This review seeks to lay the groundwork for comprehending the interactions between reindeer husbandry, land use, and climate change, highlighting the unification of scientific and Indigenous knowledge to support resilient and sustainable Arctic communities (Johnsen et al., 2022; Johnson and Mbah, 2024; Maynard et al., 2004; Madonsela et al., 2024; Pingault et al., 2020; Peterson St-Laurent et al., 2018). This integration is required to implement policies that enhance national sovereignty, welcome transboundary initiatives, harmonize science and indigenous knowledge, and promote locally imagined adaptations, hence providing effective and long-lasting solutions for the future of reindeer husbandry in the Arctic (Filho et al., 2024).

2. Theoretical Framework: Socio-ecological System (SES) thinking

The theoretical framework for the analysis of Arctic reindeer husbandry as an SES brings together the core concepts of resilience, adaptive capacity, transformation, and

vulnerability with an appreciation of its dynamic and complex nature and the interaction between ecological and social elements (Horstkotte et al., 2022). It transcends linear cause-effect relationships to complex thinking, understanding non-linear dynamics, feedback, and cross-scale interactions that are inherent in these systems (Tyler et al., 2007). Reindeer herding, cultivated among numerous Indigenous communities in the circumpolar North, such as Sámi and Nenets, is a paradigmatic SES in which human livelihood and health depend integrally on the integrity and stability of the Arctic ecosystem (Eira et al., 2008; Horstkotte et al., 2022).

The resilience of reindeer pastoralism is the ability of SES to absorb shocks and reorganize while changing to maintain largely the same function, structure, identity, and feedback (Tyler et al., 2007). For Arctic reindeer husbandry, this means handling environmental fluctuations, such as climatic extreme events, heavy snow cover, or icing conditions that reduce access to forage and fast changes in vegetation caused by climate change (Laptander et al., 2023). For example, conventional Sámi reindeer husbandry has evolved coping mechanisms based on a profound understanding of landscape processes and nature, allowing it to respond to variability and extreme weather (Johnsen et al., 2022). However, modern problems, such as industrialization, especially large mining, impose new types of pressures that can overwhelm the system beyond its conventional adaptive capacities, impact animal numbers, and call for novel adaptation forms (Fohringer et al., 2021). The irregular spatial shrubification of the Arctic, which is controlled by herbivory, makes ecological resilience more difficult and requires smart management approaches in the SES (Verma et al., 2020).

Adaptive capacity at this SES involves the capacity of both ecological and social elements to respond to actual or anticipated climate and its impacts or adapt to cope with the aftermath (Tyler et al., 2007). Critical factors that facilitate adaptive action are the dynamic characteristics of Indigenous knowledge systems, which are perpetually modified through generations of experience and observation (Eira et al., 2008; Oskal et al., 2023). This customary knowledge, including complex food preservation methods and seasonal pasture utilization, forms the core of sustainable food systems and biodiversity management (Oskal et al., 2023). Factors inhibiting adaptive capacity frequently stem from external forces, including land fragmentation by extractive industries, shifts in market reforms, and policies that do not favor traditional methods (Fohringer et al., 2021; Romanenko and Bogdanova, 2023). For example, changes in the economic model of reindeer husbandry in the Nenets Autonomous Okrug

because of globalization and urbanization require changes that challenge existing social and cultural frameworks (Romanenko and Bogdanova, 2023).

Vulnerability frameworks, in the context of reindeer pastoralism, combine the aspects of exposure, sensitivity, and adaptive capacity to understand risk from a comprehensive perspective (Tyler et al., 2007). Exposure is the character and extent to which a system is exposed to major climatic fluctuations, such as enhanced thaw-freeze incidence or shifts in precipitation patterns (Laptander et al., 2023; Tyler et al., 2007). Sensitivity concerns the extent to which a system is impacted, either negatively or positively, by climatic stimuli. Reindeer are highly sensitive to snow conditions, ice cover on pastures, and vegetation changes, which have a direct impact on foraging success and herd health (Laptander et al., 2023). The combination of these factors determines general vulnerability, underscoring that vulnerability is not only an ecological process but is significantly embedded in socio-economic and cultural elements (Tyler et al., 2007). Indigenous reindeer herders' 'safe operating space' is a major priority, underlining that governance in the Arctic must enable their adaptive capacity in the face of accelerating environmental change (Tonkopeeva et al., 2022).

Indigenous knowledge systems are cumulative, dynamic systems of knowledge, practices, and beliefs that adapt through learning processes and are transmitted from generation to generation through cultural transmission (Eira et al., 2008; Oskal et al., 2023). Traditional knowledge is supplementary to scientific knowledge, providing novel perspectives on long-term ecological dynamics and the design of suitable management actions (Eira et al., 2008; Johnsen et al., 2022). For instance, Fennoscandian and northern Russian herders recognize eight separate seasons, each critical to the annual cycle of reindeer husbandry, indicating a sophisticated understanding of their ecosystem (Laptander et al., 2023). Combining this indigenous ecological knowledge with contemporary scientific, ecological, economic, sociological, and management paradigms is crucial for managing the challenges that confront Sámi reindeer husbandry (Eira et al., 2008). This transdisciplinary integration of natural and social science perspectives is critical for inclusive SES analysis to ensure that policy and management measures are contextually tailored and do not inadvertently compromise the resilience or adaptive capacity of Arctic systems (Johnsen et al., 2022).

3. Ecological Dimensions

Reindeer herder systems in the Arctic are inherently embedded in dynamic ecological processes, and reindeer-environment interactions are key to maintaining pastoral livelihoods and ecosystem function. These interactions are multifaceted, involving the effects of grazing on various plant types, reactions to climate change, and general biodiversity relationships that together define the Arctic environment (Horstkotte et al., 2022). The ecological aspects of reindeer husbandry are not the same throughout the Arctic because of differences in climate, geography, and husbandry (Laptander et al., 2023).

Reindeer-vegetation interactions are central to these SES, with reindeer grazing serving as a major ecological agent. Reindeer foraging behavior has seasonally varying patterns, responding to either the relative scarcity of certain types of forage or the relative abundance of other types, depending on the season (Harnesk, 2022). Overgrazing, especially during critical phases, results in overgrazed pastures of lichens, which are slow-growing and essential to winter grazing (Harnesk, 2022; Pape and Löffler, 2012). Controlled grazing may also affect vegetation structure and composition, which can, in turn, reduce shrubification in some localities (Verma et al., 2020). This feedback process emphasizes the non-linear nature of the herbivory-vegetation dynamics relationship. For example, in Sweden, extensive human activities, particularly forestry, have aggravated ecological conditions for natural grazing-ground responses to shifts in snow conditions, straining Sámi reindeer pastoralism during critically important snow cover periods (Harnesk, 2022).

Climate change has multilateral effects (Table 1) on the quality of pastures, snow conditions, and the occurrence of extreme events, which in turn directly influences reindeer husbandry (Pape and Löffler, 2012; Tyler et al., 2007). The warming of the Arctic, which is proceeding at a faster rate, results in significant transformations in precipitation patterns, such as enhanced rain-on-snow episodes and the advance of snowmelt (Tyler et al., 2007). These occurrences form ice sheets inside the snowpack or on the surface, hindering reindeer access to buried feed, which significantly affects their nutrient availability and survival (Laptander et al., 2023; Tyler et al., 2007). Vegetation zone changes, especially the northward spread of shrubs, have been found to modify forage quantity and quality (Tyler et al., 2007; Verma et al., 2020). Although local reindeer grazing prevents shrubification by browsing on young shrubs, the overall Arctic greening pattern fueled by rising temperatures poses an important challenge to traditional reindeer pastures (Verma et al., 2020). These impacts are not isolated; they

interact with prevailing land-use pressures to provide multiple challenges for reindeer populations (Pape and Löffler, 2012).

Table 1: Impacts of climate change on the ecological components of Reindeer Husbandry

Driver	Direct Ecological Effects	Cascading Impacts	Evidence
Warmer Temperatures and Arctic Amplification	• Increased shrub growth/ encroachment (shrubification): Promotes transition of open tundra to willow scrubland and forest (Bernes et al. 2015). • Altered tundra vegetation composition: Can lead to 'greening' but also to shifts in dominant growth forms; effects on vascular plant species richness can vary with temperature (Loffler and Pape, 2008; Pajunen et al. 2008; Bernes et al. 2015). • Increased parasite and insect activity: Harasses reindeer, affecting grazing behavior and energy expenditure (Pape & Löffler, 2012). • Earlier spring snowmelt: Alters the timing of nutrient pulses for plants (Bernes et al. 2015).	• Reduced albedo effect: Shrubs trap heat, accelerating snowmelt and further warming the local environment. • Suppression of native species: Shrubs outcompete low-growing lichens, mosses, and berry bushes, reducing forage diversity. • Changes in migratory timing and routes: Reindeer may follow the retreating snowline to access fresh plant growth (Bernes et al. 2015). • Increased heat stress for reindeer (Pape & Löffler, 2012).	• Compensatory Grazing: On the Yamal Peninsula, a 75% increase in reindeer population helped maintain stable vegetation despite warming, suggesting grazing can mitigate shrubification. • Economic Pressure: Warmer winters can increase reindeer populations, leading to overgrazing of lichen pastures and creating a long-term bottleneck for herding (Pekkarinen et al. 2023).

Changing Snow Properties (Rain-on-Snow events, deeper snow)	• Formation of ground-ice layers (basal ice): Creates impenetrable barriers that block access to forage (Pekkarinen et al. 2023). • Increased snowpack density: Makes 'cratering' (digging for food) more energetically costly (Vistnes and Nellemann, 2007; Skarin et al. 2008; Pekkarinen et al. 2023). • Delayed snowmelt in spring: Can cause a phenological mismatch if plant growth is delayed (Pekkarinen et al. 2023).	• Restricted access to winter forage: Leads to starvation and famine events (Pekkarinen et al. 2023). • Increased energy expenditure for cratering: Worsens reindeer's energy balance in winter (Pekkarinen et al. 2023). • Higher mortality rates and lower calf production: Poor winter conditions directly decrease spring body weight, calf size, and adult survivability (Pekkarinen et al. 2023). • Shift to supplementary feeding: Herders provide hay/pellets, which is economically costly and alters traditional practices (Pekkarinen et al. 2023).	• Winter as a Bottleneck: Winter pastures are often the limiting factor for herd sizes due to their limited spatial extent and low productivity (Pape & Löffler, 2012). • Economic Impact: Difficult winters decrease net revenues, though they can temporarily protect lichens from grazing. Overall, variability in winter conditions decreases herders' income compared to stable climates (Tveraa et al. 2007; Lundqvist et al. 2009; Pekkarinen et al. 2023).
Phenological Mismatches	• Earlier onset of plant growth in spring: Driven by warmer temperatures (Bernes et al. 2015). • Mismatch between peak plant nutrition and calving: The highest	• Reduced body condition of reindeer: Inability to gain sufficient weight in summer affects survival through the winter (Bernes et al. 2015).	• Summer Importance: The quality of summer ranges is critical for reindeer to gain enough weight to

	nutritional value of plants may pass before newborn calves can optimally utilize it (Bernes et al. 2015).	• Lower reproductive success: Poor maternal condition leads to lower calf weights and survivability (Bernes et al. 2015).	survive the winter (Bernes et al. 2015). • Complex Interactions: The mismatch is often interconnected with other drivers, such as winter conditions that weaken animals before spring (Pekkarinen et al. 2023).
Permafrost Thaw and Hydrological Changes	• Increased thermokarst formation: Ground collapses as permafrost ice melts (Istomin & Habeck, 2016). • Altered soil moisture and drainage patterns: Soils can become waterlogged as ice-rich ground thaws. • Lake drainage: Sudden changes in hydrological systems (Pape & Löffler, 2012).	• Destruction and fragmentation of pastures: Erosion and ground instability damage lichen pastures. • Increased danger for herders and animals: Makes navigation difficult and risky for both herders on snowmobiles and the reindeer themselves (Istomin & Habeck, 2016). • Carbon release: Thawing permafrost stimulates microorganisms to convert soil organic matter into CO_2 and methane, positive	• Potential Mitigation by Reindeer: Intensive grazing may help cool soils by removing heat-trapping shrubs and promoting snow cover with high albedo, thereby stabilizing permafrost. • Direct Impact on Herding: Nenets and Komi herders must account for the probability of thermokarst when choosing campsites and migration

		feedback to climate change.	routes (Istomin & Habeck, 2016).

The dynamics of Arctic ecosystem shrubification have a dual role for reindeer. As climate warming is a major cause of shrub expansion, reindeer herbivory can play a regulatory role in the development of shrubs in certain regions (Verma et al., 2020). Satellite data analysis has revealed that the effect of herbivory on shrub growth is spatially variable and that reindeer management techniques may be utilized to drive vegetation change (Verma et al., 2020). However, the general trend of shrub increase also implies diminished availability of the reindeer's favored food, with a subsequent change in diet for the animals and possible implications for herd health and migration routes.

Outside vegetation, reindeer grazing affects biodiversity and landscape processes. Grazing can be used to keep habitats open, favoring species adapted to grazed systems. Severe grazing pressure can have detrimental effects on fragile plant communities and soil formation (Pape & Löffler, 2012). Reindeer migration patterns, commonly driven by seasonal rounds over large territories, play a role in cycling nutrients through biomass and fecal matter redistribution, thus affecting soil fertility and primary productivity. This migration is an essential part of Arctic ecosystem functioning, and disruption of migration corridors can have ripple effects (Fohringer et al., 2021).

Feedback processes in the climate within the reindeer husbandry SES are also important. Vegetation cover changes resulting from grazing and climate change can influence surface albedo, and thus solar radiation absorption and local temperatures (Verma et al., 2020). For instance, a reduction in lichen cover and an increase in shrub cover can result in a darker surface that absorbs more heat and may even boost warming in a feedback loop. Permafrost stability and carbon cycling shifts under warming temperature regimes have implications for vegetation development and soil microbial processes, ultimately influencing the amount and quality of reindeer forage (Tyler et al., 2007). The intricacy of such interactions speaks to an integrated understanding that is not oversimplified and is attentive to the interrelated nature of ecological functioning across scales (Horstkotte et al., 2022).

4. Socio-cultural Dimensions

The sociocultural aspects of Arctic reindeer herding are inextricably connected to the resilience and sustainability of these distinctive SES, comprising extensive traditional knowledge, cultural practices, and intergenerational transmission, which are crucial for coping with environmental and social change. Traditional knowledge systems constitute the foundation of reindeer herding, including detailed observations and subtle comprehension of reindeer ecology, pasture regimes, and weather trends that can extend over centuries of experiential knowledge (Oskal et al., 2023). For instance, Fennoscandian and northwestern Russian herders demarcate their annual cycle into eight seasons, each of which is required for husbandry tasks, indicating the developed local ecological knowledge that informs their movements and management choices (Laptander et al., 2023). Traditional ecological knowledge is dynamic and not fixed; it is an evolving and adaptive set of practices and beliefs transmitted over generations (Maynard et al., 2004; Oskal et al., 2023).

Reindeer herding is a cornerstone of the identity of many Indigenous peoples, such as Sámi and Nenets, and serves as a strong determinant of language, social organization, and worldview (Horstkotte et al., 2022). This activity strengthens cultural values, indigenous languages, and special spiritual relationships with animals and the land (Horstkotte et al., 2022). The culture, traditional language, and knowledge of reindeer herders form the core basis for constructing sustainable food systems, conserving biodiversity, and a specialized way of living (Oskal et al., 2023). This profound cultural embeddedness makes reindeer husbandry more than an economic undertaking; it is a complete lifestyle that embodies community identity and cohesion (Romanenko and Bogdanova, 2023).

Gender in reindeer pastoralism is complicated and dynamic, with women traditionally having significant, albeit often underappreciated, roles within the overall pastoral system. Although husbandry activities have been gendered in the past, women play an important role in food preservation, processing reindeer products, household economy management, and maintaining social networks in which husbandry communities exist (Oskal et al., 2023). Over the last few decades, these have undergone changes with modernization, market incorporation, and evolving educational opportunities, which have brought challenges and emerging opportunities for the involvement and leadership of women within the industry (Romanenko and Bogdanova, 2023). It is by considering these gender-specific differences in experience and knowledge that understanding of reindeer husbandry is achieved and understanding of how they construct adaptive responses to change.

Knowledge transmission across generations is important for the continuity of reindeer husbandry, yet it is strongly challenged (Table 2). Informal learning processes, such as direct apprenticeship and oral transmission in the family and community, are increasingly affected by formal education systems and urbanization (Oskal et al., 2023). The temptation of urban living, the challenging nature of husbandry, and the effects of climate change may contribute to youth disengagement, undermining the passing on of precious traditional skills and knowledge (Horstkotte et al., 2022). Thus, guaranteeing the rejuvenation of reindeer husbandry requires measures that facilitate youth engagement, integrate traditional education with modern learning, and respond to the socioeconomic determinants of participation.

Table 2: Frameworks of Indigenous and Local Knowledge (ILK) in Arctic Reindeer Husbandry

Knowledge Category	**Scope**	**Application**	**Role in Adaptation**	**Evidence**
Ethno-Meteorological Knowledge	Detailed understanding of snow properties (e.g., >200 terms for snow/ice in Sámi languages), wind patterns, ice safety, and weather forecasting based on animal behavior and atmospheric signs.	Deciding daily movement routes; predicting safe crossing points on frozen water bodies; preparing for adverse weather events (Laptander et al. 2024).	Vital for short-term tactical decisions and navigating increasingly unpredictable weather, especially frequent rain-on-snow events.	Herders identify critical seasonal conditions throughout the 8-season herding year, where precise weather assessment is crucial for survival.
Landscape and Pastoral Knowledge	Intimate mental maps of pasture quality, topography, vegetation types, and historical use	Planning seasonal migration cycles; selecting optimal calving	Forms the basis for long-term strategic mobility and herd	Traditional knowledge includes strategies like calf marking

	patterns; knowledge of reindeer behavior and health indicators.	grounds; identifying medicinal plants for reindeer; assessing herd health and condition.	management under environmental change. Enables flexible pasture use as a primary adaptation (Brännlund & Axelsson, 2011).	on snow patches to avoid disease, demonstrating a deep understanding of landscape hygiene.
Systemic and Cyclical Knowledge	Understanding ecological interactions and feedback loops (e.g., reindeer grazing effects on vegetation); knowledge based on multi-generational observation of animal populations and environmental cycles.	Implementing rotational grazing practices; managing predator impacts; interpreting long-term environmental changes and distinguishing them from short-term fluctuations.	Provides the foundational context for understanding change, distinguishing cycles from permanent shifts, and innovating new practices (Pape & Löffler, 2012).	Historical studies show herders have long coped with profound environmental variability, viewing the environment as in 'ceaseless motion'. Reindeer populations naturally exhibit density-dependent fluctuations, knowledge of

				which is key to management.
Historical & Governance Knowledge	Understanding the long-term history of land use, colonization, and shifting governance structures, such as the impacts of national borders and land rights (Brännlund & Axelsson, 2011).	Informing land claims and legal struggles; navigating complex modern permitting processes for land use; advocating for rights within state governance systems (Båld, 2025).	Critical for responding to anthropogenic stresses. Loss of authority over land is a primary constraint on adaptability, making this knowledge key to political resilience (Brännlund & Axelsson, 2011).	Historical analysis reveals that vulnerability is shaped by a long history of colonization, border creation, and top-down governance that curtails pastoral flexibility. The 'green transition' is described as a new form of colonialism, repeating historical patterns.
Community & Organizational Knowledge (Siida System)	Principles of collective resource management, inter-family cooperation, and dynamic workload sharing within the traditional Siida (community) structure.	Organizing the herding labor; making collective decisions on migration routes; distributing tasks and	Social networks provide critical support, knowledge, and workforce. A robust Siida system enhances the	The Siida is an ancient Sámi community system and working partnership, which is foundational to the social

		benefits among community members.	community's capacity to respond to disturbances collectively (Brännlund & Axelsson, 2011).	organization of herding. This social capital is a recognized factor promoting adaptation.

Herders' lives are closely attuned to the seasonal cycles that govern migratory routes, calving seasons, and resource access (Laptander et al., 2023). Such seasonal understandings are not passive observations of the environment but are thoroughly embedded in the cultural realm, impacting decision-making, social events, and religious practices (Laptander et al., 2023). The capacity of husbandry societies to sense and respond to such cycles, despite being perturbed by swift climate change, is a testament to the adaptive potential of communities and the resilience of traditional knowledge systems (Laptander et al., 2023).

In addition to economic livelihoods, reindeer husbandry is inescapably connected to the health, nutrition, and cultural welfare of Indigenous communities. Reindeer meat is a significant source of protein and traditional food that ensures nutritional security (Oskal et al., 2023). A physically active outdoor life linked with husbandry ensures physical health, while attachment to land and cultural activity fosters mental health and a sense of belonging (Oskal et al., 2023). Nonetheless, the rising pressures of climate change, industrialization, and socio-economic changes can culminate in enhanced stress and mental health effects among husbandry communities, pointing towards the necessity of integrated support that acknowledges the inherent connection between traditional practices and wellness (Horstkotte et al., 2022).

5. Economic and Governance Dimensions

Although firmly embedded in cultural tradition, Arctic reindeer husbandry systems are also economic and governance arenas defined by dynamic income strategies, market forces, and complex policy regimes in different parts of the Arctic region. The economic sustainability of such systems is frequently multi-faceted, going beyond the straightforward sale of reindeer products to encompass multiple income-generating enterprises. Herders pursue multiple

income approaches, often integrating traditional and customary practices with contemporary economic enterprises, yet largely with difficulty in accessing markets and coping with variable economic stress. The indigenous knowledge, culture, and language of reindeer herders form a strong foundation on which sustainable food systems may be created, which, by their very nature, hold economic worth through local consumption and, at least potentially, niche markets for specialty products (Oskal et al., 2023). However, economic models are diverse, with deep differences found throughout regions, such as the unique changes in the Nenets Autonomous Okrug that were driven by collectivization and later market reforms (Romanenko and Bogdanova, 2023).

Governance models in reindeer husbandry systems are varied, including different types of co-management, self-governance, and regulatory systems that differ regionally. These configurations seek to reconcile customary Indigenous governing frameworks with national and provincial policies, sometimes with mixed results (Horstkotte et al., 2022). The efficacy of these models is significant for resource management, conflict resolution, and adaptation to changes. However, power asymmetries may make it difficult to carry out fair and equitable decision-making processes. For example, states such as Norway have adopted sustainable reindeer husbandry policies since the early 1990s, which tend to have varying conceptualizations of sustainability compared to those of Sámi traditional husbandry societies (Johnsen et al., 2022). This indicates sustained tensions and negotiations to merge different governance views.

Land-use conflicts pose a significant threat to the economic and environmental sustainability of reindeer husbandry. Extractive sectors such as large-scale mining, conservation, and tourism vie for land with competing claims, subjecting reindeer pastures to high pressure (Fohringer et al., 2021). Industrialization triggers land conversion cascades that directly impact animal populations and compound issues for husbandry communities (Fohringer et al., 2021). In Sweden, for instance, extensive human actions, specifically forestry, have strongly affected ecological circumstances for natural grazing, putting pressure on Sámi reindeer pastoralism during critical snow cover periods (Harnesk, 2022). The resolution of these conflicts usually demands governance institutions and policy integration that acknowledge the fundamental value of reindeer husbandry in Indigenous livelihoods and Arctic ecosystems.

Policy integration is needed to support reindeer husbandry; however, it often faces challenges during its implementation. National and regional policies must appropriately integrate the distinctive needs of reindeer pastoralism, considering its cultural, economic, and environmental factors. Industrial development in Arctic areas in an active form and social-cultural transformations call for changes in economic systems, which should be framed in policy frameworks (Romanenko and Bogdanova, 2023). Resource access for adaptation to climate change and diversification of livelihood is crucial for husbandry communities that are undergoing accelerated environmental change. This also involves economic assistance in adjusting to unreliable weather conditions, such as more rain-on-snow events and extremely hot temperatures, which have a considerable influence on reindeer herders' occupational health, safety and well-being (Ocobock et al., 2022).

The development of the value chain offers opportunities to make reindeer husbandry more economically sustainable than raw material sales. Value addition to reindeer products through processing, branding, and direct marketing can boost earnings and market stability for herders (Oskal et al., 2023). Diversification in this manner will further minimize dependence on external markets and support the local economy. However, such efforts must be well-planned, lest they undermine conventional practices and create new avenues of economic stress. At the core of the development of sustainable food systems is the integration of indigenous knowledge, culture, and language, which can be applied to establish culturally suitable and economically viable value chains (Oskal et al., 2023). In confronting the economic and governance aspects of reindeer husbandry, there is a need for sensitivity to these interrelated variables in understanding that they have regional peculiarities and require adaptive and inclusive policy frameworks to respond.

6. Multidimensional Interactions

6.1. Eco-Social Interactions

Arctic reindeer pastoralism is a classical SES in which the complex relationships between ecological and social aspects are pivotal for survival and resilience of the pastoralists. The central ecological aspect focuses on reindeer and their environment, mainly the quality and quantity of pasture, mainly lichens, which are critical in winter feeding (Harnesk, 2022). Ecological processes, including snow depth, ice formation, and vegetation phenology, directly determine the health, distribution, and migration of reindeer herds (Laptander et al., 2023; Pape

and Löffler, 2012). For example, more frequent rain-on-snow events, a key consequence of climate change in Fennoscandia and northwestern Russia, result in ground icing, rendering lichens inaccessible and inducing nutritional stress and higher mortality in reindeer (Laptander et al., 2023). This environmental challenge has a direct effect on the livelihoods of herders and requires the development of adaptive strategies. The productivity of reindeer pastures is also influenced by large environmental changes, such as permafrost thawing and changes in vegetation zones (Pape & Löffler, 2012).

The social aspects of reindeer husbandry are strongly rooted in Indigenous cultures and traditional knowledge systems. Husbanding reindeer is not just an economic practice but the foundation of identity, language, and social forms for numerous Indigenous groups, such as Sámi in Northern Europe and several communities in Russia (Eira et al., 2008; Pape & Löffler, 2012). Traditional ecological knowledge (TEK) is also central to herds and landscape management, with a deep understanding of weather dynamics, reindeer behavior, and sustainable pasture use accumulated over generations (Johnsen et al., 2022; Maynard et al., 2004). TEK guides herders in making decisions regarding migration pathways, herd size regulation, and seasonal pasture use, which are major adaptive strategies for environmental fluctuations (Laptander et al., 2023). The societal structure of husbandry communities, usually under communal land use and inter-family collaboration, enables collective adaptation to environmental challenges (Oskal et al., 2023).

However, the interactions between the two dimensions are increasingly typified by pressures and conflicts. Competition from outside industries, such as mining, forestry, and tourism, for land use is a major interface of ecological and societal pressure. Massive mining activities, for instance, have been reported to trigger cascades of land conversion that immediately impact reindeer populations and their habitats in the form of pasture fragmentation and the breaking up of migration corridors (Fohringer et al., 2021). Commercial forestation has dramatically worsened critical winter grazing conditions in Sweden, thus influencing Sámi reindeer pastoralism (Harnesk, 2022). These industrial intrusions lower the ecological carrying capacity of the land, compelling herders to adjust or risk reduced herd viability, thus directly affecting the social and cultural lives of their groups. The greater development of tourism and infrastructure in the Arctic region puts extra pressure on reindeer pastures, causing human-wildlife conflicts and breaking up traditional ranges (Pape and Löffler, 2012).

SESs are further complicated by policy regimes and governance arrangements, which usually do not sufficiently incorporate the unique vulnerabilities and needs of reindeer herding communities. Although sometimes designed for sustainability, state policies may conflict with herders' long-standing practices and understandings, producing policy mismatches (Johnsen et al., 2022). For instance, the Nenets Autonomous Okrug's economic model of reindeer husbandry has dramatically changed as a result of collectivization during the 1930s and market reforms during the 1990s, illustrating how larger governance and economic policies directly redefine local practices (Romanenko and Bogdanova, 2023). Barriers to entry in decision-making and inadequate recognition of the rights of Indigenous lands and the ability to self-govern tend to create power imbalances, silencing herders' voices in land-use planning and resource management (Tonkopeeva et al., 2022; Johnsen et al., 2022). This constrains the capacity of husbandry societies to introduce efficient, locally adjusted measures to address ecological and economic pressures, demonstrating the irreplaceable contribution of governance in facilitating ecological and social interactions (Tonkopeeva et al., 2022).

The combined effects resulting from the synergistic consequences of climate change, land use stress, and socioeconomic changes instigate feedback cycles in the SES. For example, climate-related variations in forage quantity could drive reindeer towards territories with greater human presence, increasing land-use conflicts and possibly raising the risk of predation (Pape & Löffler, 2012). These co-occurring stressors do not work in combination; their combined action is often more than the sum of their individual parts, resulting in heightened stress and compromised well-being in husbandry communities (Pape and Löffler, 2012). Understanding these intricate, multidirectional interactions across local, regional, and global scales is essential for comprehending the current state and future trajectories of Arctic reindeer husbandry.

6.2. Ecological-Economic Interactions

The connection between the ecological and economic aspects of Arctic reindeer husbandry is crucial to its SES, illustrating how environmental conditions directly impact economic sustainability and how economic forces influence the ecological sustainability of Arctic reindeer husbandry. Studies in different parts of the Arctic emphasize these complex interlinkages, frequently unmasking the tensions and adaptive measures that ensue as a result.

Ecologically, reindeer pasture quality and quantity, especially winter lichens, form the bedrock of economic production from husbandry. Research in Fennoscandia and northwestern Russia has reported how shifts in snow cover, including more rain-on-snow events, contribute to ground icing, rendering lichens inedible for reindeer (Laptander et al., 2023). This, in turn, directly affects reindeer health, lowering their body condition and raising mortality, which ultimately reduces herd size and productivity, which are the major economic indicators for herders (Laptander et al., 2023). The ecological process of shrubification, associated with climate change and witnessed throughout the Arctic region, also influences pasture quality by changing vegetation composition, which may restrict forage availability for reindeer (Verma et al., 2020). This environmental decline leads to higher expenses for supplemental feeding and lower revenue from reindeer products. Successful pasture management based on long-term traditional ecological knowledge (TEK) for generations helps sustain grazing capacity and, thereby, the economic sustainability of livestock production (Eira et al., 2008).

Economic aspects, including industrial growth and market pressures, exert strong pressure on the environmental integrity of the reindeer range. The economic need for increased production or efficiency occasionally induces ecologically irresponsible methods. For example, the economic pattern of reindeer herding in the Nenets Autonomous Okrug has been directly impacted by collectivization during the 1930s and market reform in the 1990s, which transformed management principles and herd dynamics (Romanenko and Bogdanova, 2023). Extractive industries motivated by economic profit are key contributors to ecological disturbances. Large-scale mining, forestry, and construction, as seen in Sweden, fragment pastures, interfere with migration routes, and directly reduce grazing lands (Harnesk, 2022; Fohringer et al., 2021). All these land-use changes have direct ecological impacts, including habitat loss and degradation, which incur economic costs for herders in the form of smaller herd sizes, additional husbandry effort, and reduced access to traditional hunting and fishing resources (Fohringer et al., 2021). These interactions show interactivity, in which economic activities degrade the ecological basis of husbandry, with possible effects in terms of economic stress.

The long-term sustainability of Arctic reindeer husbandry depends on balancing ecological and economic pressures. The problem is to construct economic models that are compatible with the ecological carrying capacity of the Arctic region and that sustain, rather than erode, traditional husbandry strategies. For instance, although economic diversification is

frequently proposed as a remedy, its implementation must be carefully controlled to prevent it from putting pressure on the ecological foundation or alienating herders from their conventional livelihoods. Empirical studies of Sámi reindeer husbandry over centuries demonstrate that the capacity to respond to shifting ecological circumstances has always been linked to economic resilience (Brännlund and Axelsson, 2011). Nonetheless, contemporary economic constraints, augmented by accelerated climate change, pose unparalleled challenges requiring original answers synthesizing ecological methods of conservation with effective economic solutions for husbandry societies throughout the circumpolar North (Horstkotte et al., 2022). This encompasses the recognition of the economic benefits of balanced ecosystems for long-term reindeer populations, directly supporting Indigenous cultural and economic welfare.

6.3. Socio-economic Interactions

The economic and social aspects of Arctic reindeer herding are highly integrated, creating an SES in which human subsistence, traditional practices, and market factors drive reindeer population management and sustainability. Research in different parts of the Arctic has continually emphasized such complex interactions, illustrating how social organization, traditional knowledge, and economic imperatives drive the path of critical pastoral systems in the Arctic.

Sámi reindeer herding in northern Europe is a valuable case study, wherein the activity is not only an economic activity but also a pillar of Sámi identity, language, and cultural heritage, as attested by centuries (Eira et al., 2008; Johnsen et al., 2022). This social embeddedness suggests that economic choices are frequently governed by cultural values and practice. For example, the health and welfare of the herd, informed by generations of traditional ecological experience, have a direct impact on the herd's economic productivity, since healthy reindeer provide improved products. Market pressures, including unpredictable market prices for reindeer meat and other products, may encourage herders to expand their herds, which may create ecological impacts, such as overgrazing, unless they are well managed. The historical social structure of Sámi reindeer pastoralism, usually encompassing the common administration of grazing lands and cooperation in work, enables adaptive reactions to environmental change, which in turn promote economic security (Johnsen et al., 2022).

In Russia, especially in areas such as the Nenets Autonomous Okrug, reindeer pastoralism has undergone profound economic and social changes over the past few decades. The period of collectivization during the 1930s and market reforms in the 1990s transformed the economic model of reindeer husbandry from traditional, to a large extent subsistence-based, into more centralized and market-based systems (Romanenko & Bogdanova, 2023). Economic changes have had direct social implications, changing management practices, herd behavior, and social organization within husbandry communities. For instance, the economic need to maximize output in certain areas has resulted in larger herds, which can put pressure on pasture resources and require modifications in husbandry methods, often deviating from the conventional and ecologically sound methods (Romanenko and Bogdanova, 2023; Klokov, 2020). The deterioration of the sector in certain regions due to technological lag also illustrates an economic issue of important social significance, since reindeer husbandry shapes the lifestyle of numerous Indigenous communities in the Russian North (Koshelev et al., 2023; Loginov et al., 2020).

External economic evolution, such as the growth of extractive sectors (mining, oil, gas, and forestry), generates important interfaces between the social and economic spheres of society. These sectors, based on international economic needs, intrude on traditional reindeer grazing lands, breaking up habitats and disturbing the migration patterns. For instance, vast mining ventures have been proven to trigger land conversions that adversely impact reindeer herds, which are the economic foundation of husbandry communities (Fohringer et al., 2021). In Sweden, commercial forestry has seriously undermined critical winter grazing conditions, threatening Sámi reindeer pastoralism with serious economic challenges and necessitating herders to shift to areas with lower lichen availability (Harnesk, 2022). The economic benefits from these off-farm industries come at the cost of the long-term economic sustainability and social welfare of husbandry communities, as they decrease access to key resources and undermine traditional livelihoods.

The transgenerational exchange of information and participation of youth are key social elements with immediate economic consequences for the future of reindeer husbandry in Sápmi. The preservation of the cultural practice of husbandry guarantees an expert labor force that can handle reindeer and respond to new circumstances, hence ensuring the industry's economic future. However, socio-economic development can result in youth outmigration or a loss of interest in the old livelihoods, threatening the social continuity and economic future of the

husbandry society in the region. Policies and programs that facilitate young people's participation and combine traditional knowledge with new methods are essential for preserving both the social fabric and economic productivity of Arctic reindeer husbandry. The resilience of Arctic reindeer husbandry depends on the precarious equilibrium between these intertwined social and economic aspects, such that adaptive measures respect customary practices while supporting economic sustainability in an environment of rapid transformation (Horstkotte et al., 2022).

7. Impacts of Policies in Arctic Reindeer husbandry

7.1. International

International policies have a multidirectional impact on Arctic reindeer husbandry, both promoting and hindering SESs in the region. These policies usually manifest themselves in the form of agreements, rules, and financing devices on regional, multinational, and global levels, influencing reindeer herding communities from the circumpolar North.

The UN Declaration on the Rights of Indigenous Peoples (UNDRIP) sets the legal benchmark for Free, Prior, and Informed Consent (FPIC), safeguarding herders' rights to land against industrial trespass on essential pastures. The UN Framework Convention on Climate Change (UNFCCC) Paris Agreement offers countries a framework to craft climate adaptation plans that should, but do not always, include targeted assistance for pastoralist communities under Arctic amplification conditions. The Convention on Biological Diversity (CBD) encourages the conservation of pasture biodiversity but causes land-use conflicts when establishing protected areas that limit customary grazing.

Positive impacts mainly result from efforts to enhance sustainable development, advance Indigenous peoples' rights, and share knowledge with them. For example, international declarations and conventions can make the legal framework for the recognition and protection of Indigenous traditional knowledge and land rights more robust, which is important for ensuring the long-term sustainability of reindeer husbandry (Eira et al., 2008; Johnsen et al., 2022). By offering an international platform for the voices of Indigenous peoples, such policies allow herders to express their interests in local and national land-use planning, thus preventing the adverse effects of industrial development and climate change (Brännlund & Axelsson, 2011). Cooperative research initiatives and information-sharing networks,

generally funded internationally, serve to comprehend reindeer husbandry challenges, including the effects of climate change on pasture and reindeer health in Fennoscandia and northwestern Russia (Tyler et al., 2007; Laptander et al., 2023). These efforts, ongoing for the last several decades, create opportunities for sharing best practices and adaptation strategies between herders and researchers across national borders (Laptander et al., 2023).

International policies can also exert negative pressure, particularly when they fail to adequately consider the unique socio-ecological context of Arctic reindeer husbandry or prioritize other interests over traditional livelihoods. For instance, international economic treaties or foreign trade policy could indirectly promote industrial activities, such as the extraction of resources, that invade historic reindeer ranges, resulting in habitat fragmentation and loss of grazing, as seen in Sweden, where commercial forestry has compromised Sámi reindeer pastoralism since the early 2000s (Fohringer et al., 2021; Harnesk, 2022; Pape and Löffler, 2012). The pressure for economic globalization occasionally speeds up development activities without adequate attention to their collective effects on reindeer herds and herders' livelihoods. Although well-meaning, global conservation policy occasionally limits traditional pastoral activities without adequate incorporation of customary ecological knowledge or consideration of involvement from local Indigenous people, risking the sabotage of adaptive management measures and cultural activities that have maintained reindeer husbandry for centuries (Eira et al., 2008). For example, policies governing the economic model of reindeer husbandry in the Nenets Autonomous Okrug have been changing for decades, driven by different global and national factors (Romanenko and Bogdanova, 2023; Koshelev et al., 2023; Loginov et al., 2020).

The success of international policies is largely dependent on their ability to promote adaptive governance frameworks that are responsive, inclusive, and resilient to local conditions and needs of the region. Policies that enable Indigenous self-rule and co-management of resources entrust herding communities with decision-making power that is both culturally meaningful and ecologically viable (Johnsen et al., 2022). Top-down policy strategies that ignore local knowledge or mandate one-size-fits-all solutions in heterogeneously structured Arctic environments tend to create policy mismatches and negative unintended effects (Laptander et al., 2023). Since the 1990s, there has been increasing recognition of the significance of mainstreaming Indigenous voices in international policy, although the process has lagged. It is imperative that there be a movement towards policies that enable inter-regional

and circumpolar learning about policy, enabling the different regions of the Arctic to learn from and share best practices in responding to similar challenges. These strategies bolster the adaptive resilience of reindeer husbandry to global environmental change and economic stress, favoring a more sustainable and resilient future for these critical SESs in the Arctic.

7.2. National

National policies have a double impact on the SES of reindeer husbandry in the Arctic, playing both enabling and constraining roles that determine the practices, resilience, and sustainability of this traditional Arctic livelihood. National policies are frequently created at the national level but have ripple-down impacts on regional, local, and occasionally global levels, expressing governmental agendas that are sometimes not necessarily based on the needs and capacities for adaptation of the herding communities.

Canada's Arctic and Northern Policy Framework (ANPF) informs its Arctic priorities and investments, prioritizing co-development with Indigenous peoples, environmental conservation, and sustainable economic growth. Canada's Arctic Foreign Policy (AFP) is a foreign policy approach to defend sovereignty, promote national interests, and ensure a stable and prosperous Arctic that complements the ANPF. The Norwegian Arctic Policy (NoAP) is centered on security, stability, and international cooperation in the Arctic, emphasizing presence, alertness, and knowledge-driven decision-making to enhance sustainable reindeer husbandry in the region. Finland's Strategy for the Arctic Region (FSAR) targets the diversification of the economy in the Arctic and the promotion of traditional Sámi livelihoods, including reindeer husbandry, through sustainable development and innovation. Denmark's Strategy for the Arctic (KDS) establishes shared political goals for Denmark, Greenland, and the Faroe Islands regarding sustainable development and the conservation of cultural heritage, such as reindeer herding. Sweden's Reindeer Husbandry Act (Rennäringslagen 1971:437) prescribes land use rights for reindeer herding, separating land into year-round and winter pastures, and organizing transboundary grazing rights with Norway. The Strategy of Spatial Development of the Russian Federation (SSDRF) emphasizes the development of infrastructure in the Russian Arctic, such as transport, energy, and resource extraction, affecting reindeer pastures and migration corridors in the Arctic. The Reindeer Husbandry Agreement (RHA) in Norway is a yearly agreement between the state and reindeer herders to discuss industry requirements, problems, and policies to secure sustainable reindeer herd management.

These national policies are key to controlling land use, underpinning economic sustainability, and safeguarding the cultural and environmental dimensions of Arctic reindeer husbandry. On the positive front, national policies can be central to ensuring and enhancing reindeer husbandry through several mechanisms.

For example, in Norway, state policies introduced since the early 1990s have targeted the development of sustainable reindeer husbandry (Johnsen et al., 2022). These policies recognize the profound traditional knowledge contained within pastoral systems regarding landscape dynamics and nature, thus facilitating the adaptive capacity of Sámi reindeer herding to control changing environmental conditions and extreme climatic events (Johnsen et al., 2022). Such national programs tend to be critical sources of financial support, finance the development of infrastructure (such as corrals and transport systems), and sponsor education projects aimed at enhancing herd health, pasture management, and the economic value of reindeer products. These interventions, noted throughout Fennoscandia, help to stabilize herding populations economically, allowing them to recover more robustly from external shocks and maintain their cultural heritage (Eira et al., 2008). National policies can facilitate crucial scientific research and monitoring programs by providing invaluable data on the impacts of climate change, pasture degradation, and disease prevalence. This policy-backed research, exemplified by studies conducted over recent decades in Fennoscandia and northwestern Russia, aids in identifying vital seasonal conditions and events in the annual reindeer herding cycle, which in turn informs more effective adaptive management strategies for herders (Laptander et al., 2023).

National policies often impose important negative pressures, usually originating from competing land-use priorities, inadequate knowledge of traditional practices, or excessive focus on modernization, which disrupts the sensitive socio-ecological balance of such communities. In the Russian Arctic, national policies have molded reindeer husbandry and created paradigm shifts of major proportions. This encompasses the period of collectivization during the 1930s and the market reforms of the 1990s, which transformed the economic model of reindeer husbandry (Romanenko & Bogdanova, 2023). Economic models influenced by policy have sometimes led to technological lag and sector deterioration, especially in the Russian Federation's Arctic Zone (Koshelev et al., 2023). For instance, there is constant evaluation of the possibility of converting reindeer husbandry to modern fencing technology from traditional grazing to better organize slaughter and processing (Koshelev et al., 2023).

Although potentially providing some economic savings, such a shift radically changes conventional nomadic uses and land-use patterns, which are central to both the ecological health of pastures and the cultural identity of herders (Koshelev et al., 2023).

Government policies that favor large-scale industrial use, such as mining, oil and gas development, commercial forestry, and infrastructure construction, often result in heavy habitat degradation and pasture fragmentation of reindeer. Commercial forestry in Sweden has also degraded essential winter grazing grounds by diminishing the availability of lichens, which critically affects Sámi reindeer pastoralism (Pape & Löffler, 2012; Fohringer et al., 2021). These economic-interest-based national-level decisions typically lead to the permanent loss of traditionally used grazing grounds, upsetting vital migratory corridors and increasing reindeer population stress (Fohringer et al., 2021). These consequences directly compromise the economic sustainability and cultural traditions of the herding societies. The combined impact of such pressures, as seen across different areas, such as the Nenets Autonomous Okrug, distinguishes a long-term process in which state interests and foreign economic pressures drive the underlying economic model of reindeer husbandry (Romanenko and Bogdanova, 2023; Klokov, 2020).

Finally, national policies can inadvertently exclude Indigenous people and traditional ecological knowledge if they are developed without sufficient consultation or co-management arrangements. Policies that set blanket regulations for heterogeneous ecological and cultural settings without considering local differences in herding techniques or environmental conditions can produce strong mismatches that impede adaptation and resilience (Klokov, 2020; Eira et al., 2008). For instance, views on significant seasonally varying conditions differ between Fennoscandian and north Russian reindeer herders owing to differences in climatic, geographic, and herd management factors, highlighting the need for context-based policy interventions (Laptander et al., 2023). The lack of national policies that unequivocally secure Indigenous herders' land tenure and resource rights exposes these communities to outside pressures, undermining their ability to self-govern and sustainably manage their traditional lands (Loginov et al., 2020; Eira et al., 2008). Therefore, while national policies are indispensable for regulating and supporting Arctic reindeer husbandry, their design and implementation critically determine whether they contribute to its long-term sustainability and resilience or exacerbate existing vulnerabilities.

7.3. Local

Local policies have a dual function in conditioning the SES of Arctic reindeer herding, both positively supporting and negatively constraining herding communities' practices and their livelihoods. Local policies are usually created and enacted at the municipal, regional, or community level, directly impacting how reindeer herding is practiced on the ground.

Finnish Reindeer Herding Districts (Paliskunnat / Bálggosat) organize reindeer husbandry work within strictly delineated geographic areas, such as pasture management, damage avoidance, and the application of local herding regulations. Norwegian Siida Units (Siida Oassi) are Sámi family-based units with practical responsibility for reindeer herding operations (e.g., seasonal migrations, grazing management) within districts, authorized under the Reindeer Herding Act. Swedish Sámi Communities (Samebyar) are legal entities that possess sole reindeer herding rights in specified regions, administer grazing resources, and negotiate with industries (forestry and mining) according to the Reindeer Husbandry Act. The Lapp Codicil (Lappekodicillen) provisions were historic local arrangements for cross-border grazing between Norway and Sweden for Sámi herders, but only applied to limited modern practices. The Finnish Sámi Reindeer Herding Area Designation focuses on safeguarding Sámi herding practices within designated geographic areas, necessitating special attention to land use intrusions. Norwegian District Land Use Plans (Bruksplaner) are local-level plans developed by reindeer herding districts for the management of pasture use, herd numbers, and migration routes according to the ecological capacity. SCA-Sámi Community Consultation Frameworks in Sweden are company-community deals at the local level that prevent forestry activities (e.g., harvesting and road planning) from interfering with reindeer grazing and migration routes. The Finnish Association of Reindeer Herding Districts, or Paliskuntain yhdistys, provides coordination of district-level policy, earmark registries, and national-level advocacy for local herders' rights. Norwegian Reindeer Herding Area Boards (Reindriftsområdestyrer) are state-level organizations that manage local districts, resolve conflicts, and execute national policies that are adapted to regional contexts. Sámi Traditional Siida Systems are loose but culturally rooted systems of resource sharing, cooperative herding, and adaptive management among familial units. These local structures and policies directly affect everyday herding routines, access to land, and community-scale adaptability to environmental and industrial stress.

Positive local policies also play an extremely important role in adapting rules to particular ecological and cultural conditions, promoting adaptive management routines essential to reindeer husbandry. For example, local planning of land use efforts undertaken in cooperation with herders can reserve and safeguard critical reindeer pastures from encroachment by other uses, such as development or agriculture. These localized strategies, typically based on the traditional ecological knowledge (TEK) of local Indigenous peoples, enable adaptive reactions to changing environmental contexts, such as varying grazing rotations according to snow cover or pasture levels. Environmental policies facilitating the maintenance of traditional herding infrastructure, including corrals or migration paths, or those offering local subsidies for herding gear and training, can substantially boost the economic feasibility and operational effectiveness of reindeer husbandry. These actions can also support the social fabric by understanding the significance of herding to local identity and culture, facilitating the passing of information from one generation to the next, and enhancing community resilience to external pressure. Local policies can also present significant challenges to Arctic reindeer husbandry, especially when driven by conflicting local interests or a poor understanding of herding dynamics. Policies favoring other local economic activities, such as small-scale mining, logging, or tourism development, can fragment traditional grazing lands and interfere with reindeer migration routes in the same way as the large-scale impacts of industrial development are experienced in areas such as Sweden's Sámi reindeer pastoralism. This can lead to higher herding efforts, supplementary feeding costs, and decreased herd productivity. Local laws that are not harmonized across administrative lines or are too rigid can hamper the nomadic migrations necessary for reindeer to access varied pastures throughout the year, particularly under shifting climatic patterns. For instance, local regulations specifying fixed grazing grounds without regard to seasonal fluctuations or unexpected ecological occurrences can place excessive stress on reindeer and herders. The challenge becomes more serious when there is an ineffective local governance framework for co-management with herding communities; thus, policies that are seen as externally imposed and not cooperatively developed. The long-term sustainability of Arctic reindeer husbandry depends on making local policies flexible, place-specific, and fundamentally collaborative with herding communities. This means acknowledging and incorporating customary knowledge systems into policymaking and implementation. Local policies that promote the processing and marketing of reindeer products in the local economy can provide direct economic advantages to herders, enhancing the local economy and reducing dependence on external markets. Local policies can be critical for alleviating human-wildlife conflict, such as from rising traffic or uncontrolled

recreational uses in the reindeer range. By proactively involving herders in decision-making, local governments can ensure that policies are ecologically responsible, socially fair, and culturally sensitive, thus enhancing the overall sustainability and resilience of the Arctic reindeer SES.

8. Challenges

Arctic reindeer husbandry systems are confronted by an interaction of climatic, environmental, socioeconomic, and governance-related challenges (Table 3), all of which act synergistically to influence the sustainability of these important SESs. The interdependence of these stressors implies that tackling one challenge will often affect others, and it is thus necessary to think holistically and in an integrated manner to combat the challenge.

Climate change is a leading and exacerbating challenge to reindeer husbandry in the Arctic. Excessive warming in the Arctic regions causes substantial changes in snow conditions, with a higher number of rain-on-snow events and resulting ice layer formation in the snowpack or on the ground (Laptander et al., 2023). These cold conditions significantly hamper reindeer access to essential winter forage, including lichens, causing nutritional stress, decreased herd health and enhanced mortality (Laptander et al., 2023; Tyler et al., 2007; Pape and Löffler, 2012). Severe weather events, such as extremely warm spells or intense storms, further intensify these vulnerabilities, influencing reindeer behavior, migration, and the well-being and security of herders (Tyler et al., 2007; Laptander et al., 2023). Phenological mismatches between plant growth stages (e.g., green-up) and reindeer calving or migration following changes in climatic cues can interrupt vital life cycle phases and decrease forage quality and quantity (Tyler et al., 2007). Climatic stressors are chronic and widespread, impacting reindeer husbandry across Fennoscandia, Russia, and other circumpolar areas (Laptander et al., 2023; Tyler et al., 2007; Pape and Löffler, 2012).

The pressure on land use due to various human activities exacerbates the effects of climate change. The development of infrastructure, extraction of natural resources (mainly large-scale mining), forestry, and tourism have synergistic effects on reindeer habitats (Fohringer et al., 2021; Pape and Löffler, 2012). They cause habitat fragmentation, direct loss of grazing lands, disruption of migration corridors, and additional stress on reindeer herds (Fohringer et al., 2021). For example, massive mining activities trigger land conversion

cascades and, consequently, influence animal populations and habitats (Fohringer et al., 2021). In Sweden, widespread forestry has significantly deteriorated natural grazing conditions, especially during periods of extensive snow cover, imposing considerable pressure on Sámi reindeer herding (Pape & Löffler, 2012). Such industrialization not only decreases the amount of land available but also degrades its quality and ecological value, creating barriers to reindeer movement and requiring them to spend more energy (Fohringer et al., 2021; Pape & Löffler, 2012).

Predation management adds further complications, usually in the form of human-wildlife conflict. While predators naturally form part of Arctic ecosystems, fluctuations in predator populations, combined with modifications in reindeer vulnerabilities due to climate change and habitat degradation, can increase the predation pressure on herds (Pape and Löffler, 2012). Managing these conflicts is complex, as it aims to balance conservation objectives for large carnivores with the economic and cultural sustainability of reindeer husbandry. Regimes and practices regarding predator control frequently cause conflicts and issues with governance, pointing to the complex interdependencies in SES (Pape and Löffler, 2012).

Socio-economic pressures have a significant impact on reindeer husbandry today. Market forces, such as changing prices of reindeer products and industrial competition, threaten the profitability of husbandry (Romanenko & Bogdanova, 2023). Modern education systems, although offering opportunities, can also lead to youth disconnection from traditional husbandry ways of life as other career prospects become increasingly appealing (Oskal et al., 2023). Cultural urbanization and assimilation processes can degrade traditional knowledge systems and compromise the intergenerational transfer of husbandry habits, thus undermining the cultural basis of this type of reindeer husbandry (Romanenko and Bogdanova, 2023; Oskal et al., 2023). These stresses are especially apparent in areas experiencing rapid economic and social change, such as the Nenets Autonomous Okrug, where market reforms and collectivization have forced major modifications to the reindeer husbandry economic model (Romanenko & Bogdanova, 2023).

Lack of adequate governance, such as policy incompatibility, impediments to participation, and discrepancies in rights recognition, compromises the potential for reindeer husbandry systems to adapt to climate change. National and regional policies do not necessarily incorporate the specific needs and weaknesses of reindeer pastoralism, tending to favor other

economic branches such as industry or tourism (Horstkotte et al., 2022). This creates competition for land use and resource distribution, with the voices and traditional knowledge of Indigenous reindeer herders overlooked (Horstkotte et al., 2022; Fohringer et al., 2021). For instance, state-level policies for sustainable reindeer husbandry could materially deviate from conceptualizations of Sámi traditional husbandry communities, generating repetitive tensions and challenges around their realization (Tyler et al., 2007). Insufficient appreciation of Indigenous land rights and self-governance potential can amplify these challenges, reducing the capacity of husbandry communities to provide for themselves by making autonomous decisions about their livelihoods and land (Eira et al., 2008). These governance challenges are not siloed but interact with climatic and socioeconomic drivers, forging power imbalances that limit adaptive action and heighten the exposure of husbandry groups (Horstkotte et al., 2022; Romanenko and Bogdanova, 2023; Eira et al., 2008).

The combined effect of these various stressors is substantial because of their synergistic interaction, which tends to be greater than the effect of any one factor. Climate change, land use pressures, predation, and socioeconomic factors do not operate independently; they interact to generate feedback loops and non-linear effects within the SES (Pape and Löffler, 2012). For example, climate-driven changes in the availability of forage might drive reindeer into more human-dominated areas, thereby increasing land-use conflicts and predation pressure. This can have psychosocial impacts on herders, leading to elevated stress levels and poorer well-being in husbandry societies (Tyler et al., 2007). The nature and extent of these cumulative effects differ locally, mirroring variations in local ecological settings, governance frameworks, and particular mixes of outward pressures (Horstkotte et al., 2022; Fohringer et al., 2021). Knowledge of these cross-scale interactions, ranging from local grazing processes to global climate regimes, is vital for constructing successful integrated management approaches that enhance the long-term sustainability and resilience of Arctic reindeer husbandry systems (Horstkotte et al., 2022; Pape and Löffler, 2012).

Table 3: Challenges in Arctic Reindeer Husbandry

SES Component	**Challenge(s)**	**Drivers and Manifestations**	**Inter-SES linkages and Cascading Effects**

Ecological	Pasture Degradation and Shrubification	• Climate warming and borealisation (Baker et al. 2025). • Changes in snow cover, including ground-icing from rain-on-snow events (Riseth et al. 2016). • Overgrazing in areas fragmented by other land uses. • Ecological feedback loops from reduced grazing pressure.	• Reduces carrying capacity (Economic). • Increases vulnerability to extreme weather (Social). • Forces longer migrations, increasing energy expenditure (Economic/Animal Welfare). • Has a net negative economic effect due to increased variability (Economic).
	Climate-Induced Phenological Mismatch	• Earlier spring green-up versus fixed calving seasons based on photoperiod. • Unpredictable freeze-thaw cycles. • A mismatch between peak plant nutrition and the timing of reindeer calving and grazing.	• Reduces calf survival and body condition (Economic). • Disrupts traditional migration schedules (Cultural/Social). • Increases reliance on supplementary feeding (Economic).
Social	Erosion of Indigenous and Local Knowledge (ILK)	• Formal education systems disconnected from pastoral life. • Youth out-migration and reduced time on land. • Language loss. • A long history of top-down governance driving	• Reduces adaptive capacity based on historical context (Ecological/Economic). • Threatens cultural identity and mental well-being (Social).

		changes that disrupt traditional knowledge transmission (Landauer et al. 2021).	• Hinders intergenerational equity and knowledge transfer (Social/Cultural). • Undermines the siida system, a source of social capital (Social).
	Mental Health and Socio-Ecological Stress	• Cumulative pressures from climate uncertainty. • Economic marginalization. • Land conflicts and legal struggles. • The perceived loss of cultural heritage.	• Impacts decision-making capacity and resilience (Economic). • Contributes to community health crises (Social). • Can lead to abandonment of husbandry livelihoods (Social/Cultural).
Economic	Market Pressures and Economic Viability	• Rising operational costs (e.g., fuel, equipment). • Price volatility for meat and products. • Competition with subsidized agriculture. • High costs of adaptation strategies like supplementary feeding (Pekkarinen et al. 2023). • Economic losses from predation.	• Forces intensification or expansion, straining pastures (Ecological). • Creates debt and financial stress (Social). • Undermines the economic rationale for maintaining traditional practices (Economic/Cultural). • Can incentivize larger herds, leading to pasture overutilization (Ecological).
	Lack of Economic Diversification	• Geographic remoteness and poor infrastructure. • Lack of capital for investment.	• Increases vulnerability to market and ecological shocks (Social/Economic).

		• A skills mismatch in the local labor force. • A historical focus on a single commodity (reindeer meat).	• Can lead to over-exploitation of reindeer stock (Ecological). • Reduces community resilience (Social).
Governance	Land Use Conflicts and Cumulative Impacts	• Mineral extraction and mining projects (Landauer et al. 2021). • Renewable energy projects ('green transition'). • Tourism infrastructure and conservation areas. • Forestry and other industrial activities.	• Directly destroys and fragments key habitats (Ecological). • Disrupts migration routes, increasing herder workload (Social/Economic). • Creates legal and social conflicts (Social). • Raises fundamental questions of social justice (Governance/Social).
	Policy Mismatch and Lack of Adaptive Co-Management	• Rigid, top-down regulations that ignore local context. • Lack of meaningful inclusion of herders in decision-making. • Sectoral policies that fail to address SES complexity. • Power imbalances, as highlighted by Political Ecology research.	• Creates barriers to implementing flexible adaptation strategies (Ecological/Social). • Fosters distrust in institutions (Social). • Perpetuates ineffective and sometimes harmful policies (Governance). • Is seen in policies like predator management, imposing costs on herders (Economic/Social).

9. Promising Solutions and Adaptation Strategies

Arctic reindeer husbandry systems are confronted with numerous challenges arising from climate change, land use pressures, and socioeconomic transformations, and are proactively applying diverse hopeful solutions and adaptation measures based on scientific and indigenous community knowledge (Table 4). These solutions focus on husbandry adaptations, innovations in governance, co-production of knowledge, suitable technological solutions, diversification of the economy, and involving youth, all of which seek to build the resilience and sustainability of these crucial SESs in the region.

Husbandry adaptations are first-order responses to environmental variability and changes. Reindeer pastoralists use centuries of conventional ecological knowledge and adopt adaptable movement strategies to manage shifting snow cover and pasture abundance (Johnsen et al., 2022; Laptander et al., 2023). This involves modifying migration routes and times and optimizing pasture rotation to avoid overgrazing and ensure ecosystem integrity (Harnesk, 2022). Herd composition reformulation, including herding and structuring herd size, is necessary for synchronizing grazing pressure with accessible forage resources, particularly during severe winters involving rain-on-snow incidents that limit access to lichens (Harnesk, 2022). Innovations in monitoring, usually combining conventional observations with scientific inputs, facilitate better decision-making regarding the movement of herds and resource utilization (Maynard et al., 2004). These adaptations are crucial for coping with the acute and chronic stressors that climate change brings, enabling herders to preserve reindeer health and productivity (Johnsen et al., 2022; Laptander et al., 2023).

Innovations in governance are central to facilitating such adaptations and providing a long-term future for the reindeer husbandry. Collaborative management regimes that bring together Indigenous peoples, national governments, and other players are proving to be powerful tools for resolving land-use conflicts and resource allocation issues (Johnsen et al., 2022). Conservation programs led by Indigenous communities that incorporate traditional land management principles into national conservation objectives are critical for the protection of reindeer range and migration routes from industrialization and fragmentation (Eira et al., 2008; Fohringer et al., 2021). Participatory planning procedures, wherein the voices and expertise of herders are fundamental to policy formulation, assist in reducing policy mismatches and improving the legitimacy and efficacy of regulatory systems (Johnsen et al., 2022). The identification of and respect for Indigenous land rights and self-ruling abilities are prerequisites

for effective adaptation, enabling husbandry communities to independently decide on their livelihoods and land (Eira et al., 2008).

Knowledge co-production is an effective approach to bridging the gap between scientific and Indigenous ecological knowledge. This entails a process of mutual learning, where herders' observational descriptions of reindeer, pasture, and weather patterns over extended periods are merged with scientific information and analytical techniques (Maynard et al., 2004; Tyler et al., 2007). For example, the Indigenous herders of Fennoscandia and northwestern Russia have advanced knowledge of seasonal cycles, defining eight contrasting seasons that inform their husbandry practices, which can be used to improve scientific models of climate effects and ecosystem processes (Laptander et al., 2023). This participatory process enhances both knowledge systems and promotes locally effective and appropriate adaptation measures that are scientifically acceptable and culturally suitable (Maynard et al., 2004). The incorporation of indigenous knowledge, culture, and language is also at the core of developing resilient food systems, conserving biodiversity, and maintaining the continued applicability of husbandry methods (Johnsen et al., 2022).

Technological solutions provide useful devices for making husbandry management, monitoring, and communication more practical, as long as they are suited and combined with local practices. Monitoring technologies for reindeer migration, pasture status (e.g., snow cover and ice layers), and predator presence can provide herders with real-time data to support decision-making and minimize risks (Maynard et al., 2004). Communication technologies enhance connectivity along extensive Arctic terrain, allowing coordination among herders and timely responses to emergencies and changes in the environment. However, such technologies should enhance, but not supplant, conventional techniques and avoid undermining cultural values or autonomy (Maynard et al., 2004).

Economic diversification techniques are crucial for enhancing the economic sustainability of reindeer husbandry against market fluctuations and environmental changes. This entails seeking sustainable livelihood options compatible with pastoralism, such as value-added processing of reindeer products, cultural tourism, and artisanal crafts (Johnsen et al., 2022). Value chain development for reindeer meat, hides, and by-products can increase market access, herder income, and reduce exposure to external economic shocks (Johnsen et al., 2022). Such initiatives should be well implemented to ensure that they do not collide with cultural

values and do not undermine the distinctive traditional husbandry practices among husbandry communities, as suggested by Johnsen et al. (2022). For example, adjusting to changing market situations without abandoning conventional practices has been an ongoing process in areas such as the Nenets Autonomous Okrug, highlighting the necessity of flexible economic models (Romanenko & Bogdanova, 2023).

Youth participation is crucial for passing down knowledge and sustaining this practice over the long term. Education systems that successfully link conventional and contemporary systems of knowledge can motivate future generations to sustain husbandry customs while providing them with skills appropriate for the challenges of the contemporary world (Eira et al., 2008). This involves incorporating Indigenous cultures and languages into curricula, promoting the appreciation of traditional ecological knowledge, and offering the possibility of experiential learning within the framework of animal husbandry (Eira et al., 2008). Through the facilitation of youth participation and compensation for socioeconomic reasons for disengagement, husbandry communities can provide for the sustainability of their distinctive cultural heritage and adaptive capacity (Eira et al., 2008). These integrated strategies, though varied, have one thread in common: they all aim to be context-oriented, draw upon multiple forms of knowledge, and allow local communities to steer the future of Arctic reindeer husbandry in a sustainable direction.

Table 4: Adaptation strategies for sustainable Arctic Reindeer Husbandry

Strategy	**Objective**	**Specific Actions**	**Key Concept**	**Enabling Conditions**	**Potential Trade-offs**
Ecological-Managerial	To adjust husbandry practices directly in response to environmental changes.	• Rotational grazing: Conscious management of pasture use to prevent degradation and promote recovery	• Incremental Adaptation: Aims to maintain the current system's function	Secure access to large, contiguous pasture areas is the fundamental prerequisite (Tonkopeeva et al. 2023). Strong	Increased mobility requires more labor and fuel costs. Flexibility is directly constrained by competing

		(Bostedt et al. 2025). • Altered herd composition: Increasing the proportion of fertile females or more resilient animals. • Strategic mobility: Flexible use of pastures is the foremost historical strategy to cope with change; includes moving herds to unused grazing land in early summer to avoid disease (Bostedt et al. 2025; Pape & Löffler, 2012). • Strategic slaughtering: Adjusting	(Landauer et al. 2021). • Winter Pasture Bottleneck: Winter pastures limited spatial extent and productivity are a key ecological constraint (Pape & Löffler, 2012). • Density Dependence: Herd sizes naturally fluctuate based on pasture availability, a core ecological mechanism (Pape & Löffler, 2012).	traditional knowledge and decentralized decision-making within the siida/community are crucial.	land uses that fragment the landscape (Bostedt et al. 2025; Tonkopeeva et al. 2023).

		timing and numbers based on pasture conditions to avoid overgrazing. • Countering Shrubification: Intensive grazing can mitigate climate-driven shrub expansion, as shown on the Yamal Peninsula where a 75% increase in reindeer population helped maintain stable vegetation (Pape & Löffler, 2012).			
Technological-Tools Based	To augment human senses and	• Digital tools: GPS collars, satellite	• Maladaptive Pathway: May lead to	Initial investment capital, technical	High costs can increase debt. Supplementar

	capabilities with technology for improved efficiency and safety.	imagery (NDVI), drone monitoring of herds and pastures. • Transportation: Use of snowmobiles, helicopters for efficient husbandry and transport. • Supplementary feeding: Targeted provision of feed during important periods of extreme weather (Landauer et al. 2021). • Climate Services: Using co-produced sub-seasonal to seasonal (S2S) climate	an 'alternative system state' (e.g., a sedentary, feed-dependent husbandry) that undermines ecological and cultural foundations (Landauer et al. 2021). • Coping Strategy: Effective for short-term crisis management (e.g., preventing starvation during ice-locked pastures) but not a long-term solution (Landauer et al. 2021).	training, reliable energy/connectivity. For climate services, a transdisciplinary co-production framework is essential for usability (Terrado et al. 2024).	y feeding can increase the risk of disease transmission within concentrated herds. May detach herders from intimate knowledge of animals and land.

		predictions to inform herding decisions (Terrado et al. 2024).			
Economic-Institutional	To improve economic resilience and secure the legal-territorial foundation of pastoralism.	• Value-chain development: Certification (e.g., 'Tundra-Reindeer'), niche marketing, product diversification. • Land tenure security: Legal recognition and protection of migration routes and seasonal pastures (Tonkopeeva et al. 2023). • Payment for Ecosystem Services (PES): Compensatin	• Goal Mismatch: A persistent conflict exists between state governance (often prioritizing meat production) and herders' holistic goals (sustaining a way of life) (Gallardo et al. 2017; Landauer et al. 2021). • Political Ecology View: Highlights how such	Supportive policy frameworks, market access, cooperative structures among herders. Requires governance models that are transparent and fitted to herders' understanding of the land.	Certification/ PES can create new dependencies and commodify nature in undesirable ways. A persistent 'goal mismatch' exists between state governance (often prioritizing meat production) and herders' holistic goals.

		g herders for maintaining biodiversity and carbon storage.	strategies can commodify nature and create new market dependencies, potentially reinforcing power imbalances (Gallardo et al. 2017).		
Socio-Cultural	To strengthen the social fabric and knowledge systems that underpin the pastoral livelihood.	• Knowledge co-production: Formal platforms that integrate ILK with scientific knowledge for decision-making (Terrado et al. 2024; Tonkopeeva et al. 2023). • Youth engagement: Mentorship programs, mobile	• Erosion of IK: Explosion of extractive research that fails to involve Indigenous institutions undermines resilience. • Historical Self-Governance: Sami societies have a long history of self-	Recognition of the value of ILK, dedicated funding, intergenerational dialogue. Protection of Indigenous languages is a key enabling condition.	Slow to show results; can be undermined by broader socio-economic pressures like youth out-migration. Research that extracts knowledge without benefiting communities erodes resilience.

		schools, digital tools that make husbandry attractive. • Community-based monitoring: Systematic data collection by herders to inform local and science policy. • Strengthening the siida system: Reinforcing community-based institutions for collective action and support (Bostedt et al. 2025).	governance and institutional innovation in managing common-pool resources, providing a foundation for adaptation (Larsson & Sjaunja, 2025). • Transformative Capacity: Strengthening cultural identity is key to navigating fundamental system changes (Landauer et al. 2021).		
Governance-Political	To create adaptive, participatory, and	• Adaptive co-management: Formal power-	• Addressing Tipping Points:	Strong political will, devolution of power, legislation	Can be time-consuming; risk of co-option if not

	multi-level institutions for managing the SES.	sharing arrangements between herders and state authorities. • Cumulative Impact Assessments (CIA): Mandating assessments that consider all stressors, not single projects (Bostedt et al. 2025). • Cross-border cooperation: Formal agreements for transboundary reindeer populations (e.g., between Finland/Norway). • Safeguarding a 'safe	Governance failures are a root cause of vulnerability. Land use, climate change, and governance can drive the SES toward tipping points (Landauer et al. 2021). • Social-Ecological Collapse: Defined by the loss of system identity (economic, socio-cultural, ecological), which can occur rapidly and have lasting consequences	requiring meaningful participation and CIA. New, transparent governing models are overdue.	designed equitably. Current permitting processes often fail to account for cumulative impacts, leading to death by a thousand cuts for pastures (Bostedt et al. 2025).

		operating space': A governance priority to ensure herders have the land and resource base necessary to adapt (Tonkopeeva et al. 2023).	(Landauer et al. 2021). • Political Ecology Lens: Emphasizes that vulnerability is often driven more by historical power imbalances and marginalization than by environmental change alone (Gallardo et al. 2017).		

10. Policy Recommendations

Successful policy implications and recommendations for reindeer husbandry in the Arctic necessitate a multi-scalar framework that combines secure land rights, climate policy, co-production of knowledge, adaptive governance, cumulative impact assessment, and international cooperation while prioritizing husbandry community autonomy and participation (Table 5).

The secure protection of land rights and guaranteed access to traditional lands and seasonal migration pathways are indispensable to the long-term sustainability of reindeer husbandry. Policies must legally acknowledge and uphold Indigenous land tenure so that herders remain in control of their traditional grazing lands and essential migratory corridors

(Johnsen et al., 2022). This includes safeguarding areas from encroachment by extractive industries, infrastructure expansion, and other competing land uses that fragment pastures and interfere with traditional migratory routes (Fohringer et al., 2021). Such safeguards are critical for facilitating herders to employ adaptive management measures in the face of environmental change and uphold the integrity of their SESs (Harnesk, 2022). With insecure access, herders' ability to adapt to shifting circumstances, such as rising rain-on-snow occurrences or changes in forage supplies, is significantly compromised (Laptander et al., 2023).

The inclusion of reindeer husbandry aspects within a more comprehensive climate adaptation policy is crucial, considering the uneven effects of climate change on pastoral livelihoods and Arctic areas. Policies must address climate-related issues, including changes in snow conditions, permafrost degradation, and phenological mismatches, by offering targeted assistance for adaptation actions (Laptander et al., 2023). This may involve funding alternative feeding tactics across severe winters, early warning systems for severe weather events, and funding for climate-resilient forage species research (Maynard et al., 2004). Such policies must recognize and integrate herders' indigenous knowledge of climatic variation and environmental change, which provides critical insights into the formulation of effective localized adaptation measures (Laptander et al., 2023; Maynard et al., 2004).

Encouraging knowledge democracy, as defined by epistemological pluralism, is essential for policy creation. This involves actively acknowledging and incorporating Indigenous knowledge systems alongside scientific information in policymaking and research exercises (Maynard et al., 2004). Herders' extensive knowledge of reindeer behavior, pasture ecosystems, and seasons, typically acquired over several generations, offers critical information that science may not independently detect (Laptander et al., 2023). Policies must require participatory research and decision-making models so that husbandry societies become co-producers of knowledge and policy and not mere objects (Johnsen et al., 2022). This will lead to culturally context-specific solutions and enhance the legitimacy and effectiveness of policies.

Models of adaptive governance are required to address built-in uncertainties and rapid changes in the Arctic ecosystem. Regulatory systems need to be adaptive to enable ongoing learning and adaptation in response to new scientific data and herder experiences (Johnsen et al., 2022). This is a shift away from static, centralized approaches to more inclusive and

decentralized management regimes, enabling local communities and herder associations (Johnsen et al., 2022). Policies must provide clear frameworks for revision and feedback to ensure that governance systems can effectively respond to new challenges and opportunities, thereby improving resilience rather than perpetuating dependency (Johnsen et al., 2022).

Process reform in impact assessments to incorporate CIAs is critical for eliminating the synergistic impacts of combined stressors on reindeer husbandry. Existing impact assessments tend to consider individual projects rather than the total impacts of industrial development, climate change, and other drivers on reindeer pastures and migration routes (Fohringer et al., 2021). CIAs should be made obligatory, considering not only environmental but also socio-ecological and cultural aspects, such as effects on traditional livelihoods, cultural well-being, and food security (Fohringer et al., 2021). These assessments must involve husbandry communities throughout the process, ensuring that their knowledge and concerns are central to decision-making and mitigation planning.

Finally, enhancing international cooperation and circumpolar knowledge exchange is important for sharing best practices and fostering policy learning across different Arctic regions. Since reindeer husbandry cuts across countries and has parallel challenges, joint research activities, policy discussions, and knowledge platforms can accelerate the advancement and adaptation of efficient solutions (Horstkotte et al., 2022; Eira et al., 2008). Global institutions and nation-state governments should promote these exchanges, catering to Indigenous-led organizations and networks at the center of this collaboration, hence amplifying the collective Arctic voice in international policy spaces. This encompasses seeking new funding channels for livelihood diversification and climate adaptation that are affordable and culturally acceptable to husbandry communities (Koshelev et al., 2023).

Table 5: Policy Recommendations for Supporting Arctic Reindeer Husbandry

Policy Level	Strategic Goal	Actionable Recommendations	Context
International/ Global	Mainstream reindeer husbandry	• Develop Arctic ethical standards for industry, ensuring involvement of Indigenous peoples in development	A ‘no net loss’ policy for grazing land is recommended,

	into global climate and biodiversity agendas.	processes and mitigating impacts on their ability to adapt to climate change. • Fund co-produced research that integrates scientific and Indigenous knowledge to identify key drivers of change and assess adaptive capacity, as seen in projects like ReiGN. • Promote an integrated management plan for the Barents region that balances industrial development, climate change, and the long-term sustainability of reindeer husbandry.	where indirect losses from new development are compensated with restoration, adaptation support, or increased access to ranges elsewhere.
National	Secure the legal and territorial basis for pastoralism.	Mandate Cumulative Impact Assessments (CIAs) that consider the combined effects of all land-use stressors (mining, forestry, tourism, infrastructure), not just single projects (Gallardo et al. 2017; Rasmus et al. 2021). • Legally recognize and protect crucial migration routes from fragmentation by competing land uses like mining, forestry, and renewable energy projects, which are a primary concern for herders (Gallardo et al. 2017). • Reform governance to address 'goal mismatch' between state objectives and herders' holistic goals, potentially by drawing on lessons from political ecology that highlight power imbalances (Gallardo et al. 2017).	Research highlights that vulnerability is often driven more by governance failures and cumulative land-use impacts than by environmental change alone (Gallardo et al. 2017; Uboni et al. 2020).

Regional/ Municipal	Facilitate adaptive co-management and daily operations.	• Support practical restoration actions in collaboration with herders: thinning dense production forests to 800-1,200 trees/hectare, removing invasive Lodgepole Pine, and accelerating lichen recovery on degraded lands. • Promote reindeer-sensitive forestry practices: extend harvest cycles in lichen-rich forests, remove logging debris, avoid fertilizing key pastures, and improve dialogue between forestry and Sámi communities. • Establish functional co-management boards with real decision-making power to address regional heterogeneities in land-use pressures and herding traditions (Rasmus et al. 2021).	Adaptive co-management is essential, but its effectiveness depends on genuine power-sharing and addressing spatial differences in land-use impacts (Rasmus et al. 2021).
Local/ Community	Strengthen knowledge transmission and community resilience.	• Formalize knowledge co-production platforms where herders' perceptions of biophysical factors like basal icing and pasture access are systematically integrated into local planning (Rasmus et al. 2021). • Implement community-based monitoring to document pasture quality and environmental changes, helping to combat 'shifting baseline' syndrome, where perceptions of 'good' pasture decline over generations due to degradation (Uboni et al. 2020).	Strategies that increase costs without improving economic returns can have strong effects on long-term sustainability, highlighting the need for financial support that considers both economic and psychosocial well-

		• Develop targeted support for adaptive strategies like supplementary feeding and modern equipment, while acknowledging these are costly and may provide low economic return, increasing psychosocial stress (Uboni et al. 2020).	being (Uboni et al. 2020).

11 Conclusion

Arctic reindeer herding research demonstrates an SES that contends with a complex set of interrelated issues. The major findings in each case regularly identify the widespread effects of climate change on access to pasture and the multiplicative forces of industrial land use, which fragment habitats and interfere with migration (Laptander et al., 2023; Verma et al., 2020).

The SES approach is valuable for researching Arctic reindeer husbandry because it can shed light on the complex feedback loops and cross-scale interactions between changing environments, human action, and governance systems. This approach illustrates how Indigenous herders' traditional ecological knowledge (TEK), built up across generations, provides paramount information about reindeer and pasture management, informs adaptation to seasonal rhythms, and sustains biodiversity (Oskal et al., 2023; Laptander et al., 2023). However, the economic sustainability of husbandry is often threatened by market dynamics and financial pressures, as well as governance failures in the form of policy incoherence and a lack of recognition of rights that often sideline the views of herders and curtail their self-governance potential (Johnsen et al., 2022). Therefore, the integration of Indigenous knowledge systems and scientific data is a key strategy for developing effective and culturally appropriate solutions to these challenges (Maynard et al., 2004).

Despite extensive research, several significant knowledge gaps persist that require urgent interdisciplinary attention. There is a need for further broad-scale, long-term studies quantifying the cumulative effects of various stressors, namely climate change, industrial growth, and socioeconomic change, on reindeer populations, pasture ecosystems, and the well-being of herders in a variety of Arctic regions. In particular, more information is required on

the precise mechanisms and thresholds above which various stressors cause irreversible SES changes. Although the psychological effects of climate change and land-use disputes on the mental well-being and health of herders have been recognized, further qualitative and quantitative investigations are needed to guide specific support mechanisms for them (Agho et al., 2018). To be effective, work on the effectiveness and transference of alternative governance frameworks, such as co-management and Indigenous self-governance, needs to progress beyond descriptive studies to comparative assessments of their performance across various political and ecological settings.

Transdisciplinary methods are necessary to bridge these knowledge gaps and promote solutions that are scientifically and culturally sound. Future research needs to explicitly involve husbandry communities as co-producers of knowledge by merging their TEK with state-of-the-art scientific methods, such as remote sensing, ecological modeling, and social science research (Maynard et al., 2004; Peterson St-Laurent et al., 2018). This epistemological pluralism informs research results, making them relevant, legitimate, and actionable for those directly impacted. Participatory action research, for example, can enable the co-design of adaptation measures to meet local priorities and cultural values.

Strengthening the policy-practice-research interface is critical for the operationalization of research outputs into actionable benefits for the society. Knowledge exchange and co-production mechanisms must encompass recurring dialogue forums, workshops, and collaborative projects among herders, policymakers, scientists, and industry stakeholders. Such collaboration can feed into adaptive governance frameworks that are dynamic, responsive, and able to integrate ongoing learning from both customary practices and scientific observations (Peterson St-Laurent et al., 2018). Policy suggestions should consider the moral implications of future studies to preserve Indigenous data sovereignty and intellectual property rights and ensure fair sharing of research dividends with husbandry communities.

An envisioned future for sustainable reindeer husbandry in a transforming Arctic is one in which husbandry communities are empowered through secure land rights and autonomous decision-making abilities, allowing them to make independent decisions regarding their livelihoods and land use (Johnsen et al., 2022; Peterson St-Laurent et al., 2018). This vision means incorporating reindeer husbandry considerations into national and international climate adaptation policies, with specific financing for livelihood diversification and the backing of

resilient practices (Oskal et al., 2023). It also means developing economic opportunities that fit the culture, such as building value chains for products from reindeer that benefit herders directly (Oskal et al., 2023). It is one of intensified international cooperation and circumpolar policy learning, in which best practices and creative solutions are disseminated across borders, and the particular cultural heritage and environmental benefits of reindeer husbandry are valued and fêted across the world (Eira et al., 2008). However, we need to be honest about the pace and scale of forthcoming change and accept that adaptive strategies are an ongoing exercise that cannot provide premature closure to unfolding challenges.

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