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A review of reindeer (*Rangifer tarandus tarandus*) disturbance research in Northern Europe: towards a social-ecological framework?

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ABSTRACT
Disturbance of wild reindeer from human activity is a key challenge for wildlife management. We reviewed recent literature on reindeer disturbance in Northern Europe and discuss a major lacuna in this field of research, namely knowledge about the complexity of human behaviour, which is the major agent of disturbance. Past studies have rarely included detailed data on human activities, but instead treated fixed infrastructure as valid proxies for human presence. However, ignoring the dynamic and flexible nature of human agency as a driver of disturbance may bias our interpretation of the observed responses. We argue that incorporating information about the spatiotemporal patterns of human use of infrastructure and the characteristics of the users may greatly improve our knowledge of the potential impacts on wild and semi-domestic reindeer populations and contribute to improved management of their ranges.

KEYWORDS
Human disturbance; population effects; reindeer behaviour; protected areas; management

Introduction

Loss, fragmentation, and degradation of habitat are the principal threats to biodiversity worldwide (IPBES, 2019). In addition to the direct changes to the habitat caused by human activity, the mere presence of humans can prevent wildlife from accessing otherwise intact patches of habitat (Gutzwiller, D'Antonio, & Monz, 2017). In wide-ranging species such as *Rangifer tarandus* (caribou and wild or semi-domesticated reindeer—hereafter collectively called reindeer) in Northern Europe (Figure 1), loss and fragmentation of habitat combined with increased human presence in their environment have created an ever-evolving disturbance regime. Humans and reindeer have occupied the same land for millennia. Cave paintings dating back to the Old Stone Age (approx. 30 000 BP) in Spain and France depict reindeer along with many other extinct species (Jones & Elliott, 2019). Reindeer was probably the key species that attracted human colonisation in the Arctic and sub-Arctic following the last glacial period (Aaris-Sørensen, Mühldorff, & Petersen, 2007). Humans have since interacted with reindeer in a consumptive sense through hunting, and since the 1500 s through semi-domestication and pastoralism in parts of the range (Røed et al., 2014). Both systems

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Figure 1. Seasonal migration of wild mountain reindeer at the Hardangervidda range in Southern Norway. Photo: Norwegian Institute of Nature Research.

have developed management practices in accordance with political, economic and social trends ranging from grazing districts in pastoral systems (e.g. Forbes et al., 2006; Sarkki et al., 2016), to harvest regulations in wild populations (Strand, Nilsen, Solberg, & Linnell, 2012). Today, reindeer range management is focussed on human disturbance (Kaltenborn, Hongslo, Gundersen, & Andersen, 2015; Skarin & Åhman, 2014), both to conserve access to habitat for wild populations (Kjørstad et al., 2017) and to ensure economic and cultural viability for the Sámi pastoralists (Tyler, Hanssen-Bauer, Førland, & Nellemann, 2021).

The advent of reindeer disturbance research in the 1970s signalled the growing awareness of these novel pressures (Klein, 1971), and the accumulation of knowledge since then has been crucial to understanding the effects of increasing fragmentation, isolation and habitat loss on reindeer populations (Flydal, Tsegaye, Eftestøl, Reimers, & Colman, 2019). The ecological effects of infrastructure and human disturbance on wild reindeer have been reviewed in the past with various aims (Flydal et al., 2019; Reimers & Colman, 2009; Skarin & Åhman, 2014; Vistnes & Nellemann, 2008), but less attention has centred on quantifying the various components of the human presence, i.e. the spatial extent, temporal extent and variability, volume, and type of use. Attaining the levels of human activity associated with fixed structures (e.g. mountain huts) that are tolerated by the animals could improve the precision of management actions (Gutzwiller et al., 2017; Hammitt, Cole, & Monz, 2015). We investigated a hypothesis that disturbance studies on wild and semi-domestic European mountain reindeer to date have mainly used physical infrastructure as an indicator of human disturbance. Here, we perform a synthetic critical review of the literature to highlight the strengths and weaknesses of the disturbance research to date, and to identify knowledge gaps and methodological challenges.

An appropriate conceptual framework to understand the complex human-reindeer co-existence is the concept of social-ecological systems (SES) (Forbes et al., 2006; Heikkinen, Kasanen, & Lépy, 2012; Pape & Löffler, 2012). Key to understanding and adapting a SES approach within reindeer ranges is the integration of physical, ecological, economic, social and institutional systems, which require interdisciplinary and multidisciplinary research across different spatiotemporal scales. Typical factors in complex human-reindeer systems include highly dynamic ecological conditions (e.g. pests, disease, and variable phenology), a rapidly changing landscape (e.g. land-use and zoning decisions that depend on political motives), variable acceptance and legitimacy of management actions embedded in the ecological and social setting, and varying social and ecological vulnerabilities in the system, i.e. herding and hunting practices (Forbes et al., 2006; Heikkinen et al., 2012; Kofinas, Osherenko, Klein, & Forbes, 2000). Even after more than 20 years, the SES concept lacks a clear definition (Colding & Barthel, 2019; McGinnis & Ostrom, 2014). Pragmatically speaking, the SES approach requires detailed knowledge about each factor at a scale that is relevant for managers. Nowadays, human presence plays a greater role in reindeer ranges due to increased participation in outdoor activities and easier access, as reindeer ranges become increasingly fragmented by heavy infrastructure development (Kaltenborn et al., 2015). Hence, to better inform management, disturbance research needs to include data on human behaviour and use of infrastructure in space and time, as well as key characteristics of human perception such as motives, environmental preferences, and attitudes towards management. One of the main challenges in contested reindeer habitats is to regulate human behaviour through different types of site-specific measures (Gundersen, Myrvold, Rauset, Selvaag, & Strand, 2020). However, there are often social compliance issues for management actions that involve area-use restrictions by law or different kinds of physical interventions in the landscape (Manning, 2010). Implementation of management actions without knowledge about the visitors and involvement of key stakeholders in the area increases the uncertainty related to the success of implementing management strategies (Hammitt et al., 2015). Sometimes social and ecological uncertainty is so high that it undermines the ability to manage adaptively, or manage at all (Heikkinen et al., 2012; Tyre & Michaels, 2011).

We summarise the key insights from the current research on wild and semi-domestic mountain reindeer disturbance in Northern Europe, and discuss the usefulness of adopting elements of a SES approach to understanding and managing impacts of infrastructure and associated human use on reindeer in an alpine zone with increasing competition for space. In this review, we apply the framework of SES, emphasising that people make conscious choices as individuals or in groups, thus defining the action space in which natural resources and ecosystems can be managed (McGinnis & Ostrom, 2014).

Material and methods

The focal species

Rangifer tarandus is the only species in the genus *Rangifer* and has a circumpolar distribution. There are several subspecies, broadly referred to as reindeer in Eurasia and caribou on the North

American continent. In this review, we will focus only on mountain reindeer in Norway, Sweden and Finland (*R. tarandus tarandus*), including wild and semi-domestic reindeer populations. Wild mountain reindeer (winter population of 30 000–35 000 animals) are only found in Southern Norway. There, they inhabit most of their historical range (primarily alpine landscapes), but effectively exist as 24 distinct populations with limited gene flow between them (Kjørstad et al., 2017) due to habitat fragmentation. Consequently, they are managed on a population-by-population basis. The semi-domestic reindeer (winter population approx. 700 000 animals in Fennoscandia) are mainly managed by indigenous Sami people in Norway and Sweden and herded in a pastoral system, where the animals move freely in the landscape during the year. Many of these herds still make migrations between seasonal ranges and experience similar threats, such as habitat loss and human disturbance (Pape & Löffler, 2012; Skarin & Åhman, 2014). All reindeer populations in Northern Norway, Sweden and Finland are semi-domesticated, with the exception of two small populations of wild forest reindeer (*R. tarandus fennicus*) in

Figure 2. Map showing the current ranges of semi-domestic reindeer and wild mountain reindeer (*Rangifer tarandus tarandus*) in Fennoscandia. Shown in green is the Finnish forest reindeer (*Rangifer t. fennicus*), which was not included in this review.

central Finland (Figure 2, Nieminen, 2013). Not included in the review are the subspecies of the reindeer only found on the isolated island group of Svalbard (*R. tarandus platyrhynchus*) and wild forest reindeer, and neither were studies of North American caribou and domestic reindeer in the Russian Federation. The extensive wilderness in North America is not directly comparable to the small, fragmented ranges of Northern Europe (Røed et al., 2014). Within these limits we included 73 peer-reviewed papers from 35 different journals on reindeer disturbance since 1971.

Literature reviewed and classification

Our literature study is based on five international databases (Web of Science, Google Scholar, Cristin, Oria, and Scopus). We searched each database with a diversity of terms related to the disturbance of reindeer in combination with the word *Rangifer* or reindeer: human use (recreation, tourism, hunting), infrastructure development (roads, railways, trails, tracks, dams, power lines, wind farms, private cabins, tourist cabins, resorts) and ecological effects (flight response, avoidance, migration barriers, aversion, habituation). To ensure that we obtained all relevant literature we subsequently performed a nesting analysis. Here we took all selected works from the search in databases as a reference point and then reviewed the literature backward and forward in time. This approach can be viewed as a type of snowball or chain sampling (Miles & Huberman, 1994), used in this case in conjunction with written sources instead of informants.

For the purposes of the discussion here, we define disturbance in accordance with Frid and Dill (2002) as avoidance responses by *R. tarandus* to occurrences of humans or human-made infrastructure in their habitat. Most of the early disturbance studies in reindeer ranges can be categorised as local impact assessments and were not included in this review. In the 1980s, disturbance studies were increasingly published in the international literature (Skogland, 1986) and since 2000 there has been a noticeable increase in the number of published articles (Figure 3). These publications indicate a trend that has shifted from local to regional studies, reflecting the

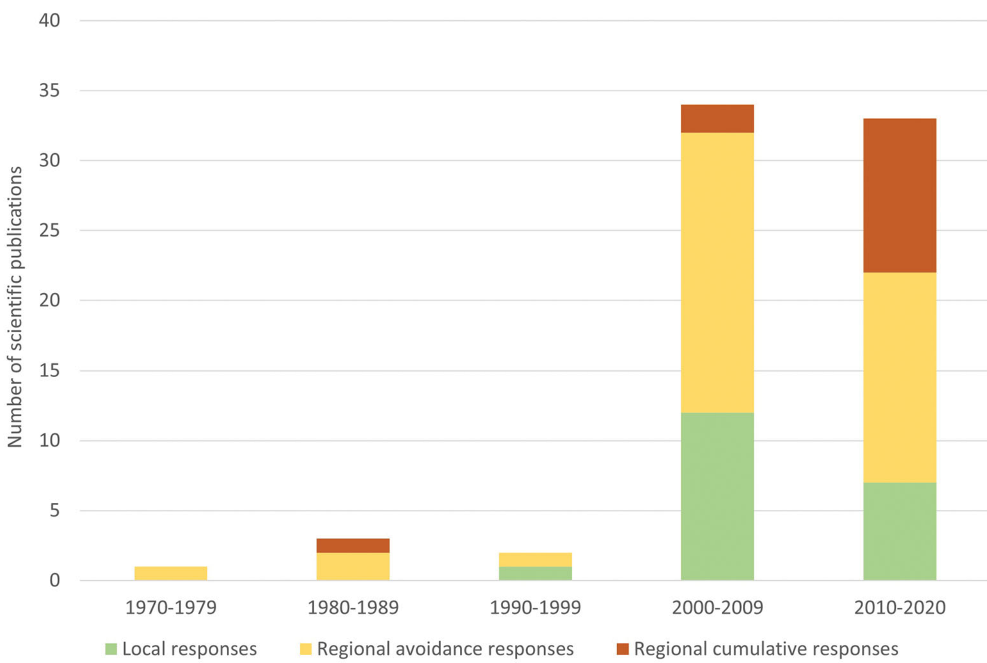

Figure 3. Number of peer-reviewed publications ($n = 73$) per decade on human disturbance on semi-domestic and wild mountain reindeer (*Rangifer tarandus tarandus*) in Fennoscandia since 1970, divided into local responses, regional avoidance responses and regional cumulative responses.

scientific community's awareness of disturbance regimes (Vistnes & Nellemann, 2008). Types of infrastructure studied include: main roads (i.e. paved), minor roads (i.e. gravel), railways, dams and reservoirs, power lines, wind farms (wind turbines and access roads), tourist shelters, second-home development areas, settlements, resorts, marked trails, unmarked trails and groomed ski trails.

We summarised a number of factors considered important for disturbance research and categorised them into three main levels depending on the scale of effects (Vistnes & Nellemann, 2008): (1) Local responses, (2) regional avoidance responses, and (3) regional cumulative responses (Figure 4). *Local responses* concerned acute responses in reindeer behaviour or physiological state, i.e. measured by either vigilance behaviour (alertness, fright, flight initiation, escape) and reduced foraging time, or increased heart rates and stress hormone levels (Colman et al., 2003). To provoke stress in the herds it is common to arrange an artificial situation of approaching humans in different modes (on foot, skis, kite, snowmobile etc.). *Regional avoidance responses* focus on distribution of reindeer over time, i.e. area avoidance and shift in relative abundance due to different kinds of infrastructure in a minor part of the population's range. In most cases the data have been derived from on-site or aerial surveys, telemetry data, or indirect estimation of reindeer abundance via scat counts and grazing-intensity indices. Finally, telemetry studies on *regional cumulative responses* focus on functional habitat at population level, carrying capacity and changes in demography as survival, reproduction and migration pattern (Panzacchi, Van Moorter, & Strand, 2013a; Panzacchi, Van Moorter, Strand, Loe, & Reimers, 2015b; Panzacchi et al., 2015a). These studies typically include GPS collared reindeer, aerial survey and satellite imagery technologies. We do not distinguish in this article (unless explicitly stated) between

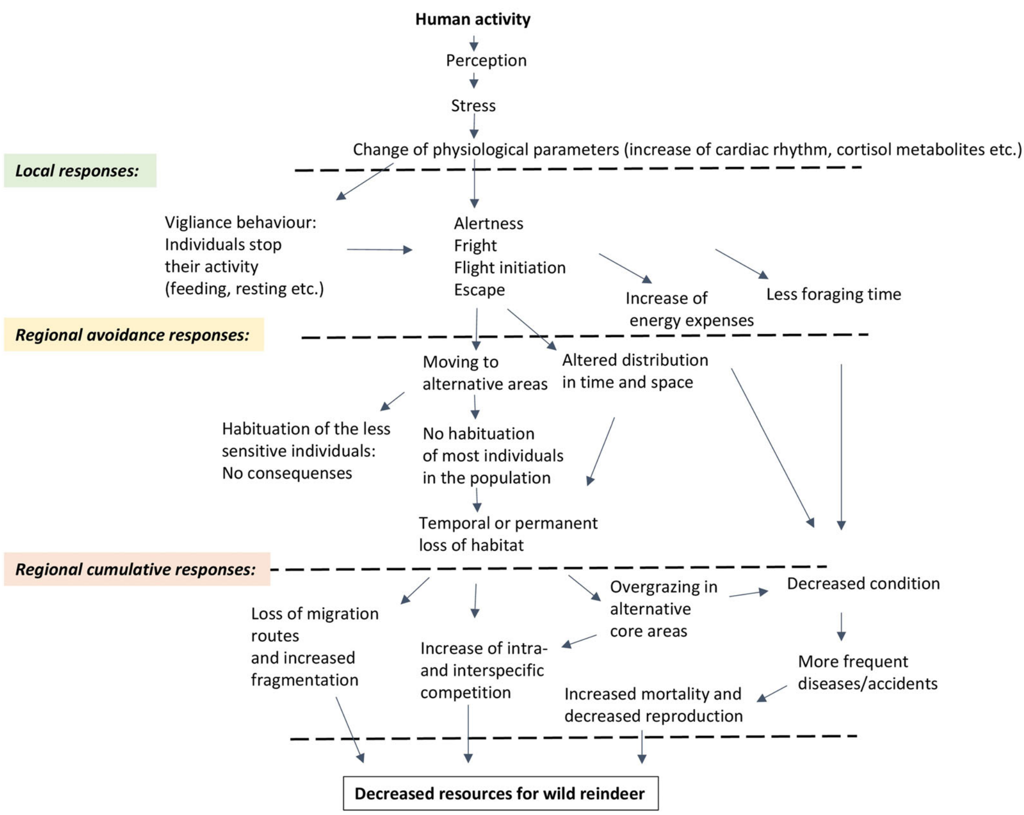

Figure 4. Main theoretical impacts and effects of disturbance on reindeer population derived from the former studies. See text for further descriptions.

research conducted in wild or semi-domestic reindeer areas, because they have similar genetics, ecology, and show similar responses to humans.

Summary of the human use component from past reindeer disturbance research

Local responses

This category of research has mainly concerned wild reindeer populations. The studies include data on humans, because humans are actively approaching the herd to provoke reaction. For a herd that is grazing or resting, disturbance by humans is very similar to an approaching predator to which the herd reacts (Frid & Dill, 2002; Reimers, Loe, Eftestøl, Colman, & Dahle, 2009). Two characteristics are typically recorded in such studies, namely vigilance behaviour and flight initiation distance. *Vigilance behaviour* means that individuals stop their current activity in order to be on alert to the potential threat, whereas *flight initiation distance* is the distance at which an animal begins to evade an approaching threat (Colman, Lilleeng, Tsegaye, Vigeland, & Reimers, 2012). Both are modulated by the size of the herd, sex and reproductive status, the time of year, and habituation to the threat, making the reactions by one herd variable over time (Dahle, Reimers, & Colman, 2008; Eftestøl, Tsegaye, Flydal, & Colman, 2016; Reimers, Miller, Eftestøl, Colman, & Dahle, 2006; Stankowich, 2008; Vistnes & Nellemann, 2008). For example, large herds may allow the observer to approach closer than do small herds, and groups with offspring are more sensitive than groups without offspring.

Flight initiation distance is often used to explain differences in fright responses between wild and domestic reindeer (Nieminen, 2013), but can vary considerably between populations of wild reindeer (Røed et al., 2014). Fearfulness depends on the herd's genetic origin, degree of habituation to infrastructure, and the level of human presence in their range (Reimers, Røed, & Colman, 2012; Reimers, Røed, Flaget, & Lurås, 2010). Because of the diverse history of domestication, the levels of vigilance behaviour and fearfulness vary among the extant wild reindeer populations (Table 1). Today, only four of the ancient wild mountain reindeer populations in Europe remain, namely Snøhetta, Knutshø, Sølnkletten and Rondane (Røed et al., 2014), with flight initiation distance of 400–500 metres.

Importantly, the responses to human disturbance can be dynamic and diverse. The types of human activities are important study objects in the reviewed studies of local responses. All the examined studies of local responses involved only one person approaching directly towards the herds. These studies, however, did not describe reindeer responses to different group-sizes of people, nor responses to different movements of these groups relative to the herd. Wild reindeer showed stronger fright responses towards skiers than snowmobiles, and ski-kiters caused more disturbance than cross-country skiers (Reimers, Eftestøl, & Colman, 2003; Colman et al., 2012). Higher speed and larger objects (i.e. a kite) invoked stronger responses at farther distances

Table 1. Local responses categorised as mean flight initiation distance for semi-domestic and wild reindeer herds in Fennoscandia.

Flight distance (metres)	Reindeer range
0–99	Semi-domestic reindeer
100–199	Forollhogna, Reinheimen-Breheimen, Setesdal Austhei, Skaulen-Etnefjell, Våmur-Roan, Brattfjell-Vindeggen, Blefjell, Norefjell-Reinsjøfjell, Oksenhalvøya, Fjellheimen, Laerdal-Årdal, Vest-Jotunheimen, Sunnfjord, Førdefjella, Svartebotnen, Tolga Østfjell, Raudafjell
200–299	Hardangervidda, Nordfjella, Setesdal Ryfylke
>300	Snøhetta, Rondane, Knutshø, Sølnkletten

Some of the areas have been estimated based on genetic similarity and geographic proximity to other ranges, or by using local knowledge from e.g. hunters (Reimers & Colman 2009). Methodologically, the studies reviewed are based on a person that is calmly approaching a medium-sized herd in a straight line in flat terrain in summer, i.e. before the hunting season.

resulting in longer escape distances (Reimers, Eftestøl, & Colman, 2003). Over time however, wild reindeer appeared to habituate to the observer because they initiated flight at shorter distances when the number of approaches on the same day increased (Reimers et al., 2009).

Studies of local responses to human activity often mention that the consequences of disturbance are reduced time for foraging and resting. Colman et al. (2003) indicate that less time spent on foraging (irrespective of the cause, e.g. due to insect harassment) limits weight gain. Similarly, recurring and prolonged disturbances may therefore increase energy expenditure and have negative consequences for reindeer activity patterns, nutrition, and in turn, individual performance (Skogland & Grøvan, 1988), but we did not identify studies that have tested this. However, inferring effects on population viability is largely tentative because of the short duration and small scale of such studies relative to the gradual changes in population vital rates and the inability to control for other factors.

Regional avoidance responses

This category includes research on both wild and semi-domestic reindeer populations. Habitat selection in most animal taxa is considered a trade-off if perceived risk is positively correlated with potential rewards of using a certain area. The effects of human disturbance on reindeer reflect perceived predation risk, and the herd's response to the threat is modulated by the intensity and type of disturbance relative to other risks and rewards in the environment (Gill, Sutherland, & Watkinson, 1996). Several studies concern the short-term effects of development of new infrastructure such as wind farms, main roads, and power lines in the fringe of the range; comparing habitat use before, during, and after construction, as well as comparing developed and undeveloped areas (e.g. Colman, Eftestøl, Tsegaye, Flydal, & Mysterud, 2013; Colman et al., 2015; Eftestøl et al., 2016; Tsegaye et al., 2017; Vistnes, Nellemann, Jordhøy, & Strand, 2004). Some studies have tested reindeer avoidance as a function of distance from the disturbance source, e.g. tourist resorts (Dahle et al., 2008; Helle et al., 2012; Nellemann, Vistnes, Jordhøy, & Strand, 2001), while others have removed, relocated or added new infrastructure to a landscape to study the effects on reindeer habitat use (e.g. Nellemann et al., 2010). To validate studies of avoidance effects, the animals must have access to alternative areas (Vistnes & Nellemann, 2008). Given the basic assumption that reindeer fear humans, the animals will congregate in areas with less infrastructure, and consequently, the grazing pressure will increase in those areas. Such functional effects have been identified from the Nordfjella and Hardangervidda ranges in Southern Norway (Nellemann et al., 2001). Here, the density of wild reindeer was higher in areas with less infrastructure. The impacts from wear on the vegetation was also significantly larger in the heavily grazed part of these ranges (Nellemann, Vistnes, Jordhøy, Strand, & Newton, 2003). It might seem counter-intuitive that the herd chose to use areas with diminishing food resources, but it suggests that the benefits of reduced perceived risk in the remote areas outweighed the costs of poorer grazing quality. Recent studies have indicated that avoidance behaviour depends largely on the extent and intensity of human use of infrastructure. Several studies have qualitatively shown a positive correlation between increasing human activity and the level of avoidance (e.g. Colman et al., 2013, 2015; Eftestøl et al., 2016; Helle et al., 2012; Skarin & Åhman, 2014; Tsegaye et al., 2017).

None of the studies included quantitative data (i.e. spatial extent, temporal extent and variability, or volume) on the human use of infrastructure. Infrastructure alone does pose an obstacle for reindeer habitat use, thus to fully understand disturbance effects we cannot ignore human presence and the level of activity. Similar to sub-optimal foraging explained by avoidance, overlapping range with human use does not imply general habituation and must be viewed comprehensively in light of other stressors and the *type and level* of human use. Observations of decreased flight responses by reindeer over time in areas with frequent human use

(Reimers et al., 2009) or by comparing areas with high and low levels of human use (Reimers et al., 2010, Reimers, Røed, & Colman, 2012; Skarin, Danell, Bergström, & Moen, 2004), are attributed to a habituation process. Hence, avoidance effects are highly contextual and dynamic, and depend on multiple interacting factors (Anttonen, Kumpula, & Colpaert, 2011; Helle et al., 2012; Skarin, Danell, Bergström, & Moen, 2008; Skarin et al., 2004; Vistnes, Nellemann, Jordhøy, & Stoen, 2008).

Regional cumulative responses

This category primarily concerns research of wild reindeer populations, but also includes some studies of semi-domestic reindeer. Due to their large home ranges (10^2–10^4 km^2), it is necessary to match the scale of the investigation with the scale at which the suite of pressures is acting, while at the same time accounting for the natural dynamics of the populations (Colman et al., 2017; Flydal et al., 2019). Most studies in cumulative responses did not include quantitative data on human presence. The only exceptions are Gundersen, Vistad, Panzacchi, Strand, and Van Moorter (2019; Gundersen et al., 2020) who used data on human use of marked and unmarked trails from field surveys and automatic counters. The recent applications of location data from GPS-collared wild reindeer have enabled large-scale analyses of functional habitat use and migration (Colman et al., 2015; Eftestøl et al., 2016; Panzacchi, Van Moorter, Jordhøy, & Strand, 2013a,b, Panzacchi et al., 2015a, 2015b). Location data have revealed functional effects in terms of barriers to migration to historic ranges, between seasonal grazing areas, calving grounds, and insect refugia. Reindeer likely perceive an anthropogenic barrier mainly in the form of linear infrastructure (e.g. roads) in combination with human presence, and the strength of the barrier effect probably depends on the sum of these two factors. Cumulative effects can be substantial in valleys and mountain passes that contain multiple parallel structures such as highways, railways, power lines and recreational infrastructure with dynamic human use patterns (Panzacchi et al., 2015b; Sarkki et al., 2016). Panzacchi et al. (2013a, 2015b) showed that high densities of marked trails have significant negative effects on animal distribution and movements in several wild reindeer ranges. The effects can be observed both through changes in reindeer behaviour (increased movement speed close to the trails) and avoidance of certain trails, which ultimately prevent the animals from accessing their historic range (Panzacchi, Van Moorter, & Strand, 2013b). In many places, old migration corridors have been abandoned altogether. For other migration corridors only a small portion of herds use them, and for some the total use has decreased significantly (Panzacchi et al., 2013a). However, a few perceived barriers are seasonal; most gravel roads and some main roads in the mountain ranges are only open to traffic in summer and may not act as complete barriers during winter when they are snowed in.

Recent studies also suggest that the effects vary considerably between different types of infrastructure (Table 2). Effects have been documented for roads, tourist cabins, and other forms of recreational infrastructure, but depend on the intensity and type of human use of said infrastructure. Furthermore, the total influence of infrastructure greatly exceeds the area over which reindeer directly sense the structures and humans through smell and sight. Reindeer typically sense a potential disturbance from 1 to 2 km away in alpine areas, whereas heavily trafficked roads can have an influence zone of 5-10 kilometres (Panzacchi et al., 2013a; 2015a, 2015b). Whether this comes from learning or is strictly a product of instantaneous sensory stimulation has not been investigated. However, it is likely that areas of high traffic, such as roads over mountain passes, are avoided by the herds using the same mechanisms as learned migration routes and other knowledge of their range.

These recent studies included all types of existing infrastructure within a whole reindeer range, long-term GPS data (e.g. from the Hardangervidda range since 2001), and data on many of the confounding habitat factors that may explain changes in the population's area use and

Table 2. Recent studies that have documented avoidance of infrastructure and associated human use at regional levels based on GPS-positions from radio-collared female reindeer.

Type of infrastructure	Avoidance >50% decreased use	Partial avoidance <50% decreased use	References
Main roads	1 km	10–15 km	Panzacchi et al., 2015a, 2015b.
Gravel roads	1 km	10 km	Panzacchi et al., 2015a, 2015b.
Tourist cabins	1 km	10 km	Panzacchi et al., 2015a, 2015b.
Marked trails	Very variable effects, depending on the trail density and the intensity of use.	1 km	Panzacchi et al., 2015a, 2015b; Gundersen et al., 2019, 2020.
Power lines	Indirect effects. Often additional infrastructure. Strongly context dependent.	Indirect effects. Often additional infrastructure. Strongly context dependent.	Colman et al., 2015; Panzacchi et al., 2013a, 2015b; Eftestøl et al., 2016. Panzacchi et al. (2013a) indicate large impact depending on associated road infrastructure. New hypotheses for UV radiation indicate larger effects (Tyler et al., 2016).
Wind turbines	Not studied	3–5 km	Skarin, Nellemann, Rönnegard, Sandström, & Lundqvist, 2015.

Avoidance distance is here expressed as reduced probability of use of historically important areas for the reindeer (Panzacchi et al., 2013a).

migration. Still there may be a set of habitat factors that have not been included in the analyses (e.g. Flydal et al., 2019). First, highly dynamic factors such as weather conditions, available foraging resources, and individual random movement are challenging or even impossible to include. Second, most of the disturbance research has investigated the effects of existing infrastructure in the landscape (Panzacchi et al., 2015b), and has not tested the changes before, during, and after construction of new infrastructure (Flydal et al., 2019). One way to do this is to establish long-term study following the different phases of construction (2015, Eftestøl et al., 2016; Colman et al., 2013; Flydal et al., 2019), or to build habitat and step-selection models with existing long-term GPS data series that predict disturbance effects by adding or removing infrastructure (Panzacchi et al., 2015b). However, the diversity and variation of human use of these kinds of infrastructures have not been mentioned as a factor in any of the disturbance studies, not even in a recent review of confounding factors (Flydal et al., 2019).

The missing link – data on the human use of the landscape

In short, we discovered that avoidance and cumulative disturbance studies to date have mainly used infrastructure as a proxy for human presence, or not explicitly partitioned the effect of the infrastructure from the effect of the human presence at relevant scales. This oversight potentially misses important information about the real drivers of disturbance effects, which in turn might limit management actions. The intensity, diversity and trends in human presence in the disturbance literature is often presented as an unknown exogenous factor- 'context'- and different types of infrastructure have been used as proxies of human use of the reindeer ranges. While this has been a useful heuristic in most cases of reindeer responses to heavy infrastructure, we propose to partition infrastructure and human presence as a set of interacting effects, depending on their contributions to limiting reindeer movement and causing disturbance.

First, heavy linear infrastructure such as roads, railroads, and hydropower reservoirs act as barriers to reindeer movement, and represent the main agent of habitat loss and fragmentation (Panzacchi et al., 2015b). For example, hydropower reservoirs inundate reindeer habitat and act as barriers to movement, and radiation and visual obstruction from the associated power lines can further limit movement (Tyler, Stokkan, Hogg, Nellemann, & Vistnes, 2016). Additionally, cabins and recreational infrastructure are developed along the hydropower dam access roads (Panzacchi et al., 2013a), which form clusters of recreational areas. Based on the literature to date it is therefore difficult to determine the extent to which the infrastructure acts as a barrier in its own right or in concert with human activity. Most studies seem to imply that infrastructure causes disturbance to reindeer because humans use the infrastructure, and that similar types of infrastructure have the same, constant disturbance levels associated with them regardless of their differences in size, physical attributes, human use or geographic location. However, human presence is highly dynamic in time and space within a given reindeer range, and it varies considerably between ranges (Kjørstad et al., 2017). It is therefore misleading to assign a constant barrier effect of a given type of infrastructure, and it can be misleading or wrong to assign a level of disturbance to an entire area irrespective of the types of infrastructure that exist therein (Flemsaeter, Gundersen, Rønningen, & Strand, 2018; Gundersen et al., 2019, 2020). This can be illustrated by two studies from North America. Dyer, O'Neill, Wasel, and Boutin (2001) who studied avoidance effects of roads on caribou and concluded that '*Avoidance effects were highest during late winter and calving and lowest during summer, possibly as a result of lower traffic then*', but provide no data on the human traffic. LeBlond et al. (2013) included the temporal use of infrastructure when they tested avoidance effects on caribou of main roads. There was a positive correlation between caribou avoidance of roads and disturbance level on the roads, and they concluded that: '*Our study showed that the avoidance behaviour of a large, disturbance-sensitive herbivore is related to disturbance intensity*'.

Secondly, light infrastructure such as hiking trails, ski trails and associated recreational facilities can intermittently act as barriers depending on the level of human activity, the season and their location (Gundersen et al., 2019, 2020). Because their habitats have been fragmented, reindeer often congregate in refugia with often low levels of human presence (Nellemann et al., 2001, 2003). These refugia typically constitute only a small proportion of the range that is unaffected by heavy infrastructure. As a result, overgrazing and density-dependent effects such as higher frequencies of parasites and disease are evident (e.g. Skarin et al., 2004; Vistnes et al., 2008). At this level of barrier and disturbance assessments there is a need for detailed data on human use of light recreational infrastructure in seemingly remote areas (Gundersen et al., 2019, 2020). Finally, many activities are dispersed. Hunting, berry picking, kiting, and ski touring are examples of activities that are carried out irrespective of infrastructure, but that can disturb reindeer. Relying on infrastructure as a proxy for human presence would miss this type of use. For example, Lesmerises, Johnson, and St-Laurent (2017, Lesmerises, Dery, Johnson, & St-Laurent, 2018) studied the effects of backcountry skiing and hiking on caribou, with trail cameras and overnight stays at a tourist cabin as proxies for the use of the area. They found that there exists a vigilance-feeding trade-off related to the intensity of hikers, and a functional loss of habitat as result of the intensity of backcountry skiing. These studies from North America illustrate that the responses of reindeer to human activity are complex and that our understanding of them can be improved by precise data on human usage intensity.

Relevant metrics describing human presence can be categorised as spatial extent (scale and area affected), temporal extent and variability (time of use and season), volume (amount of use), and type of activity (Table 3). Additional factors that could be relevant include speed (e.g. speed of cycling versus hiking), size (e.g. skier versus kiter), range (e.g. cycling versus hiking), and number of people in the group. In most cases, outdoor recreation is a social activity involving groups of people in organised forms (Leask, 2016), and this is a factor that has not been considered in any of the studies of local responses away from infrastructure.

Managing people in reindeer ranges

Including data on human behaviour is necessary for the management of today's fragmented reindeer ranges because the primary instruments for human use management are indirect measures such as education, guiding, information, physical intervention, or direct measures like

Table 3. Metrics and monitoring methods for the various components of human presence in reindeer ranges.

Human use component	Relevant metrics or measurements	Monitoring methods
Spatial extent	Area and locations visited, association with (nearby) infrastructure.	GPS surveys, route drawings, location data from mobile phones, and mobile applications (e.g. STRAVA).
Temporal extent and variability	Duration of visits, seasonal variation in visits, trends over longer time frames.	Mechanical and electronic counting devices, location data from mobile phones, mobile applications (e.g. STRAVA), and indirect measurements such as toll road fees and overnight stays.
Volume	Total number of visitors in a given time interval.	Mechanical and electronic counting devices, and indirect measurements such as toll road fees and overnight stays.
Type of activity	Character, speed, size, and range of the different activities.	Visual observations, self-registration surveys, questionnaires, and camera / video monitoring.
Visitor characteristics	Attitudes, preferences, behaviour intentions, and responses to different management measures.	Self-registration surveys, questionnaires, personal interviews, focus groups and expert panels.

restrictions and prohibitions by law (Leask, 2016; Manning, 2010). The principle of common access rights to all uncultivated land in Norway (Outdoor Recreation Act, 1957), grants anyone the right (within certain bounds), to move freely across private and public land. Thus, management using direct measurements by law is very controversial in reindeer ranges and the management authorities need to prioritise indirect measurements.

Understanding visitors' motives, experiences, preferences, and sensitivity to management-generated information about responsible behaviour in reindeer areas can help managers design information strategies that are better able to direct human activity in environmentally friendly directions (Haukeland, Grue, & Veisten, 2010; Haukeland, Veisten, Grue, & Vistad, 2013; Scolozzi, Schirpke, Detassis, Abdullah, & Gretter, 2015). Simple surveys, either physical questionnaires at trailheads or web-based via QR codes, can collect information about numbers of visitors and their basic demographic profiles, the purpose of their visit, and the locations visited (Gundersen, Mehmetoglu, Vistad, & Andersen, 2015). Follow-up surveys can shed more detail on visitor characteristics, knowledge and preferences for landscapes, facilities and management (Vistad & Vorkinn, 2012). Adding these dimensions to the overall knowledge base can help understand current numbers and distribution of visitors, and help guide future management based on trends in the data.

Decision makers and planners need actionable general rules-of-thumb (Skjeggedal, Flemsaeter, & Gundersen, 2020), e.g. threshold values and knowledge about the impacts of new infrastructure, as well as more comprehensive knowledge of solutions to restore migration corridors and functional areas in a way that takes the physical context of the range into account (Nellemann et al., 2010). Management of remote refuge areas primarily concerns trail use since most visitors to reindeer ranges utilise marked trails (Panzacchi et al., 2015b; Gundersen et al., 2019). A recent study at Hardangervidda in Southern Norway tested trail crossings by GPS collared wild reindeer for 2241 km marked and unmarked trails. The study identified significant reduction in reindeer crossing if the number of people on the trails exceed 30 persons per day (Gundersen et al., 2020). Trail restrictions and manipulation of the trail infrastructure (i.e. re-routing trail corridors or removing mountain cabins) can affect visitor volumes and the types of visitors (Gundersen et al., 2015).

Obtaining location-specific data on humans and integrating them with reindeer location data has become easier since they can be logged on similar platforms (e.g. Cretois et al., 2021). New technology now enables us to sample location and physiological data on reindeer (from GPS-tags) and humans (from in-situ automatic counters, GPS surveys of study subjects, citizen science data, crowdsourced data such as STRAVA, Flickr, and aggregated location data from smartphones; Table 3) at an affordable cost. This kind of dynamic location data could be used to develop a multi-step analytical framework to quantify cumulative impacts and guide sustainable land use planning and management (Panzacchi et al., 2015b). Furthermore, if the location data are combined with knowledge of the visitor characteristics as outlined above from surveys or smartphones (with some restrictions cf. personal privacy considerations), it represents an opportunity to learn more about the visitors, their responses to management intervention and the reindeer responses to the visitors.

Towards a social-ecological system approach?

SES provide a framework for understanding the interactions between humans and the environment within a geographic unit. The framework was born out of the need to add meaning to what was previously coined context outside of a disciplinary boundary, i.e. 'environment' for social scientists or 'humans' for ecologists. Recent studies on the spatial and temporal overlap of reindeer and humans have started to address the gap between the scale of investigation and the scale of the disturbance. Much of the progress has come from our ability to obtain more detailed information on reindeer sensitivity, habitat use, and seasonal migration patterns (Flydal et al., 2019). However, our review revealed a simultaneous lack of detail on human use on and off infrastructure in reindeer ranges, such as the spatiotemporal pattern, volume and type of use. We believe that adding detail on the human component can represent an important step towards closing the gap, especially to provide more precise disturbance diagnostics and manage cumulative impacts on reindeer from a diversity of land uses (Forbes et al., 2006; Pape & Löffler, 2012).

Data on the human use component are useful because interventions to reduce disturbance of reindeer are essentially interventions to *manage people*. A range of methodologies have been developed to deal with the complex dynamics of SES (McGinnis & Ostrom, 2014), including management strategies that explicitly aim at increasing knowledge about effects of different measures on reindeer through experience or learning processes; reducing uncertainty of which measures are acceptable among the public; and to increase the legitimacy of the measures in the implementation phase by involving the stakeholders (Kaltenborn, Andersen, & Gundersen, 2014; Tyre & Michaels, 2011). Policy makers are faced with the challenge to harmonise the complexity of competing societal needs, stakeholders, individual requirements, and reindeer management goals (Sarkki et al., 2016; Skjeggedal et al., 2020). Such challenges have to be tackled in light of a certain degree of uncertainty associated with each of these layers. Reducing uncertainty about human presence can improve the precision of management decision processes and increase legitimacy among the stakeholders in the implementation phase (Tyre & Michaels, 2011). The main appeal of adopting components of a SES approach is that it calls for a more explicit treatment of the human component, as future management of wild reindeer ranges will need to build on a framework where wildlife and humans increasingly share the same landscapes.

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Author contributions

V.G. conceived the idea, designed the study and wrote the first draft. All authors commented on and approved further drafts.

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