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Review

The effects of power lines on ungulates and implications for power line routing and rights-of-way management

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Thousands of kilometres of power lines exist and more are planned. Ungulates that range over large areas are likely to encounter power lines, but a synthesis of power line effects on ungulates is lacking. Reindeer (*Rangifer tarandus tarandus*) are suspected to avoid power lines up to distances of 4 km. In contrast, some forest ungulates preferentially forage in power line rights-of-way, cleared areas under power lines. We reviewed the factors that possibly influence avoidance and attraction effects of power lines on ungulates, construct a conceptual framework, and make suggestions on how to mitigate avoidance effects through power line routing and rights-of-way management. Power line construction, noise and electromagnetic fields are possible sources of disturbance, while rights-of-way management influences habitat use under power lines. Disturbance and altered habitat use can induce barrier and corridor effects, thereby influencing connectivity. Species-specific effects influence behavioural disturbance and habitat use. We found little evidence for behavioural disturbance of reindeer or forest ungulates under power lines. Forest ungulates could benefit from browsing in power line rights-of-way if they are managed to provide abundant and preferred forage as well as sufficient cover. However, power lines may facilitate access for hunters and predators. As a precaution, construction of power lines should be avoided in calving areas. To establish a causal relationship between the construction of power lines and potential avoidance, before-after-impact-control studies are recommended. More research is needed to make recommendations for the optimal design of power line networks.

Key words: Power lines, rights-of-way, ungulates, disturbance.

INTRODUCTION

The transmission network for central grid power lines of at least 220 kV covers about 300,000 km in Europe (European Network of Transmission System Operators for Electricity, 2012) and 250,000 km in the USA (Abraham, 2002). Power lines above 220 kV may only constitute a small proportion of the total grid. About 200,000 and 450,000 km of overhead power lines carrying various voltages exist in Norway (Statistics

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Norway, 2011a) and Sweden (Grusell and Miliander, 2004), respectively.

In Norway, the central power line grid covers over 20% more surface than the central road network due to required corridor widths (740 versus 630 km^2), even though it is only half as long (28,000 versus 55,000 km) (Appendix A). The footprints of the distribution power line grid and road network are similar (Appendix A). We estimated that over 60% of central grid power lines traverse forests, while circa 40% of the Norwegian land area is covered by forest (Appendix B). The Norwegian central grid operator Statnett is planning to increase the construction of power lines to 300 km per year by 2020 (Statnett, 2013). 3,600 km of new power lines are planned in Germany until 2023 (German Transmission System Operators, 2013).

An extensive body of research on potential effects of roads on wildlife is available (reviewed in: Forman and Alexander (1998), Spellerberg (1998), Seiler (2001), Coffin (2007), Fahrig and Rytwinski (2009), Benitez-Lopez et al., (2010)), but knowledge on power line effects is scattered. Power lines may influence wildlife through disturbance, clearing of forest habitat under power lines, edge, barrier and corridor effects (Willyard and Tikalsky, 2004; Ball, 2012). Fragmentation by power lines could induce genetic drift, as for roads (Epps et al., 2005, Kuehn et al., 2007), and reduce population productivity and persistence (Griffen and Drake 2008; Haanes et al., 2013). Wide-ranging and mobile species as some ungulates will likely encounter power lines within their home ranges (Tables 1 to 7).

If disturbance by power lines is analogous to predation risk, it can cost energy for fleeing, increased vigilance, lost resources in habitats associated with danger and impaired mating and parental investment (Frid and Dill, 2002). If ungulates are disturbed by power lines, they can be expected to avoid power lines to reduce these costs. However, cleared areas under power lines (rights-of-way or ROW) are maintained as early- to mid-successional habitats (Bramble and Byrnes, 1982) and provide benefits through additional browse for forest ungulates (Bramble and Byrnes, 1972). This may result in attraction effects towards power line ROW.

The aim of this article is specifically to review the factors that possibly influence avoidance and attraction effects of power lines on ungulates (Tables 1 to 7), set into a conceptual framework (Figure 1). The review is based on both peer-reviewed and grey literature found through the Web of Science (isiknowledge.com) and Google Scholar, proceedings from the symposia on Environmental Concerns in Rights-of-Way Management (http://rights-of-way.org/1content.htm) and reviews on road ecology (see above). We searched for the keywords power line or transmission line in combination with ungulate, deer, elk, reindeer, sheep or cow; and subsequently scanned the papers for relevant references that did not show in the search engine. Research has mainly been undertaken on reindeer (*Rangifer tarandus tarandus*) in open alpine areas in Norway and on other ungulates in forests in Canada, USA and Norway (Table 1 to 7).

We identified proximate and ultimate causes of avoidance and attraction effects resulting from power line routing, construction, ROW management and species-specific effects (Figure 1). Power line construction may induce behavioural disturbance. ROW management and routing is expected to affect the use of ROW habitat. Sensitivity to disturbance and habitat preferences, which are species-specific, should further affect behavioural disturbance and habitat use. Both behavioural disturbance and habitat use determine avoidance and attraction effects. Therefore, power line routes could function as barriers and/or corridors, with consequences for connectivity and functional loss of habitats. Finally, we suggest how to mitigate avoidance effects through power line routing and ROW vegetation management.

EFFECTS OF POWER LINES ON UNGULATES

Behavioural disturbance from power line constructions

Power lines could disturb ungulates because they are artificial structures that can emit noise, light and electromagnetic fields. Frid and Dill (2002) reported that disturbance should be analogous to predation risk. Ungulates can be expected to alter their behaviour close to power lines if they are disturbed by power lines.

Noise

Electrical discharge by power lines produces crackling or hissing corona noise (Straumann, 2011). Wind can produce Aeolian noise though vibrations of the physical structure (Tsujimoto et al., 1991). An audiogram suggests that reindeer can hear corona noise from power lines (300 and 420 kV) up to 79 m (Flydal et al., 2010). Although little is known on the effects of corona noise, noise of a 500 kV transmission line did not significantly influence cattle behaviour (Ganskopp et al., 1991).

Electromagnetic fields

Power line electromagnetic fields are suspected to disturb the hypothesized magnetic alignment of cattle and roe deer (*Capreolus capreolus*) (Burda et al., 2009). However, ungulates may align themselves in the direction of power lines (Burda et al., 2009), supposedly interrupted in their north south alignment (Begall et al., 2008), for other reasons that were not accounted for such as wind and solar conditions for thermoregulation (Hetem

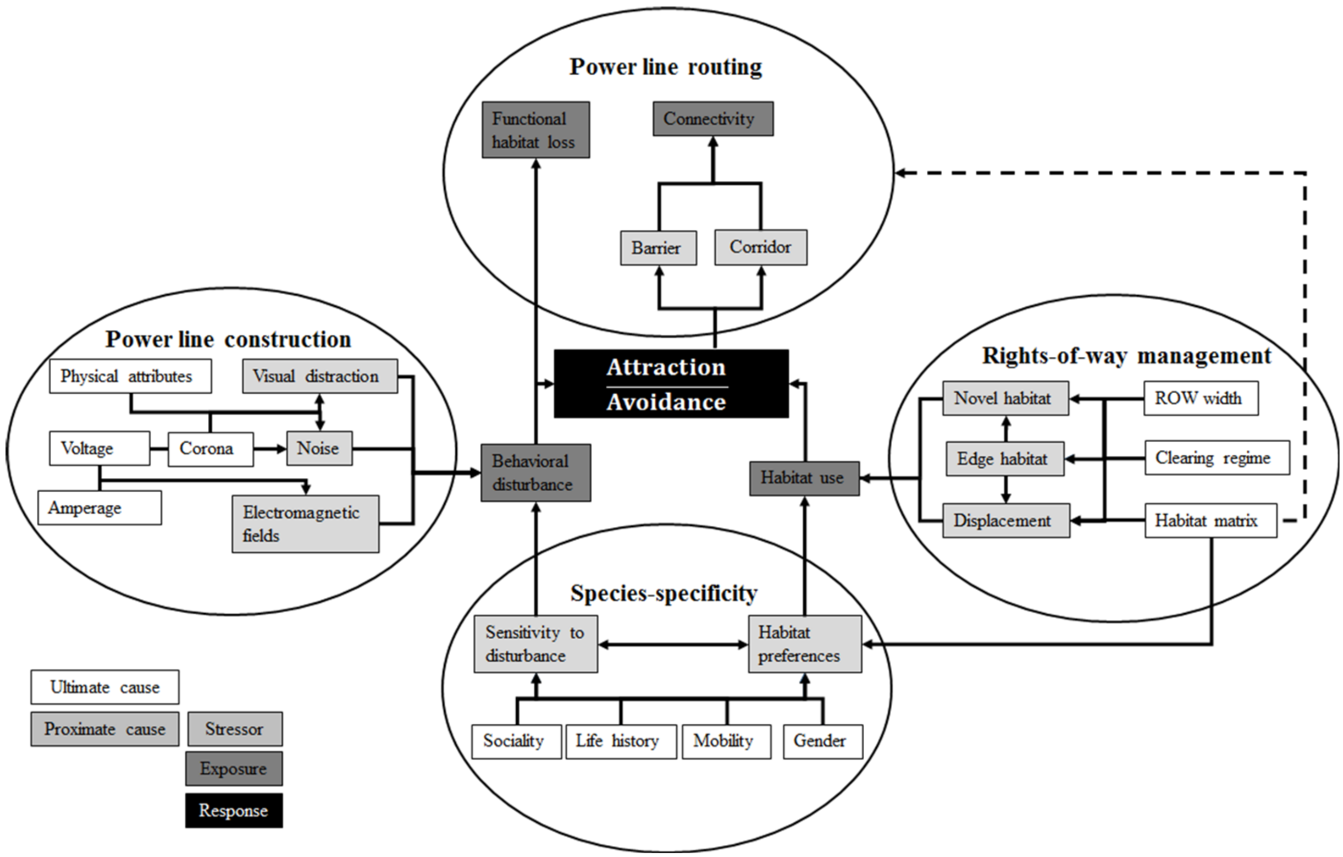

Figure 1. Possible factors influencing avoidance and attraction effects of power lines on ungulates.

et al., 2011). Fluctuations in electric fields of a 500 kV power line did not influence cattle behaviour (Ganskopp et al., 1991). Domestic-tame reindeer in enclosures became more restless and moved away from power lines (132 and 300 kV) when transmission load increased, although these results were ambiguous (Flydal et al., 2009).

Visual distraction

Visual distraction of power lines in the absence of noise and electromagnetic fields has apparently not been tested. Reindeer are suspected to see ultraviolet (UV) light (Hogg et al., 2011) and consequently corona flashes from power lines (Tyler et al., 2014). Reindeer's sensitivity to UV light is suspected to aid in detecting predators and forage in arctic environments (Hogg et al., 2011). The strongest emission of UV light by power lines was centred on 337 nm wavelength according to a patent application for a corona detector (Le et al., 1994). The eye lens of ungulates however blocked the largest proportion of light at this wavelength (Douglas and Jeffery, 2014). This may explain the lack of rentinal response towards UV light of 325 nm wavelength by other ungulates (Jacobs et al., 1994).

The lack of behavioural disturbance under power lines in general may indicate that the sight of power lines was not a source of disturbance. Deer (*Odocoileus* spp.), elk (*Cervus canandensis*) and other ungulates fed in a power line ROW (500 kV, 41 m wide) without signs of disturbance apart from a five-minute motionless period when entering the ROW (Goodwin Jr, 1975). Also semi-domestic reindeer in an enclosure experiment did not clearly avoid power lines (132 and 300 kV) (Flydal et al., 2009).

White-tailed deer (*Odocoileus virginianus*) (Bramble and Byrnes, 1972; Doucet et al., 1979; Doucet et al., 1983), moose (*Alces alces*) (unpublished data), bighorn sheep (*Ovis canadensis canadensis*) and elk (Goodwin Jr, 1975) bedded under power lines. Feeding positions and activity of cattle were similar in pens with and without power lines (Ganskopp et al., 1991). Other studies indicate that the vegetation in power line ROW rather than disturbance by power lines influences the use of those areas by ungulates (Goodwin Jr, 1975; Morhardt et al., 1984). Energy spent in response to indifferent stimuli may be wasted (Reimers and Colman, 2009).

Table 1. Possible disturbance effects of power lines on the behaviour of ungulates.

Species	Result	Reference	Location
Cattle Roe deer (*Capreolus capreolus*)	Cattle and roe deer align themselves in the direction of power lines, supposedly interrupted in their north-south alignment.	Burda et al. (2009)	Morocco South Africa, India, Australia, Belgium, Denmark, France, Germany, Ireland, Netherlands, Russia, UK, USA, Argentina
Semi-domestic reindeer (*Rangifer tarandus tarandus*)	Deer are suspected to hear power line (300 and 420 kV) noise up to 79 m distance.	Flydal et al. (2010)	Southern Norway
Reindeer (*Rangifer tarandus tarandus*)	Reindeer are suspected to see UV corona flashes from power lines.	Tyler et al. (2014)	

Although the given examples provide little evidence for the disturbance of ungulate behaviour by power lines, it does not necessarily mean that ungulates are not impacted by power lines. Human disturbance increased cardiac rates of bighorn sheep without changing their behaviour (MacArthur et al., 1979, 1982). Chronic stress can have adverse effects on reproductive, immune and neural systems and suppress growth in the absence of behavioural changes (Wingfield et al., 1997).

Altered habitat use at power line rights-of-way

Displacement from rights-of-way

Besides possible disturbance effects of power lines, forest ungulates may be displaced from cleared habitats under power lines because they lack canopy cover (Rieucau et al., 2007) and forage in the first years after clearing (Bramble and Byrnes, 1982; Lamothe and Dupuy, 1984; Garant and Doucet, 1995; Ricard and Doucet, 1999; Hydro-Québec, 2013) (Table 2).

Moose tracks and white-tailed deer tracks and pellets were less abundant in power line ROW (220 and 735 kV; 90 to 140 m wide) as compared to forests at 2 km distance (Joyal et al., 1984) and forests adjacent to ROW (120 - 735 kV, 30 - 150 m wide), respectively (Doucet et al., 1979; Lamothe and Dupuy, 1984; Jackson and Hecklau, 1995). White-tailed deer abandoned significantly more food provided in feeders in a power line ROW (30 m wide) as compared to adjacent forest when regeneration was absent (Rieucau et al., 2007). White-tailed deer browsed a smaller proportion of stems despite higher availability in power line ROW as compared to adjacent forest, except where the abundance of browsed stems exceeded that of the forest approximately six-fold (Mayer, 1976).

These results indicate that forest ungulates may be displaced by power line ROW (Table 2), especially when food, cover or both are lacking (Joyal et al., 1984). Increased food abundance may however compensate for the lack of cover (Mayer, 1976; Rieucau et al., 2007).

Rights-of-way as novel habitat

Following regrowth, habitats in power line ROW can also create novel habitats for forest ungulates through the provision of attractive feeding opportunities (Bramble and Byrnes, 1979; Ricard and Doucet, 1999; Hydro-Québec, 2013) (Table 3). White-tailed deer deposited more pellet groups, foraged more intensely and left more signs in power line ROW as compared to forests adjacent to ROW or control forest (Bramble and Byrnes, 1972; Cavanagh et al., 1976). The ROW provided more stems for browsing. Black-tailed deer (*Odocoileus hemionus columbianus*) used a power line ROW significantly more than adjacent mature forest, indicated by pellet groups (Loft and Menke, 1984). Deer use increased with shrub and herbaceous cover as well as foraging plants. These results indicate that food availability in power line ROW habitat is important for the use of that habitat by forest ungulates.

Not only the amount of forage, but also its composition may influence the use of power line ROW for browsing (Milligan and Koricheva, 2013). Moose and white-tailed deer browsing intensity in power line ROW appeared to be influenced by the proportion of preferred browse species rather than browse availability (Garant et al., 1987; Ricard and Doucet, 1999).

Trees that have been cut in power line ROW could provide higher quality browse because they prioritize growth instead of defence against herbivore damage through secondary metabolites (Rea and Gillingham, 2001). However, the increased availability of light in power line ROW clearings may promote both growth and defence (Nybakken et al., 2013). Herbs in a power line ROW provided higher concentrations of protein and

Table 2. Displacement of ungulates from power line rights-of-way.

Species	Result	Reference	Location
White-tailed deer (*Odocoileus virginianus*)	Deer browsed a smaller proportion of stems in power line ROW compared to adjacent woods except where browsed stems were approximately six times as abundant as in woods.	Mayer (1976)	Eastern USA
	Significantly fewer deer tracks and fewer pellets groups were found in a power line ROW (120 kV, 30 m wide, cleared two years before the study) compared to transect in forest at 30 distances from the ROW except on one survey for tracks.	Doucet et al. (1979)	Eastern Canada
	Significantly fewer pellets were found in cleared areas of a power line ROW (twin power lines, 735 kV, 150 m wide) compared to lateral forest in three of four sites.	Lamothe and Dupuy (1984)	Eastern Canada
	Significantly fewer tracks and fewer pellet groups were found in a power line ROW (345 kV, 45.7 - 90 m wide) compared to adjacent forest. Fewer tracks and pellet groups were found in the ROW compared to the edge of the ROW.	Jackson and Hecklau (1995)	North-eastern USA
	Deer left more food inside feeders placed in a power line ROW (30 m wide) compared adjacent forest when regeneration was absent.	Rieucau et al. (2007)	Eastern Canada
Moose (*Alces alces*)	Significantly fewer tracks were found in power line ROW (220 kV and 735 kV; 90 - 140 m wide) compared to transects in forests at 2 km distance.	Joyal et al. (1984)	Eastern Canada

Table 3. Power line rights-of-way as novel habitats for ungulates.

Species	Result	Reference	Location
White-tailed deer (*Odocoileus virginianus*)	Deer deposited two to three times more pellets and browsed more intensely in a power line ROW (55 m (expressed in feet in Bramble and Bymes (1982); 1 foot = 0.3048) wide) compared to forest at 10 m (expressed in chain; 1 chain = 20.1 m) distance from edge of the ROW.	Bramble and Byrnes (1972)	North-eastern USA
	Signs of deer use were several times more frequent inside a newly cleared power line ROW (72 m (expressed in feet; 1 foot = 0.3048 m) wide) compared to control forest.	Cavanagh et al. (1976)	North-eastern USA
Black-tailed deer (*Odocoileus hemionus columbianus*)	Deer deposited significantly more pellets inside a power line ROW compared to adjacent mature forest.	Loft and Menke (1984)	Western USA
Moose (*Alces alces*)	Moose browsed seven times more intensely in a power line ROW compared to forests at 2 km distance. There was no significant difference in the count of pellet groups.	Ricard and Doucet (1999)	Eastern Canada

Table 4. Edge effects at power line rights-of-way on ungulates.

Species	Result	Reference	Location
White-tailed deer (*Odocoileus virginianus*)	The proportion of browsed stems was in-between the proportion in power line ROW and adjacent woods in two study areas and lower than in both ROW and wood in another study area.	Mayer (1976)	Eastern USA
	More tracks were found at the edge of a power line ROW (twin power lines, 735 kV, 150 m wide) compared to the ROW and lateral forest. Fewer pellets were found in the ecotones between cleared areas and lateral forests compared to lateral forest.	Lamothe and Dupuy (1984)	Eastern Canada
	Fewer tracks and generally fewer pellet groups were found along the edges of a power line ROW (345 kV, 45.7 - 90 m wide) compared to adjacent forest.	Jackson and Hecklau (1995)	North-eastern USA

minerals and contained less fiber as compared to woody browse (Bramble and Byrnes, 1972). Forbs in power line ROW contained more protein and minerals as compared to grasses and woody browse (Harlow et al., 1995). The quality of the forage can be expected to influence the attractiveness of power line ROW habitat for forest ungulates.

Edge habitat along rights-of-way

Forest ungulates can benefit from the increased availability of forage not only inside power line ROW but also along edges (Bramble and Byrnes, 1979). Stem availability within 3-10 m from power line ROW edges was elevated as compared to forests at further distances from the edge (Luken et al., 1991; Luken et al., 1992; Rieucau et al., 2007; Powell and Lindquist, 2011). 18 of 20 shrub species were significantly more likely to be found at the edge of a 60 m wide power line ROW as compared to its centre (Brisson et al., 1997).

Lamothe and Dupuy (1984) noted more white-tailed deer tracks along the edge of a power line ROW (twin power lines, 735 kV, 150 m wide) as compared to the ROW and lateral forest (Table 4). However, fewer pellets were found in the ecotones between cleared areas and lateral forests as compared to further inside the forests (Lamothe and Dupuy, 1984; Jackson and Hecklau, 1995), indicating that deer may have spent more time in areas of better cover. The abundance of stems along power line ROW edges as compared to ROW and adjacent woods and the proportion of those stems that were browsed by white-tailed deer did not follow a consistent pattern across study areas (Mayer, 1976). Shrub availability along power line ROW edges may favour ungulate browsing and habitat use along those edges but a link between the two has, as far as we know, not been established.

Functional loss of habitat

Disturbance by power lines may not only affect the use of areas directly under power lines but also habitats adjacent to it. Power lines contributed to a reduction in area use of wild female reindeer within 1 km from pitfall traps and hunting blinds (Panzacchi et al., 2013). The density of semi-domesticated reindeer was significantly (73%) lower within 4 km of a power line (132 kV) than further away during calving in areas of rugged terrain (Vistnes and Nellemann, 2001) (Table 5). However, more favourable snow conditions and lower predation rates at higher elevations further away from power lines may have influenced this result (Reimers and Colman, 2009).

Wild reindeer were significantly less abundant than expected within 2.5 km of power lines (300 and 420 kV) in six of eight sampling years (Nellemann et al., 2001) (Table 5). Areas transected by power lines (66 - 420 kV) were also used less than expected (Vistnes et al., 2001). However, the accessibility of lichen forage, provided by an index of snow depth and hardness, was approximately three times lower in areas transected by power lines and other infrastructure (Vistnes et al., 2001). The influence of forage accessibility, although not significantly different between areas, can be discussed.

Wild reindeer became less abundant within 4 km from power lines (300 and 420 kV) or roads after they were built and more abundant beyond this distance (Nellemann et al., 2003). However, the shift in abundance coincides with the flooding of an area close to power lines and roads following the construction of a dam (Nellemann et al., 2003).

In contrast, counts of wild reindeer were disproportionately high within 5 km of power lines and minor roads above 1,400 m a.s.l. in summer (Vistnes et al., 2008). There was no clear evidence for aversion by wild reindeer along a 66 kV power line indicated by lichen

Table 5. Functional loss of habitat surrounding power line rights-of-way for ungulates.

Species	Result	Reference	Location
Semi-domesticated reindeer (*Rangifer tarandus tarandus*)	The density of deer was significantly (73 %) lower below compared to above 4 km from a power line (132 kV) during calving in areas of rugged terrain.	Vistnes and Nellemann (2001)	Northern Norway
Wild reindeer (*Rangifer tarandus tarandus*)	Deer were significantly less abundant than expected in areas within 2.5 km from power lines (300 and 420 kV) in six of eight sampling years.	Nellemann et al. (2001)	Southern Norway
	Deer were less abundant in areas transected by power lines (66 - 420 kV) than expected.	Vistnes et al. (2001)	South-central Norway
	Deer became less abundant in areas within 4 km from power lines (300 and 420 kV) or roads after they were built and more abundant in areas above that distance.	Nellemann et al. (2003)	South-western Norway
	Power lines contributed to a reduction in area use of female deer within 1 km from pitfall traps and hunting blinds.	Panzacchi et al. (2013)	Southern-Norway

measurements (Reimers et al., 2007). Moose did not avoid moving towards central grid power lines except in certain habitats during autumn (Bartzke et al., in press). Hydro-Québec (2013) reported that the use of winter feeding grounds by white-tailed deer was not inhibited by power line ROW (120 - 735 kV, 30 - 164 m wide) close to them.

Connectivity and power line routing

Power line routes as barriers

Disturbance by power lines and the lack of canopy cover in power line ROW may prevent animals from crossing power lines. Vistnes et al. (2004) concluded that wild reindeer refrained from crossing power lines based on lichen measurements on two sides of parallel power lines (132 and 300 kV) indicating differential grazing. However, these power lines were routed along a dam in the northern part of the study area that could have impeded crossings. The side that was apparently less grazed in the southern part of the study area was closer to a main road and urban settlements at lower elevations. Reimers et al. (2007) suggested that harvesting along a summer open road close to power lines could have been another alternative explanation for reduced area use.

Wild reindeer crossed a 66 kV power line in 14 of 22 years according to aerial surveys (Reimers et al., 2007). Strand et al. (2001) hypothesized that wild reindeer cross barriers when the need to migrate is extra-large based on the difference in the availability and accessibility of forage, disturbances, predation risk and distance between alternative feeding areas. Moose did not refrain from crossing power lines (735 kV) with ROW that were 90 m wide (Joyal et al., 1984). Neither did white-tailed deer refrain from crossing power line (120 - 735 kV) ROW of 30 - 146 m width (Hydro-Québec, 2013). Only two animals of 87 elk and nine deer (*Odocoileus* spp.) failed to cross a power line ROW (500 kV, 41 m wide) (Goodwin Jr, 1975) (Table 6).

However, white-tailed deer reduced crossings away from a planted area within a power line ROW (120 kV, 30 m wide) (Doucet et al., 1983). Moose refrained from crossing power line (230 - 735 kV) ROW that were 140 m wide (Joyal et al., 1984). The need to cross power lines, the size of the power line construction, transmission load, the width of the corridor and the availability of cover may influence the willingness of ungulates to cross power lines.

Power line routes as corridors

Food availability along power line ROW forest edges or routes for easy travel may encourage movement of ungulates along power lines. Moose increased movements along central grid power lines over movements towards and away from power lines when approaching them (Bartzke at al., 2014). However, when close enough to cross power lines (25 m), moose moved randomly with respect to the power line.

White-tailed deer were reported to start travelling along power line ROW (345 kV, 47.5 - 90 m wide) after construction (Jackson and Hecklau, 1995). Goodwin Jr (1975) observed an elk (*Cervus canandensis*) cow with two calves travelling along a power line ROW (500 kV, 41 m wide). Forman and Deblinger (2000) sighted a moose

Table 6. Power line routes as barriers or corridors.

Species	Result	References	Location
Elk (*Cervus canadensis* spp.) Deer (*Odocoileus* spp.)	Two of 87 elk and nine deer failed to cross a power line ROW (500 kV, 41 m wide).	Goodwin Jr (1975)	North-western USA
Moose (*Alces alces*)	Moose refrained from crossing power line ROW (230 - 735 kV, 140 m wide) significantly.	Joyal et al. (1984)	Eastern Canada
	Movements along central grid power lines increased over movements towards and away from power lines when getting closer.	Bartzke et al. (2014)	Central Norway
Wild reindeer (*Rangifer tarandus tarandus*)	Significantly different lichen measurements on two sides of parallel power lines (132 and 300 kV) indicated differential grazing on each side.	Vistnes et al. (2004)	South-central Norway
	Wild reindeer herds crossed a 66 kV power line in 14 of 22 years according to aerial surveys.	Reimers et al. (2007)	South-central Norway

that travelled along a power line ROW and a railroad. We found no further evidence for the use of power line ROW as movement corridors. However, bison (*Bison bison*) were shown to move along roads (Bjornlie and Garrott, 2001; Bruggeman et al., 2007), although surrounding terrain can be confounding (Bruggeman et al., 2006).

Species-specific ultimate and proximate causes

Sociality

Reindeer in Norway may in general be more sensitive to power lines than other ungulates like moose or white-tailed deer because they live in large groups in open alpine habitat experiencing comparatively low human use but intense seasonal hunting. These attributes were shown to increase ungulate flight responses (Stankowich, 2008). In open habitats, ungulates should detect and react to disturbances at greater distances because there are no escape habitats to seek refuge (Stankowich, 2008).

In theory, ungulates in larger groups may spend more time being disturbed because they have a greater chance of detecting disturbances (Taraborelli et al. (2012) for guanacos (*Lama guanicoe*)), and disturbance might be transmitted between group members (Stankowich, 2008). Groups of West Greenland caribou (*Rangifer tarandus groenlandicus/tarandus*) became aware of humans at larger distances than solitary individuals (Aastrup, 2000). Although feral reindeer fled at shorter distances from humans in larger groups (Reimers et al., 2006) and larger groups of Svalbard reindeer (*Rangifer tarandus platyrhynchus*) did not discover observers earlier, they were reported to correspond cooperatively (Colman et al., 2001).

The ability to quickly detect and react to disturbances could be an evolutionary advantage to protect against real predators but a disadvantage if the source of the disturbance is not lethal. Then animals loose time and energy in being unnecessarily disturbed. The degree of reindeer domestication may also influence their sensitivity to disturbances (Flydal et al., 2009; Reimers et al., 2012).

Mobility

The lack of power line avoidance by forest ungulates may also in part be explained by the mobility of the species of concern. Stationary species and species with small home ranges may not have alternative habitats available, or the costs of reaching those habitats outweigh the costs of remaining close to power lines (Gill et al., 2001). This could occur in times or areas of resource limitations. White-tailed deer increased stationary browsing time in a power line ROW from 7 to ~40% in cold winter as compared to a mild winter (Doucet et al., 1987). Possibly forest ungulates cannot afford to avoid power line ROW when overall food availability is insufficient in relation to their densities (Ytrehus et al., 1999; Lamoureux et al., 2001). Hagen et al. (2007) speculated that reindeer will also react less to disturbances when the population size increases.

Gender and life history

Throughout a species' life cycle, its disturbance tolerance towards power lines may vary with life history traits and states such as gender, age, reproductive status, social

Table 7. Potential demographic impacts of power lines and associated clearings on ungulates.

Species	Result	References	Location
White-tailed deer (*Odocoileus virginianus*)	Tracks and pellet groups increased significantly after the construction of a power line ROW (345 kV, 45-90 m wide).	Jackson and Hecklau (1995)	North-eastern USA
Wild reindeer (*Rangifer tarandus tarandus*)	Calf/cow ratio declined significantly with the construction of human infrastructure including power lines.	Nellemann et al. (2003)	South-western Norway
	Hunters harvested more, although not significantly more, moose in power line ROW sites compared to control sites.	Ricard and Doucet (1995)	Eastern Canada
Moose (*Alces alces*)	89 of 107 hunters said they were hunting in a power line ROW (500 kV, 41 m wide), control clearings or along roads.	Goodwin Jr (1975)	North-western USA
	A power line (500 kV) ROW was reported to be a traditionally preferred hunting area.	Perry et al. (1997)	Eastern USA

status and/or season (for example, rut) (Frid and Dill, 2002; Stankowich, 2008).

Several, although not all (Frid, 2003; Mahoney et al., 2011), studies indicate that groups with calves (Aastrup, 2000), females with young (Ciuti et al., 2008) and females in times of calving or raising calves (Maier et al., 1998; Vistnes and Nellemann 2001; Bartzke et al., in press) are most sensitive to human disturbance (Wolfe et al., 2000). However, no clear evidence for gender-specific effects towards power lines was found (Vistnes and Nellemann, 2001; Bartzke et al., in press). Possibly, power lines are not disturbing enough to promote gender-specific effects in contrast do direct harassment by humans or motorized vehicles.

Potential demographic impacts

Fragmentation effects by power lines have been argued to contribute to population decline (Nellemann et al., 2003), impair migration (Vistnes et al., 2004) and could induce genetic drift, as for roads (Epps et al., 2005; Kuehn et al., 2007). Yet we found no evidence that the construction of power lines alone influenced population dynamics of ungulates. Tracks and pellet groups of white-tailed deer increased significantly after the construction of a power line (345 kV, 45-90 m wide) (Jackson and Hecklau, 1995) (Table 7).

Although power line ROW can provide additional forage, they could also be an "ecological trap" (Battin, 2004). Ecological traps are thought to occur when the attractiveness of a habitat (through increased browse) increases disproportionately relative to its value for survival and reproduction. An increased rate of disturbance in connection with an increased rate of predator encounters can result in a reduction of population size (Frid and Dill, 2002) due to increased antipredator investment (stress) (Ydenberg and Dill, 1986; Cassirer et al., 1992; Maier et al., 1998; Rumble et al., 2005), reduced net energy intake (Stockwell et al., 1991) and body condition (Bradshaw et al., 1998; Luick et al., 2011). Power line ROW along with access roads may provide access for hunters (Goodwin Jr, 1975; Ricard and Doucet, 1995; Perry et al., 1997). Natural predators were reported to travel along power line ROW (Foster, 1956 in Ball, 2012; Paquet et al., 1996; Gurarie et al., 2011). Power lines provide nesting and perching opportunities for golden eagle (*Aquila chrysaetos*) (Steenhof et al., 1993; Prather and Messmer 2010), which preys on ungulates (Nybakk et al., 2002; Norberg et al., 2006; Johnsen et al., 2007; Hamel and Côté, 2009; Nadjafzadeh et al., 2013).

Increased predation risk, coupled with disturbance and fragmentation induced by power lines, could affect the demography of ungulate populations. The availability of forage in power line ROW may however favour forest ungulate populations locally.

KNOWLEDGE GAPS

A more causal relationship between the construction of power lines and possible avoidance by ungulates may be established from before-after-impact-control studies

(Beyers, 1998). Observing wild ungulate behaviour under power lines as compared to similar control areas would be necessary to find out if ungulate behaviour is disturbed by power lines. Wildlife cameras (Dunne and Quinn, 2009; Kuijper et al., 2009) or GPS collars with cameras can be used for this purpose. Measuring faecal glucocorticoid concentrations possibly in combination with other disturbance indicators (Tarlow and Blumstein, 2007) could help to show if power lines are anthropogenic stressors. Separating the causes of possible disturbances like visual distraction, noise or electromagnetic fields would require further experiments. Ideally, experimental and control animal populations should be established. Experiments using reindeer with different degree of domestication should be made as in Flydal et al. (2009).

A number of the reviewed studies lacked statistical analyses (Bramble and Byrnes, 1972; Cavanagh et al., 1976; Mayer, 1976; Doucet et al., 1983; Doucet et al., 1987; Garant et al., 1987), did not precisely report the methodology (Loft and Menke 1984), power line voltage and/or ROW width (Mayer, 1976; Ricard and Doucet, 1999; Rieucau et al., 2007; Burda et al., 2009; Panzacchi et al., 2013). There were also large differences in scale ranging from few metres (Lamothe and Dupuy, 1984; Jackson and Hecklau, 1995; Rieucau et al., 2007) up to several kilometres (Vistnes and Nellemann, 2001). The scale considered may invert the conclusions (Vistnes and Nellemann, 2008). The ability to see or hear power lines may be an important factor to be considered, as for roads (Montgomery et al., 2012).

Knowledge gaps exist on the extent of power line ROW edge effects on forest ungulates, the factors influencing barrier effects and the preference of human and natural predators for hunting near power lines (Table 7). Addressing these gaps would help to show if ungulate populations may be impacted by power lines.

Routing power lines along existing power lines and roads may reduce further fragmentation of ungulate habitat but at the same increases avoidance and barrier effects. Jaeger et al. (2005) concluded from a modelling exercise that bundling roads would have less negative impacts on population persistence than distributing them evenly across the landscape. However, female wild reindeer reduced area use within 1 km from ancient pitfall traps and hunting bows when accounting for the effects of power lines and roads more than roads or power lines alone (Panzacchi et al., 2013).

The food availability in power line ROW could attract forest ungulates away from roads and railroads, similarly to supplemental feeding (Wood and Wolfe, 1988; Andreassen et al., 2005), and reduce vehicle collisions. Power line ROW could also attract ungulates towards areas surrounding roads. Further studies are necessary to make recommendations for the optimal design of power line networks.

MITIGATION MEASURES

Implications for power line routing

The reviewed literature suggests that power lines induce minor negative behavioural responses to ungulates. Benefits from additional food in power line ROW for forest ungulates may be expected if they are routed through old coniferous forests with little food but good canopy cover (Bjørneraas et al., 2011). Moose browsed four times more intensely in power line ROW traversing coniferous forests as compared to those traversing mixed forests (Ricard and Doucet, 1999). When power lines traverse food-rich young, mixed or deciduous forests, the availability of browse may not compensate for the lack of cover (Rieucau et al., 2007).

In contrast to forest ungulates, several studies suggest that power lines may disturb reindeer inhabiting open alpine areas. However, the lack of clear evidence for the disturbance of semi-domestic reindeer behaviour in the proximity of power lines (Flydal et al., 2009) and the maximum distance at which reindeer may hear power lines (79 m) (Flydal et al., 2010) indicates that power lines themselves were not necessarily the main cause of the reduced area use close to power lines reported by Vistnes et al. (2001), Nellemann et al. (2001, 2003) and Panzacchi et al. (2013). Earlier, Vistnes et al. (2004) suggested that building power lines should be avoided in wild reindeer habitats. This recommendation could be debated.

To minimize inference with reproduction, the construction of power lines, which may require the use of helicopters and building access roads, should be avoided calving areas. Disturbance after the construction of power lines can be minimized by prohibiting hunting, vehicles and pets along them (Bergerud et al., 1984; Miller et al., 2001; Clair and Forrest, 2009). Power line corona noise, flashes and magnetic fields can be reduced through engineering solutions (Teich and Weber, 2002; Conti et al., 2003; Kalhor and Zunoubi, 2005; Semmler et al., 2005).

Implications for power line ROW management

It is possible to provide attractive power line ROW habitat for forest ungulates with appropriate management (Bramble and Byrnes, 1972; Cavanagh et al., 1976; Mayer, 1976). Experimental studies on the management of power line ROW have been undertaken in the USA, where the application of herbicides appears to be a common practice to reduce tree regrowth (Cavanagh et al., 1976; Mayer 1976; Bramble and Byrnes, 1982; Ballard et al., 2002; Haggie et al., 2008) in addition to mowing, burning and fertilizing (Harlow et al., 1995). This may not be an option in other countries.

A stem height of 4 m for birch and 3.5 m for pine may be be the optimal size to provide maximum ungulate forage (Kalén and Bergquist, 2004). Felling trees that reach heights of 5 m may ensure continuous high browse availability without complete removal of cover. The removal of single large trees would also create gaps for the growth of forbs, ferns and bilberry (*Vaccinum myrtillus*), which can be an important part of forest ungulates diet (Hjeljord et al., 1990; Mysterud and Ostbye, 1995; Krojerová-Prokešováa et al., 2010). Alternatively, trees could be cut at a height of 1 m instead of full removal to shorten the period of low browse availability after clearing. Adjustments can be made dependent on the ability to reach the vegetation by the respective species (Garant and Doucet, 1995). Cutting during winter instead of summer resulted in higher browse production in spring, supposedly because of a better ability of plants to allocate reserves for regrowth (Garant and Doucet, 1995).

During construction, hinge cutting, that is, cutting deciduous large trees only half way through, would maintain cover availability and facilitate regrowth of forage (Global Wildlife Management, 2013). Less preferred coniferous trees like spruce (*Picea* spp.) could be removed entirely in favour of deciduous trees. Stable scrublands are more resistant to tree invasion, potentially reducing the need for clearing (Niering and Goodwin, 1974). The applicability of the suggested management techniques would have to be tested in the field.

Disclosure or conflict of interest

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Appendix A. Land area traversed by power lines and roads in Norway. Line lengths were derived from official statistics (Brunvoll and Monsrud, 2011; Statistics Norway, 2011a, b). *Lengths were retrieved from a road database (Norwegian Mapping Authority, 2012). Corridor widths are provided following Bevanger and Thingstad (1988) for power lines and E Englien (Statistics Norway, pers. comm.) for roads. The width of roads consists of road width plus road edge.

Area	Type	Length (km)	Corridor width (m)	Tied-up surface area (km^2)
Central power line grid	220 - 420 kV	7,907	38	300
	110 - 145 kV	10,407	25	260
	33 - 66 kV	9,868	18	177
	Total	28,182		738
Distribution power line grid	0.2 - 24 kV	165,789	Variable (ca. 5 - 10)	829 - 1,658
Central road network	Highways	6,639*	17	113
	National roads	20,837*	13	271
	County roads	27,281	9	246
	Total	54,757		630
Distribution road network	Local roads	38,591	8	309
	Private roads	75,453*	7	528
	Forest roads	48,571	7	340
	Total	162,615		1,177

Appendix B. Habitat types and their re-classification of the Norut vegatation map (Johansen et al., 2009), percentage of centage of central power lines and road grid length traversing different habitat types and the percentage of those habitat types of the area in Norway. Power line routing data from the central grid operator Statnett was clipped with the contours from the Norwegian land area. We determined the percentage of the line length routed through different habitat types with the function isectlinerst in the program geospatial modeling environment (Beyer undated). For a comparison, we did the same analysis with data of the central road network (Norwegian Mapping Authority 2012) including highways, national and county roads.

To capture habitats surrounding power lines and roads, we resampled the 30 × 30 m habitat raster to a 60 × 60 m raster. Raster cells that overlapped urban settlement polygons were classified as settlements. The percentage of the different habitat types of the Norwegian land area was the percentage of the respective raster cells. No accurate power line routing data of lower voltage power lines was available. We used ArcGIS version 10 (ESRI, 2011) to handle and modify spatial data.

Habitat	Class of the Norut vegetation map	Percentage of central grid power line length	Percentage of central grid road length	Percentage of land area
Forest	Dense coniferous woodland. Open coniferous and mixed woodland. Lichen-rich pine woodland. Low-herb woodland and rich deciduous woodland. Tall-herb and tall-fern deciduous woodland. Bilberry and small-fern downy birch woodland. Crowberry downy birch forest. Lichen-rich downy birch forest.	61	45	39
Mire and freshwater	Ombrotrophic hummock bog and lawns. Minerotrophic flat fen. Hollow mire and open swamp. Freshwater.	7	5	11
Alpine areas and ridges	Exposed ridges, scree, talus and rock. Gras and wood-rush ridges. Heather ridges. Lichens, heather and pigmy birch Heather rich lee side. Grass and dwarf willow snow patch. Late snow patch vegetation. Glaciers, permanently snow-covered areas and extreme snow patch plant communities.	14	8	31
Grass and heather	Heather and fresh brushwood (lowland and mountain areas). Herb-rich grassland (lowland and mountain areas).	11	10	15
Agriculture		5	21	3
Towns and villages		<1	11	<1
Not classified		<1	<1	<1