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**A boreal invasion in response to climate change? Range shifts and
community effects in the borderland between forest and tundra**

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MATERIALS AND METHODS – EXTENDED VERSION

In this paper, we review observed changes in the distribution, abundance and dynamics of birds and mammals in boreal and alpine Sweden since the 19th century, as well as suggested drivers of change.

The first part of the review is an overview of known changes in southern and northern birds. According to our definition (see paper), 118 of the 196 species which regularly breed in boreal or alpine Sweden had a southern or northern distribution (Table S1). The remaining 78 species, i.e. the ones not included in the paper (Table S2), were species which did not have one distinct latitudinal or altitudinal distribution limit in boreal or alpine Fennoscandia. Their distribution could instead be, for example, eastern or western (i.e. they have both a southern and a northern distribution limit in boreal/alpine Fennoscandia), patchy (e.g. including both alpine tundra and coasts), coastal, omnipresent (i.e. the distribution covered all of Fennoscandia), or a distribution caused by an introduction or large-scale European range expansion during the 20th century which meant that the species was not present at the beginning of the study period (Table S2). To not exclude southern species which might have expanded north throughout Sweden since the 19th century and at present consequently have a northern distribution limit slightly north of Sweden, we classified species as southern based on their northern distribution limit in Fennoscandia. However, our source of information on long-term range shifts and population trends in Swedish birds (Svensson et al. 1999), only reported the present distribution within Sweden. We therefore based our classification on distribution maps in Grant and Svensson (1999). For Sweden, the distribution maps in Svensson et al. (1999) correspond highly with those in Grant and Svensson (1999).

Svensson et al. (1999) compiled quantitative and qualitative information on

Swedish bird species, including a section on the history of each species since the 19th century. For each of the 118 southern and northern species, we used the historical information provided by Svensson et al. (1999) to assess long-term trends, defined as the net change in the range or abundance of each species between the 19th century and late 20th century. Firstly, we noted whether the distribution limit was known to have changed (range contraction or expansion). Such information on range shifts were found for 6 northern and 28 southern species. Secondly, if the distribution limit had not changed, we noted whether the information provided could be interpreted as a net change in abundance (long-term increasing or declining trend). This was the case for 11 northern and 23 southern birds. For one declining species (*Charadrius morinellus*), this trend classification was based on sources from Finland, which substantiated a general declining trend in Europe. For all other species, the trend classification was based on information from Sweden. We classified the remaining 50 species as having "no long-term trend", which meant that we could not interpret the provided information as an overall increase or decline. This category included (1) species where the population size had been stable; (2) species which had experienced fluctuations without a directional trend, e.g. decline(s) followed by recovery; (3) species where there had been locally different trends within the study area; (4) species where no information was available.

The second part of the review includes information which we assessed from yearly reports on forestry published by Sweden's Official Statistics between 1870 and 1966. We refer to these reports as one source (Sweden's Official Statistics 1870-1966). The reports summarize information provided by e.g. foresters to the person(s) writing the reports. The contents vary somewhat over time, suggesting it was partly up to the writer(s) to decide what information to include. In most years, however, the reports include brief qualitative statements on the status of game species and predators

in different parts of Sweden. For example, it could be stated in which parts of Sweden a persecuted species still was found, or which areas an expanding species had reached. For game species, the availability in a particular district, county or over a larger region could be described as e.g. "plenteous", "abundant", "good", "average", "scanty", "abysmal", "increasing/declining since last year", or "no change since last year". We refer to the reports both to describe change in species distributions, and to describe the local dynamics of some game species in the county of Västerbotten in 1870-1966. For the latter, we reclassified the qualitative descriptions of the status of each species each year into five categories; abundant, good, average, below average and scarce. In years when a species was described as increasing or decreasing since last year, we changed the classification one step up or down, respectively. If a species was described as increasing or decreasing for several years, we extrapolated the yearly status during this time period. For example, if the availability of a species was described as scarce in year 1, increasing in the next three years, and then as average in year 5, we extrapolated the degree of increase from scarce to average in the intermediate years. Regarding the quality of the reports, we think it is reasonable to assume that the overall picture is reliable, although the accuracy of each individual piece of information probably varies depending on the meticulousness of individual reporters and writers.

To illustrate temperature trends in northern Sweden, we retrieved temperature data from the Swedish Meteorological and Hydrological Institute. Four weather stations were operating continuously from 1862 to the early 2000s. We used this data to calculate a 10-year running mean in yearly temperature.

We use data from a survey of a raptor guild in Stora Sjöfallet National Park (67°29'N 18°21'E) to illustrate potential northern advancement in Eurasian kestrels (*Falco tinnunculus*) since the 1970s. For comparison, we also showed data on rough-

legged buzzards (*Buteo lagopus*). Surveys were carried out at this location, comprising the same nest sites, in 1970-1978 and 2001-2011 (Broo and Lindberg 1981, Hellström 2014). The densities of the two species were estimated as the number of breeding pairs per 10 km², where breeding pairs were defined as pairs which initiated egg clutches. Number of breeding pairs varied between 0 to 35 for kestrels and 0 to 70 for rough legged buzzards.

We exemplify northern and northwestern advancement in game species using estimated hunting bags provided by the Swedish Association for Hunting and Wildlife Management. The association collects yearly reports from hunters throughout Sweden and estimate regional hunting bags by extrapolating the number of animals killed in reported areas to the area of counties (Elmhagen et al. 2011). Since 1997, hunting bags are also estimated for hunting districts within counties.

References

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Table S1. The 118 species that were classified as having either a southern (S) or northern (N) distribution in boreal/alpine Sweden. For each species, the change assessed from Svensson et al. (1999) is described as a range shift (contraction or expansion), a long-term trend in abundance (increase or decline) or as no change (none). The category “no change” includes both species which did not show a long-term change in abundance (see text) and species for which no data were available. For all species which showed either a range shift or a long-term trend, suggested drivers of change were assessed from Svensson et al. (1999). Nomenclature following Dyntaxa (2013).

Species	Common name	S or N	Change	Suggested drivers of change
<i>Accipiter gentilis</i>	northern goshawk	S	None	
<i>Accipiter nisus</i>	Eurasian sparrowhawk	S	None	
<i>Acrocephalus scirpaceus</i>	Eurasian reed warbler	S	Expansion	land-use change (agriculture and eutrophication)
<i>Aegithalos caudatus</i>	long-tailed bushtit	S	None	
<i>Aegolius funereus</i>	boreal owl	S	None	
<i>Alauda arvensis</i>	Eurasian skylark	S	None	
<i>Anas crecca</i>	Eurasian teal	S	Decline	land-use change (drainage of wet habitats)
<i>Anas penelope</i>	Eurasian wigeon	N	None	
<i>Anas platyrhynchos</i>	mallard	S	Increase	unknown
<i>Anser erythropus</i>	lesser white-fronted goose	N	Decline	hunting, predation, change in overwintering areas
<i>Anser fabalis</i>	bean goose	N	Decline	hunting, land-use change (agriculture and drainage of wet habitats)
<i>Anthus cervinus</i>	red-throated pipit	N	None	
<i>Anthus trivialis</i>	tree pipit	S	Decline	land-use change (agriculture), change in overwintering areas
<i>Apus apus</i>	common swift	S	Increase	other human-related factors (more nesting sites)
<i>Asio otus</i>	long-eared owl	S	None	
<i>Aythya marila</i>	greater scaup	N	Decline	unknown
<i>Bubo scandiacus</i>	snowy owl	N	Contraction	disrupted rodent dynamics
<i>Buteo buteo</i>	common buzzard	S	None	
<i>Buteo lagopus</i>	roughleg	N	None	
<i>Calcarius lapponicus</i>	Lapland longspur	N	None	
<i>Calidris alpina alpina</i>	dunlin	N	None	
<i>Calidris falcinellus</i>	broad-billed sandpiper	N	Contraction	land-use change (agriculture) and drainage of wet habitats
<i>Calidris maritima</i>	purple sandpiper	N	None	
<i>Calidris temminckii</i>	Temminck's stint	N	Decline	land-use change (agriculture)
<i>Caprimulgus europaeus</i>	European nightjar	S	Decline	land-use change (agriculture), change in overwintering areas
<i>Carduelis cannabina</i>	common linnet	S	Decline	land-use change (agriculture)
<i>Carduelis chloris</i>	European greenfinch	S	Expansion	other human-related factors (e.g. favored by feeding and associated with built-up areas)
<i>Carduelis flammea flammea</i>	common redpoll	N	None	
<i>Carduelis hornemanni</i>	Arctic redpoll	N	None	
<i>Carduelis spinus</i>	Eurasian siskin	S	None	
<i>Certhia familiaris</i>	Eurasian treecreeper	S	None	
<i>Charadrius dubius</i>	little ringed plover	S	Expansion	other human-related factors (associated with exploited areas)
<i>Charadrius morinellus</i>	Eurasian dotterel	N	Decline	hunting, change in overwintering areas
<i>Chroicocephalus ridibundus</i>	black-headed gull	S	Expansion	unknown
<i>Clangula hyemalis</i>	long-tailed duck	N	None	
<i>Columba oenas</i>	stock dove	S	None	

<i>Columba palumbus</i>	common wood pigeon	S	Increase	land-use change (agriculture), other human-related factors (associated with built-up areas)
<i>Corvus corone</i>	hooded crow	S	None	
<i>Corvus monedula</i>	western jackdaw	S	Expansion	land-use change (agriculture), other human-related factors (associated with built-up areas)
<i>Cuculus canorus</i>	common cuckoo	S	Decline	unknown
<i>Cyanistes caeruleus</i>	Eurasian blue tit	S	Expansion	land-use change (agriculture), other human-related factors (e.g. favored by built-up areas, feeding and nesting boxes)
<i>Cygnus olor</i>	mute swan	S	Expansion	land-use change causing eutrophication, climate change
<i>Delichon urbicum</i>	common house martin	S	None	
<i>Dendrocopos major</i>	great spotted woodpecker	S	Increase	land-use change (forestry), other human-related factors (feeding)
<i>Dendrocopos minor</i>	lesser spotted woodpecker	S	Decline	land-use change (forestry)
<i>Dryocopus martius</i>	black woodpecker	S	None	
<i>Emberiza citrinella</i>	yellowhammer	S	None	
<i>Eremophila alpestris</i>	horned lark	N	Decline	unknown
<i>Erithacus rubecula</i>	European robin	S	None	
<i>Falco columbarius</i>	merlin	N	Decline	land-use change (agriculture)
<i>Falco rusticolus</i>	gyrfalcon	N	None	
<i>Falco tinnunculus</i>	common kestrel	S	None	
<i>Ficedula hypoleuca</i>	European pied flycatcher	S	None	
<i>Fringilla coelebs</i>	chaffinch	S	None	
<i>Fulica atra</i>	Eurasian coot	S	Expansion	land-use change (drainage of wet habitats specifically lowered water level in lakes, eutrophication)
<i>Gallinago media</i>	great snipe	N	Contraction	land-use change (drainage of wet habitats), hunting
<i>Garrulus glandarius</i>	Eurasian jay	S	Expansion	unknown
<i>Gavia stellata</i>	red-throated loon	N	Decline	land-use change (agriculture, drainage of wet habitats)
<i>Glaucidium passerinum</i>	Eurasian pygmy owl	S	None	
<i>Hippolais icterina</i>	icterine warbler	S	None	
<i>Hirundo rustica</i>	barn swallow	S	Decline	land-use change (agriculture)
<i>Jynx torquilla</i>	Eurasian wryneck	S	Decline	land-use change (agriculture)
<i>Lagopus lagopus</i>	willow ptarmigan	N	Contraction	unknown
<i>Lagopus muta</i>	rock ptarmigan	N	Decline	reindeer grazing
<i>Lanius collurio</i>	red-backed shrike	S	Decline	land-use change (agriculture), change in overwintering areas
<i>Larus canus</i>	mew gull	S	Expansion	unknown
<i>Limosa lapponica</i>	bar-tailed godwit	N	None	
<i>Lophophanes cristatus</i>	European crested tit	S	Expansion	climate change
<i>Loxia curvirostra</i>	red crossbill	S	None	
<i>Loxia pytyopsittacus</i>	parrot crossbill	S	None	
<i>Luscinia luscinia</i>	thrush nightingale	S	None	
<i>Luscinia svecica</i>	bluethroat	N	None	
<i>Lyrurus tetrix</i>	black grouse	S	Decline	land-use change (drainage of wet habitats)
<i>Melanitta nigra</i>	black scoter	N	None	
<i>Mergus merganser</i>	common merganser	S	None	
<i>Mergus serrator</i>	red-breasted merganser	S	Decline	land-use change causing eutrophication
<i>Motacilla flava thunbergi</i>	yellow wagtail	S	Increase	land-use change (forestry)
<i>Muscicapa striata</i>	spotted flycatcher	S	None	
<i>Numenius arquata</i>	Eurasian curlew	S	Expansion	land-use change (agriculture, drainage of wet habitats)

<i>Numenius phaeopus</i>	whimbrel	N	Expansion	unknown
<i>Parus major</i>	great tit	S	Expansion	unknown
<i>Passer domesticus</i>	house sparrow	S	Decline	land-use change (agriculture)
<i>Passer montanus</i>	Eurasian tree sparrow	S	Expansion	other human-related factors (associated with gardens)
<i>Periparus ater</i>	coal tit	S	Expansion	land-use change (forestry)
<i>Pernis apivorus</i>	European honey buzzard	S	Decline	change in overwintering areas
<i>Phalaropus lobatus</i>	red-necked phalarope	N	None	
<i>Phoenicurus phoenicurus</i>	common redstart	S	Decline	Land-use change (forestry)
<i>Phylloscopus sibilatrix</i>	wood warbler	S	Expansion	unknown
<i>Phylloscopus trochilus</i>	willow warbler	S	None	
<i>Pica pica</i>	Eurasian magpie	S	Expansion	land-use change (agriculture), other human-related factors (decreased hunting)
<i>Picus viridis</i>	European green woodpecker	S	Decline	land-use change (agriculture, forestry)
<i>Plectrophenax nivalis</i>	snow bunting	N	None	
<i>Pluvialis apricaria</i>	European golden plover	N	Decline	land-use change (agriculture, forestry)
<i>Podiceps cristatus</i>	great crested grebe	S	Expansion	Land-use change (eutrophication)
<i>Poecile montanus</i>	willow tit	S	Decline	land-use change (forestry)
<i>Prunella modularis</i>	dunnock	S	Expansion	land-use change (forestry)
<i>Pyrrhula pyrrhula</i>	Eurasian bullfinch	S	Expansion	unknown
<i>Regulus regulus</i>	goldcrest	S	None	
<i>Riparia riparia</i>	sand martin	S	None	
<i>Saxicola rubetra</i>	whinchat	S	None	
<i>Scolopax rusticola</i>	Eurasian woodcock	S	None	
<i>Sitta europaea</i>	Eurasian nuthatch	S	Expansion	unknown
<i>Stercorarius longicaudus</i>	long-tailed jaeger	N	None	
<i>Strix aluco</i>	tawny owl	S	None	
<i>Sturnus vulgaris</i>	common starling	S	Expansion	land-use change (agriculture)
<i>Sylvia atricapilla</i>	Eurasian blackcap	S	Expansion	land-use change (agriculture)
<i>Sylvia borin</i>	garden warbler	S	Expansion	unknown
<i>Sylvia communis</i>	common whitethroat	S	None	
<i>Sylvia curruca</i>	lesser whitethroat	S	Expansion	land-use change (forestry)
<i>Tetrao urogallus</i>	western capercaillie	S	Decline	land-use change (drainage of wet habitats, forestry), predation
<i>Tringa glareola</i>	wood sandpiper	N	Decline	land-use change (drainage of wet habitats)
<i>Tringa ochropus</i>	green sandpiper	S	Expansion	unknown
<i>Troglodytes troglodytes</i>	Eurasian wren	S	Increase	land-use change (forestry), climate change
<i>Turdus merula</i>	common blackbird	S	Expansion	unknown
<i>Turdus philomelos</i>	song thrush	S	None	
<i>Turdus torquatus</i>	ring ouzel	N	Contraction	land-use change (agriculture)
<i>Turdus viscivorus</i>	mistle thrush	S	None	
<i>Vanellus vanellus</i>	northern lapwing	S	Expansion	unknown

Table S2. The 78 species breeding in alpine or boreal Sweden that did not have a southern or northern distribution according to our definition, and thus were excluded from part one of the review. Nomenclature following Dyntaxa (2013).

Species	Common name	Distribution
<i>Acrocephalus schoenobaenus</i>	sedge warbler	patchy
<i>Actitis hypoleucos</i>	common sandpiper	omnipresent
<i>Alca torda</i>	razorbill	coastal
<i>Anas acuta</i>	northern pintail	patchy
<i>Anas querquedula</i>	garganey	patchy
<i>Anser anser</i>	greylag goose	coastal
<i>Anthus petrosus</i>	rock pipit	coastal
<i>Anthus pratensis</i>	meadow pipit	omnipresent
<i>Aquila chrysaetos</i>	golden eagle	patchy
<i>Arenaria interpres</i>	ruddy turnstone	coastal
<i>Asio flammeus</i>	short-eared owl	eastern
<i>Aythya ferina</i>	common pochard	eastern-coastal
<i>Aythya fuligula</i>	tufted duck	eastern-patchy
<i>Bombycilla garrulus</i>	Bohemian waxwing	eastern
<i>Branta canadensis</i>	Canada goose	introduced during study period
<i>Bubo bubo</i>	Eurasian eagle-owl	eastern-patchy
<i>Bucephala clangula</i>	common goldeneye	eastern
<i>Calidris pugnax</i>	ruff	eastern-patchy
<i>Carpodacus erythrinus</i>	common rosefinch	eastern-patchy
<i>Cephus grylle</i>	black guillemot	coastal
<i>Charadrius hiaticula</i>	common ringed plover	coastal-patchy
<i>Cinclus cinclus</i>	white-throated dipper	western (both southern and northern distribution limits)
<i>Circus cyaneus</i>	northern harrier	eastern
<i>Corvus corax</i>	northern raven	omnipresent
<i>Corvus frugilegus</i>	rook	patchy
<i>Cygnus cygnus</i>	whooper swan	eastern
<i>Emberiza hortulana</i>	ortolan bunting	eastern
<i>Emberiza pusilla</i>	little bunting	eastern-patchy (colonized during the 20th century)
<i>Emberiza rustica</i>	rustic bunting	eastern
<i>Emberiza schoeniclus</i>	reed bunting	omnipresent
<i>Falco peregrinus</i>	peregrine falcon	eastern-patchy
<i>Falco subbuteo</i>	Eurasian hobby	eastern
<i>Fringilla montifringilla</i>	brambling	eastern
<i>Gallinago gallinago</i>	common snipe	omnipresent
<i>Gavia arctica</i>	black-throated loon	southern distribution limit south of boreal Sweden
<i>Grus grus</i>	common crane	eastern
<i>Haematopus ostralegus</i>	Eurasian oystercatcher	coastal
<i>Haliaeetus albicilla</i>	white-tailed eagle	patchy
<i>Hydrocoloeus minutus</i>	little gull	patchy
<i>Hydroprogne caspia</i>	Caspian tern	coastal
<i>Lanius excubitor</i>	great grey shrike	eastern
<i>Larus argentatus</i>	European herring gull	coastal-patchy
<i>Larus fuscus</i>	lesser black-backed gull	coastal
<i>Larus marinus</i>	great black-backed gull	coastal
<i>Locustella naevia</i>	common grasshopper warbler	eastern (colonized during the 20th century)
<i>Lymnocyptes minimus</i>	jack snipe	eastern
<i>Melanitta fusca</i>	velvet scoter	coastal-patchy
<i>Mergellus albellus</i>	smew	eastern
<i>Motacilla alba alba</i>	white wagtail	omnipresent
<i>Motacilla cinerea</i>	grey wagtail	colonized Sweden in the 20th century
<i>Numenius phaeopus</i>	whimbrel	eastern

<i>Oenanthe oenanthe</i>	northern wheatear	omnipresent
<i>Pandion haliaetus</i>	osprey	eastern
<i>Perisoreus infaustus</i>	Siberian jay	eastern
<i>Phylloscopus borealis</i>	Arctic warbler	eastern
<i>Phylloscopus collybita</i>	common chiffchaff	patchy
<i>Picoides tridactylus</i>	Eurasian three-toed woodpecker	eastern
<i>Picus canus</i>	grey-headed woodpecker	eastern-patchy
<i>Pinicola enucleator</i>	pine grosbeak	eastern
<i>Podiceps auritus</i>	horned grebe	eastern-patchy
<i>Podiceps grisegena</i>	red-necked grebe	patchy
<i>Poecile cinctus</i>	Siberian tit	eastern
<i>Regulus regulus</i>	goldcrest	eastern-patchy
<i>Somateria mollissima</i>	common eider	coastal
<i>Stercorarius parasiticus</i>	parasitic jaeger	coastal
<i>Sterna hirundo</i>	common tern	coastal-patchy
<i>Sterna paradisaea</i>	Arctic tern	coastal-patchy
<i>Streptopelia decaocto</i>	Eurasian collared dove	colonized Sweden in the 20th century
<i>Strix nebulosa</i>	great grey owl	eastern-patchy
<i>Strix uralensis</i>	Ural owl	eastern
<i>Surnia ulula</i>	northern hawk-owl	eastern
<i>Tetrastes bonasia</i>	hazel grouse	eastern
<i>Tringa erythropus</i>	spotted redshank	eastern
<i>Tringa nebularia</i>	common greenshank	eastern
<i>Tringa totanus</i>	common redshank	patchy
<i>Turdus iliacus</i>	redwing	southern distribution limit south of boreal Sweden
<i>Turdus pilaris</i>	fieldfare	omnipresent-eastern (20th century western range expansion in Europe)
<i>Uria aalge</i>	common murre	coastal
