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Levels and temporal trends of persistent organic pollutants (POPs) in arctic foxes (*Vulpes lagopus*) from Svalbard in relation to dietary habits and food availability

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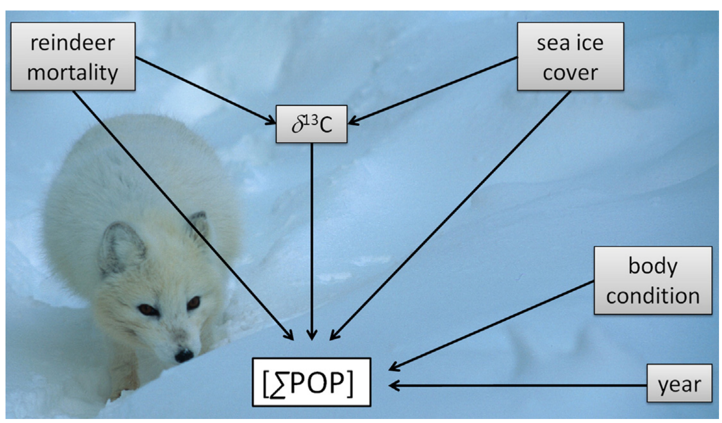
HIGHLIGHTS

- POPs were analyzed in the arctic foxes' liver (n = 141) from Svalbard collected in 1997–2013.
- PCBs, chlordanes, *p,p′*-DDE, mirex and PBDEs decreased 4–11% per year.
- Concentrations of all compounds increased with marine diet.
- Increasing reindeer mortality was related to decreasing HCB concentrations.
- *β*-HCH concentrations in arctic foxes increased with increasing sea ice cover.

GRAPHICAL ABSTRACT



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ABSTRACT

Temporal trends of persistent organic pollutants (POPs) in arctic foxes (*Vulpes lagopus*) from Svalbard, Norway, were investigated in relation to feeding habits and seasonal food availability. Arctic foxes from Svalbard forage in both marine and terrestrial ecosystems and the availability of their food items are impacted by climatic variability. Concentrations of polychlorinated biphenyls (PCBs), organochlorinated pesticides (OCPs) and brominated flame retardants (polybrominated diphenyl ethers [PBDEs] and hexabromocyclododecane [HBCDD]) were analyzed in the liver of 141 arctic foxes collected between 1997 and 2013. Stable carbon isotope values ($\delta^{13}C$) were used as a proxy for feeding on marine versus terrestrial prey. The annual number of recovered reindeer carcasses and sea ice cover were used as proxies for climate influenced food availability (reindeers, seals). Linear models revealed that concentrations of PCBs, chlordanes, *p,p′*-DDE, mirex and PBDEs decreased 4–11% per year, while no trends were observed for hexachlorobenzene (HCB) or *β*-hexachlorocyclohexane (*β*-HCH). Positive relationships between POP concentrations and $\delta^{13}C$ indicate that concentrations of all compounds increase with increasing marine dietary input. Increasing reindeer mortality was related to lower HCB concentrations in the foxes based on the linear models. This suggests that concentrations of HCB in arctic foxes may be influenced by high mortality levels of Svalbard reindeer. Further, *β*-HCH concentrations showed a positive association with

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sea ice cover. These results in addition to the strong effect of $\delta^{13}C$ on all POP concentrations suggest that climate-related changes in arctic fox diet are likely to influence contaminant concentrations in arctic foxes from Svalbard.

1. Introduction

Studies on temporal trends have revealed a general decrease in concentrations of polychlorinated biphenyls (PCBs) and "legacy" organochlorine pesticides (OCPs) in arctic biota, which has been traditionally interpreted as a consequence of emission history and regulation (AMAP, 2014; Dietz et al., 2013a; Rigét et al., 2010). Due to their potential for long-range transport, biomagnification, persistence and toxicity, PCBs and a wide range of OCPs have been banned under the Stockholm Convention (Stockholm Convention, 2001). At the same time, concentrations of several brominated flame retardants (BFRs) continue to increase in arctic apex predators (de Wit et al., 2010; Dietz et al., 2013b; McKinney et al., 2009). Among BFRs, polybrominated diphenyl ethers (PBDEs) including penta- and octa-brominated diphenyl ethers (BDEs) were added under the Stockholm Convention in 2009 (Stockholm Convention, 2009) and amendment listing of hexabromocyclododecane (HBCDD) has recently entered into force (Stockholm Convention, 2013). There is recent evidence indicating that temporal changes of POPs are not only influenced by emission patterns and regulation, but also by direct impact of climate variability and variation in prey availability derived by climatic conditions (Bustnes et al., 2010, 2011; Gaden et al., 2012; McKinney et al., 2009, 2013), which are rapidly changing in the Arctic (IPCC, 2013).

The arctic fox (*Vulpes lagopus*) population inhabiting Svalbard is a good model species to investigate the effect of changing climate and food availability on temporal trends of POPs. This population is among the highest contaminated apex predators of arctic ecosystems (Fuglei et al., 2007; Klobes et al., 1998; Severinsen and Skaare, 1997), and opportunistically predates and scavenges on highly variable diet items throughout the year (Eide et al., 2005). The arctic fox forages in both marine and terrestrial ecosystems (Angerbjorn et al., 2004; Braestrup, 1941) and a study using stable isotope values of nitrogen and carbon ($\delta^{15}N$, $\delta^{13}C$), as a dietary tracer showed that foxes feeding from the marine food web had higher POP concentrations compared to foxes feeding from the terrestrial food web (Fuglei et al., 2007). The only terrestrial resident species available as food items in both summer and winter on Svalbard are the Svalbard reindeer (*Rangifer tarandus platyrhynchus*) and Svalbard rock ptarmigan (*Lagopus muta hyperborea*). As such, these species constitute a major part of the arctic fox diet (Eide et al., 2005, 2012; Frafjord, 2002; Fuglei et al., 2003). In spring and summer additional food items for foxes are migrating seabirds and geese, such as Brünnich's Guillemot (*Uria lomvia*), little auk (*Alle alle*), kittiwake (*Rissa tridactyla*) northern fulmar (*Fulmarus glacialis*), barnacle goose (*Branta leucopsis*) and pink-footed goose (*Anser brachyrhynchus*) (Eide et al., 2005; Frafjord, 1993). However, the proportion of these birds in the diet of arctic foxes varies depending whether their breeding den is located close to bird breeding areas or not. Because the migratory birds arrive in spring and leave Svalbard by October, food sources might be scarce during winter, and previously cached food is thought to be important (Frafjord, 1993). In the presence of sea ice during winter and spring arctic foxes may also follow polar bears (*Ursus maritimus*) on the sea ice scavenging remains of seals killed by bears or hunt ringed seal (*Pusa hispida*) pups in March–April (Gjertz and Lydersen, 1986; Hiruki and Stirling, 1989).

Several studies have addressed the possible effects of climate induced variability on arctic fox diet, and possible explanations may be related to changes in the availability of reindeer carcasses and/or sea ice cover (Eide et al., 2012; Fuglei and Ims, 2008; Fuglei et al., 2003; Hansen et al., 2013; Pamperin et al., 2008). Food items from the terrestrial ecosystem are strongly influenced by winter climate (Aanes et al., 2002, 2003; Solberg et al., 2001). Warmer winters with increased events of "rain-on-snow" can cause ground ice and locked pastures leading to higher mortality rates and an increase in available reindeer carcasses on the tundra (Hansen et al., 2011, 2013). Recent studies have found that arctic fox reproduction is greatly influenced by this seasonal access to reindeer carrions (Eide et al., 2012; Hansen et al., 2013). As an alternative habitat arctic foxes also feed in the marine ecosystem utilizing the sea ice in search for food, namely seal carcasses or pups, in winter (Hiruki and Stirling, 1989; Pamperin et al., 2008; Roth, 2002). The large variation in sea ice cover recently seen inside the fjords on Spitsbergen (Pavlov et al., 2013; Zhuravskiy et al., 2012) may thus influence the availability of seals and access to marine resources for arctic foxes (Pamperin et al., 2008; Roth, 2002).

The main objective of this study is to investigate temporal trends of POPs in arctic foxes from Svalbard, Norway, while taking into account climate related changes between years in food availability and feeding habits. We hypothesize: 1) that foxes feeding from the marine food web have higher levels of contaminants compared to foxes feeding from the terrestrial food web, and 2) that availability of specific prey types between years will vary due to climatic conditions and consequently influence concentrations and temporal trends of POPs in arctic foxes.

2. Materials and methods

2.1. Sample collection

Arctic foxes ($n = 141$) were trapped on Spitsbergen, Svalbard, mainly around the Isfjorden area and Nordenskiöld Land (two foxes were trapped further north on Spitsbergen) (Fig. 1). The trappers used baited traps during the annual harvest between the 1st of November and the 15th of March. Number of individuals as well as sex, age and body condition of the sampled foxes were balanced over the trapping seasons from 1997/98 to 2012/13 (Table S1). The foxes were weighed, sex determined and skinned before dissection. To evaluate body condition, a subjective fat index based on visual inspection of the skinned carcasses was used to estimate body fat content which may range from zero to 40% (Prestrud and Nilssen, 1992). The visible amount of subcutaneous and abdominal fat on each fox was evaluated during autopsy using the index ranging from 0 to 4. "None" or 0 means no visible fat. "Low" or 1 means barely measurable fat. "Moderate" or 2 means fat deposits subcutaneously over the rump and abdominally. "Considerable" or 3 means fat deposits subcutaneously over the rump, belly and flanks and abdominally. "Extensive" or 4 means fat deposits subcutaneously covering most of the body and abdominally. As very few foxes had fat index 0, only foxes of conditions 1–4 were used in the present study. The age of the foxes was determined by counting the annuli in the cementum of a sectioned canine tooth (Grue and Jensen, 1976). To avoid possible confounding effects of sex and age (reproducing females tend to have lower levels of POPs than males due to lactational transfer (Debier et al., 2003)), only foxes between 1 and 2 years old were used in this study. Although most arctic vixens in Svalbard do not reach maximum pregnancy rates before the age of four (Eide et al., 2012), all vixens were still investigated for dark placental scars in the uteri and none of the foxes used in this study had given birth. The highest age of a fox registered in Svalbard is 16 years (unpublished results E. Fuglei), but most arctic foxes live until they are three to four years old (Eide et al., 2012). Samples of skeletal muscle and liver were packed in aluminium foil and stored at −20 °C until further analysis.