Mandibular shape in farmed Arctic foxes (*Vulpes lagopus*) exposed to persistent organic pollutants

Madison M. Bradley[1,*], Megan Perra[2], Øystein Ahlstrøm[3], Bjørn M. Jenssen[4,5,6], Even H. Jørgensen[7], Eva Fuglei[8], Derek C.G. Muir[9], Christian Sonne[6,*]

[1] Department of Archaeology and Anthropology, University of Calgary, 2500 University Drive N.W., Calgary, Alberta, T2N 1N4, Canada (mmbradle@ucalgary.ca)

[2] Independent Researcher, 97231, Portland Oregon USA (megan.perra@gmail.com)

[3] Department of Animal and Aquacultural Sciences, Faculty of Biosciences, Norwegian University of Life Sciences, P.O. Box 5003, NO-1433 Ås, Norway (oystein.ahlstrom@nmbu.no)

[4] Department of Biology, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway (bjorn.munro.jenssen@ntnu.no)

[5] Department of Arctic Technology, The University Centre in Svalbard, PO Box 156, NO-9171 Longyearbyen

[6] Aarhus University, Faculty of Science and Technology, Department of Bioscience, Arctic Research Centre, P.O. Box 358, DK-4000 Roskilde, Denmark (cs@bios.au.dk)

[7] Department of Arctic and Marine Biology, UiT the Arctic University of Norway, N, NO-9037 Tromsø, Norway (even.jorgensen@uit.no)

[8] Norwegian Polar Institute, Fram Centre, NO-9296 Tromsø, Norway (eva.fuglei@npolar.no)

[9] Aquatic Contaminants Research Division, Environment and Climate Change Canada, Burlington ON Canada L7S 1A1 (derek.muir@canada.ca)

*Corresponding author: Professor Christian Sonne, DScVetMed, PhD, DVM, Vice President and Dipl. ECZM-EBVS (Wildlife Health), Aarhus University, Faculty of Science and Technology, Department of Bioscience, Frederiksborgvej 399, PO Box 358, DK-4000 Roskilde, Denmark. Tel. +45-30-78-31-72; Email address: cs@bios.au.dk.

Abstract

We investigated if dietary exposure to persistent organic pollutants (POPs) affect mandibular asymmetry and periodontal disease in paired male-siblings of Arctic foxes (*Vulpes lagopus*). During ontogeny, one group of siblings was exposed to the complexed POP mixture in naturally contaminated minke whale (*Balaenoptere acutorostarta*) blubber (n=10), while another group was given wet feed based on pig (*Sus scrofa*) fat as a control (n=11). The ∑POP concentrations were 802 ng/g ww in the whale-based feed compared to 24 ng/g ww in the control diet. We conducted a two-dimensional geometric morphometric (GM) analysis of mandibular shape and asymmetry in the foxes and compared the two groups. The analyses showed that directional asymmetry was higher than fluctuating asymmetry in both groups and that mandibular shape differed significantly between the exposed and control group based on discriminant function analysis (T^2=58.52, p=0.04, 1000 permutations). We also found a non-significantly higher incidence of periodontal disease (two-way ANOVA: p=0.43) and greater severity of sub-canine alveolar bone deterioration similar to periodontitis (two-way ANOVA: p=0.3) in the POP-exposed group. Based on these results, it is possible that dietary exposure to a complexed POP mixture lead to changes in jaw morphology in Arctic foxes. This study suggests that extrinsic factors, such as dietary exposure to POPs, may affect mandibular shape and health in a way that could be harmful to wild Arctic populations. Therefore, further studies using GM analysis as an alternative to traditional morphometric methods should be conducted for wild Arctic fox populations exposed to environmental contaminants.

Key words: *Balaenoptera acutorostrata*; Fluctuating asymmetry, geometric morphometric; GM; Periodontal disease, Minke whale; POPs; Organochlorines; OCs; Polychlorinated Biphenyls; PCB.

Introduction

Arctic animals are exposed to long-range transported environmental contaminants, such as persistent organic pollutants (POPs). Since POPs and their derived metabolites are associated with lipids and proteins, and biomagnify in Arctic food chains, apex predators like the Arctic fox (*Vulpes lagopus*) experience greater exposure to POPs than species foraging at lower trophic levels (Fuglei et al. 2007, Letcher et al. 2010). This results in adverse effects on several organ-tissue systems, which presumably influences their overall health (Letcher et al. 2010; Sonne 2010; Sonne et al. 2012). Of the affected systems, the immune, skeletal, and endocrine systems may be of the greatest concern because of their potential population-level effects in species such as polar bears (*Ursus maritimus*) and Arctic foxes (Desforges et al. 2016; Letcher et al. 2010, Sonne 2010; Sonne et al. 2015, 2017). As climate warming accelerates the melting of the polar ice caps, POPs can be remobilized into the atmosphere and further biomagnify in Arctic food webs (Letcher et al. 2010). Furthermore, climate change has been suggested to change food sources, trophic position and pathogen exposure co-morbidities (Jenssen et al. 2015; Sonne 2010).

Bone serves as a multi-purpose tissue, and the integrity of the skeletal system is vital for mammals (Sasaki et al. 2000, 2013). Primarily, bones are essential for maintenance of calcium homeostasis, production of red and white blood cells, and for the anatomical and physical properties of the organism (Ganong 2010). Bone is continuously remodelled according to a complex cascade of hormones, vitamins, elements and mechano-transduction from daily loading (Van Langendonck et al. 2002; Turner 2006; Tung and Iqbal 2007). Multiple stressors such as nutritional and heat stress as well as infectious and parasitic diseases are known to lead to early changes in bone composition and morphology often referred to as developmental instability (Lens et al. 2002; Møller 1997).

Studies of various wildlife in the Arctic and Baltic Sea have shown that exposure to a complex environmental mixture of POPs may affect skeletal development and composition (Bergman et al. 1992; Lind et al. 2003; Sonne 2010; Sonne et al. 2015). Only few studies have investigated how dietary oral exposure to environmental POPs may affect bone asymmetry and periodontal disease in Arctic top predators (Sonne 2010). To fill that gap and to test the effects of POP exposure on adult skeletal phenotypes, we used farmed Arctic foxes of the same genetic line i.e. 20 male siblings and one additional non-sibling in the exposed group. These were divided into two brother-paired groups; one exposed group that was fed minke whale (*Balaenoptera acutorostrata*) blubber rich in POPs and a control group that was fed pork fat with significantly lower POP levels. Here we tested the hypothesis whether dietary OC exposure had an effect on 1) mandibular asymmetry and 2) mandibular periodontal diseases in Arctic foxes.

Materials and methods

Housing and feeding

Twenty-one newly weaned sibling-pairs of male foxes (54 days old) were separated into two groups, one POP exposed group (n=10) and one control group (n=11) (Table 1). The groups were balanced with respect to body mass and all foxes were individually housed in semi-outdoor cages (1.5×1.2×1.0m) exposed to natural photoperiod and ambient temperature at the Norwegian University of Life Sciences, Ås, Norway. The exposed group received wet feed containing minke whale blubber as main fat source, whereas the control group received wet feed with lard from pigs as main fat source. The whale-based feed had a ∑POP concentration of 802 ng/g ww, while the source of fat had a ∑POP concentration of 24 ng/g ww. Further information on the composition of the two diets with respect to various ingredients and POP concentrations and compositions are available in previous report from the same study (Helgason et al. 2013; Sonne et al. 2008). To simulate the changes in annual feeding and body fat content of wild Arctic foxes, both groups were given high-energy feed for 3-5 month (Aug 2003-Jan 2004 and Aug 2004-28 Nov 2004) and low energy feed for 7 month (Jan 2004-Aug 2004 and Nov 2004-June 2005) as described in detail by Helgason et al. (2013). Three control foxes and two exposed foxes were euthanized in Dec 2004 after 16 month of experimental exposure and mandibles and abdominal adipose tissue was sampled for morphological and contaminant analyses, respectively. Similar, 8 control and 8 exposed foxes were euthanized and sampled in June 2005 after 22 month of experimental exposure. Age and time of exposure was thereby the same among the group of exposed and control foxes. The study was carried out on a license granted by the Norwegian Animal Research Committee (www.fdu.no). All experimental procedures followed Norwegian protocols for ethical standards for the use of live animals and the experiments were performed in accordance with national and international guidelines for animal research.

Persistent organic pollutants (POPs) measurements

Abdominal adipose tissue for POP analyses was only available from 16 of the 21 animals (Sonne et al. 2017). The analyses were conducted using methods described in Johansen et al. (2004). In brief, all samples were homogenized and Soxhlet extracted with dichloromethane. PCB/OCPs (organochlorine pesticides) were isolated from lipid co-extractives by gel permeation chromatography followed by fractionation on a silica gel column. Extracts were analysed for 104 PCB congeners and 35 OCPs and chlorinated by-products using gas chromatography with electron capture detection (Table S1). The compounds used in the present investigation included ∑PCB, $\sum PCB_{10}$, ∑DDT (dichlorodiphenyltrichloroethane), ∑CHL (chlordanes), ∑HCH (hexachlorohexane), ∑CBZ (chlorobenzenes) and ∑POPs (sum of all PCBs and OCPs). Certified reference materials from the National Institute of Standards and Testing (NIST 1774b mussel, NIST 1588a cod liver oil), and laboratory blanks consisting of all reagents, were analysed with each batch of samples (Helgason et al. 2013). Briefly, internal recovery standards, 1,3-dibromobenzene, 1,3,5-tribromobenzene, 1,2,4,5-tetrabromobenzene, delta-HCH, PCB 30, and PCB 204 were added at the extraction step. Certified reference materials from the National Institute of Standards and Testing (NIST 1588a cod liver oil) and laboratory blanks consisting of all reagents were also analyzed with each batch of 10 samples. Results for PCBs and OC pesticides in NIST 1588a were generally within 30% of certified values, whereas recoveries of internal standards were >80%, and method blanks <1% of values in fox adipose tissue. All concentrations are given as ng/g ww.

Geometric morphometric (GM) and periodontal analyses

Left and right mandibles were photographed in buccal view using a Canon Rebel T5I with an 18-55mm lens. Treatment groups of images were blinded during analyses. Images were digitized in two dimensions using tpsDig232 (x86) version 2.26 (copyright 2016) according to the landmark definitions summarized in Table 2. The landmarks are placed on the apex of the coronoid process (landmark 1), at the junction of the ascending ramus and the lower second molar (landmark 2), the junction of the canine and the alveolar bone (landmark 3), the mandibular symphysis (landmark 4), along inferior edge of the jaw (landmarks 5 and 6), the apex of the angular process (landmark 7), between the angular and condyloid processes (landmark 8), the condyloid process (landmark 9), and between the condyloid and coronoid processes (landmark 10). The number and position of landmarks were chosen to optimize shape descriptions and accuracy, while minimizing type I statistical error. Intra-observer error was tested using a repeated stack of randomly selected images. Periodontal disease was quantified by the number of teeth affected by degradation of alveolar bone. In addition to periodontitis, many foxes had sub-canine porosity of the mandibular corpus around the medial mental foramen. This was quantified according to relative severity (Figure 1).

Statistical analyses

Analyses of shape were conducted in MorphoJ (Klingenberg 2011). To compare mandibular shape, a Procrustes fit was performed on the landmarked image stack, whereby each set of landmarks in a shape are superimposed by optimally rotating, translating and uniformly scaling. This was performed to enable direct shape comparisons independent of the placement (orientation and position) and scaling (size) of the objects. If two shapes are identical they would have a perfect procrustes fit (Klingenberg 2011). A discriminant function analysis with 1000 permutations was performed to investigate side-averaged (the average shape of the right and left halves) shape differences between the exposed and control groups. To describe these shape differences between the groups, a principal component analysis (PCA) was performed. Subsequently, separate Procrustes fits were performed for the exposed and control groups to test the degree and nature of mandibular asymmetry focusing on both directional (left and right sides differ and always in the same direction) and fluctuating (small random deviations away from perfect bilateral symmetry) asymmetry. Procrustes ANOVAs were performed on each group to quantify intra-group shape differences between the right and left mandible halves while a two-way ANOVA was used to test for periodontitis and sub-canine alveolar bone porosity among side and groups. Finally, a Welch's t-test was used to test for fluctuating and directional asymmetry between the exposed and control groups. The free software R version 2.14.0 (R Development Core Team 2013) was used for all statistical analyses and the level of significance was set to $p=0.05$.

Results

Biometrics and POP concentrations

A summary of biometrics and POP concentrations is shown in Table 1. Biometrics and age were similar between the two groups while the exposed foxes had a significantly higher liver weight (Welch's t-test, $p<0.01$). POP concentrations analysed in adipose tissue showed that the levels were significantly highest in the exposed group for all compounds (Welch's t-test: all $p<0.01$). According to Table 1, concentrations of especially PCBs, DDTs and Chlordanes were several folds higher in the exposed group.

Geometric morphometrics

Principal component (PC) analysis showed that PC1 and PC2 accounted for 39.7% of overall variance between the groups. PC1 was associated with height of the mandibular body around the medial and caudal mental foramina, the height of the ascending ramus, the rostral-caudal length of the mandible, the angle of the ascending ramus relative to the corpus, and the projection of the condyloid process. PC2 was associated with height of mandibular corpus around first molar, orientation of the rostral-most projection of the mandible (landmark 4), orientation and length of the condyloid process and positioning of the medial mental foramen and the orientation of the rostral-most projection (landmark 4) relative to the angular process (landmark 7) which in turn affects the measurement of landmark 6.

Discriminant function analysis showed that the overall mandibular shape was significantly different between the two groups of foxes with individual variation being highest in the exposed group (Figure 2, 3) (T^2=58.5, p=0.04, 1000 permutations). It is seen that there is little overlap in the discriminant function analysis, thus dietary exposure to POPs can be predictive of jaw shape. According to Table 3, the individual variation was highest in the group of exposed foxes and was generally the best predictor of shape in both groups. Furthermore, directional asymmetry was higher than fluctuating asymmetry in both groups with the degree of fluctuating asymmetry higher in the exposed group.

Periodontal disease

We observed a relatively high incidence of periodontal disease including periodontitis with alveolar bone deterioration in both groups (Figure 1, S1a-c). The incidence of periodontitis and severity of sub-canine alveolar bone deterioration was non-significantly highest in the exposed group (Two-Way ANOVA, p=0.24) (Table 4; Figure S2, S3). There was also a high incidence of abnormal, but likely non-pathogenic, non-metric deviant morphology in both groups. Foxes were missing caudal mental foramina, and elongate bone spurs on the condyloid and coronoid processes were observed. The significance of this finding cannot be established without a better understanding of the frequency of these discrete osteological changes in domestic foxes.

Discussion

In the present study, we identified that changes in overall shape and mandibular fluctuating asymmetry may be related to developmental instability from the complexed mixture of dietary POP exposure. Previous studies have shown that fluctuating asymmetry increases in wildlife species exposed to PCBs (Borisov et al. 1997; Bustnes et al. 2002; Jenssen et al. 2010; Maul and Farris 2005; Schandorff 1997a, 1997b; Zakharov and Yablokov 1990; Zakharov et al. 1997). While the mechanisms behind this disruption are not fully understood, stress is known to cause endocrine disruption, which can disrupt homeostasis and normal foetal and neonatal development (Lens et al. 2002; Møller 1997; Sonne 2010). In marine mammals, fluctuating asymmetry has been linked to exposure to organochlorines when comparing different historical periods (Zakharov and Yablokov 1990; Bergman et al. 1992; Mortensen et al. 1992; Schandorff 1997a, 1997b). Concurrent with the increase in fluctuating asymmetry in seal populations, sterility and population declines were observed (Bergman 1999; Bergman and Olsson 1985; Roos et al. 2012). It is therefore possible that fluctuating asymmetry and bone pathology can be used as an indicator of individual and population health status including those of wild Arctic foxes. Studies of other Arctic predators such as polar bears have not previously been able to link POP exposure and fluctuating asymmetry likely because of confounding effects from other important factors such as climate change and food availability (Sonne et al. 2005, Bechshøft et al. 2008; Sonne 2010). Applying the GM method to museum collections of wild arctic foxes may give a better understanding of potential POP effects in this species (Jenssen et al. 2015; Pedersen et al. 2015; Sonne 2010).

Periodontal disease

We observed non-significantly higher prevalence of periodontal diseases and mandibular bone deterioration in the POP exposed group of Arctic foxes that may affect their ability to chew and feed. According to Stirling (1969), tooth wear and periodontal diseases are major mortality co-factors in Weddell seals (*Leptonychotes weddelli*) from Antarctica, and it is therefore important to investigate the oral health of the highest contaminated free living or wild *Vulpes lagopus* populations in the Arctic. In humans, endocrine disrupting organochlorines such as dibenzofurans, dioxins and PCBs have been associated with abnormally early eruption of teeth (Gladen et al. 1990; Rogan 1979; Wang et al. 2003). Lee et al. (2008) investigated the relationship between exposure to POPs and effects on periodontal diseases and leucocytes in more than 1200 adult North Americans. They found that clinical tooth attachment loss and reduced pocket depth were especially associated with organochlorine exposure.

Arctic foxes depend on normal muscular-mandibular and masticatory function when feeding (Sasaki et al. 2013), thus pathologies that affect their ability to chew can be especially detrimental to their performance and overall health (Sonne 2010). Prenatal POP exposure is known to impair tooth development and induce associated pathological alveolar bone changes (Kattainen et al. 2001; Lukinmaa et al. 2001; Wang et al. 2003). Previous laboratory studies on mink (*Neovison vison*) (Render et al. 2000a, 2000b, 2001) have shown that POPs may induce periodontal disease similar to those in the present study. However, tooth wear in carnivores and secondary periodontitis has also been associated with age, altered prey composition and more aggressive behaviour (van Valkenburgh 1988a, 1988b; Stirling 1969; Fenton et al. 1988; Patterson et al. 2003; Persson et al. 2004; Sonne et al. 2007). Environmental stress is also known to reduce calcium concentrations in teeth, along with being a co-factor in the deterioration of alveolar bone and changes in other non-metric bone structures (Siegel et al. 1992).

Considerations and implications

The results from the present study may not be directly extrapolated to wild populations due to differences in genetic diversity, food quality, texture and composition. However, the concentrations of POPs measured in the adipose tissue of the exposed foxes are within the range of those found in Arctic foxes in the wild where concentrations exceed known thresholds for adverse health effects (AMAP 2004; Pedersen et al. 2015). Some of the exposed foxes may show no effects due to decreased sensitivity to POPs. Alternatively, the genetic background of farmed foxes could mean their mandibular development is more tightly canalized compared to other individuals, which would result in a more "normal" phenotype. However, this is purely speculative. Farmed foxes were given wet feed with no abrasive effect on the teeth. Dental plaque and calculus formations were thereby formed, which initiate inflammation and periodontal diseases that can affect teeth mobility and alveolar bone loss (own observations). Wild living foxes will have whole bones from prey in their diet, which will keep calculus low. In addition, the relatively low sample size could mask significant differences in fluctuating asymmetry and periodontal disease among the exposed and control group of foxes.

Altogether, the present results showed that overall mandibular shape was modified by POP exposure and that it is possible that mandibular asymmetry and periodontal disease could be affected. Previously published results from the present cohort of exposed and control foxes have shown that plasma level of multiple hormones, such as testosterone, thyroid hormones and vitamins, were affected by POP exposure in the exposed group (Hallanger et al. 2012; Rogstad et al. 2017; Sonne et al. 2017). Likewise, lesions in internal organs (liver, kidney and thyroid glands) were found to be more prevalent in the exposed group (Sonne et al. 2008, 2009). Altogether, these effects on multiple organ-systems, hormones and vitamins may explain the mode of action for the observed mandibular differences among the exposed and control groups found in the present study.

Conclusions

Here we show that POPs affect overall mandibular shape and asymmetry and may increase periodontal disease. It is therefore important to investigate the oral health of contaminated and at-risk wild Arctic fox populations. Furthermore, our study provides a further basis for using GM in wild populations exposed to environmental contaminants as an alternative to traditional morphometric methods for detecting effects of persistent organic pollutants on Arctic foxes.

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TABLES

Table 1. Data on biometrics mean±SD (Min-Max) and concentrations of persistent organic pollutants (POPs) in adipose tissue of farmed Arctic foxes dietary exposed to POPs for up to 22 months. POP data are given as mean±SD (Sonne et al. 2017).

	Control (n=11)	**Exposed (n=10)**
Biometrics		
Age (months)	22.91±1.87 (20-24)	23.2±1.69 (20-24)
Body weight (kg)	6.59±1.84 (4.8-9.4)	6.09±1.54 (4.8-9.04)
Body length (cm)	70.79±2.81 (65.5-74.5)	70.61±2.28 (66.5-74.5)
Liver weight (g)**	160.1±12.01 (139.7-181.9)	184.78±19.83 (162-215.5)
POPs (ng/g ww)		
∑PCB	443±193	2771±798*
∑DDT	3±1	362±684*
∑CHL	73±31	1041±733*
∑HCH	2±0.3	25±7
∑CBZ	5±1	21±15
∑POPs	816±3	5859±1984*

*: significant difference between control and exposed group at $p<0.05$. **: significant difference between control and exposed group at $p<0.001$. Modified from Sonne et al. (2017).

Table 2. Landmark definitions for geometric morphometric analyses. Landmarks are on the lateral/buccal view of the mandibles. Type i: where two tissue types meet or a landmark based on measurements, type ii: maximal projection or point, type iii: minimum or maximum of a curve.

Landmark	**Type**	**Description**
1	ii	Caudal-most apex of coronoid process.
2	iii	Concave-most portion of the slope between the ascending ramus and the mandibular corpus where it meets the back of m2.
3	i	Caudal-most junction of canine enamel and alveolar bone.
4	i	Rostral-most, superior-most projection of mandibular symphysis (visible as a point between central incisors).
5	i (measurement)	Point along inferior edge of jaw taken from the inferior-most point of a line drawn from the caudal-most peak of alveolar bone of p1 through the caudal edge of the medial mental foramen.
6	i (measurement)	Mid-point perpendicular to length measurement from LM4 to LM7 along inferior edge of jaw.
7	ii	Superior-most apex of angular process.
8	iii	Most concave point along the curve between the angular process and the condyloid process.
9	ii	Superior-most point of maximal projection of the condyloid process.
10	iii	Most concave point along the curve between the condyloid process and the coronoid process.

Table 3. F statistics and p-values of Procrustes ANOVA comparing right-left shape differences in the control group of arctic foxes.

	Controls	**Exposed**
Individual	4.39**	8.93***
Directional asymmetry	1.26	1.96$^{\text{n.s.t.}}$
Fluctuating asymmetry	0.62	0.46

n.s.t.: non-significant trend at p<0.1.
*: significant difference between control and exposed group at p<0.05.
**: significant difference between control and exposed group at p<0.01.
***: significant difference between control and exposed group at p<0.001.

Table 4. Results of Two-Way ANOVA analysis of number of teeth affected with periodontitis (periodontitis) and the degree of sub-canine alveolar bone porosity (porosity) in farmed arctic foxes.

	DF	SS	F value	P value
Periodontitis				
Group	1	1.7924	0.6339	0.4309
Side	1	2.3809	0.8421	0.3646
Group:Side	1	1.715	0.6064	0.4410
Porosity				
Group	1	1.250	1.0928	0.30245
Side	1	3.429	2.9970	0.09153
Group:Side	1	1.753	1.5325	0.22333

FIGURE LEGENDS

Figure 1. The degree of sub-canine porosity rated from ‘normal’ to ‘severe’ in control and POP exposed farmed arctic foxes.

Figure 2. Discriminant function comparing the average of the left and right sides mean shape of the control group of farmed arctic foxes (left red) and the exposed group (blue right) in teal with 1000 permutations (T^2=58.5244, p=0.04). The averaged shape phenotype is depicted as a wireframe diagram, with differences set to 5×true difference. Numbers represent landmark position. The red control bar in the blue section is due to overlap between the shape of the control and exposed groups. The red bar shows that there are 2 control individuals that have mandibular shape that clusters closer to the mandibular shape of the exposed group.

Figure 3. Transformation grid (top) and wireframe diagram (bottom) of mean right (in red) and left (in green) shape differences in the control and exposed groups of farmed arctic foxes. Scale is set to 5×true difference to visually amplify the shape changes. The transformation grid shows which regions of the jaw are distorted and asymmetrical, while the wireframe diagram shows how the arrangement of landmarks differs. The asymmetry shown in this figure is directional in nature, where the left side of the jaw tends to deviate most.

FIGURES

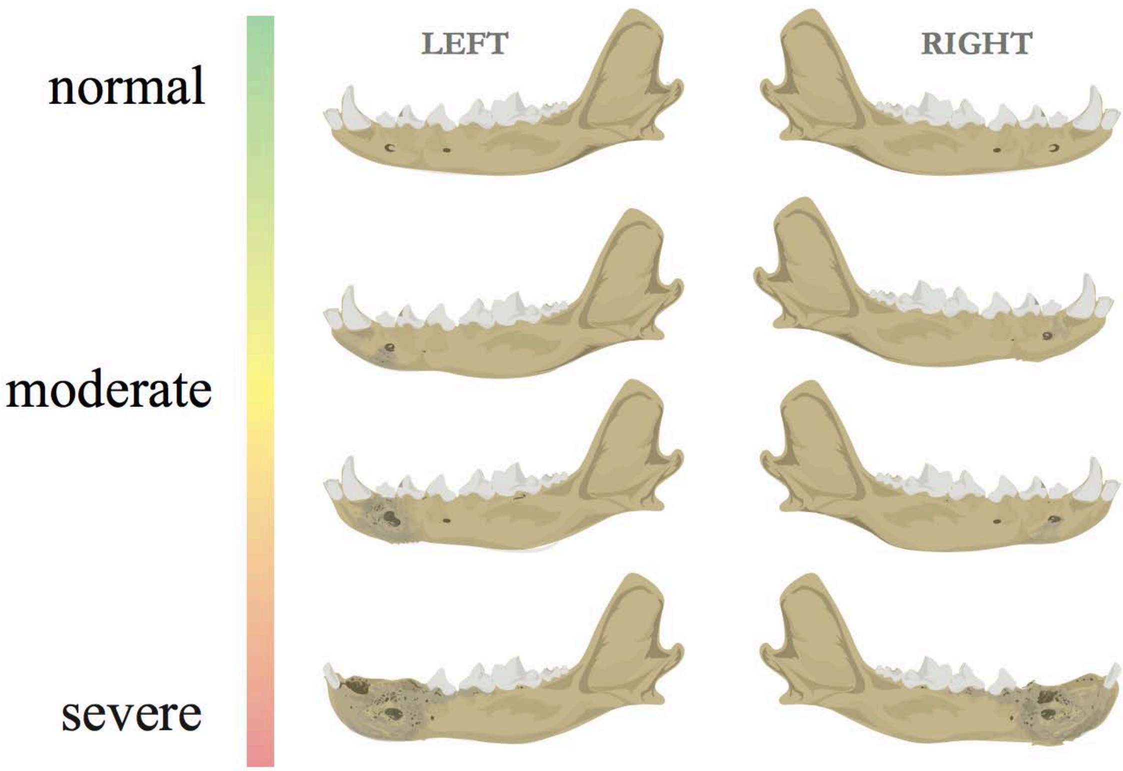
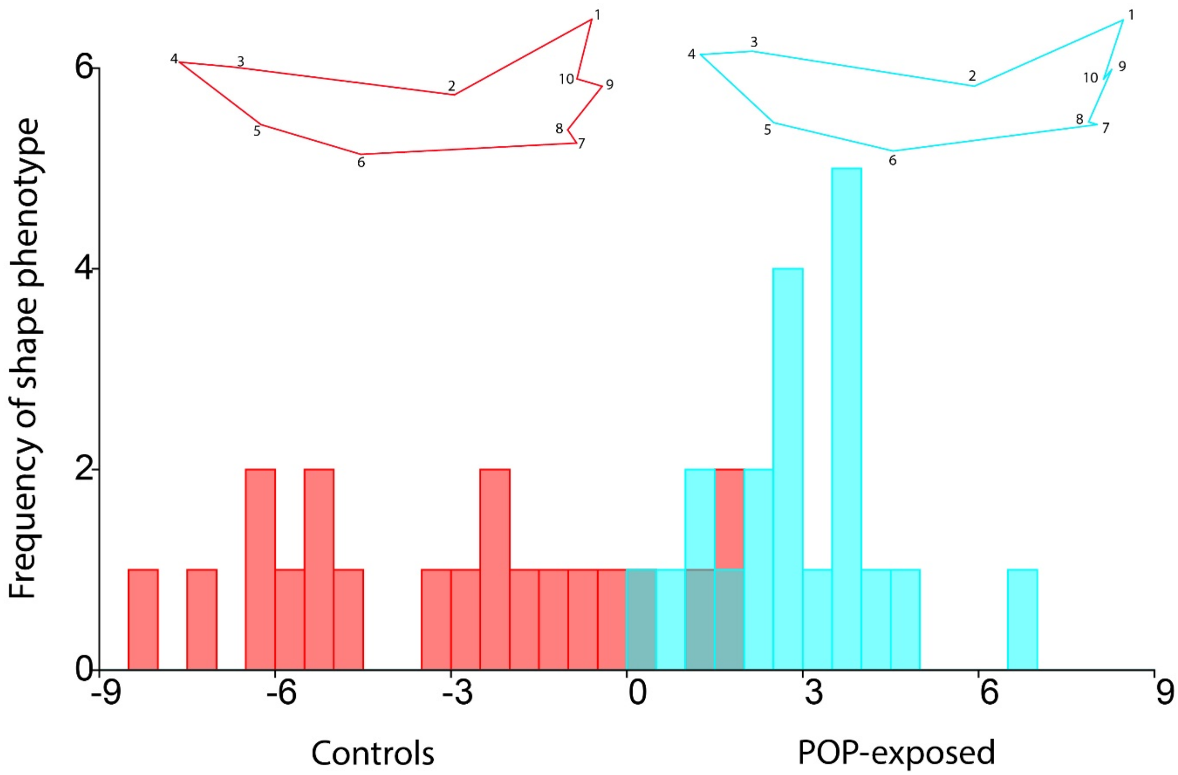
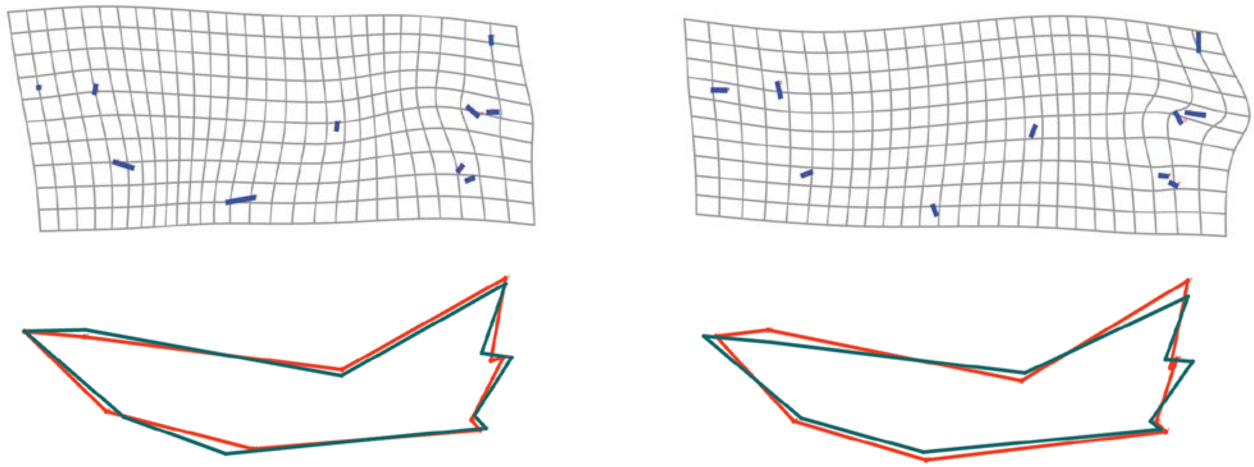


FIGURE 1


Frequency of shape phenotype
6
4
2
0
-9
-6
-3
0
3
6
9
Controls
POP-exposed
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5
6
7
8
9
10

491 **FIGURE 2**



Control **POP-exposed**

FIGURE 3

SUPPLEMENTARY INFORMATION

Table S1. List of all PCB/OCP analytes.

Group	Individual analyte	Common name
ΣPCBs	CB-1	monochlorobiphenyl
ΣPCBs	CB-3	monochlorobiphenyl
ΣPCBs	CB4/10	dichlorobiphenyl
ΣPCBs	CB7/9	dichlorobiphenyl
ΣPCBs	CB6	dichlorobiphenyl
ΣPCBs	CB8/5	dichlorobiphenyl
ΣPCBs	CB12/13	dichlorobiphenyl
ΣPCBs	CB15	dichlorobiphenyl
ΣPCBs	CB19	trichlorobiphenyl
ΣPCBs	CB18	trichlorobiphenyl
ΣPCBs	CB17	trichlorobiphenyl
ΣPCBs	CB27/24	trichlorobiphenyl
ΣPCBs	CB16/32	trichlorobiphenyl
ΣPCBs	CB 54-29	tetra/trichlorobiphenyl
ΣPCBs	CB26	trichlorobiphenyl
ΣPCBs	CB25	trichlorobiphenyl
ΣPCBs	CB31	trichlorobiphenyl
ΣPCBs	CB50	tetrachlorobiphenyl
ΣPCBs	CB20/33/21	trichlorobiphenyl
ΣPCBs	CB53	tetrachlorobiphenyl
ΣPCBs	CB51	tetrachlorobiphenyl
ΣPCBs	CB22	trichlorobiphenyl
ΣPCBs	CB45	tetrachlorobiphenyl
ΣPCBs	CB46	tetrachlorobiphenyl
ΣPCBs	CB73/52	tetrachlorobiphenyl
ΣPCBs	CB43	tetrachlorobiphenyl
ΣPCBs	CB49	tetrachlorobiphenyl
ΣPCBs	CB48/47/75	tetrachlorobiphenyl
ΣPCBs	CB44	tetrachlorobiphenyl
ΣPCBs	CB59	tetrachlorobiphenyl
ΣPCBs	CB42	tetrachlorobiphenyl
ΣPCBs	CB71/41/68/64	tetrachlorobiphenyl
ΣPCBs	CB40	tetrachlorobiphenyl
ΣPCBs	CB100	pentachlorobiphenyl
ΣPCBs	CB63	tetrachlorobiphenyl
ΣPCBs	CB74/61	tetrachlorobiphenyl
ΣPCBs	CB70/76/98	tetrachlorobiphenyl
ΣPCBs	CB80/66	tetrachlorobiphenyl
ΣPCBs	CB95/93	pentachlorobiphenyl
ΣPCBs	CB91	pentachlorobiphenyl
ΣPCBs	CB55	tetrachlorobiphenyl
ΣPCBs	CB56/60	tetrachlorobiphenyl

ΣPCBs	CB92	pentachlorobiphenyl
ΣPCBs	CB84/90	pentachlorobiphenyl
ΣPCBs	CB89-101	pentachlorobiphenyl
ΣPCBs	CB99	pentachlorobiphenyl
ΣPCBs	CB119	pentachlorobiphenyl
ΣPCBs	CB82	pentachlorobiphenyl
ΣPCBs	CB97	pentachlorobiphenyl
ΣPCBs	CB87/81	pentachlorobiphenyl
ΣPCBs	CB136	hexachlorobiphenyl
ΣPCBs	CB110	pentachlorobiphenyl
ΣPCBs	CB82	pentachlorobiphenyl
ΣPCBs	CB120/85	pentachlorobiphenyl
ΣPCBs	CB135/144	hexachlorobiphenyl
ΣPCBs	CB147	hexachlorobiphenyl
ΣPCBs	CB107/109	pentachlorobiphenyl
ΣPCBs	CB139/149	hexachlorobiphenyl
ΣPCBs	CB118/106	pentachlorobiphenyl
ΣPCBs	CB133	hexachlorobiphenyl
ΣPCBs	CB114	pentachlorobiphenyl
ΣPCBs	CB131/165/142	hexachlorobiphenyl
ΣPCBs	CB146	hexachlorobiphenyl
ΣPCBs	CB153	hexachlorobiphenyl
ΣPCBs	CB132/168	heptachlorobiphenyl
ΣPCBs	CB105/127	pentachlorobiphenyl
ΣPCBs	CB141	hexachlorobiphenyl
ΣPCBs	CB179	hexachlorobiphenyl
ΣPCBs	CB137	hexachlorobiphenyl
ΣPCBs	CB176	heptachlorobiphenyl
ΣPCBs	CB130	hexachlorobiphenyl
ΣPCBs	CB163/164/138	hexachlorobiphenyl
ΣPCBs	CB158/160	hexachlorobiphenyl
ΣPCBs	CB129	hexachlorobiphenyl
ΣPCBs	CB178	hexachlorobiphenyl
ΣPCBs	CB175	hexachlorobiphenyl
ΣPCBs	CB182/187	heptachlorobiphenyl
ΣPCBs	CB183	heptachlorobiphenyl
ΣPCBs	CB128	hexachlorobiphenyl
ΣPCBs	CB167	hexachlorobiphenyl
ΣPCBs	CB185	heptachlorobiphenyl
ΣPCBs	CB174/181	heptachlorobiphenyl
ΣPCBs	CB177	heptachlorobiphenyl
ΣPCBs	CB202/171	octa/heptachlorobiphenyl
ΣPCBs	CB156	hexachlorobiphenyl
ΣPCBs	CB173	heptachlorobiphenyl
ΣPCBs	CB157/200	hexa/octabiphenyl
ΣPCBs	CB172/192	heptachlorobiphenyl

ΣPCBs	CB197	octachlorobiphenyl
ΣPCBs	CB180	heptachlorobiphenyl
ΣPCBs	CB193	heptachlorobiphenyl
ΣPCBs	CB191	heptachlorobiphenyl
ΣPCBs	CB199	octachlorobiphenyl
ΣPCBs	CB170/190	heptachlorobiphenyl
ΣPCBs	CB198	octachlorobiphenyl
ΣPCBs	CB201	octachlorobiphenyl
ΣPCBs	CB196/203	octachlorobiphenyl
ΣPCBs	CB189	heptachlorobiphenyl
ΣPCBs	CB208/195	nona/octachlorobiphenyl
ΣPCBs	CB207	nonachlorobiphenyl
ΣPCBs	CB194	octachlorobiphenyl
ΣPCBs	CB205	octachlorobiphenyl
ΣPCBs	CB206	nonachlorobiphenyl
ΣPCBs	CB209	decachlorobiphenyl
ΣCBZs	TCBz	1,2,4,5-Tetrachlorobenzene
ΣCBZs	PeCBz	Pentachlorobenzene
ΣCBZs	HCB	Hexachlorobenzene
ΣHCH	α-HCH	α-hexacyclohexane
ΣHCH	β-HCH	β- hexacyclohexane
ΣHCH	γ-HCH	γ- hexacyclohexane
ΣCHL	heptachlor	
ΣCHL	heptachlorEpoxide	
ΣCHL	oxychlordane	
ΣCHL	trans-chlordane	
ΣCHL	cis-chlordane	
ΣCHL	trans-nonachlor	
ΣCHL	cis-nonachlor	
o,p'-DDE	2,4-dichlorodiphenyldichloroethylene	
ΣDDT	p,p'-DDE	4,4'-dichlorodiphenyldichloroethylene
ΣDDT	o,p'-DDD	2,4-dichlorodiphenyldichloroethane
ΣDDT	p,p'-DDD	4,4'-dichlorodiphenyldichloroethane
ΣDDT	o,p'-DDT	2,4-dichlorodiphenyltrichloroethane
ΣDDT	p,p'-DDT	4,4'-dichlorodiphenyltrichloroethane

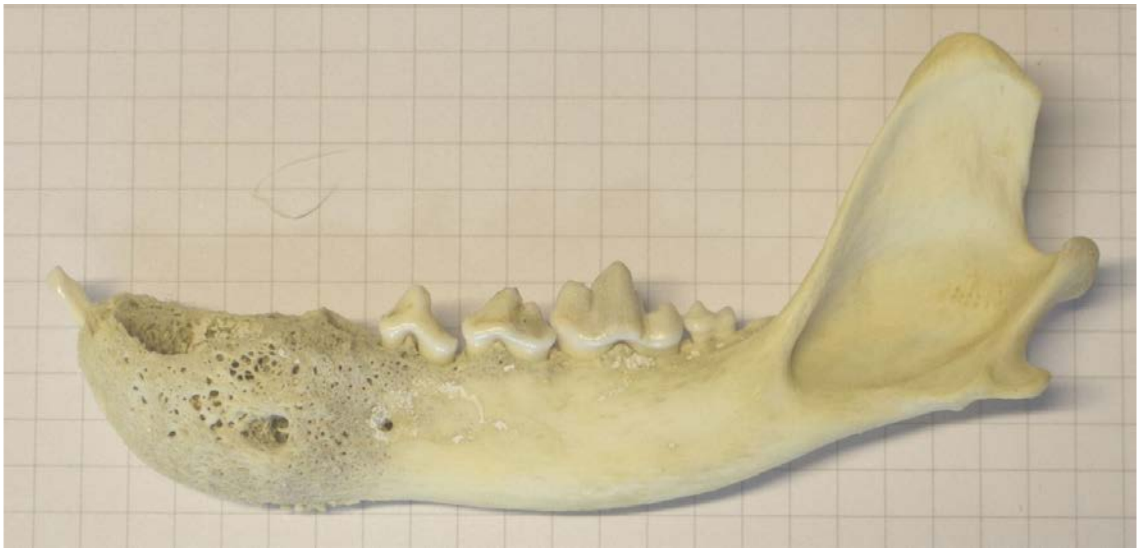


Figure S1a. A left mandible that demonstrates severe alveolar bone decay from an exposed farmed arctic fox (specimen 184).

Figure S1b. A right mandible from the control group (specimen 373) that displays periodontal disease beneath P3, P4 and M1.

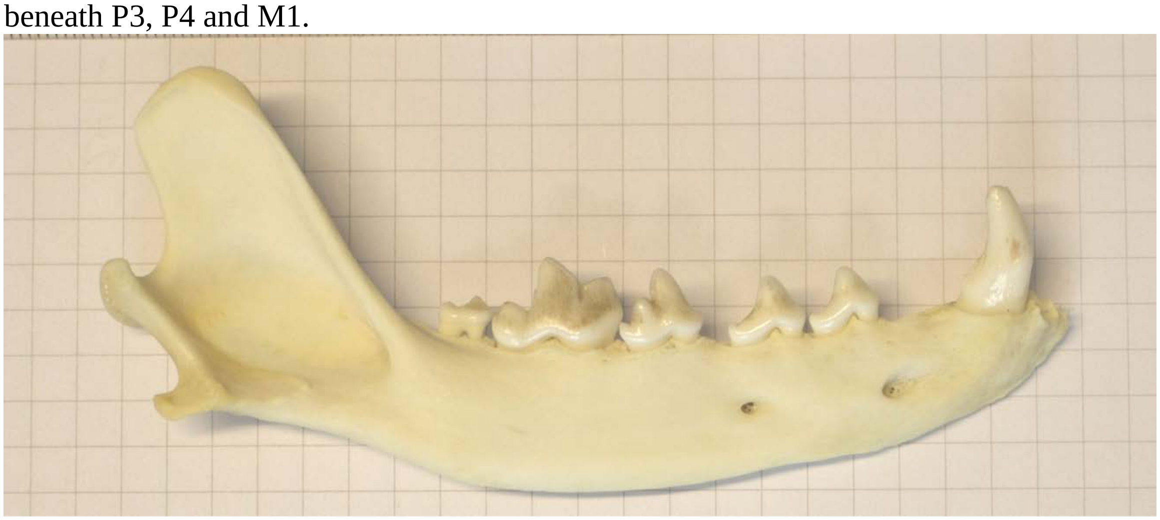


Figure S1c. A right mandible from an exposed individual (specimen 406) that demonstrates no pathologies.

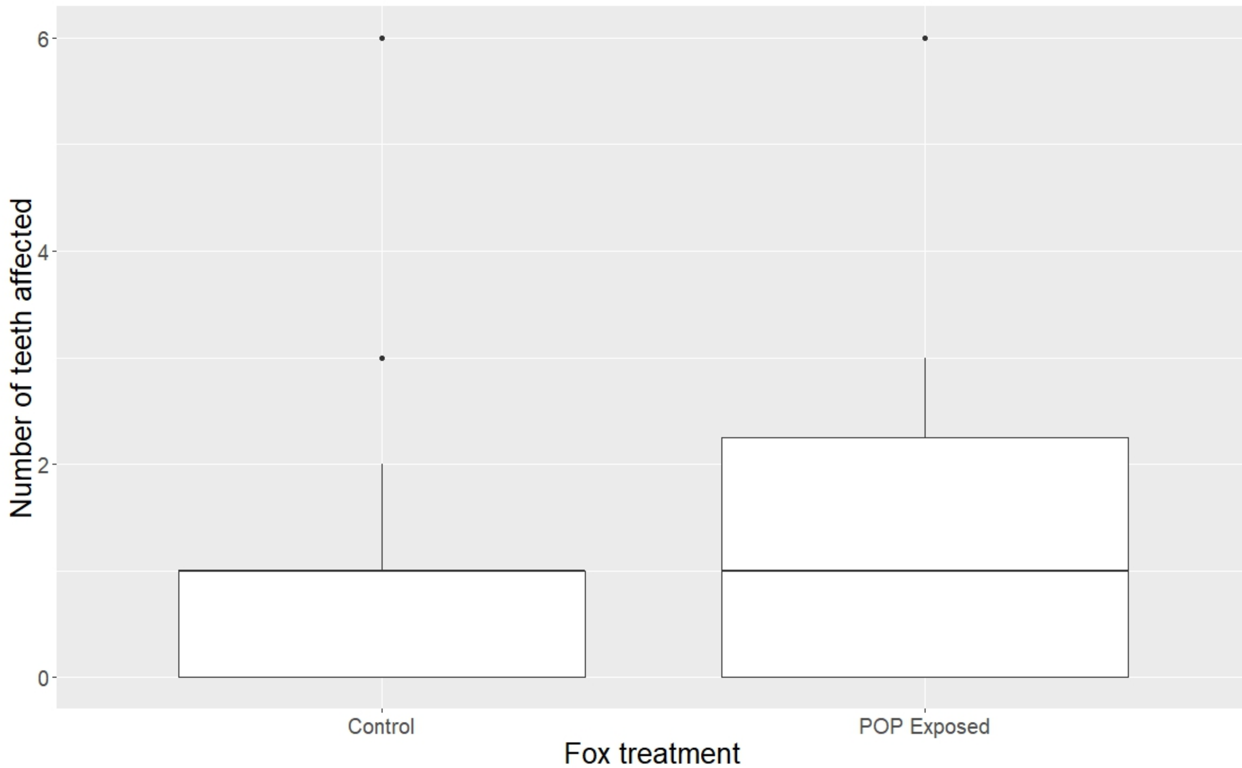


Figure S2. Box and whisker plot for number of teeth affected by periodontitis. Controls tend to have fewer teeth affected, but the variance about the mean is high and contains the variance seen in the exposed farmed arctic foxes.

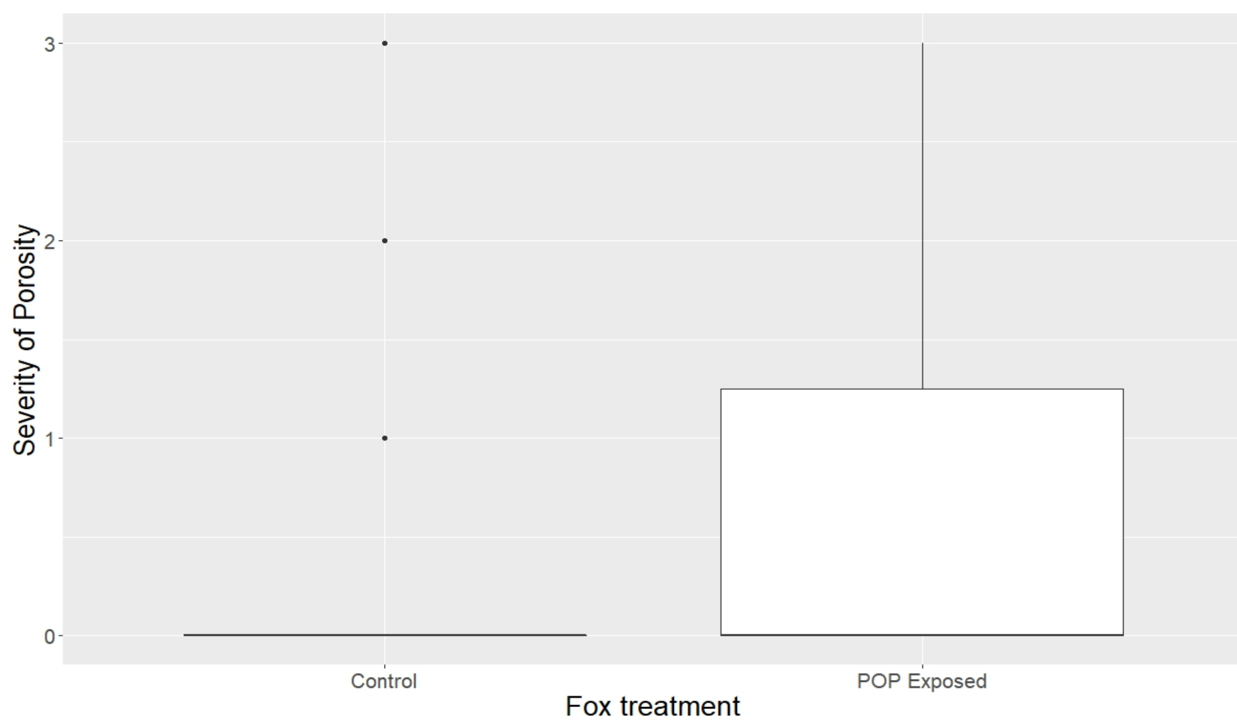


Figure S3. Box and whisker plot representing the severity of sub-canine alveolar bone porosity. Porosity was more severe and common in the exposed group, but outliers within the control group were as porous as the exposed group of farmed arctic foxes.