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Raptors are still affected by environmental pollutants: Greenlandic Peregrines will not have normal eggshell thickness until 2034

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Abstract The DDT-induced effects, eggshell thinning and breeding failure in Peregrine Falcon *(Falco peregrinus)* populations were reverted with restrictions on the use of the compound from the 1970s, and in most studied populations, the eggshell thickness is back to normal. In Greenland, a previous study of eggshell thinning in Peregrines found that shells had not yet reached pre-DDT levels. In this study, we extend the time series and reinterpret shell thinning data for 196 clutches covering a 45-year time span (1972–2017). There was a significant ($P<0.001$) increase in the eggshell thickness of 0.23% per year. This corresponds to a change in eggshell thinning from 14.5% to 5.4% in 2017 compared to the pre-DDT mean. With the current rate of change, pre-DDT shell thickness is predicted to be reached around the year 2034. However, a few clutches are still below the critical limit. The relatively slower recovery of the shell thickness in the Greenland population is likely indicative of the slower phasing out of DDT in the Greenlandic Peregrines' wintering grounds in Latin America. The shell thinning in the Greenlandic population probably never crossed the 17% threshold associated with population declines, contrary to the populations in many other parts of the world.

Keywords: Arctic, Greenland, DDT, pollutants, egg, shell thinning, monitoring

Összefoglalás A DDT okozta hatások, tojáshéj-vékonyodás és költési sikertelenség visszaállítása a vándorsólyom *(Falco peregrinus)* populációiban a szer használatának korlátozásával (betiltásával) az 1970-es évek óta eredményesnek bizonyul, hiszen a legtöbb vizsgált populáció esetében a tojáshéj vastagsága visszaállt a normális szintre. Azonban egy korábbi tanulmány kimutatta, hogy Grönlandon a tojáshéjak vastagsága még nem érte el a DDT-használat előtti időszakra jellemző értékeket. Jelen tanulmányban a vizsgálati időszak kiterjesztésével egy 45 évet átölelő (1972–2017) időszakban igyekszünk a tojáshéj-vékonyodás adatait áttekinteni 196 fészekalj bevonásával. Jelentős növekedés figyelhető meg ($P<0,001$) a héjak vastagságában, ami körülbelül 0,23%-os változást jelent évente. Ez az érték megfelel a tojáshéjak vékonyodásában mutatkozó változásnak, hiszen 2017-re 14,5%-ról 5,4%-ra változott a DDT használat előtti időszak átlagához viszonyítva. Ekkora mértékű változás hatására 2034-re a tojáshéjak vastagsága elérheti a normál értéket. Azonban néhány fészekalj továbbra is a kritikus érték alatt van. A tojáshéj vastagságának lassú helyreállítódása valószínűleg a grönlandi vándorsólymok dél-amerikai telelőterületein kimutatható hatásoknak köszönhető, ahol a DDT viszonylag lassan tűnik el. A héjvékonyodás mértéke a grönlandi populációban valószínűleg soha nem érte el a kritikus, 17%-os tűréshatárt, amely határ összefüggésben lehet a vándorsólyom populációk világméretű csökkenésével.

Kulcsszavak: sarkvidék, Grönland, DDT, szennyezőanyagok, tojás, héjvékonyodás, monitorozás

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Introduction

Ever since it was first shown that the insecticide DDT caused eggshell thinning and breeding failure in wild Peregrine Falcon *(Falco peregrinus)* populations (Ratcliffe 1970) the effects of persistent organic pollutants (POPs) on the eggshell thickness and breeding success in high-trophic level birds have been widely documented. Especially DDT and its degradation products have been identified as a key group of POPs responsible for the widespread reduction in breeding success and subsequent population decline in the Peregrine Falcon in large parts of its distribution area (Hickey 1969, Cade *et al*. 1988) and in other top predators (e.g. Newton, 1979). The top predators turned out to be sensitive indicators of certain environmental pollutants and the discoveries of those side effects of pesticide usage led to the phasing out of DDT and subsequently a global ban on the use (except for restricted disease vector control) with the 2001 UN Stockholm Convention on Persistent Organic Pollutants taking effect in 2004 (UNEP 2009).

Over the past 40 years Peregrine (and other top predator) populations have recovered from the setback caused by the most harmful pollutants. But the top predators still serve as indicators of the pollutant level and in the case of DDT it was not until early in this millennium – 30 years after the ban in Europe – that eggshell thickness in German Peregrines and Swedish Ospreys *(Pandion haliaetus)* were back to normal (pre-DDT) levels (Wegner *et al*. 2005, Odsjö & Sondell 2014). In Greenland the shell-thinning in Peregrines has been much slower to recover (Falk & Møller 1990, Falk *et al*. 2006, Vorkamp *et al*. 2017), suggesting a slower change rate of DDT in the Greenlandic Peregrines' environment – from the Arctic breeding grounds to wintering areas in Latin America (see mapping of wintering grounds in Vorkamp *et al*. 2017) – compared to northern Europe.

In this study we extend the time series for eggshell measurements and reinterpret data for a 45-year time span (1972–2017) for the Greenlandic Peregrines *(F. p. tundrius)*.

Material and Methods

Samples

The Greenland Peregrine Falcon population has been the subject of long-term studies since the 1970s (Burnham & Mattox 1984, Falk & Møller 1988, 2018, Mattox & Seegar 1988), which have provided samples of eggshells over decades. This study combines samples from two study areas: West Greenland (samples from 1972–1988) and South Greenland (samples from 1981–2017).

Active nests were visited at least once post-hatching and the nest scrape carefully searched for eggshell fragments deriving from the hatched eggs. In addition, shells from whole dead eggs sampled and analysed for contaminants (Vorkamp *et al*. 2017, Vorkamp *et al*. 2018) were included in this analysis. Egg clutches from Greenland Peregrines collected between 1881 and 1930 (before DDT was introduced) stored at the Zoological Museum, University of Copenhagen, were used as the reference for normal eggshell thickness in the pre-DDT era (Falk & Møller 1990), so the total samples available cover a 136 year time span.

Measurements and statistical analyses

The eggshell thickness was determined as in previous studies (Falk *et al*. 2006, Vorkamp *et al.* 2017), in summary:

The shell fragments were measured with a computer-connected Mitutoyo Digital Micrometer (type 293-521-30) with a small stainless steel ball glued to the rotating jaw in order to fit the inner curved surface of the eggshell fragments. Measurements were performed only on (parts of) fragments without any membrane. We included only clutches that provided 20 or more measurable fragments, assuming they represent the thickness of the entire clutch (cf. Odsjö & Sondell 1982).

Whole, addled eggs were opened in the laboratory and the content removed for the contaminant analyses; the eggs were cut along the equator and the empty half shells washed with water before left to dry for 3 months at room temperature before measurements were taken along the equator cut line.

In this analysis, mean shell thickness was estimated for 196 clutches providing at least 20 fragments, and for 56 whole addled eggs from 44 clutches (a total of > 6600 measurements). From 19 clutches samples from both fragments and whole eggs were available; a paired t-test showed no significant difference ($t = 0.38$, $p = 0.71$) between those two sub-samples, thus data from fragments and whole eggs were combined for analysis. When comparing measurements with and without membranes, a membrane factor of 0.071 mm was applied, based on measurements of neighbouring shell areas with and without membranes (Falk *et al*. 2006).

For the analyses of the temporal trend, the mean annual shell thickness was analysed by log-linear regression analysis (AMAP 2016, Rigét *et al.* 2016) using the free software R version 3.13 (R Core Team 2015).

Results and Discussion

Over the 45-year time span 1972–2017 there was a significant increasing trend in the average eggshell thickness ($P < 0.001$). The slope of the linear regression shows an average increase of 0.23% per year, corresponding to a change in eggshell thinning from 14.5% in 1972 to 5.4% in 2017 when compared to pre-DDT eggs; these values are a slight adjustment to earlier estimates (Falk *et al*. 2006, Vorkamp *et al*. 2017). Shell thickness may continue to increase and level out when normal, pre-DDT average (0.336 mm) will be reached; based on the current rate of change it is predicted to be in 2034. However, the 95% confidence limit on the predicted value (black dotted lines) indicates that the year for the eggshell to obtain unaffected thickness can also be earlier or much later. A few clutches are still below the critical limit, as indicated by the red dashed line in *Figure 1*.

Some studies suggest that embryo development may affect shell density and/or thickness (Ratcliffe 1970, Bunck *et al*. 1985, Bennett 1995, Castilla *et al*. 2010) and shell thickness varies across different parts of the shell. The potential error introduced by those factors might slightly influence the reported *value* of the shell thickness in Greenlandic Peregrine Falcons and, hence, the predicted timing of full recovery. But since it is a random error across the years and the same methods have been applied over the entire 45-year study period, the *trend* remains unaffected. The empirical threshold for shell thinning causing negative population effects is around 17% (Peakall & Kiff 1988). As discussed by Falk *et al*. (2006), the shell thinning in the Greenlandic Peregrine population was probably near or below that

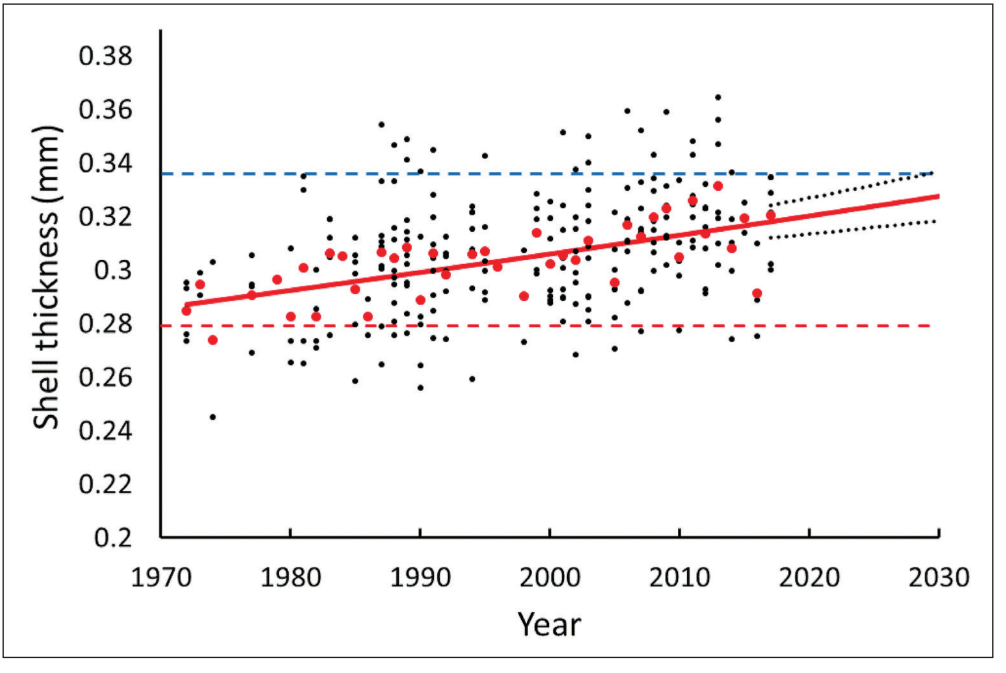

Figure 1. Shell thickness of Peregrine Falcons eggs from Greenland shown as clutch means (black symbols), annual means (red symbols) and projected trend line (red) with confidence limits (black dottet lines) for projections according to which the mean shell thickness may reach pre-DDT normal thickness in 2034 (0.336 mm, blue line, Falk & Møller 1990, Falk *et al*. 2006). The red dashed line indicates the empirical "17% threshold" (0.279 mm) associated with population declines across the world (Peakall & Kiff 1988)

1. ábra A grönlandi vándorsólyom tojások héjvastagsága a fészekaljak átlagában (fekete jelek), évenkénti átlag (vörös jelek) és a változás becsült mintája (vörös vonal) a megbízhatósági határértékekkel (fekete szaggatott vonalak), miszerint az átlagos héjvastagság 2034-re éri el újra a DDT-használat előtti időszakra jellemző értékeket (0,336 mm, kék vonal, Falk & Møller 1990, Falk *et al*. 2006). A szaggatott vörös vonal jelöli a 17%-os tűréshatárt (0,279 mm), amivel a világ vándorsólyom populációinak csökkenését hozták összefüggésbe (Peakall & Kiff 1988) critical limit only for a very short time span, if ever, and avoided the population crash that effected many other populations.

In Germany, Peregrine Falcon shell thinning was back to normal 30 years after the legal ban of DDT in 1972 (Wegner *et al*. 2005). Similarly, a long term study of shell thinning in Swedish ospreys showed that it took 30 years to reach full thickness again after the lowest level in 1973; from the beginning of the decrease it took more than 50 years to reach unaffected conditions (Odsjö & Sondell 2014). Hence, the much slower recovery of the shell thickness in the Greenland Peregrine population in this study might be indicative of the slower phasing out of DDT in the Americas (Vorkamp *et al*. 2009).

The continued change in exposure to DDT and its metabolites in the areas the Peregrines inhabit during their annual cycle can be monitored by continued low-cost collection of eggshell material. Although the Peregrine populations around the world are recovering from the pesticide-related population collapse, they continue to be important indicator species for environmental contaminants.

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