RED-SHOULDERED HAWK (*Buteo lineatus*) EGG MORPHOLOGY BEFORE AND AFTER THE INTRODUCTION OF DDT

Amber De Jong and William Brown
Division of Natural Sciences at Keuka College
adejong@keuka.edu

ABSTRACT—Dichlorodiphenyltrichloroethane (DDT) was introduced as a pesticide in the 1940s and subsequently caused a general decrease in egg production and eggshell thickness among raptors. We examined potential eggshell thinning and other morphological changes in Red-shouldered Hawk (*Buteo lineatus*) eggs as a consequence of DDT use. Eggshell thinning in this species is not well studied. Measurements were taken from 90- to 120-year-old Red-shouldered Hawk eggs contained in Keuka College's collection (n=313), including eggshell length, width, mass, and a thickness index calculated from these three measurements; actual thickness was determined for 30 eggs. Length and width data from seven other pre-DDT eggs were available in Croccol (2008). Eggshell thickness data from seven post-DDT eggs were included in Henny et al. (1973). Eggshell length, width, mass, and thickness were measured from ten eggs in Cornell University's collection that were collected shortly after DDT was introduced. For Keuka College eggs, the correlation between actual shell thickness and the eggshell thickness index was 0.67. Based on t-tests, eggshells from Keuka College were shorter and narrower than eggs from the Croccol (2008) and Cornell University samples. There was no difference in eggshell thickness between the pre-DDT eggs from Keuka College and the post-DDT eggs described by Henny et al. (1973), nor was there a difference in eggshell thickness between Keuka College eggs and eggs from Cornell University. The mean eggshell thickness index of Keuka College eggs, however, was significantly larger than the mean index of Cornell University eggs. We could not determine if the unexpected lack of eggshell thinning was due to inadequate post-DDT egg samples available for comparison, geographical variability, or was a naturally occurring phenomenon.

Eggshells provide calcium and minerals for developing embryos (Castilla 2010), allow for gas exchange and water retention (Solomon 2010), and afford protection during incubation. The introduction of dichlorodiphenyltrichloroethane (DDT) resulted in a general decrease in eggshell thickness (Green 1998, King et al. 2003) and an increase in eggshell breakage in some species (Ratcliffe 1970). High levels of DDT also impaired development of the skeletal, nervous, and reproductive systems among young that hatched and reduced the fertility of egg-laying females (Fry 1995).

Raptors were particularly vulnerable to the effects of DDT due to bioaccumulation, but not all raptors were equally affected. DDT was most damaging to Ospreys (*Pandion haliaetus*), Cooper's Hawks (*Accipiter cooperii*), Bald Eagles (*Haliaeetus leucocephalus*), and Peregrine Falcons (*Falco peregrinus*; Howe 1992). DDT was not observed to reduce the eggshell thickness of other species, such as the Great Horned Owl (*Bubo virginianus*; Seidensticker and Reynolds 1971).

Very few studies have examined Red-shouldered Hawk (*Buteo lineatus*) egg morphology before and after the introduction of DDT. Henny et al. (1973) noted a 9% decrease in eggshell thickness and the presence of organochlorine insecticides in seven post-DDT eggshells from Maryland compared to a large sample of pre-DDT eggs from the eastern United States and Canada. A study in California found a 14% decrease in Red-shouldered Hawk eggshell thickness between pre-1947 eggs and eggs collected in 1973 (Wiley 1975). Here, we compared length, width, and eggshell thickness from pre-DDT Red-shouldered Hawk eggshells from the Finger Lakes region of New York to similar measurements from several small samples of pre- and post-DDT eggs. Our expectation was that eggshell thickness would be thinner in post-DDT eggs and that the eggshell thickness index would be smaller in post-DDT eggs. We did not have *a priori* expectations about length and width differences among samples.

METHODS

Data were obtained from a collection of Red-shouldered Hawk eggs at Keuka College in Keuka Park, New York. The collection included 313 eggs from 105 separate clutches of eggs assembled from various locations in central New York between 1894 and 1914 by Clarence F. Stone. Egg length (mm) was defined as the average distance of three measurements taken from pole to pole of each egg using a Westward Electronic Caliper (to the nearest 0.004 mm). Egg width (mm) was defined as the average distance of three measurements of the maximum diameter of each egg. Mass (g) was determined using an electronic balance to the nearest 0.01 g.

Eggshell thickness (mm) was measured using an adapted micrometer, as described by Green (1998). A narrow tungsten rod, 2.4 mm in diameter, was secured on a micrometer and slid into the blowhole of the egg in order to measure the thickness of the adjacent side of the shell to the nearest 0.002 mm. A random sampling of 30 eggs with a blowhole larger than 2.4 mm, and from different clutches, was used to determine eggshell thickness. An eggshell thickness index was created for each egg by dividing its mass by the product of width and length (Osbourne and Winters 1977).

In addition to the Red-shouldered Hawk eggs in the Keuka College collection, published eggshell measurements from eggs collected in other parts of New York State before the introduction of DDT were available from Croccol (2008; n=7; we assumed measurements in this study were from pre-DDT eggs). Eggs with possible or likely exposure to DDT, collected between 1949 and 1957, were available from Cornell University (n=10). One clutch of eggs from the Cornell University sample was from New York (n=4 eggs) and three clutches were from Florida (n=6 eggs). Measurements of eggs collected after the introduction of DDT were available from a study in Maryland (n=7; Henny et al. 1973).

Length, width, mass, eggshell thickness, and eggshell thickness indices from the sample of Red-shouldered Hawk eggs at Keuka College were compared, where possible, to measurements from samples of eggs collected before and after the introduction of DDT using *t*-tests. Length and width comparisons were available from the Cornell University sample and from Croccol (2008). Mass comparisons were available from the Cornell University sample. Eggshell thickness comparisons to Keuka College eggs were possible with the sample from Cornell University and the published values of post-DDT eggs from Henny et al. (1973).

RESULTS

Red-shouldered Hawk eggs from Cornell University, collected shortly after DDT was introduced, were longer (t=4.4, df=321, p<0.0001) and wider (t=3.3, df=321, p=0.0012) than those from Keuka College (Table 1). Similarly, eggshell length measurements of pre-DDT eggs from Croccol (2008) averaged longer (t=3.5, df=318, p=0.0005) and wider (t=2.2, df=318, p=0.03) than those from Keuka College (Table 1).

There was no significant difference in the mass of eggshells from Keuka College and Cornell University (t=1.2, df=324, p=0.2; Table 1). No other mass comparisons were possible.

Although not significant, the pre-DDT eggs from Keuka College eggs were nominally thinner than the eggs collected in Maryland after the introduction of DDT (t=1.77, df=35, p=0.09), counter to expectations. Similarly, there was no difference in eggshell thickness between the pre-DDT eggs from Keuka College and eggs in Cornell University's collection taken shortly after the introduction of DDT (t=0.6, df=38, p=0.50). Finally, there was no difference in eggshell thickness between the sample of eggs from Cornell University and the sample of post-DDT eggs from Maryland (Henny et al. 1973; t=1.2, df=15, p=0.24).

The correlation coefficient between actual eggshell thickness and the eggshell thickness index of Keuka College eggs was 0.67 (Figure 2). Despite no difference in actual thickness measurements, the pre-DDT eggs from Keuka College had a larger eggshell thickness index than eggs from Cornell University that, again, were collected around the time DDT was introduced (t=3.0, df=38, p=0.004).

Table 1. Red-shouldered Hawk egg measurements (± 1 SD) from the samples compared in this study. [1]Keuka College egg collection, [2]Henny et al. 1973, [3]Cornell University egg collection, [4]Croccol et al. 2008.

Site	n	Years	Length (mm)	Width (mm)	Mass (g)	Index	Thickness
NY[1]	312	1894-1914	53.39 ± 2.35	42.82 ± 1.32	4.29 ± 0.39	1.90 ± 0.12	
NY[1]	30	1894-1914					0.306 ± 0.017
MD[2]	7	1971-1972					0.332 ± 0.076
FL, NY[3]	10	1949-1957	56.71 ± 2.63	44.20 ± 1.00	4.4 ± 0.37	1.77 ± 0.10	0.302 ± 0.014
NY[4]	7	pre-DDT	56.54 ± 1.93	43.93 ± 0.90			

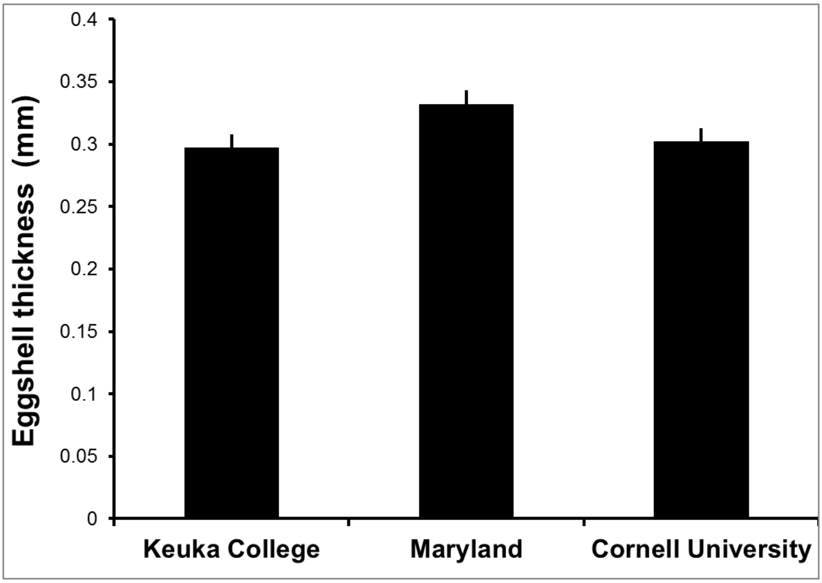

Figure 1. Average eggshell thickness of 30 pre-DDT eggs from Keuka College, seven post-DDT eggs from Maryland (Henny et al. 1973), and ten eggs from Cornell University with possible contact with DDT. Error bars represent one standard error. No pair-wise comparisons of eggshell thickness were significantly different from each other.

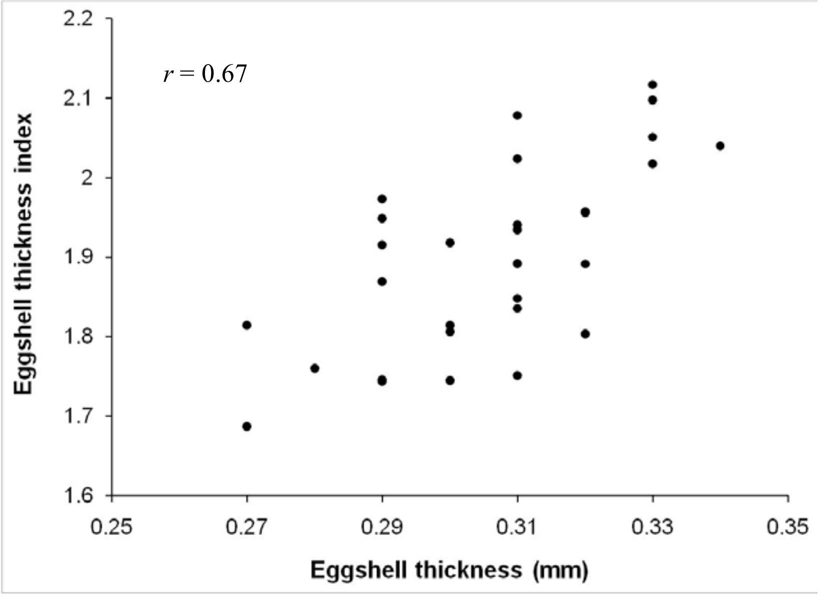

Figure 2. The relationship between actual eggshell thickness and an eggshell thickness index, determined by dividing mass by the product of length and width (Osbourne and Winters 1977), of 30 Red-shouldered Hawk eggs collected in the late 1800s and early 1900s.

DISCUSSION

We found no difference in the eggshell thickness of pre-DDT Red-shouldered Hawk eggs from Keuka College and any other sample for which information could be located, including another sample of pre-DDT eggs, one sample collected shortly after the introduction of DDT, and one sample of post-DDT eggs. In general, past studies found a decrease in eggshell thicknesses among raptors after the introduction of DDT (Ratcliff 1970, Henny et al. 1973, Green 1998). Henny et al. (1973) noted a 9% decrease in eggshell thickness between Red-shouldered Hawk eggshells collected before 1947 and after 1973. Although the post-DDT eggs included components of organochlorine pesticides, the sample was small (n=7). Similar to our findings, not all comparisons reported by Henny et al. (1973) indicated a significant decrease in eggshell thickness: pre-DDT Red-shouldered Hawk eggs from Florida and post-DDT eggs from Maryland did not differ in eggshell thickness.

If Red-shouldered Hawk eggshell thickness generally decreased after the introduction of DDT, the lack of difference in eggshell thickness between the pre-DDT and post-DDT eggs in our study may be due to geographical or environmental differences among collection sites. The pre-DDT eggs in the Keuka College collection were taken from Potter Swamp (Yates County) and Finger Lakes region of New York. The eggs sampled from Cornell Univeristy's collection were from Florida and New York. Measurements of the seven post-DDT eggs reported in Henny et al. (1973) were mostly taken from a single location in Maryland. The application of DDT may have differed among these regions. Additionally, eggshell thickness is influenced by factors other than DDT, including the amount of calcium found in forest litter and pH of local water (Green 1998). These other factors may have influenced the lack of differences in eggshell thickness between the pre- and post-DDT eggs in our samples. The degree to which the geographical variability or inconsistent exposure to DDT confounded results in other studies is likewise unknown. There were no reported differences in the thickness of White Ibis (*Eudocimus albus*) eggs among nine sites in Florida (Klaas et al. 1974).

The lack of difference in eggshell thickness in our study may also be influenced by small comparative sample sizes. Large samples of eggs collected at approximately the same time as those in the Keuka College collection (late 1800s to early 1900s) were available, but egg samples collected after the introduction of DDT were difficult to locate (see Table 1). The lack of independence that results if eggs from the same clutch are included in samples is also potentially confounding. Only ten eggs from four different clutches were available from Cornell University and an unknown number of clutches occurred in the post-DDT sample from Maryland.

Eggshell thickness may also differ due to the state of embryonic development when eggs were collected (Klaas et al. 1974). Embryonic development of eggs from Keuka College ranged from "early embryos" to "complete embryos" while other samples included addled eggs (Henny et al. 1973), or did not indicate the state of embryonic development among eggs.

Calcium uptake from the eggshell by the embyro is a potential source of eggshell thinning. Eggshells containing fully developed embryos may be thinner than eggshells with non-developed embryos (Castilla et al. 2010), and addled eggs may have thinner eggshells than those of viable eggs (Springer 1980). The unknown state of development and addled post-DDT eggs could explain why there was no difference in the eggshell thickness of such eggs compared to the pre-DDT eggs from Keuka College.

Collecting actual eggshell thickness measurements is not always possible and many studies instead report an eggshell thickness index (see Maurer et al. 2012). Comparing eggshell thickness indices of unclear derivation are a concern (Maurer et al. 2012). Based on a correlation of 0.67, the eggshell thickness index for Red-shouldered Hawks reported here was a moderately strong indicator of actual shell thickness. Much stronger correlations were reported by Maurer et al. (2012), but they examinated correlations among mean values, where stronger correlations are expected. Due to variability among individual measurements, we recommend caution when using egg shell thickness indices for comparisons among eggs collected before DDT and after DDT. We found conflicting results when using actual eggshell thickness measurements and eggshell thickness indices: based on actual shell thickness, we found no difference between the sample of 30 eggs from Keuka College and the ten eggs from Cornell University. The eggshell thickness indices of Keuka College eggs, however, were significantly larger than those from Cornell University.

Greater resolution in eggshell thickness differences between pre-DDT and post-DDT eggs can be achieved by identifying larger samples of post-DDT eggs, controlling for geographical variability, controlling for variability within clutches, and accounting for embryonic development among eggs.

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