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Historical and Geographical Patterns in Eggshell Thickness of African Fish Eagles *Haliaeetus vocifer*, in Relation to Pesticide Use within Southern Africa

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ABSTRACT

Ratcliffe's indices of shell thickness were determined for 90 eggs of African Fish Eagles (*Haliaeetus vocifer*) collected within southern Africa. Historical and geographical patterns in shell index were similar to those previously observed for raptor species in North America and Europe. Eggshell thickness declined progressively in relation to increased use of DDT. Thinnest eggs were sampled in regions of intense agriculture and fall below levels considered critical for similar species. Shells of eggs collected from coastal sites were significantly thicker than eggs collected from inland sites, even before the advent of DDT. African Fish Eagles have proved useful indicators of the degree of contamination of entire drainage systems. The geographical pattern of current expenditure on pesticides described 41% of the geographical variation in shell index. Production of cotton in South Africa also showed a significant negative correlation with shell index. The direct route of large quantities of DDT applied to this crop into waterways could be largely responsible for contamination of these systems. Within South Africa, rivers in the eastern Transvaal appeared to be the most contaminated. A monitoring programme should be initiated, especially in trouble-spots outside South Africa, where the liberal use of organochlorines continues.

INTRODUCTION

Changes in eggshell thickness provided the first evidence that the insecticide DDT or other organochlorines were largely responsible for drastic declines of raptor populations in Europe and North America (Ratcliffe 1967, 1970; Hickey & Anderson 1968; Anderson & Hickey 1974). Experiments confirmed that DDE, the principal metabolite of DDT, can cause eggshell thinning and reproductive failure (Heath *et al.* 1969; Porter & Wiemeyer 1969; Haegele & Hudson 1973; Cooke 1975). DDE thins eggshells by inhibiting shell gland enzymes responsible for calcium deposition in the laying female (Miller *et al.* 1976). Thinned eggs break on incubation or interfere with gas exchange. In this way DDE can cause a population decline before it reaches levels sufficient to kill adult birds. After the withdrawal of DDT from agricultural use in Europe and North America during the early 1970s, many raptor populations showed recovery (Spitzer *et al.* 1978; Ratcliffe 1980; Wiemeyer *et al.* 1984; Newton 1986).

DDT was used liberally in the western world between 1945 and 1969. Annual production of DDT in North America between 1959 and 1969 varied between 48,000 and 82,000 tons. Much of this production was exported to the southern hemisphere and global use of DDT was still increasing during the 1970s (Goldberg 1975). DDT was introduced to southern Africa in 1945 to help production of crops such as maize and cotton, and to combat disease vectors. In 1982 Zimbabwe imported 1,000 tons of DDT (Thomson 1984). Agricultural sales of DDT within South Africa averaged 950 tons per annum between 1974 and 1976 (J. Bot, *in litt.*). DDT was withdrawn from agriculture in South Africa by the early 1980s, but in 1985 approximately 121 tons were still being used annually for malaria control (E. K. Hartwig, *in litt.*), and circumstantial evidence suggests that considerable stockpiling for agricultural use took place.

Earlier raptor studies implied that the African situation was not as serious as it had been in North America or Europe (Brown 1971; Koeman *et al.* 1972; Whitwell *et al.* 1974; Frank *et al.* 1977). Later, researchers in southern Africa discovered pesticide residues in raptors at levels that have been associated with reproductive failure in similar species (Tannock *et al.* 1983; Snelling *et al.* 1984; Mendelsohn *et al.* 1988).

Attention was drawn to the potential of the African Fish Eagle *(Haliaeetus vocifer)* for indicating levels of contamination in river systems (Tarboton & Allan 1984). African Fish Eagles are widespread in southern Africa and are not considered endangered. In 1985 the South African Ornithological Society (SAOS) organised the collection of 26 African Fish Eagle eggs to investigate pesticide residues. De Kock & Lord (1986) reported on the pesticide residues in 18 of these eggs. This paper reports on the eggshell thicknesses of these and other eggs collected throughout southern Africa since 1900. We used Ratcliffe's Index (Ratcliffe 1967) as a measure of thickness. We consider this measure appropriate as the relationship between shell index and population trends is fairly precise and is consistent for raptor species studied so far (Newton 1979).

Our results suggest that eggs of African Fish Eagles can indicate contamination of drainage regions. Overall levels of eggshell thinning detected in this study fall below levels considered critical for similar species, but certain waterways of South Africa are still highly polluted and irrigation farming with crops such as cotton is implicated.

METHODS

Sampling

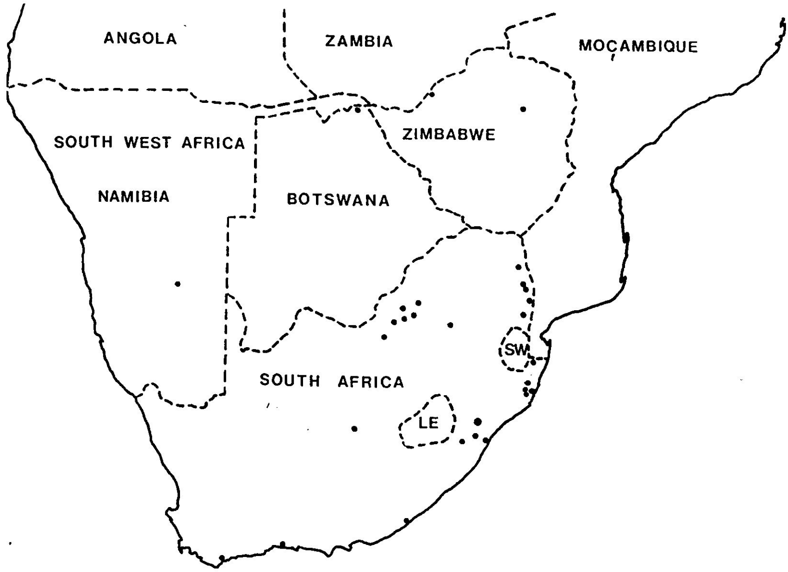
Our sample comprised 26 eggs collected for the SAOS and a further 64 eggs accessed from museums. These eggs were collected from 29 localities in southern Africa (Figure 1). Four countries contributed to the collection which we divided into five periods roughly by decade (Table 1).

The SAOS eggs were collected during the months June and July in 1985 and 1986, just after the laying peak (Steyn 1982). Three entire clutches and 17 single eggs were collected. Various criteria were used to select the first-laid egg (e.g. large size, pointed shape, accumulation of dirt on shell). Nine sites were chosen in cultivated areas where heavy use of pesticides was suspected. Five sites draining low-intensity farming areas, and two sites draining within conservation areas were chosen as controls.

TABLE 1: The distribution of 90 Fish Eagle eggs collected over five periods from four countries within southern Africa. Numbers in brackets denote number of clutches.

	< 1945	1945-60	1961-70	1971-80	1981-86	TOTAL
SOUTH AFRICA	26 (13)	4 (2)		19 (11)	27 (20)	76 (46)
ZIMBABWE		2 (1)	7 (3)	2 (1)		11 (5)
NAMIBIA					2 (2)	2 (2)
BOTSWANA			1 (1)			1 (1)
TOTAL	26 (13)	6 (3)	8 (4)	21 (12)	29 (22)	90 (54)

FIGURE 1: Distribution of the 29 sites in southern Africa from which 90 eggs of African Fish Eagles were collected between 1901 and 1986. KEY: LE - Lesotho; SW - Swaziland.



Egg measurement

Eggshell thickness was determined indirectly using the Ratcliffe Index (Ratcliffe 1967). This is subsequently referred to as shell index. Length and greatest breadth were measured with dial calipers, and the mean of three measurements was taken. Emptied eggshells were weighed to the nearest mg, after being air-dried for at least six months.

Egg contents were extracted through holes of differing sizes. We conducted an experiment to ascertain the amount of weight loss attributable to this drilling. Two freshly-laid eggs of the African Penguin (*Spheniscus demersus*) were chosen on account of their similarity in size, shape and weight to African Fish Eagle eggs. Egg contents were removed through holes of 1.5mm diameter. Shells were weighed after air-drying for five months. The holes were then enlarged in a series of steps to 8mm diameter. At each step, hole diameter and eggshell weight were recorded.

Proportional weight loss was regressed on hole diameter. A power curve yielded the best fit to the data and was similar for the two eggs. The smoother of the two curves had the following relationship:

$$y = 0.01\ x^{2.16}$$

where y = percentage weight loss, and x = hole diameter (mm). This relationship was then used to calculate the weight loss resulting from the holes drilled, which was then added to the measured weight to give a corrected weight.

Egg contents had been extracted from the SAOS eggs by removing a large oval section with a stone cutting drill. Similar sectioning of the two penguin eggs led to losses of 1.16% and 1.18% total weight. A figure of 1.17% was used to calculate the corrected weights of these eggs.

Partial loss of egg membranes occurred in 12 of the SAOS eggs during extraction of contents. Egg membranes and attached traces of albumen can comprise up to 10% of eggshell weight (Ratcliffe 1970).

We extracted intact membranes from five eggshells of healthy thickness (approximating the pre-DDT mean) after soaking in water for one hour. These membranes were dried at 80oC for one hour and then weighed to the nearest mg. Dried membranes were found to comprise 7.48% of total eggshell; weight (range 7.17 - 9.23). We used this figure to predict an expected membrane mass for the 12 affected eggs. The proportion of membrane missing was estimated visually and multiplied by the expected membrane mass to give the amount to be added to the eggshell weight in compensation.

Statistical analysis

Shell indices were determined for both eggs and clutches and considered separately. We used one-way ANOVA for comparisons of the length, breadth and corrected weight of eggshells over the five time periods.

Only samples for South Africa, and the last two periods, were large enough to make geographical comparisons of eggshell thinning (n=46). These eggs were collected during, and just after, the period of maximum DDT use. They could be allocated to 18 separate major drainage regions. The number of eggs collected within each region ranged from 1 to 10 (mean 2.5). From these data we determined a mean shell index for each drainage region. We then used correlation analyses to investigate the relationships between shell index and 18 environmental variables. Area, average rainfall and water catchment were determined for each drainage region from information supplied by the Department of Water Affairs (pers. comm.). Data were obtainable by magisterial district, for the year 1980, on agricultural sales, expenditure on pesticides, the production of various crops, area under irrigation and farm size (Anon 1981 a, b & c). This information is derived from a questionnaire sent out to all landowners. For our analysis we summed the values for all magisterial districts encompassed by a particular drainage region.

We estimated the annual amount of DDT used for malaria control in each of our drainage regions from the quantities of DDT used in the seven minor political areas situated along the north-eastern border of South Africa for the years 1983 through 1986 (E. K. Hartwig, Dept. of Health *in litt.*).

RESULTS

Temporal variation in shell index

A comparison of the sizes of the eggs showed that there were no statistically significant differences in the lengths or breadths over time. There was, however, a statistically significant difference in eggshell weight over time (Table 2).

Shell index declined after 1945 (Figure 2), and showed a downward trend, reaching a low during the 1970s which represented 11.7% thinning of the eggshells (same for clutches). Shell index during the last period appeared to return to levels comparable with the 1950s. Eggshells for the last period were on average 3.5% thinner than the historical mean (7.4% thinner when expressed for clutches only).

If the 12 eggshells that had lost parts of their membranes are included in the 1980s sample (with compensation, see methods), then mean shell index for this sample drops to 2.65, representing 6.3% thinning (or 8.4% when expressed for clutches only).

Geographical variation in shell index

Looking at eggs from all periods (n=90), we found that coastal eggs had thicker shells (mean shell index 2.98; n=27) than inland eggs (mean shell index 2.53; n=63). This difference was statistically highly significant ($z=7.52$; $p < 0,01$), and held even for the pre-DDT sample ($t=18.5$; $p < 0.01$). Mean shell index for the seven localities sampled during the pre-DDT period showed a highly significant negative correlation with distance from the coast ($r_s = -0.94$; $p < 0.01$).

The 46 eggs collected in South Africa after 1977 came from 18 drainage regions (Figure 3). Thinnest eggshells came from rivers draining central and eastern Transvaal (sample sites 7-12). Thickest eggshells came from coastal areas (sites 14, 17 & 18) and the vicinity of Bophutatswana (sites 2 - 5).

Six of the 18 environmental variables measured for each drainage region showed correlations with shell index that were statistically significant (Table 3). Eggs were significantly thinner in areas where expenditure on pesticides was high. This variable described 41.0% of the geographical variation in shell index. Eggshells also tended to be thin in regions where DDT use for malaria control was high, and in areas of high agricultural production. Field crops and horticultural products described roughly equal amounts of the regional variation in shell index. Only two crops (citrus and irrigated cotton) correlated significantly with shell index, although there was a slight trend for eggs to be thinner in areas of high maize production.

TABLE 2: **Changes in the length, breadth and weight of eggshells of African Fish Eagles from southern Africa. The unit of weight used is the corrected weight. Numbers in brackets refer to calculations performed inclusive of the corrected values for 12 eggs (from the last period) which had suffered loss of membranes. Corrections are explained in the section on methods.**

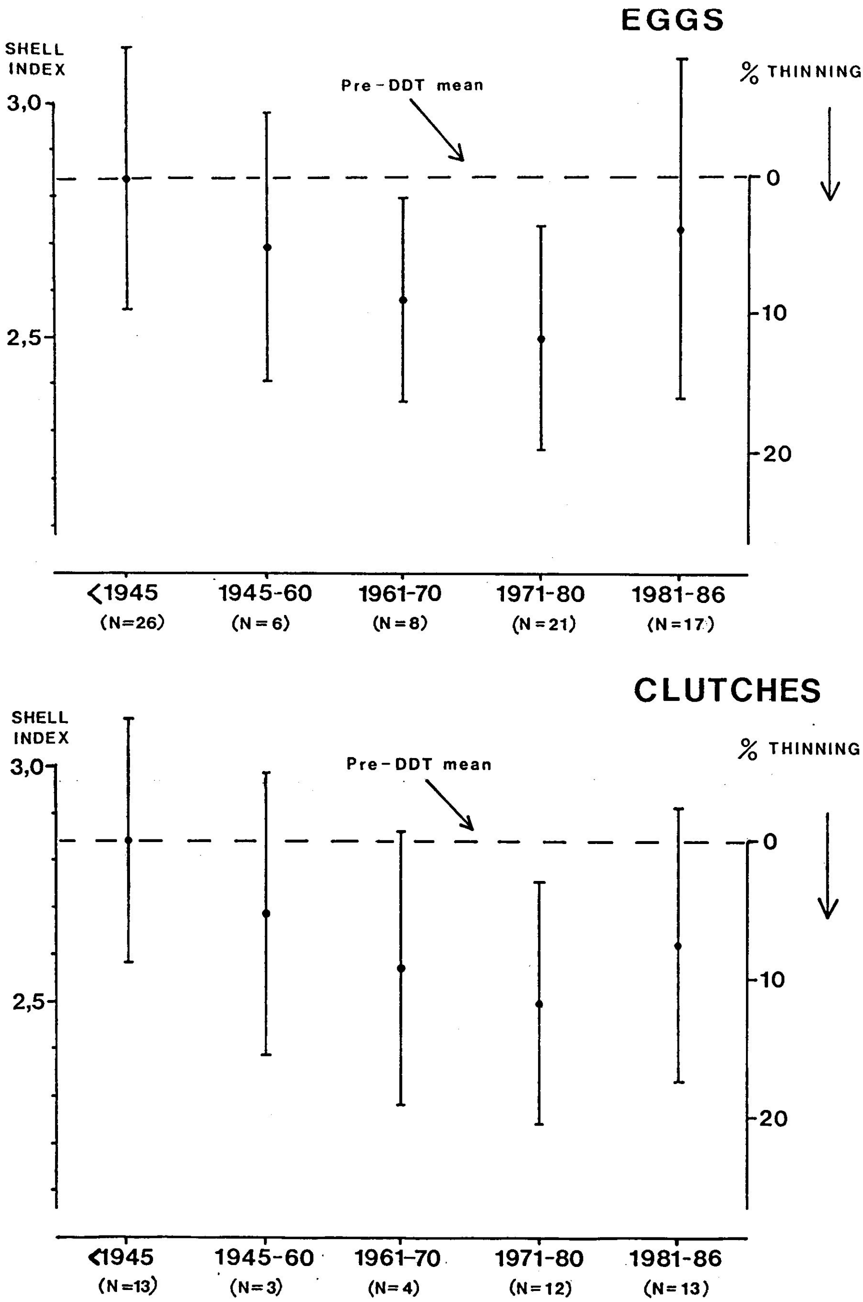
Means and standard deviations are given for each period.

DIMENSION	PERIOD					ANOVA
	<1945	1945-60	1961-70	1971-80	>1981	
n	26	6	8	21	17 (29)	
LENGTH x	70.69	72.34	73.64	70.38	70.27 (71.36)	F =2.49 (1,82)
(mm) sd	3.16	2.03	1.90	2.51	3.61 (4.13)	P>0.05 (0.13)
BREADTH x	54.36	54.91	53.16	54.23	53.32 (53.69)	F =1.79 (1,22)
(mm) sd	1.50	1.11	1.95	1.36	2.62 (2.56)	P>0.14 (0.30)
WEIGHT x	10,858	10,687	10,062	9,539	10,166(10,064)	F =5.46 (5,12)
(mg) sd	1,228	1,071	643	901	799 (1,021)	P<0.01 (0.01)

TABLE 3: **The relationships between mean shell indices of African Fish Eagle eggs and eighteen environmental variables measured for each drainage region sampled within South Africa. The coefficient of determination (R^2) represents the percentage regional variation in shell index described by each variable. Data sources given in methods.**

ENVIRONMENTAL VARIABLE	CORRELATION WITH SHELL INDEX		
	r	PROB.	R^2(%)
Area of drainage region (ha)	-	n.s.	
Mean annual rainfall (mm)	+	n.s.	
Catchment (area*rainfall)	-	n.s.	
Average farm size (ha)	-	n.s.	
Area under irrigation (ha)	-	n.s.	
Expenditure on pesticides (R/annum)	-0.640	<0.01	41.0
Expenditure on dips/drenches (R/annum)	-0.459	(<0.01)	
Sales of agricultural products (R/annum)	-0.516	<0.05	26.6
Sales of field crops (R/annum)	-0.480	<0.05	23.0
Sales of horticultural products (R/annum)	-0.474	<0.05	22.4
Production of maize (T/annum)	-0.451	(<0.01)	
Production f wheat (T/annum)	-	n.s.	
Production of sugar (T/annum)	+	n.s.	
Production of citrus (T/annum)	-0.587	<0.05	34.4
Production of cotton (irrigated, kg/ann)	-0.541	<0.05	29.2
Production of cotton (dry land, kg/ann)	-0.422	(<0.10)	
Production of tobacco (kg/annum)	-	n.s.	
Quantity DDT used for malaria control	-0.407	(<0.10)	

FIGURE 2: Historical change in Ratcliffe's shell index of African Fish Eagle eggs collected within southern Africa. Mean values and their standard deviations are given for each period. Twelve eggshells missing parts of their membranes were excluded from the 1980s sample.



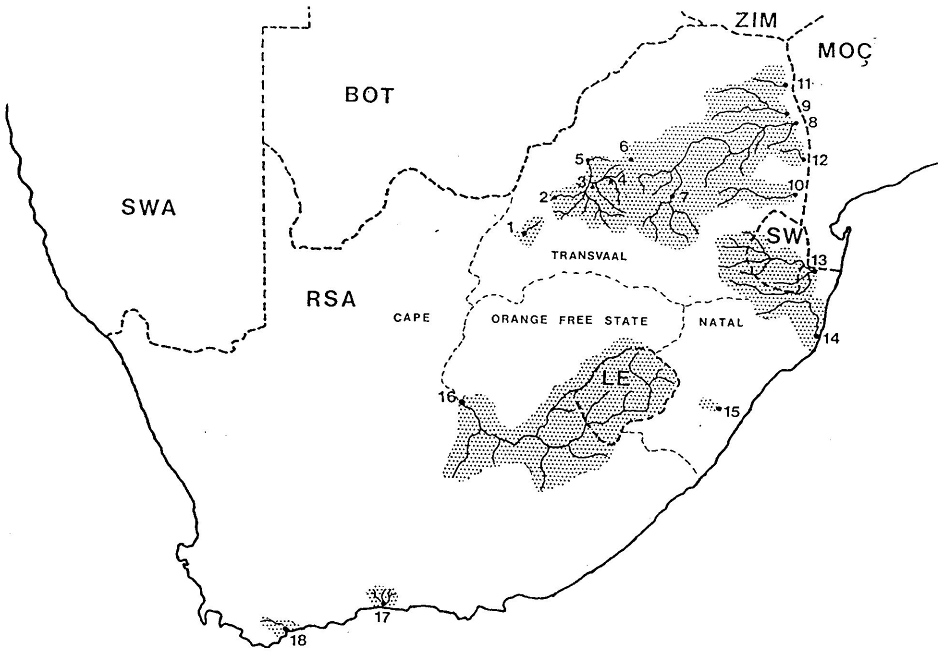


FIGURE 3: The distribution of 18 sampling sites from which 46 African Fish Eagle eggs were collected in South Africa between 1978 and 1986. Stippling represents the extent of the catchment area for each water system sampled. Sample size and shell index were as follows:

Site	REGION	N	shellindex
1	Barberspan	3	2,45
2	Swartruggens	2	2,70
3	Borakolalo	3	2,66
4	Bophutatswana	4	2,77
5	Crocodile river (west)	1	2,72
6	Nylsvlei	9	2,50
7	Loskop dam	2	2,13
8	Olifants river	1	2,02
9	Letaba river	1	2,39
10	Crocodile river (east)	3	2,15
11	Shingwidsi river	1	2,22
12	Nwanedsi river	1	2,22
13	Usutu/Pongola confluence	1	2,47
14	Lake St. Lucia	10	3,05
15	Shongweni dam	1	2,59
16	P K le Roux dam	1	2,40
17	Sedgefield lakes	1	2,70
18	De Hoop reserve	1	2,62

Key:
SWA..........South West Africa/Namibia.
BOT.......... Botswana.
ZIM.......... Zimbabwe.
MOC........ Mozambique.
RSA.......... Republic of South Africa.
SW............ Swaziland.
LE............ Lesotho.

DDE residues

A negative relationship existed between shell index and the logarithm of the DDE residue levels in the 18 SAOS eggs analysed by De Kock & Lord (1986), but the relationship was weak and a significant correlation could not be demonstrated ($r = -0.198$; $p > 0.20$).

DISCUSSION

Temporal variation in shell index in relation to pesticide use

The absence of any statistically significant difference over time in the lengths or breadths of African Fish Eagle eggs examined during this study shows that changes in egg size could not account for the observed changes in weight or shell index. Similar declines in shell index observed in other raptor populations were mainly due to decreases in shell thickness, rather than shell density (Ratcliffe 1970).

In accordance with the situation in Europe and North America, it appears that thinning of African Fish Eagle eggs occurred after the introduction of DDT in southern Africa. The progressive decline in eggshell thickness through to the 1970s might then be attributed to increased use of DDT together with a time-lag in its rate of bioaccumulation.

South African eggs comprised 92% of our samples for the last two periods. Restrictions on the agricultural use of DDT in South Africa began in 1970. These restrictions had little effect on total sales (Van Dyk *et al.* 1982), so DDT was withdrawn, first as a stock remedy in 1974 and later as an agricultural remedy in 1976. In two years between 1974 and 1976, 1,900 tons of agricultural DDT were sold. This represented 57.6% of total organochlorine sales and 15.8% of total pesticide sales for that period (J. Bot pers. comm.). Before the restrictions, DDT probably comprised a greater proportion of total pesticide sales.

The quantity of DDT sold during 10 months between 1975 and 1976 was almost four times the quantity sold in the previous year. If these figures are correct, such stockpiling would probably have lasted the rest of the decade, so the withdrawal of DDT from South African agriculture probably became effective at the beginning of the 1980s when there was a total ban on the product.

Now the only legal use of DDT in South Africa is approximately 121 tons/year for malaria control along the north-eastern border. This is probably about 15% of the total quantity used formerly. For the control of malaria, DDT is applied to the interior of dwellings and such operations are under strict control, so the environmental hazard is markedly reduced when compared with agricultural spraying of DDT. As dwellings in South Africa become more westernised, DDT will be phased out in favour of other insecticides (E. K. Hartwig, *in litt.*).

Insecticides in tropical Africa are considered to have higher rates of volatilization and co-distillation than in temperate climes (Koeman & Pennings 1970; Everaarts *et al.* 1971; Koeman *et al.* 1972). Where 90% of DDT is recoverable from temperate soils two years after application (Fleming & Maines 1953; Roberts *et al.* 1962), only 20% is recoverable from South African soils after the same period (Wiese & Basson 1966). If the withdrawal of DDT from South African agriculture became effective in 1981, then approximately four years of minimal DDT input elapsed before the collection of the last sample of eggs. Most ambient DDT should have volatilized over that period. Consequently one might expect reduced contamination of African Fish Eagles, and the observed increase in shell index during the 1980s would appear to bear this out. However, we consider that this apparent recovery and the 'exaggerated' levels of thinning witnessed in the three other post-DDT periods are largely a consequence of the predominance of thicker coastal eggs in our pre-DDT and 1980s samples. Coastal eggs comprised 50% of our pre-DDT sample and 41% of our 1980s sample. No coastal eggs were collected during the other periods.

The existence of a highly significant difference between shell indices of coastal and inland eggs in the pre-DDT sample implies that some factor other than pesticide use is involved. Genetically determined geographical variation in eggshell thickness has been observed in other birds (Anderson & Hickey 1970). It is also possible that some environmental difference, such as higher calcium content in fish from marine or brackish waters, is responsible for the difference in eggshell thickness.

Extremely high levels of thinning reported in previous studies on African Fish Eagle eggs can be attributed to a pre-DDT mean consisting entirely of coastal eggs (Thomson 1984; Mendelsohn *et al.* 1986).

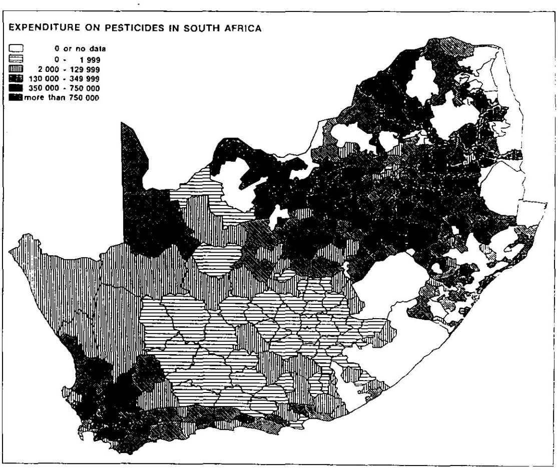
If all coastal eggs are removed from our samples, then mean shell index is reduced from 2.83 to 2.65 (sd 0.23) in our pre-DDT sample, and from 2.65 to 2.41 (sd 0.26) in our 1980s sample (including eggs compensated for membrane loss). Percent changes from the pre-DDT mean then become: +1.0% for the 1950s; -2.6% for the 1960s; -5.7% for the 1970s; and -9.1% for the 1980s. Mean shell indices for the 1950s and 1960s now show no significant difference from the pre-DDT mean. Thinning becomes significant in the 1970s ($t=6.72$; p 0.01) and the 1980s ($t=9.33$; $p < 0.01$). This analysis implies that the influence of DDT became detectable much later and that there has been no recovery in the 1980s. The collection of highly thinned eggs from the eastern Transvaal may well have contributed to the latter effect, as no eggs were collected from these regions in previous samples. While most ambient DDT in the South African environment may have broken down or volatilized by the time the 1980s sample was collected, this period may have been insufficient for reduced contamination of African Fish Eagles. Black Ducks continued to produce fewer young and thinner eggs two years after experimental feeding with DDE ended (Longcore & Stendell 1977). We consider that removing the coastal eggs allows a more appropriate interpretation of the situation.

Population declines were observed for both White-tailed Sea Eagles (*Haliaeetus albicilla*) and Bald Eagles (*Haliaeetus leucocephalus*) when their eggshells approached and exceeded 16% thinning (Anderson & Hickey 1974). Whichever samples we chose to use in our analysis, mean shell indices for all periods considered fall well below such critical levels of thinning. Population trends of African Fish Eagles in southern Africa have not been monitored, but there has been no evidence of egg breakages and consequent reproductive failure for this species in its southern range (Tarboton & Allan 1984; and the present investigation). It should be noted however, that little is known about contamination of African Fish Eagles outside South Africa, where the use of organochlorines continues unabated. We feel that a monitoring programme of African Fish Eagle populations should be initiated in such trouble spots.

Geographical variation in shell index in relation to pesticide use

Ratcliffe (1970) and Anderson & Hickey (1974) observed that eggshells of European and North American raptors were thinner in regions of intense agriculture and higher pesticide use. The same trend was evident in our sample of southern African Fish Eagle eggs. The geographical pattern of expenditure on pesticides in South Africa is displayed in Figure 4. The highly significant correlation between shell index and expenditure on pesticides, indicates that African Fish Eagles are useful indicators of environmental contamination.

FIGURE 4: Expenditure on pesticides (Rands/annum) in South Africa by magisterial district during 1980 (Anon 1981a). Map compiled by the Institute for Cartographical Analysis, University of Stellenbosch.



Three factors may have influenced this correlation. First, African Fish Eagles may move from polluted to unpolluted regions and vice versa. Secondly, three of our 18 drainage regions are coastal, where factors other than pesticide use appear to influence eggshell thickness. Lastly, present expenditure on pesticides as a whole may not accurately reflect past expenditure on DDT. DDT had a widespread application, but was predominantly used on maize and cotton (J. Bott, pers. comm.). Most South African maize is produced in the Transvaal and the Orange Free State. These two provinces accounted for 96% of DDT sold between 1973 and 1976 by Agricura, the main agent in South Africa (Jooste, pers. comm.).

As described earlier, DDT used in malaria control presents less of an environmental hazard than agricultural DDT. We consider that the statistically significant tendency for shell index to be lower in areas of high malaria control results from overlap of these areas with regions where agricultural use of DDT was high in the past. We found a strong correlation between DDT used in malaria control and expenditure on pesticides ($r=0.717$; $p < 0.001$).

By separating the various components of agriculture, we hoped to identify the elements that were more associated with eggshell thinning, and thus perhaps responsible for it. Of the various crops considered, DDT was used permanently on maize and cotton (J. Bot, pers. comm.). Therefore the absence of any correlation between shell index and wheat, sugar or tobacco is expected. We consider that the highly significant correlation between shell index and citrus is not a causal relationship but the product of geographical coincidence. In contrast, the relationship between thin eggs and high production of cotton and maize might be causal.

Maize can be grown without irrigation and requires application of pesticides only once or twice in a season. Cotton is mainly grown along rivers or near dams by irrigation. It is a highly intensive crop, and pesticides are applied up to twelve times in a season. Thus DDT applied to cotton has a very direct route into a water system when compared with that applied to maize. Overall, more DDT may have been applied to maize than to cotton, but this DDT would have had more opportunity to break down before it entered a flowing water system. It is relevant that dry-land production of cotton did not show a significant correlation with shell index, whereas irrigated cotton did. The absence of a significant correlation between shell index and irrigation farming or tobacco production indicates that cotton, rather than other irrigated crops, might be largely responsible for the contamination.

The thickest eggs in this analysis came from Lake St. Lucia. These eggs showed no change in shell index from eggs collected at the same site, and further down the Natal coast, prior to the use of DDT. We have already speculated on the cause of such thickening in coastal eggs. In addition, the predominant crop in this region is sugar, the production of which did not involve DDT (J. Bot, pers. comm.). However, dieldrin was applied legally to pineapples grown on the banks of the lake until 1984. Eggs collected from this site in 1985 for the SAOS were characterised by thick shells and low viability.Eggs from two other coastal sites (Sedgefield and De Hoop) showed only moderate thinning. Unlike Lake St. Lucia, these two water systems do not have a direct connection with the sea. Low organochlorine contamination of various Sedgefield biota was detected in 1983 (De Kock & Boshoff 1987).

Remaining thick-shelled eggs came from sites in the vicinity of Bophutatswana. This is surprising in the light of heavy contamination of parts of the same drainage system in 1974 (Greichus *et al.* 1977). Small-scale farming around the actual collection sites might explain low contamination.

Eggs collected from the Shingwidzi and Nwanedsi rivers in a large conservation area in the eastern Transvaal were, on average, 16.2% thinner than the inland sample of pre-DDT eggs ($n=13$). Very little agricultural DDT could have been used within these drainage regions, so contamination of these African Fish Eagles probably occurred elsewhere. Thinning was also evident at the P K le Roux dam which drains open-range farming lands. Pesticides used in Lesotho and for irrigation along the Orange River might be responsible. These findings draw attention to the difficulty in obtaining samples free from the influence of DDT.

The thinnest eggs were sampled in the central and eastern Transvaal (including the two sites just mentioned). Eggs from five of these sites exceeded the critical level of 16% thinning, when compared pre-DDT mean. In particular, the Olifants River appeared most contaminated. This is not surprising as magisterial districts within this drainage region accounted for the greatest expenditure on pesticides, the greatest use of DDT for malaria control and the highest production of cotton for any drainage region in this analysis.

Whilst high maize production may be largely responsible for contamination at Loskop Dam, high cotton production is the most likely cause of contamination in the eastern Transvaal. Very high levels of DDE contamination have been recorded for various biota from this region (Pick *et al.* 1981; Snelling *et al.*1984).

DDE residues

The absence of a significant negative correlation between the DDE content of the eggs analysed by De Kock & Lord (1986) and shell index is surprising. A linear relationship is normally found between the logarithm of DDE and thickness index, providing DDE concentrations exceed 0.1 - 0.2 ppm and show more than a ten-fold variation (Moriarty *et al.* 1986). All 18 eggs analysed by De Kock & Lord had detectable DDE residues: mean = 0.94; median = 0.82; range 0.11-6.36 (all values ugg-1 wet weight). The residues detected by these authors showed no regional correlation with expenditure on pesticides nor any aspect of agricultural production.

CONCLUSION

The close relationship between eggshell thickness and the use of DDT, often observed in raptor populations from Europe and North America, is evident both historically and geographically in African Fish Eagles from southern Africa. Providing that the difference observed between the thicknesses of coastal and inland eggs is born in mind, eggs of African Fish Eagles have demonstrated their value as indicators of pesticide contamination, not just of the population, but of entire drainage systems. In particular, geographical trends in shell index have implicated cotton as perhaps largely responsible for contamination of water systems with DDT. Mean levels of eggshell-thinning for any period did not approach levels considered critical for similar species and the African Fish Eagle in 1985 does not appear to be threatened by the use of DDT at most localities within South Africa. However, the critical levels of eggshell thinning were exceeded in certain localities, such as the eastern Transvaal. We suggest that the initiation of a monitoring programme of population trends is more important than continued sampling for eggshells or DDE residues. This programme should concentrate in the eastern Transvaal and outside South Africa, where organochlorines are still liberally used.

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