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**Parental time-budgets, breeding behaviour and affinities of the Red
Goshawk *Erythrotriorchis radiatus***

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The breeding behaviour of the Red Goshawk *Erythrotriorchis radiatus* was studied in Kakadu National Park, Northern Territory, in 1987–89. Two active nests, for all or part of the breeding cycle from courtship and nest-building (April) to the post-fledging period (October), were observed in timed observation sessions. One nest-building male collected sticks at a rate of 0.4–0.6/h, and the female at 0.1–0.3/h; this male fed the female 0.1 prey item/h and copulated 0.3–0.4 times/h. The female attended the nest for 81 percent of observation time (incubating 50%, shading 31%). In the nestling period, females progressed from brooding, to standing on the nest (often shading the chicks) to perching in the nest area as the chicks grew, and males delivered prey (0.3–0.4 item/h). Males did not incubate, and spent little time at the nest when females were present. The prior suggestion of bigamy at one of these nests is revised on the available evidence. The behavioural data in this paper, combined with new DNA evidence, are used to evaluate the Red Goshawk's taxonomic status. The Red Goshawk's genetic link with *Accipiter*, and possibly with the harriers *Circus*, matches its behavioural, morphological and ecological characters, rather than those of the other Australian endemic hawk

genera (*Lophoictinia* and *Hamirostra*, which are perine kites). Lastly, an error in the labelling of Red Goshawk vocalisations in the primary literature is noted.

INTRODUCTION

The breeding behaviour of the Red Goshawk *Erythrotriorchis radiatus* has been described in general terms (Marchant and Higgins 1993), using ‘snapshots’ of behavioural data collated from the anecdotal literature (e.g. Cupper and Cupper 1981; Favaloro 1981; Hollands 1984; Debus and Czechura 1988; Brickhill 1991; Smith 1991). Further detail is provided by Aumann and Baker-Gabb (1991), who comprehensively described courtship and nest-building behaviour, accurately determined incubation and nestling periods, and described the minimum period of post-fledging dependence. Subsequently, following further anecdotal ‘snapshots’ (Debus *et al.* 1993; Czechura and Czechura 1994; Wilkins and Donato 1998), Czechura *et al.* (2009) described (non-quantitatively) the full breeding cycle, including elements of pre-laying behaviour, and Hollands (2003) and Carlson (in Debus 2008) provided supplementary observations on the nestling period. Video recordings of Red Goshawk breeding behaviour have been made (Young 2004), but are of limited use for further detailed description, as the order of filming is out of sequence and the narrative is highly speculative (see Debus 2007).

This paper expands on previous descriptions of Red Goshawk breeding ecology by quantifying the behaviours summarised by Aumann and Baker-Gabb (1991) and Marchant and Higgins (1993), including stick-collecting rates, parental time-budgets (nest attendance, feeding rates), and the physical and behavioural maturation of nestlings. It also details some otherwise undescribed parental

behaviour, and evaluates (based on colour-marked birds) the suggestion of possible bigamy by one breeding male (Aumann and Baker-Gabb 1991). Aspects of Red Goshawk breeding behaviour are then compared with those of other Australian hawks in the light of new DNA evidence on the taxonomic relationships of the endemic Australian hawk genera, provided by Barrowclough *et al.* (2014). Finally, an error in the labelling of Red Goshawk vocalisations in the primary literature is noted.

STUDY AREA AND METHODS

Observations of Red Goshawk breeding behaviour were recorded primarily for pairs located in Kakadu National Park, Northern Territory. Red Goshawk nests were mostly in eucalypt-dominated tall open forest in the near-coastal part of the Top End. Detailed descriptions of the habitat surrounding each nest were provided by Aumann and Baker-Gabb (1991) and Marchant and Higgins (1993). Supplementary observations were conducted at subcoastal sites where nests were located in tall riparian gallery forest.

Observations of Red Goshawk breeding behaviour were made at two main nests, using binoculars from an unconcealed position outside the Goshawks' alert distance and, in one case, from a hide on the ground approximately 50 metres from the focal pair's nest (at Kapalga). The adults were generally confiding and approachable, usually ignoring people or at least appearing not to be alarmed by human presence or activity beneath the nest. Quantified observations on the nestling period were conducted at one nest in 1987 (nest 1). At another (Kapalga, nest 2) observations were conducted throughout the breeding cycle in 1988 from courtship

and nest-building through incubation to the nestling and post-fledging periods, and in the pre-laying phase in 1989 (see Table 1 for a summary of the observation schedule).

In the pre-laying phase (courtship, copulation and nest-building), the focal (Kapalga) nest was observed in June–July 1988 for a total of 32.7 hours over 12 days, mostly in the mornings (18.7 hrs, to 10:00 h) and afternoons (10 hrs, 14:00 h to dusk), and seldom over midday (4 hrs on one day, 10:00–14:00 h), with a lapse in observations in the last week before laying. In the pre-laying phase in 1989 (Kapalga), observations were conducted for a total of 15.8 hours over eight days in May, 28.3 hours over eight days in June, and 10.25 hours over two days in early July, covering all hours of the day, with casual (unquantified) observations over the remaining days until egg-laying in late July.

In the incubation phase in 1988, the focal nest (Kapalga) was observed for 15.75 hours over six days, in the mornings (5.75 hrs, 06:30–09:00 h) and afternoons (10 hrs, 14:00–19:15 h), with casual observations over a further eight days, from the time the clutch was complete until hatching. In 1989, apart from sustained observations on the first egg-laying day, observations were casual or unquantified over the ensuing four days until monitoring ceased.

In the nestling phase in 1987 (nest 1), the nest was watched for a total of 101 hours, distributed thus: weeks 1, 13 hours over two days (covering 1000 h to dusk); week 2, 69.5 hours over six days (all-day watches, dawn to dusk, except to late afternoon on one day); week 5, 11.5 hours over two days (covering daylight hours); week 8, seven hours on one day. In 1988 (Kapalga), nest 2 was watched for a total of

44 hours, distributed thus: week 1, 31.5 hours over seven days; week 2, 9.5 hours over four days; week 3, three hours over two days (early mornings from 06:30 h; late afternoons to dusk (~19:00 h); and also mid-late mornings in week 1). Casual observations continued until beyond fledging.

The focal pair at Kapalga (nest 2) was trapped so that metal bands, colour-bands (bands supplied by the ABBBS) and radio-transmitters could be attached (Aumann and Baker-Gabb 1991). The adult female was trapped in mid-October 1988 (during the post-fledging period), and the male in mid-May 1989 (during the pre-egg phase), resulting in both members of this pair being easily identifiable during the 1989 pre-laying phase. The female lost her radio-transmitter sometime before monitoring resumed in March 1989, and progressively lost one then a second (of three) plastic colour-bands in April and June. The male lost his transmitter in late June 1989. Metal bands were also attached to nestlings. Red Goshawks were readily sexed by their extreme sexual size dimorphism, and by plumage differences between the sexes (breeding females have a whiter belly than males) (Aumann and Baker-Gabb 1991; Marchant and Higgins 1993).

RESULTS

Pre-laying phase

In 1988, the male delivered prey to the female in courtship (supplementary) feeding at least three times in 32.7 h of observation time (= 0.1 item/h), in the mornings and afternoons. The male brought 18 sticks in 32.7 hours (= 0.6/h), mostly

in the mornings (0.9 /h), few in the afternoons (0.1/h) and none during his midday absence (4 h). The female brought 10 sticks (0.3/h), all in the mornings (= 0.5/h of active building time) although she was present, resting in the nest area or attending the nest, at other times. The pair copulated (as described by Aumann and Baker-Gabb 1991 and Marchant and Higgins 1993) at least 10 times (= 0.3/h), all in the mornings during active building and nest-attendance times (= 0.5/h of nest attendance). Observations lapsed a week before egg-laying occurred, but nevertheless on the last day of observation, no building or copulation was observed during two hours of nest-watching in the morning and three hours in the afternoon.

Through March 1989 there was no sign of the Goshawks or activity at the nest until the 30th, when the pair visited the nest together and the male performed low-aerial, fast agility display-flights. Through April they (mainly the male) guarded the nest, and he performed low-aerial agility flights and perched courtship postures near the perched female, as previously described (Aumann and Baker-Gabb 1991; Marchant and Higgins 1993). One instance of incipient copulatory behaviour was cautious and abortive: after a low display-flight the male landed twice beside the female, she assumed a horizontal posture and he made as if to land on her back but landed 5 metres away, after which they perched a metre apart (the male higher).

Through early May, nest attendance by one or both increased to daily by the female, until building started on the 12th. The male collected sticks within 100 metres of the nest by short flights between trees, peering, then landing on long, dead sticks, breaking them under his weight, and flying heavily to the nest with the stick in his feet. At this stage the female started roosting in the nest area, and the male started

visiting the nest site in the early mornings. The male performed all observed building in May, e.g. four sticks in one hour over the midday period (11:30–12:30 h).

In the first half of June 1989, the male collected and added sticks in the mornings, and went hunting in the afternoons. At this stage, no sticks were added in three afternoons (8.5 hrs, 13:00–18:30 h), one morning (2 hrs, 09:00–11:00 h) or two midday periods (3.5 hrs, 11:00–13:00 h). However, the number of new sticks on the ground under the nest each day ranged from 10 to 48, and the number of sticks in the nest increased from 25 to 70 over this period.

From mid-June the female started building, and the male started working his collected sticks into the structure rather than just dropping them on the platform, including through the midday period. The male delivered at least 12 sticks in 28.3 hours (= 0.4/h), and the female three (= 0.1/h), dropping a fourth en route to the nest. There was one copulation (<0.1/h), in the afternoon on the 21st, during which the male initially seemed hesitant. After he brought a stick to the nest, calling, the female arrived, also calling, and he retreated. When she adopted a horizontal soliciting posture with calling, he approached to 3 metres; she flew 30 metres, adopted the horizontal posture with wings drooped and calling, and he landed on her back, copulating for five seconds. To late June there were more than 200 sticks in the nest, and a cumulative total of 303 dropped sticks on the ground below (9.7 kg, mean 32 g).

From early July, in 10.25 hours the male delivered five sticks (= 0.5/h) and one prey item (= 0.1/h), and there were four copulations (0.4/h: three in the afternoons, one in the morning). At this stage, there was one instance of bill contact

between the pair while they perched together. Thereafter, until egg-laying, observations were intermittent and casual, but the female was often resting near the nest or standing on it, she roosted in the nest area, and the male brought prey to her.

On one occasion in late June and on three consecutive days in early July, the colour-banded female (not the male, *contra* Aumann and Baker-Gabb 1991) from Kapalga visited the neighbouring active nest 6.5 km away. In June she roosted beside that nest, and in July she brought a stick and arranged nest material while the other nest-building female was displaced. The two females maintained some distance from each other, perching 5–40 metres apart. The nest-building and soaring male at this nest was not seen clearly enough to observe any colour-bands or lack thereof. However, on one occasion in early July, the colour-banded Kapalga male soared high (>1000 m) over his own nest site then made a long glide directly towards the neighbouring nest, which might suggest that he was active at both nest sites.

Incubation

In 1988, on the second day of incubation (21 July, the egg apparently having been laid on the previous day), the female incubated only part-time. On the following day she stood on the nest in the last half-hour of daylight, then incubated at night. Thereafter, from 23 July when (by her behaviour) the second egg was laid in the evening, the female incubated for 50 percent of observation time (in the mornings and late afternoons, after 17:50 h); stood on the nest or shaded the eggs for 31 percent (in the afternoons to 18:00 h); was off feeding on prey brought by the male for 15 percent; and was otherwise off the nest, including collecting green foliage for nest-

lining (three times = 0.2 item/h) and copulating (once, on the morning of the day that second egg was laid) for 4 percent. Her total nest attendance was 81 percent of observation time, with absences (though still in the nest area) of 47 (morning), six and 84 minutes (afternoons). On the longest of these, the male shaded the eggs in three stints of 10 minutes each, but did not incubate (= nest attendance 3% of total observation time). He brought four prey items (one morning, before copulating, and three afternoons/evenings = 0.3 item/h). During casual observations over eight other days, the female was mostly on or near the nest or incubating, and the male brought prey, to the nest for transfer to the female, on two evenings.

In 1989, on the day preceding egg-laying (i.e. 22 July) the female spent most of the day perched in the nest tree or nearby, in pre-laying lethargy with her wings drooped. On 23 July, in the morning, she was standing in the nest, lying in the nest (30+ minutes) then at 09:45 h stood up, and five minutes later appeared to gently rake an egg into the centre of the nest with her bill. Thereafter, until midday, she stood in the nest with her wings drooped and tail raised. Over the next two days she was variously standing on the nest or incubating, on the following two days she was incubating all day, and in the evening of the last day of observation (27 July) the male and female were both on the nest.

During casual observations or checks at three other nests, only the female was observed incubating.

Nestling period

Observation times were skewed among nests (1987 vs 1988) and weeks of the nestling period, such that results for respective nests 1 and 2 (Table 2) are not directly comparable because sessions were mostly all-day at nest 1, but avoided the hottest part of the day at nest 2, and sessions were biased towards the end of week 2 at nest 2. Some estimates of parental time-budgets at nest 2 are also approximate, owing to small gaps in available notes (summarised from observers' original field notes). Despite the unbalanced observation schedule, there is a clear trend of declining maternal nest attendance (brooding, standing on the nest) with chick age, and a corresponding tendency for the female to perch elsewhere in the nest area. Furthermore, the activity classified as 'female perched' at nest 2 (Table 2) included much perching in the nest tree, so 'unattended' late in week 2 is inflated because she was still effectively guarding the nest from higher in the tree. 'Standing on the nest' in the early and middle weeks included shading the chicks, especially on hot afternoons. The male's time spent perched in the nest area also declined with chick age (Table 2).

At nests 1 and 2, the female collected sprays of greenery for nest-lining at the rate of 0.1 spray/h, in the mornings and afternoons. Female absences from the nest (including drinking, bathing or defending) in the early weeks, when the chicks were downy (weeks 1–3), ranged from 1 to 15 minutes.

At nest 1, the male brought prey at the rate of 0.2 item/h, throughout the day. In weeks 1–2 he sometimes lingered on the nest with the female for 2–3 minutes or, exceptionally, once for 45 minutes (day 8) while she fed the chicks. He also appeared to feed the chicks during this period, although this was not confirmed. On one

occasion the male went to the nest alone for 2 minutes while the female prepared and brought his catch to the chicks. At nest 2, the male brought 0.3 item/h, once directly to the nest in the female's brief absence while she was collecting foliage. He also occasionally visited the nest briefly without prey while the female was on the nest.

By week 6 (day 42) the female at nest 2 was hunting and supplying some prey. In week 7, when the nestlings were nearly fledged, she was partly absent from the nest area. Supplementary observations at other nests supported the behavioural patterns reported above. At one nest, when the nestlings were within a fortnight of fledging (i.e. week 6), the female shaded them and sheltered them from rain. At four others, the female was shading a large nestling within a week or two of fledging (i.e. weeks 6 and 7).

Stages of nestling growth, supplementary to data in Marchant and Higgins (1993), are shown in Table 3.

Post-fledging period

Taking day 1 as the day that the first juvenile left the nest (nest 2, Kapalga, in 1988), on day 4 this fledgling could fly up to 100 metres from the nest. In week 3 (17 days after fledging), both juveniles were still within 200 metres of the nest and fed by both parents, mainly in a food-transfer tree 30 metres from the nest tree. In week 4 (22 days after fledging) the juveniles ranged 400 metres from the nest, were fed mainly by the male, and made unsuccessful dives at Blue-winged Kookaburras *Dacelo leachii* and smaller birds. Twenty-seven days after fledging, they were still

seen in the vicinity of the nest tree. Both banded juveniles from nest 2 were still seen in the nest area until seven weeks (49 days) after fledging, but not thereafter (D. Curl pers. comm.). It is therefore concluded that the juveniles were dependent on the adults for one month and at least partly so for almost a further month (although their departure from the natal home range was undetermined).

Vocalisations

The breeding vocalisations of the Red Goshawk were described by Aumann and Baker-Gabb (1991) and Marchant and Higgins (1993). However, we note a discrepancy in how these vocalisations have been labelled: the spectrograms and text labels in Marchant and Higgins (1993, pp. 220–221) for their respective sonagrams A, C and D were transposed, and are here corrected (Figure 1). In summary, the Red Goshawk's chattering and male food-delivery calls can be described as rather accipiter-like, though deeper, harsher and less shrill.

DISCUSSION

The quantified observations herein provide a more detailed account of the summarised versions given by Aumann and Baker-Gabb (1991) and Marchant and Higgins (1993), and also confirm the general (unquantified) account by Czechura *et al.* (2009) of the Red Goshawk's breeding behaviour. Nevertheless, there is scope for more a rigorous study and quantification of parental time-budgets (e.g. nest-building, copulation, nest-attendance and feeding rates) both for further comparison within this

species, e.g. in other parts of its range, and for interspecific comparisons (e.g. with other Australian hawks).

In the light of re-examined evidence, the suggestion of possible bigamy at one Red Goshawk nest (Aumann and Baker-Gabb 1991) should be treated with caution. It may simply have been a female investigating the neighbouring nest and territory (perhaps assessing territory quality?). The lack of aggression between the two females at that nest seems unusual for territorial raptors, and might suggest some low level of sociality between neighbours (G. Czechura pers. comm.), or perhaps even genetic relatedness. However, firmer conclusions would require further study.

Adult male Red Goshawks occasionally shaded eggs, and occasionally visited the nest while the females fed the chicks or were briefly absent. However, males took no part in incubation or brooding, and were not conclusively proved to feed the chicks in the nest. Further, although males did sometimes visit nestlings briefly (as elsewhere, e.g. Czechura *et al.* 2009), the Kapalga male sometimes appeared wary of the adult female during the early pre-laying phase, rarely had close contact with her other than when copulating (e.g. no allopreening), and rarely lingered at the nest during the chick-rearing phase. The extreme size dimorphism between males and females may partially explain this caution, as the much smaller males may be more prone to predation or injury by their mate than in other (less size-dimorphic) raptor species. Parental time-budgets (Table 2) suggest that the Red Goshawk's sex roles are more clearly defined than in Australia's other endemic hawk genera (*Lophoictinia* and *Hamirostra*), with which the Red Goshawk has sometimes been associated taxonomically (e.g. Marchant and Higgins 1993, Debus 2012 and the behavioural

studies on all three genera cited therein; see also Nunn and Pavey 2014 for *Hamirostra*).

In keeping with these behavioural findings, and *contra* Olsen *et al.* (1993) and Debus (1998), the Red Goshawk is, on DNA evidence, related to a group of Australasian accipiter-type hawks that deserve generic rank among a revised and split genus *Accipiter* (Barrowclough *et al.* 2014). The DNA evidence also contradicts the suggestion (Olsen 1995) that egg shape and volume link the Red Goshawk taxonomically with *Lophoictinia* and *Hamirostra*, which are pernine kites (Barrowclough *et al.* 2014).

Given the paraphyly of *Accipiter (sensu lato)* and the harriers *Circus*, and that *Megatriorchis* (of New Guinea) is related to *Circus* (Barrowclough *et al.* 2014), the suggestion by W.S. Clark (pers. comm. to SD), that the Red Goshawk is related to the harriers, has merit. The male Red Goshawk's perched courtship behaviour and postures (as described by Aumann and Baker-Gabb (1991) and Marchant and Higgins (1993)), e.g. bowing and head-bobbing, suggest elements of male *Accipiter* ritualised prey-plucking movements and the bowing courtship display of male Spotted Harriers *Circus assimilis* (see Marchant and Higgins 1993). These displays and other aspects of breeding behaviour are very different from those of *Lophoictinia* or *Hamirostra*, as are the foot morphology (tarsal scalation) of *Erythrotriorchis*, which is more like that of *Accipiter* and *Circus*, and its vocalisations (see Marchant and Higgins 1993). The possibility of bigamy, however unlikely, is also more aligned with *Accipiter* and *Circus* breeding behaviour than with that of the Australian pernine endemics.

The Red Goshawk's genetic link with *Accipiter* and possibly *Circus* matches its behavioural, morphological and ecological characters, and indeed in 'loping', non-hunting flight its flapping action is almost harrier-like, including a harrier-like (though shallower and less fluid) dihedral. The remarkable plumage resemblance between the Red Goshawk and the Square-tailed Kite *Lophictinia isura* therefore raises the possibility of plumage mimicry, known in various other raptors and explained as either a highly predatory species mimicking an inoffensive species in order to approach unsuspecting prey, or inoffensive species (notably *Pernis* spp.) mimicking more predatory species for protection (Edelstam 2001). It is unclear whether such mimicry has occurred multiple times in Australo-Papuan raptors, or why mottled 'red' (especially juvenile) plumages should occur, or be selected for, in different raptor lineages in Australasia. These, and the foregoing behavioural aspects of the Red Goshawk, deserve further investigation.

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Figure 1. *Spectrograms of adult Red Goshawk calls in their original layout (Marchant and Higgins 1993, pp. 220–221), correctly labelled: (a) adult female threat call; (b) adult female soliciting call; (c) adult male food-delivery call; (d) adult female nest-alighting call. Recordings by D.J. Baker-Gabb, Kakadu, NT, September 1987.*

Table 1. Summarised observation schedule at two systematically watched Red Goshawk nests, Kakadu National Park (NT), 1987–89. Nest 1 = undisclosed gorge location; nest 2 = Kapalga. Primary observer(s) in each year/stage = authors' initials.

Stage	1987	1988	1989
Pre-laying		Nest 2 (DB-G)	Nest 2 (DB-G, TA)
Incubation		Nest 2 (DB-G)	
Nestling	Nest 1 (DB-G)	Nest 2 (DB-G, SD)	
Post-fledging		Nest 2 (DB-G)	

Table 2. Parental time-budgets of two pairs of Red Goshawks in Kakadu National Park (NT) in the nestling period, 1987 (nest 1, upper row) and 1988 (nest 2, lower italicised row): % observation time spent in each activity. Stand = adult stand on nest (includes adult feed itself); perched = in tree in nest area; absent = female away from nest (collecting foliage, drinking/bathing, defending); unattended = neither adult at nest. Numbers in parentheses = *n* hrs observation in each week (1987/1988). Week 1 = first week after hatching.

Sex/activity	Week				
	1	2	3	5	8
	(14)	(67.5)	–	(11.5)	(7)
	<i>(31.5)</i>	<i>(9.6)</i>	<i>(3)</i>	–	–
Female:					
Brood	95	~80	–	0	0
	~79	19	14		
Stand	1	~10	–	66 ^c	4
	6 ^a	~27	44 ^b		
Feed chicks	4	8	–	10	0
	~9	1	11		
Perched	0	0	–	21	94
	4	~46	30		
Absent	0	2	–	3	2
	~2	~7	1		
Male:					
Stand	<1	1	–	<1	0
	<1	0	0		
Perched	39	29	–	5?	0
	20	1	17		
Unattended	0	<2	–	24	96
	<2	~53	1		
Both at nest	<1	<1	–	<1	0
	<1	0	0		

^aShading chicks

^cShading chicks for 29%

^bShading chicks for 42%

Table 3. Growth and development of nestling Red Goshawks, Kakadu National Park, NT, August–October 1987 (nest 1: one male and one female chick) and 1988 (nest 2: two male chicks). Supplementary observations from four other nests in 1988 are numbered sequentially.

Week	Day	Nest #	Comments
1	7–8	1	White, downy.
3	21	2	Downy, emerging scapular pinfeathers well developed.
5	31	2	Downy, pinfeathers on scapulars and remiges burst.
	34	1	Downy, pinfeathers ~2 cm long, scapulars emerged.
6	?	3	Two males: heads downy, otherwise well feathered with half-grown tails.
6	?	4	Male: head feathers emerging through down, body well feathered.
7	?	5	Female: large, feathered.
7	?	6	Male: well feathered, perching on rim of nest.
7	35	1	Nearly able to fly.
	43	2	Jumping and flapping on nest.
	49	2	'Branching' behaviour to 1 m from nest.
8	51	2	Older nestling fledged.