Who are the important predators of sea turtle nests at Wreck Rock beach?

Juan Lei [Corresp., 1] , **David T Booth** [1]

[1] School of Biological Sciences, The University of Queensland, Brisbane, St. Lucia, Australia

Corresponding Author: Juan Lei
Email address: lj881204@gmail.com

Excessive sea turtle nest predation is a problem for conservation management of sea turtle populations. This study assessed predation on nests of the endangered loggerhead sea turtle (*Caretta caretta*) at Wreck Rock beach adjacent to Deepwater National Park in Southeast Queensland, Australia after a control program for feral foxes was instigated. The presence of predators on the nesting dune was evaluated by tracking plots (2 x 1 m) every 100 m along the dune front. There were 21 (2014-2015) and 41 (2015-2016) plots established along the dune, and these were monitored for predator tracks daily over three consecutive months in both nesting seasons. Predator activities at nests were also recorded by the presence of tracks on top of nests until hatchlings emerged. In addition, camera traps were set to record the predator activity around selected nests. The tracks of the fox (*Vulpes vulpes*) and goanna (*Varanus spp*) were found on tracking plots. Tracking plots, nest tracks and camera traps indicated goanna abundance varied strongly between years. Goannas were widely distributed along the beach and had a Passive Activity Index (PAI) (0.31 in 2014-2015 and 0.16 in 2015-2016) eight times higher than that of foxes (PAI 0.04 in 2014-2015 and 0.02 in 2015-2016). Five hundred and twenty goanna nest visitation events were recorded by tracks but no fox tracks were found at turtle nests. Camera trap data indicated that yellow-spotted goannas (*Varanus panoptes*) appeared at loggerhead turtle nests more frequently than lace monitors (*V. varius*) did, and further that lace monitors only predated nests previously opened by yellow-spotted goannas. No foxes were recorded at nests with camera traps. This study suggests that large male yellow-spotted goannas are the major predator of sea turtle nests at the Wreck Rock beach nesting aggregation and that goanna activity varies between years.

1 **Who are the important predators of sea turtle nests at Wreck Rock beach?**

2 Juan Lei [1] and David T. Booth[1]

3 [1] School of Biological Sciences, The University of Queensland, Brisbane, St. Lucia, QLD 4072,

4 Australia.

5 Corresponding Author:

6 Juan Lei [1]

7 Email: lj881204@gmail.com

24   Abstract

25   Excessive sea turtle nest predation is a problem for conservation management of sea turtle

26   populations. This study assessed predation on nests of the endangered loggerhead sea turtle

27   (*Caretta caretta*) at Wreck Rock beach adjacent to Deepwater National Park in Southeast

28   Queensland, Australia after a control program for feral foxes was instigated. The presence of

29   predators on the nesting dune was evaluated by tracking plots (2 x 1 m) every 100 m along the

30   dune front. There were 21 (2014-2015) and 41 (2015-2016) plots established along the dune,

31   and these were monitored for predator tracks daily over three consecutive months in both

32   nesting seasons. Predator activities at nests were also recorded by the presence of tracks on

33   top of nests until hatchlings emerged. In addition, camera traps were set to record the predator

34   activity around selected nests. The tracks of the fox (*Vulpes vulpes*) and goanna (*Varanus spp*)

35   were found on tracking plots. Tracking plots, nest tracks and camera traps indicated goanna

36   abundance varied strongly between years. Goannas were widely distributed along the beach

37   and had a Passive Activity Index (PAI) (0.31 in 2014-2015 and 0.16 in 2015-2016) eight times

38   higher than that of foxes (PAI 0.04 in 2014-2015 and 0.02 in 2015-2016). Five hundred and

39   twenty goanna nest visitation events were recorded by tracks but no fox tracks were found at

40   turtle nests. Camera trap data indicated that yellow-spotted goannas (*Varanus panoptes*)

41   appeared at loggerhead turtle nests more frequently than lace monitors (*V. varius*) did, and

42   further that lace monitors only predated nests previously opened by yellow-spotted goannas.

43   No foxes were recorded at nests with camera traps. This study suggests that large male yellow-

44   spotted goannas are the major predator of sea turtle nests at the Wreck Rock beach nesting

45   aggregation and that goanna activity varies between years.

46

47   Introduction

48   Sea turtles are oviparous and construct their nests on dunes adjacent to the beach where

49   embryos take about two month to incubate. Sea turtle hatchling nest emergence success is

50   determined by nest temperature, salinity, humidity, water inundation and predation (Fowler

51   1979; Miller 1985; Reid *et al*. 2009). During incubation, a wide range of predators may attack

52   sea turtle nests and have a significant effect on hatchling recruitment and thus long-term

53   population persistence (Stancyk 1995). At many beaches nest predation is the main cause of

54   hatch failure of sea turtles with some regions reporting more than 50% of nests being

55   destroyed by predators (e.g. Fowler 1979; Blamires & Guinea 1998; Blamires *et al*. 2003;

56   Maulany *et al*. 2012; McLachlan *et al*. 2015). A large variety of non-human species have been

57   reported as sea turtle nest predators including, fire ants (*Solenopsis invicta*), crabs (*Ocypode*

58   *cursor*), turkey vultures (*Cathartes aura*), black vultures (*Coragyps atratus*), coatis (*Nasua*

59   *narica*), raccoons (*Procyon lotor*), dogs(*Canis familaris*), red foxes (*Vulpes vulpes*), golden jackals

60   (*Canis aureus*), mongooses (*Herpestes javanicus*), snakes (*Oligodon formosanus*) and goannas

61   (*Varanus spp*) in different regions of the world (Stancyk *et al*. 1980; Mora & Robinson 1984;

62   Brown & Macdonald 1995; Frick 2003; Leighton *et al*. 2008). In Australia, sea turtle nest

63   predators include several species of native goanna, the native dingo (*Canis lupus*) and the

64   introduced fox (*Vulpes vulpes*), pig (*Sus scrofa*) and wild dog (*Canis familaris*) (Limpus 1978;

65   Limpus & Fleay 1983). In particular, fox predation of sea turtle nests along the east Australian

66   coast has been problematic and therefore a major focus of sea turtle conservation programs

67   (Limpus 1978; Limpus & Fleay 1983; Limpus 2008).

68

69   The loggerhead turtle (*Caretta caretta*) is an endangered species on the IUCN Red List (IUCN

70   2016). Major breeding aggregations of loggerhead sea turtle include Africa-Mozambique, Oman,

71   the Mediterranean sea, Sri Lanka, Japan, U.S.A. and Australia (Limpus & Limpus 2003). Genetic

72   studies indicate there is little or no interbreeding between these major breeding aggregations

73   (Bowen *et al*. 1993; Limpus 2008). In Australia, two genetically distinct breeding stocks have

74   been identified: an eastern Australian population and western Australian population (Limpus &

75   Limpus 2003). If one breeding stock becomes extinct, it would be difficult to repopulate this

76   area from other genetic stocks. In order to preserve the genetic diversity of loggerheads, it is

77   necessary to protect each of the different populations.

78

79   A significant number of loggerhead turtles nest at Wreck Rock beach adjacent to Deepwater

80   National Park, Queensland, Australia (~400 nests per season, Limpus 2008). Predators of sea

81   turtle nests at Wreck Rock beach include foxes, dingoes and goannas (Limpus 2008). The fox

82   predation of loggerhead turtle nests continued to increase from a modest level when

83   monitoring commenced in 1968–1969 to 90–95% in the mid-1970s (Limpus 2008). From 1987

84   onwards, 1080 poison baits have been used to control fox predation (Limpus 2008), but a

85   recent nest survey (McLachlan *et al*. 2015) indicated that while fox predation of nests was

86   minimal, a large number of nests were predated by goannas. The lace monitor (*Varanus varius*)

87   and yellow-spotted goanna (*Varanus panoptes*) are likely to be the main goannas attacking

88   loggerhead nests because of their distribution along the coastline and ability to dig holes while

89   foraging (Cogger 1993). However, the relative activity levels and impact of these species on

90   loggerhead turtle nests at Wreck Rock beach remain unknown.

91

92   For some animal species, it is difficult to estimate population density by standard census

93   methods such a mark and recapture (Engeman & Allen 2000) because of large home ranges,

94   rough terrain habitats, relatively sparse populations and/or difficulty in capturing animals or

95   making direct observations (Pelton and Marcum 1977). To overcome these problems, Engeman

96   & Allen (2000) developed and refined a passive activity index (PAI) based on the occurrence of

97   tracks on small, pre-defined plots of substrate for monitoring wild carnivore species. This

98   method is simple and quickly applied in the field and can also provide accurate information

99   reflecting population changes over time or space, and simultaneously capture a suite of wildlife

100   species (Engeman & Allen 2000). This method has been used previously to monitor predator

101   activities, including the common water monitor (*Varanus salvator*) activity on an olive ridley

102   turtle (*Lepidochelys olivacea*) nesting beach in Indonesia over two nesting seasons (Maulany

103   2012).

104

105   Despite the anecdotal evidence that foxes and more recently goannas predate a significant

106 number of sea turtle nests at Wreck Rock beach (Limpus 2008; McLachlan *et al*. 2015), no

107 quantitative study of sea turtle nest predation has been conducted at this important nesting

108 beach, and it is not known what species of goanna is responsible for predation. Therefore, the

109 aim of this study was to fill this knowledge gap by quantifying goanna and fox activity on

110 nesting dunes during the sea turtle nesting season at Wreck Rock beach. Three methods were

111 used to achieve this aim. Firstly, tracking plots were used to monitor general activity levels of

112 goannas and foxes along the dunes where sea turtles construct their nests. Secondly, turtle

113 nests were inspected every day until turtle hatchlings emerged in order to record the activities

114 of predators at the nest. Thirdly, camera traps were used to capture predator activity at sea

115 turtle nests so that we could identify which species of goanna was the main predator of these

116 nests.

117

118 Methods

119 Study site and nest marking

120 This study was conducted along the beach for 3 km immediately to the north and south of

121 Wreck Rock adjacent to Deepwater National Park, Southeast Queensland (24°18' 58 S, 151°57'

122 55" E) (Fig. 1). This section of the beach is marked by numbered stakes every 100 m for ease of

123 marking and relocating nests. The beach was monitored nightly by personnel from Turtle Care

124 Volunteers Queensland Inc. to record the presence of emerging female turtles and successful

125 nesting activities. When a nest was located, its position was marked by a red ribbon attached to

126 a small stake and recorded using a handheld GPS (Garmin eTrex 30, Kansas, USA). All work was

127   approved by a University of Queensland Animal Ethics Committee (permit #SBS/352/EHP/URG)

128   and conducted under Queensland Government National parks scientific permit #

129   WITK15315614.

130

131   Tracking plots

132   Tracking plots were used to estimate relative activity of predators during the peak sea turtle

133   nesting time across two consecutive years (5-Dec-2014 to 4-Mar-2015 and 30-Nov-2015 to 28-

134   Feb-2016). In 2015-2016, these plots were also monitored for four days in April, a time when

135   most sea turtle clutches had finished hatching. Twenty-one tracking plots (2 m x 1 m) in 2014-

136   2015 and 41 in 2015-2016, spaced 100 m apart, were set up on the primary dune (where most

137   sea turtle nests were constructed). The plots extended along the dunes for 1 km (2014-2015)

138   and 2 km (2015-2016) north and south of Wreck Rock camping area. The monitored area of a

139   plot was marked by sticks placed at each corner of the plot and the plot's location was recorded

140   with a handheld GPS. Each plot was inspected daily during the afternoon (weather permitting),

141   and the number of goanna and fox tracks recorded. After reading, plots were resurfaced using a

142   rake to obliterate tracks, insuring the same tracks were not recorded on subsequent days. The

143   activity of predators was quantified using the passive activity index (PAI) of Engeman *et al*.

144   (1998):

145    $PAI = \frac{1}{d}\sum_{j=1}^{d}\frac{1}{Pj}\sum_{i=1}^{Pj}Xij$

146   where the *Xij* value represents the number of tracking plot tracks by an observed species at the

147   *i*th plot on the *j*th day; *d* is the number of days of inspection, and *Pj* is the number of plots

148   contributing data on the jth day. PAI was calculated for each day throughout the study for

149   statistical comparisons, and at 10-day intervals for graphical presentation of data. Because PAI

150   data failed a Kolmogorov-Sminov normally test, K-S d = 0.223, p < 0.01, n = 320; a non-

151   parametric Kruskal-Wallis ANOVA by Ranks followed by a multiple comparison test was used to

152   test for inter-species and inter-year differences in nest visitation rates.

153

154   Nest monitoring

155   Once a nest was located it was visited daily throughout the incubation period in order to

156   identify predation events and the tracks of animals visiting nests. Each nest was inspected

157   during the morning (weather permitting) and the number of goanna and fox tracks was

158   recorded. Nest area approximately $1m^2$ was resurfaced by using a rake after observation. Nest

159   visitation rate was quantified as a percentage by dividing the number of days fresh tracks were

160   found at a nest by the total number of nest inspection days (nest inspection days = total

161   number of times a nest was inspected during the season until hatchlings emerged from the nest

162   or until it was totally predated). Because goanna nest visitation data failed a Kolmogorov-

163   Sminov normally test, K-S d = 0.1442, p < 0.05, n = 121; a non-parametric Kolmogorov-Sminov

164   two sample test was used to test for inter-season differences in nest visitation rates.

165

166   Camera traps

167   Camera traps (Reconyx Hyperfire HC600, Holmen, Wisconsin, USA) were set up to capture

168   images of predators visiting a sample of 12 loggerhead turtle nests (randomly selected)

169   between 6 December 2014 and 27 January 2015 and 30 nests (randomly selected) between 1

170   December 2015 and 27 February 2016. Camera traps were at each nest for 25 days in 2014-

171   2015 and 30 days in 2015-2016. All camera traps were triggered by motion sensors and could

172   be triggered 24 hours per day. Camera traps were positioned 50 cm behind the selected turtle

173   nests, at least 30 cm above ground. Each camera trap had a 1 m^2 field of view over the nest

174   insuring that any nest visitation by predators was recorded. This enabled information on the

175   frequency, time of day and species to be collected. To compare the relative activity of goannas

176   visiting nests each year and between years, we calculated the per-nest per-day visitation rate

177   for camera trap monitored nests. For each nest the number of independent images (defined as

178   taken at least 20 minutes apart; multiple images taken within 20 minutes of each other were

179   classified as a single visitation event) of goannas recorded at that nest was divided by the

180   number of days the camera was set at that nest. Because camera trap per-nest per-day data

181   failed a Kolmogorov-Sminov normally test, K-S d = 0.292, p < 0.01, n = 84; a non-parametric

182   Kruskal-Wallis ANOVA by Ranks followed by a multiple comparison test was used to test for

183   inter-species and inter-year differences in nest visitation rates. Circular statistics were used to

184   analyze the time of day that nests were visited by yellow-spotted goannas and lace monitors.

185

186   Non-parametric statistical analysis was performed using Statistica Ver 13.1 (Dell Inc.) software,

187   and circular statistical analysis was performed using Oriana Ver 4 (Kovach Computing Services).

188

189   Results

190   Tracking plots

191   Monitored tracking plots revealed tracks of two potential egg predators, goannas (lace

192   monitors and yellow-spotted goannas combined as it was not possible to distinguish between

193   the two species on the basis of their tracks alone) and foxes. Only a few dog tracks were

194   identified in tracking plots during the course of the study. However, these dog tracks were most

195   likely made by pet dogs accompanying tourists visiting the beach, and so have been excluded

196   from analysis.

197

198   During the first nesting season (5-Dec-2014 until 4-Mar-2015), 21 plots were monitored for 71

199   days with 466 goanna and 62 fox occurrences recorded (Table 1). During the second nesting

200   season (5-Dec-2015 until 28-Feb-2016), 41 plots were monitored for 89 days with 535 goanna

201   and 70 fox occurrences recorded (Table 1). There were differences in occurrence rates detected

202   between goannas and foxes and years (Table 1), Kruskal-Wallis test: H (3, n = 320) = 180.065, p

203   < 0.001. Multiple comparison tests indicated that goanna activity was approximately 7 times

204   greater than fox activity in both seasons, and goanna activity in 2014-2015 was approximately

205   twice that in 2015-2016, but fox activity was not different between the two seasons. During the

206   2014-2015 nesting season, goanna activity on the dune front remained relatively constant

207   throughout the season (Fig. 2). Fox activity was generally much lower than goanna activity from

208   December through January, but there was a conspicuous increase in fox activity in February (Fig.

209   2). In the 2015-2016 nesting season, goanna activity was relatively low in December, increased

210   during January and February and decreased again at the end of February and was lowest in

211 April at a time when most sea turtle nests had hatched. Fox activity remained low and relatively

212 constant throughout the entire season (Fig. 2).

213

214 Nest monitoring

215 During the 2014-2015 nesting season, 52 loggerhead turtle nests were monitored, and 57.7% of

216 these nests were predated by goannas as indicated by burrows constructed into the nest egg

217 chamber. During the 2015-2016 nesting season, 46 nests were monitored, and 17.4% of these

218 nests were predated by goannas. No fox or other predators were observed to raid turtle nest in

219 either season. During 2014-2015, 520 goanna nest visits (lace monitors and yellow-spotted

220 goannas combined as it was not possible to distinguish between the two species on the basis of

221 their tracks alone) as were recorded while in 2015-2016, 343 nest visits were recorded (Table 2).

222 Daily per-nest visits were significantly greater in 2014-2015 than in 2015-2016 (Kolmogorov-

223 Smirnov two sample test, p < 0.001) being approximately two times greater (Table 2). Nests

224 that were predated could be dug open for the first time at any time during the incubation

225 period; there was no trend for the first nest attack to be associated with nest construction or

226 nest hatching (Fig. 3).

227

228 Camera traps

229 Images from camera traps showed that goannas were the only predators to visit monitored

230 nests; no images of foxes or wild dogs were recorded. All of the monitored nests had at least

231 one image of a goanna visit during the deployment period, with 55 nest visitation events being

232   recorded in the 2014-2015 nesting season, 47 (85.5%) of these visitation events were made by

233   yellow-spotted goannas and only 8 (14.5%) were made by lace monitors (Table 3). The overall

234   per-nest per-day visitation rate was 0.157 for yellow-spotted goannas and 0.027 for lace

235   monitors (Table 3). Despite all camera traps being deployed by 20 December 2014, only two

236   goannas appeared at nests in December 2014, but activity at nests increased sharply from the

237   beginning of January 2015 (Fig. 4a). Eggs were seen to be consumed on 17 occasions (14

238   yellow-spotted goannas, 3 lace monitors). Yellow-spotted goannas were seen to open a nest for

239   the first time on 17 occasions, but lace monitors were only ever seen to visit nests that had

240   already been opened. In the 2015-2016 nesting season, 107 goanna nest visiting events were

241   captured, 87 (81.3%) of these visitation events were made by yellow-spotted goannas and only

242   20 (18.7%) were made by lace monitors (Table 3). The overall per-nest per-day visitation rate

243   was 0.097 for yellow-spotted goannas and 0.022 for lace monitors (Table 3). Eggs were seen to

244   be predated by yellow-spotted goanna on 6 occasions. No lace monitors were seen consuming

245   eggs in this season. There were difference in visitations rates between monitored groups,

246   Kruskal-Wallis test: H (3, n = 84) = 26.826, p < 0.001; with multiple comparison tests indicating

247   that yellow-spotted goanna visitation rate was greater than lace monitors in both seasons, but

248   there was no difference in inter-season visitation rate in either species.

249

250   Goannas visited nests at any time of the day between 8:00 and 18:00 (Fig. 4a,b). Combining

251   data from both seasons, and plotting the data separately for yellow-spotted goannas and lace

252   monitors revealed that yellow-spotted goannas had a bi-modal nest visitation pattern, with a

253   peak in activity in the morning between 7:00 and 11:00, 8:57 ± 1:10 (mean ± circular standard

254   deviation) and again in the afternoon between 13:00 and 16:00, 15:10 ± 0:50, while the most

255   frequent time for visits from lace monitors was in the afternoon the late afternoon between

256   15:00 and 17:00, 15:46 ± 0.50 (Fig. 5). A Watson-Williams F-test ($F_{1,154}$ = 11.792, p < 0.001)

257   confirmed that when considering all nest visitation data, the mean time of lace monitor visits

258   (13:38 ± 2:53, n=29) was later than yellow-spotted goanna visits (11:27± 3:00, n=129).

259

260   An entire nest opening sequence was recorded on 23 Jan 2015. A large yellow-spotted goanna

261   first began digging at 14:12 (Fig 6a). It reached the egg chamber and consumed the first egg at

262   14:28 after 16 minutes of continuous digging activity (Fig 6b). Turtle eggs were swallowed intact,

263   one at a time, by the goanna rather than being opened and having their contents licked out (Fig

264   6c). This goanna stopped feeding and left the nest at 16:56 after almost 2.5 hours of feeding

265   and having consumed eight eggs.

266

267   Discussion

268   Nest predation decreases the recruitment of hatchlings and has become an important challenge

269   for the conservation of egg-laying reptiles (Leighton *et al*. 2010). Hence, understanding the

270   activity of predators adjacent to endangered reptilian species breeding aggregations is

271   important for designing conservation strategies. The daily checking for predator tracks on nests

272   and the deployment of tracking plots and camera traps allowed us to continuously monitor

273   activities of nest predators adjacent to a loggerhead turtle nesting beach. There were two

274   significant results from the study that provide new insights into goanna predation of sea turtle

275   nests. First, camera trap data indicated that yellow-spotted goannas are the most frequent

276   visitors and predators of sea turtle nests at Wreck Rock beach and were the only species

277   observed to open nests, suggesting they are the main cause of nest predation. Second, the nest

278   predation rate and activity of goannas on the nesting dune varied by a factor of two between

279   the two seasons that we studied.

280

281   Predator activities at nests

282   Camera traps allowed us to explore the loggerhead turtle nest predator species, predation time

283   and behavior of predators while at nests. Yellow-spotted goannas were the most frequent

284   visitors and predators of sea turtle nests in this study. Large adult yellow-spotted goannas have

285   the ability to dig up sea turtle nests and swallow turtle eggs intact, suggesting future

286   management strategies should be targeted at these individuals. Indeed, no lace monitors were

287   observed to open sea turtle nests directly, they were only observed predating nests that had

288   already been opened by yellow–spotted goannas. Hence, lace monitors appear to be

289   opportunistic nest predators on this beach. Lace monitors are frequently arboreal and are

290   equipped with long, recurved claws that facilitate climbing (Cogger 1993). Such claws are not

291   particularly useful for digging and may explain why they did not open nests. Using GPS tracking

292   methodology, Lei & Booth (2015) reported yellow-spotted goannas use the beach dunes more

293   than lace monitors and are therefore more likely to predate sea turtle nests than lace monitors.

294   Moreover, camera traps did not record foxes at nests, and no fox tracks were observed over

295   nests during this study indicating that the fox baiting program deployed by park managers is

296   currently effective at inhibiting fox predation of sea turtle nests at Wreck Rock beach.

297

298   Although camera trap records indicated that sea turtle nests were visited by yellow-spotted

299   goannas at any time of day between 7:00 and 17:30, visits were most frequent in the morning

300   and afternoon with a distinct lull during the middle of the day. This reflects the general activity

301   pattern of yellow-spotted goannas as recorded by GPS tracking data (Lei *et al*. 2017). It would

302   appear that the midday heat suppresses the foraging activity of yellow-spotted goannas, and

303   this may be particularly so in the beach dune area there are no trees to provide shade. In

304   contrast, although the data is far less numerous, lace monitors had a single peak in sea turtle

305   nest visiting activity, and this was late in the afternoon, typically after the peak afternoon

306   yellow-spotted goanna nest visiting time. Hence, lace monitors may arrange their nest visiting

307   times to avoid interacting with yellow-spotted goannas. Further investigation of this possibility

308   is needed.

309

310   Doody *et al*. (2014, 2015) reported that yellow-spotted goannas can dig warren complexes that

311   required removal of sand from up to 3 m deep and that both males and females contribute to

312   warren excavation. Hence, the job of digging into a sea turtle nest which is comparatively

313   shallow (40 - 80 cm), should be relatively easy as evidenced by it requiring only 16 minutes of

314   digging to gain access to eggs in one of our monitored nests. Our camera trap images indicated

315   that yellow-spotted goannas normally dug into the nest at an angle from one side of the nest to

316   reach the nest chamber rather than digging a hole vertically downwards from directly above

317   the nest. Hence, when covering a nest with mesh as a management strategy used to deter nest

318   predation, the mesh must be relatively large in area (at least 1 x 1 m) to prevent yellow-spotted

319   goanna burrowing into the nest (Lei & Booth 2017). Turtle nest predation rate is likely

320   dependent on cues left by the female turtle (e.g. visual, tactile, and olfactory), and many

321   predators have the ability to detect these cues (Vander Wall 1998, 2000; Geluso 2005; Leighton

322   *et al*. 2009). Goannas use their forked tongue to transfer olfactory cues to the specialized

323   chemosensory Jacobson's organ and so are adept at using olfactory cues to find prey (Blamires

324   & Guinea 1998; King & Green 1999; Vincent & Wilson 1999). We found that once a turtle nest

325   was opened, this nest was continually predated over subsequent days by multiple yellow-

326   spotted goannas.

327

328   We suspected that goannas might attack sea turtle nests more frequently immediately after

329   their construction, or after hatching at the end of incubation. These expectations were based

330   on the idea that sand disturbance and the smell of the female and or newly laid eggs around

331   the sand might give clear clues to foraging goannas immediately after nest construction, and

332   that the smell of egg fluids released during the hatching process might also attract goannas at

333   the end of incubation. This was not what we observed; a nest was equally likely to be attacked

334   for the first time at any time during incubation. We do not know why this is the case,

335   particularly as goannas crawled over the top of some nests several times during incubation

336   without attacking them, and then at a later date these nests were attacked. One possibility

337   might be that ghost crabs (*Ocypode ceratophthalmus* and *O. cordimanus*) which are numerous

338   on the nesting beach and frequently burrow into sea turtle nests, cause the release of

339   'incubating egg odor' which then attracts goannas.

340

341   Predator activity

342   Based on the PAI analysis of tracking plot data, the activity of goannas was higher than that of

343   foxes, suggesting that goannas are the main predator of sea turtle nests at Wreck Rock beach, a

344   conclusion also supported by nest track and camera trap data. We found that all of our

345   monitored nests were visited by goannas and that between 17% (2015-2016) and 58 % (2014-

346   2015) of nests were opened by yellow-spotted goannas. Goanna predation of nests had

347   previously been reported as greater than 50% at this beach (McLachlan *et al*. 2015). It is unclear

348   whether goanna predation of sea turtle nests was this high at Wreck Rock beach during pre-

349   European settlement times or whether more recent perturbations have led to increased nest

350   predation in recent times. During the 1970s-1990s goanna predation of sea turtle nests at this

351   location was not detected, but fox predation of nests was high, 90% of nests being predated in

352   the 1970's and up until 1987 (Limpus 2008). From 1987 onwards, a fox baiting program reduced

353   fox predation on sea turtle nests to negligible levels (Limpus 2008). Goanna predation of sea

354   turtle nests was first reported in the 2003-2004 nesting season when two nests were predated

355   (Limpus 2008), and since then goanna predation of sea turtle nests has increased so that over

356   50% of sea turtle nests were being attacked by goannas in the 2013-2014 season (McLachlan *et*

357   *al*. 2015). Hence, the reduction in fox numbers may have also resulted in an increased

358   recruitment of yellow-spotted goannas (because red foxes probably also predated yellow-

359   spotted goanna nests) to historically high levels. However, before European settlement and the

360   introduction of foxes, hunting of goannas by native people may have kept the density of

361   goannas on the frontal dunes at a low level.

362

363   Goanna activity in 2014-2015 was twice as high as in 2015-2016, as was the nest predation rate.

364   This suggests that nest predation is positively correlated with goanna activity. Maulany (2012)

365   reported that olive ridley turtle nests suffered 100% predation by monitor lizards at a beach

366   adjacent to Alas Purwo National Park, Banyuwangi (East Java), Indonesia, which had high

367   monitor lizard activity (PAI = 1.27 in 2009, 1.41 in 2010). This finding also suggests that goanna

368   activity on dunes is a good predictor of intensity of goanna predation on sea turtle nests.

369

370   Fox activity increased at the end of the 2014-2015 nesting season. Typically the park mangers

371   fox bait twice during the sea turtle nesting season, once in early December and again in early

372   February. In 2014-2015 the February baiting was missed, so any foxes that might have moved

373   into the beach area after the December baiting were not removed. However, in the 2015-2016

374   season, the early February fox baiting probably maintained fox activity at low levels.

375

376   The goanna predation rate of sea turtle nests in 2014-2015 was twice that in 2015-2016, and it

377   correlated with an increase in goanna activity on the dune. The nest visitation rate by recording

378   tracks on nests in 2014-2015 was nearly twice that in 2015-2016. These results suggested

379 goanna activity on the dune in 2014-2015 was higher than in 2015-2016. However, it remains

380 unclear why goanna activity and sea turtle nest predation rate varied so greatly between the

381 two nesting seasons. Because of the strong inter-annual differences in predator indices over

382 two years, additional years of research are needed to determine the long-term average

383 predation rate and its implications for turtle hatching success.

384

385 Implications for management

386 Lei & Booth (2017) compared different methods of directly protecting sea turtle nests against

387 goanna predation and found that deploying the plastic mesh on the top of turtle nests was the

388 most effective and economic way. Combined with our observations of digging behaviour of

389 yellow-spotted goanna captured on camera traps, we suggested that plastic mesh needs to be

390 at least 1 x 1m to prevent yellow-spotted goannas digging into the nest chamber. In addition,

391 camera trap data indicated turtle nest predation activities happen any time between 7:00 and

392 17:00, suggesting turtle nest management should be deployed in the early morning following

393 the night that nests are constructed. More management strategies such as temporary removal

394 of large male yellow-spotted goannas or egg relocation should be investigated in the future to

395 counteract the loss of sea turtle nests to yellow-spotted goanna predation.

396

397 Acknowledgements

398 This work would not have been possible without the help of Nev and Bev McLachlan's Turtle

399 Care Volunteers organization, the Burnett Mary Regional Group and WWF Australia.

400

401 References

402 Blamires SJ, Guinea ML. 1998. Implications of nest site selection on egg predation at the sea

403 turtle rookery at Fog Bay. *Proceedings of Marine Turtle Conservation and Management in*

404 *Northern Australia Workshop, Darwin*, 20-24.

405

406 Blamires SJ, Guinea ML, Prince RIT. 2003. Influence of nest site selection on predation of

407 flatback sea turtle (*Natator depressus*) eggs by varanid lizards in Northern Australia. *Chelonian*

408 *Conservation and Biology* **4**: 557-563.

409

410 Bowen BW, Richardson JI, Meylan AB, Margaritoulis D, Hopkins-Murphy SR, Avise J. 1993.

411 Population structure of loggerhead turtles (*Caretta caretta*) in the west Atlantic Ocean and

412 Mediterranean Sea. *Conservation Biology*. **7**: 834–844.

413

414 Brown L, Macdonald DW. 1995. Predation on green turtle *Chelonia mydas* nests by wild canids

415 at Akyatan Beach, Turkey. *Biological Conservation* **71**: 55-60.

416

417 Cogger H. 1993. *Reptiles and amphibians of Australia*. Sydney: A. H. & A. W. Reed.

418

419 Doody JS, James H, Ellis R, Gibson N, Raven M, Mahony S, Hamilton DG, Rhind D, Clulow S,

420 McHenry CR. 2014. Cryptic and complex nesting in the yellow-spotted monitor, *Varanus*

421   *panoptes*. *Journal of Herpetology* **48**: 363-370.

422

423   Doody SJ, James H, Colyvas K, McHenery CR, Clullow S. 2015. Deep nesting in a lizard, deja vu

424   devil's corkscrews: first helical reptile burrow and deepest vertebrate nest. *Biological Journal of*

425   *the Linnean Society* **116**: 13-26.

426

427   Engeman RM, Allen L, Zerbe GO. 1998. Variance estimate for the Allen activity index. *Wildlife*

428   *Research* **25**: 643-648.

429

430   Engeman RM, Allen L. 2000. Overview of a passive tracking index for monitoring wild canids and

431   associated species. *Integrated Pest Management Reviews* **5**: 197-2003.

432

433   Fowler LE. 1979. Hatching success and nest predation in the green sea turtle, *Chelonia mydas*,

434   at Tortuguero, Costa Rica. *Ecology* **60**: 946-955.

435

436   Frick MG. 2003. The surf crab (*Arenaeus cribrarhs*): A predator and prey item of sea turtles.

437   *Marine Turtle Newsletter* **99**: 16-18.

438

439   Geluso K. 2005. Benefits of small-sized caches for scatter-hoarding rodents: influence of cache

440   size, depth, and soil moisture. *Journal of Mammal* **86**: 1186-1192.

441

442   IUCN. 2016. 2016 IUCN Red List of threatened species. Available from: http://www.redlist.org/

443

444   King D, Green B. 1999. *Monitor: the biology of varanid lizards*. Sydney: NSW University Press.

445

446   Lei J, Booth DT. 2015. The use of GPS logging devices and camera traps to track goanna

447   movement on and adjacent to a south east Queensland sea turtle rookery. *Reef, Range and Red*

448   *Dust Conference, Caloundra Queensland August 2015, 17.*

449

450   Lei J, Booth DT. 2017. How best to protect the nests of the endangered loggerhead turtle

451   *Caretta caretta* from monitor lizard predation? *Chelonian Conservation and Biology* (in press).

452

453   Lei J, Booth DT, Dwyer RG. 2017. Spatial ecology of yellow-spotted goannas adjacent to a sea

454   turtle nesting beach. *Australian Journal of Zoology* (in press).

455

456   Leighton PA, Horrocks JA, Krueger BH, Beggs JA, Kramer DL. 2008. Predicting species

457   interactions from edge responses: mongoose predation on hawksbill sea turtle nests in

458   fragmented beach habitat. *Proceedings of the Royal Society B* **275**: 2465-2472.

459

460   Leighton PA, Horrocks JA, Kramer DL. 2009. How depth alters detection and capture of buried

461   prey: exploitation of sea turtle eggs by mongooses. *Behavioral Ecology* **20**: 1299-1306.

462

463   Leighton PA, Horrocks JA, Kramer DL. 2010. Predicting nest survival in sea turtles: when and

464   where are eggs most vulnerable to predation? *Animal Conservation* **14**: 186–195.

465

466   Limpus CJ. 1978. The reef: uncertain land of plenty. In: Lavery HJ. ed. *Exploration North:*

467   *Australia's Wildlife from Desert to Reef*, Richmond Hill Press, 187-222.

468

469   Limpus CJ, Fleay A. 1983. Management and turtles. *Proceedings of the Great Barrier Reef*

470   *Conference Townsville,* James Cook University Press, 535-540.

471

472   Limpus CJ, Limpus DJ. 2003. Loggerhead turtles in the Equatorial and Southern Pacific Ocean: a

473   species in decline. In: Bolten AB, Witherington BE ed. *Loggerhead Sea Turtles*, Smithsonian

474   Institution Press, 199-209.

475

476   Limpus CJ. 2008. A biology review of Australian marine turtles. 1. Loggerhead turtle, *Caretta*

477   *caretta* (Linneaus). Queensland Government Environmental Protection Agency.

478

479   Maulany RI. 2012. The Nesting Biology, Ecology, and Management of the Olive Ridley Turtle

480   (*Lepidochelys olivacea*) in Alas Purwo National Park, Banyuwangi (East Java), Indonesia. D. Phil.

481   Thesis, The University of Queensland, Australia.

482

483   McLachlan N, McLachlan B, Hof C, Giudice S, Shuster G, Bunce A, Limpus C, Eguchi T. 2015.

484   Predator reduction strategies for protecting loggerhead turtle nests at Wreck Rock beach in

485   Queensland. *Reef to Range and Red Dust Conference, Caloundra* Queensland August 2015, 15.

486

487   Miller JD. 1985. Embryology of marine turtle. In: Gans C, Billett F, Maderson PFA, ed. *Biology of*

488   *the Reptilia* Wiley-Interscience, New York, 269-328.

489

490   Mora JM, Robinson DC. 1984. Predation of sea turtle eggs *Lepidochelys* by the snake *Loxocemus*

491   *bicolor* Cope. *Revista de biologia tropical* **32**: 161-162.

492

493   Pelton MR, Marcum LC. 1977. The potential use of radioisotopes for determining densities of

494   black bears and other carnivores. *Proceedings of 1975 Predator Symposium* pp: 221-236.

495

496   Reid K, Margaritoulis D, Speakman JR. 2009. Incubation temperature and energy expenditure

497   during development in loggerhead sea turtle embryos. *Journal of Experimental Marine Biology*

498   *and Ecology* **378**: 62-68.

499

500   Stancyk SE, Talbert OR, and Dean JM. 1980. Nesting activity of the loggerhead turtle *Caretta*

501   *caretta* in South Carolina, II. Protection of nests from raccoon predation by transplantation.

502   *Biological Conservation* **18**: 289-298.

503

504   Stancyk SE. 1995. Non-human predators of sea turtles and their control. In: Bjorndal KA, ed.

505 *Biology and Conservation of Sea Turtles* Washington, DC: Smithsonian Institution Press, 139-151.

506

507

508 Vander Wall SB. 1998. Foraging success of granivorous rodents: effects of variation in seed and

509 soil water on olfaction. *Ecology* **79**: 233-241.

510

511 Vander Wall SB. 2000. The influence of environmental conditions on cache recovery and cache

512 pilferage by yellow pine chipmunks (*Tamias amoenus*) and deer mice (*Peromyscus maniculatus*).

513 *Behavioral Ecology* **11**: 544-549.

514

515 Vincent M, Wilson S. 1999. *Australian goannas*. New Holland Publishers Pty Ltd, Sydney, NSW.

516

517

Table 1. Nest visitation events by tracking plots

Passive activity index (PAI) of goannas and foxes from dune tracking plots during the 2014-2015 and 2015-2016 sea turtle nesting seasons at Wreck Rock beach.

1 Table 1. Passive activity index (PAI) of goannas and foxes from dune tracking plots during the

2 2014-2015 and 2015-2016 sea turtle nesting seasons at Wreck Rock beach.

Nesting season	2014-2015	2015-2016
Plots monitored	21	41
Monitored days	71	89
Goannas		
Total events recorded	466	535
Daily PAI		
mean ± SD	0.313 ± 0.217	0.150 ± 0.104
median, 25% - 75% quartile	0.286, 0.143 - 0.423	0.125, 0.075 - 0.200
range	0.000 - 1.048	0.000 - 0.500
Foxes		
Total events recorded	62	70
Daily PAI		
mean ± SD	0.042 ± 0.079	0.020 ± 0.033
median, 25% - 75% quartile	0.000, 0.000 - 0.048	0.000, 0.000 - 0.025
range	0.000 - 0.381	0.000 - 0.175

Visitation rate of goannas based on tracks found on top of nest

Visitation rate of goannas (based on tracks found on top of nests) at loggerhead turtle nests (visits per-nest per-day) for the 2014-2015 and 2015-2016 sea turtle nesting seasons at Wreck Rock beach.

1   Table 2. Visitation rate of goannas (based on tracks found on top of nests) at loggerhead turtle

2   nests (visits per-nest per-day) for the 2014-2015 and 2015-2016 sea turtle nesting seasons at

3   Wreck Rock beach.

Nesting season	2014-2015	2015-2016
Nest monitored	52	46
Monitored days	41	80
Total events recorded	520	343
Daily visitation rate		
mean ± SD	0.336 ± 0.187	0.110 ± 0.107
median, 25% - 75% quartile	0.312, 0.212 - 0.476	0.087, 0.022 - 0.175
range	0.000 – 0.882	0.000 - 0.455

Nest visitation rate by camera traps

The nest visitation rate (per-nest per-day) recorded by camera traps at nests during 2014-2015 and 2015-2016 sea turtle nesting seasons at Wreck Rock beach.

1   Table 3. The nest visitation rate (per-nest per-day) recorded by camera traps at nests during

2   2014-2015 and 2015-2016 sea turtle nesting seasons at Wreck Rock beach.

Nesting season	2014-2015	2015-2016
Nests monitored	12	30
Monitored days	25	30
Yellow-spotted goannas		
Total events recorded	47	87
Visitation rate		
mean ± SD	0.157 ± 0.247	0.097 ± 0.116
median, 25% - 75% quartile	0.060, 0.040 - 0.160	0.050, 0.033 - 0.133
range	0.040 - 0.920	0.000 - 0.467
lace monitors		
Total events recorded	8	20
Visitation events per nest per day		
mean ± SD	0.027 ± 0.049	0.022 ± 0.029
median, 25% - 75% quartile	0.000, 0.000 - 0.040	0.000, 0.000 - 0.033
range	0.000 - 0.160	0.000 - 0.100

Figure 1. Image of study area

A: Location of study site, Wreck Rock beach adjacent to Deepwater National Park,
Queensland, Australia. B: The locations of the loggerhead turtle nests monitored during the
2014-2015 nesting season. C: The locations of the loggerhead turtle nests monitored during
the 2015-2016 nesting season. Shaded grey area indicates the section of beach monitored in
this study.
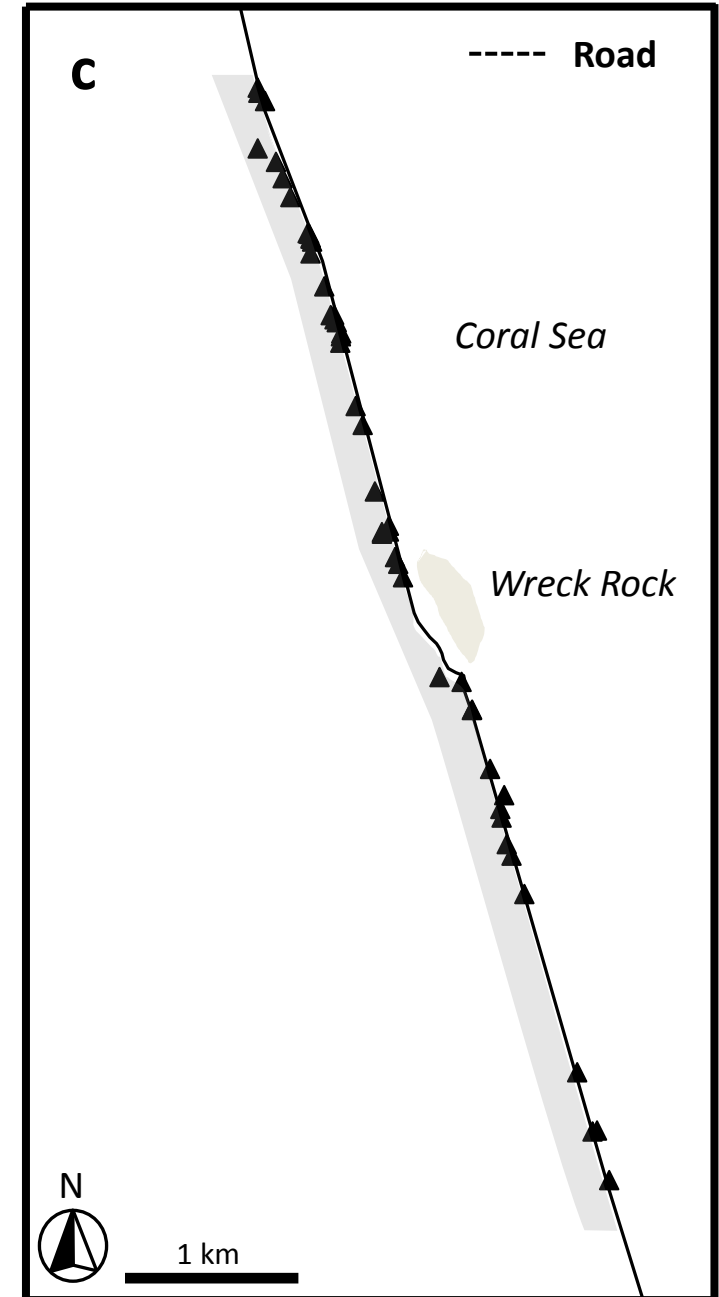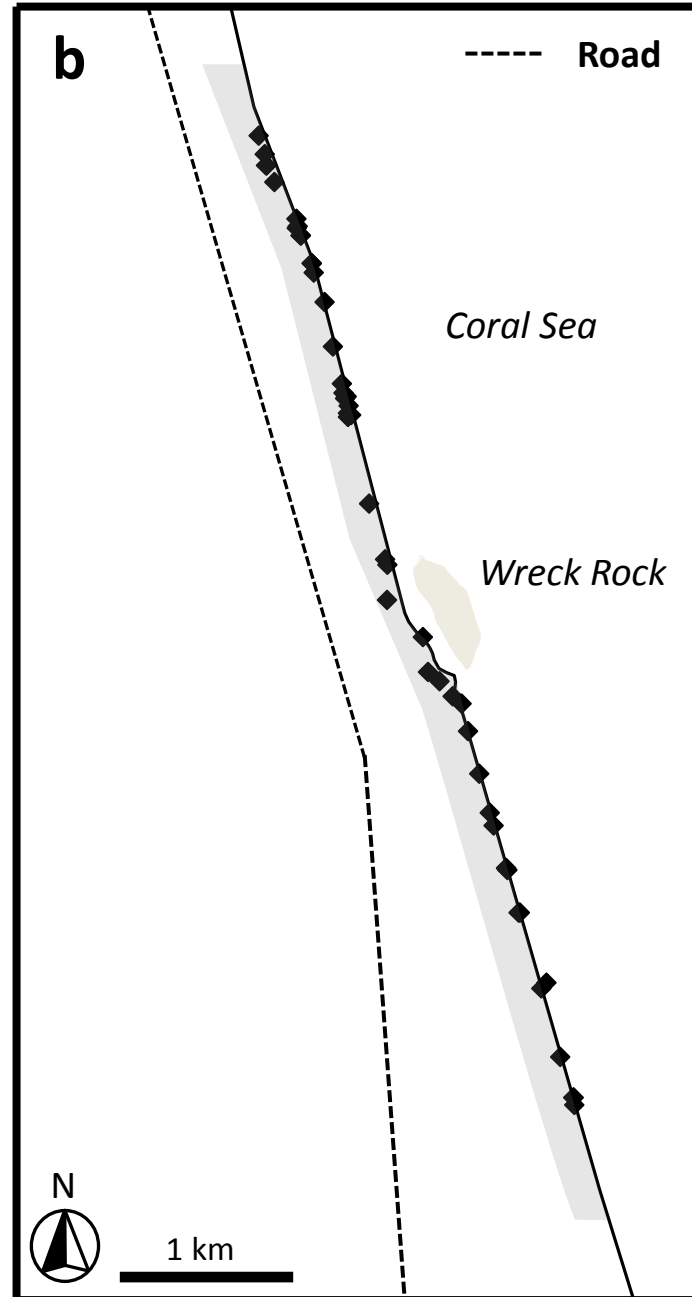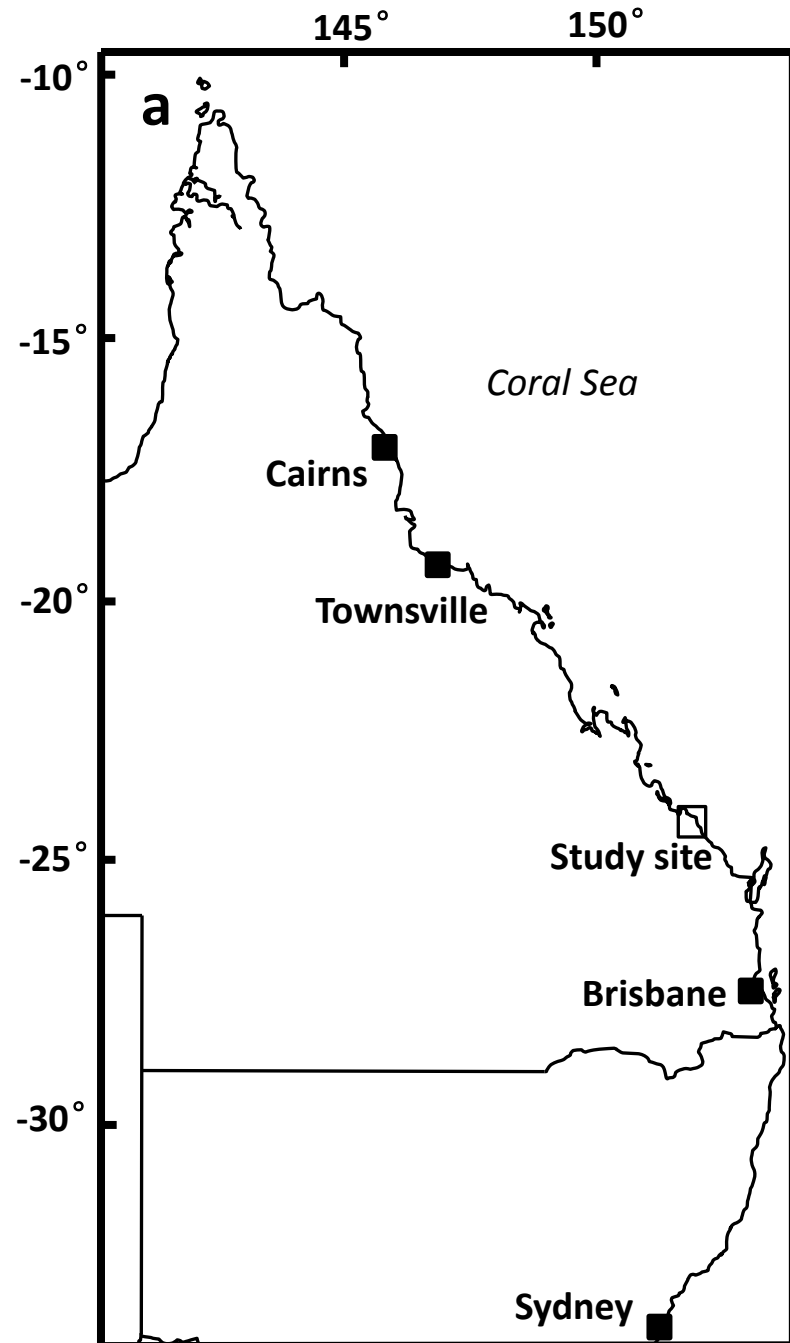
Figure 2. Figure of nest predator activity index (PAI)

Passive activity index (PAI, mean ± SD of 10-day intervals) on the front dune at Wreck Rock Beach during the A) 2014-2015 and B) 2015-2016 nesting seasons for goannas (diamonds) and foxes (triangles). Data represent the center of 10-day means.
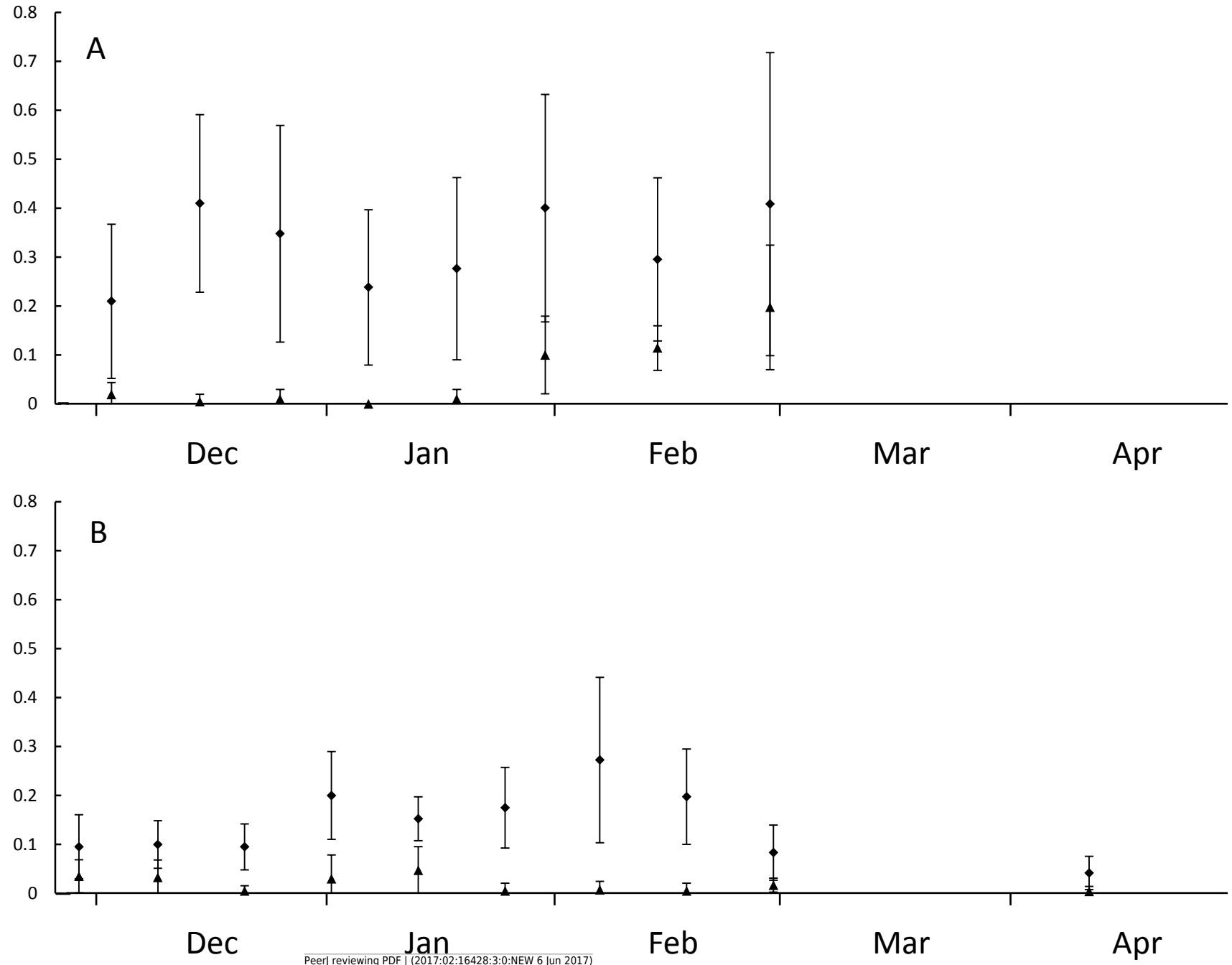
Figure 3. Plot of the frequency of nest predation events against the time since nest construction and first goanna predation event for loggerhead nests laid

Frequency of goanna first predation events in relation to the time since nest construction for loggerhead nests laid during the 2014-2015 (solid diamonds) and 2015-2016 (open triangles) nesting seasons at Wreck Rock beach.
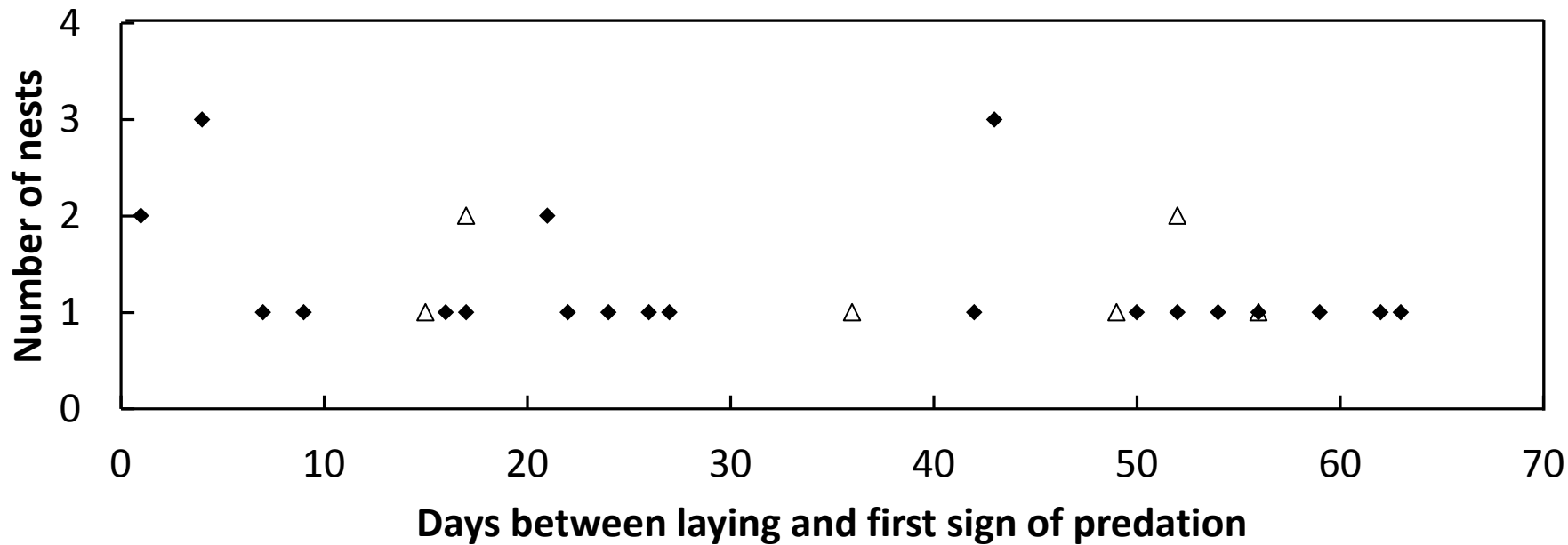
Figure 4. A figure of predators' activity on the turtle nesting beach Figure of time and date of goanna appearances at loggerhead turtle nests as determined from camera trap records

Time and date of goanna appearances at loggerhead turtle nests as determined from camera trap records. Triangle = yellow-spotted goannas, Diamond = lace monitors. A. Three hundred camera days (12 cameras set for 25 days each) during the 2014-2015 season. B. Nine hundred camera days (30 cameras set for 30 days each) during the 2015-2016 season.
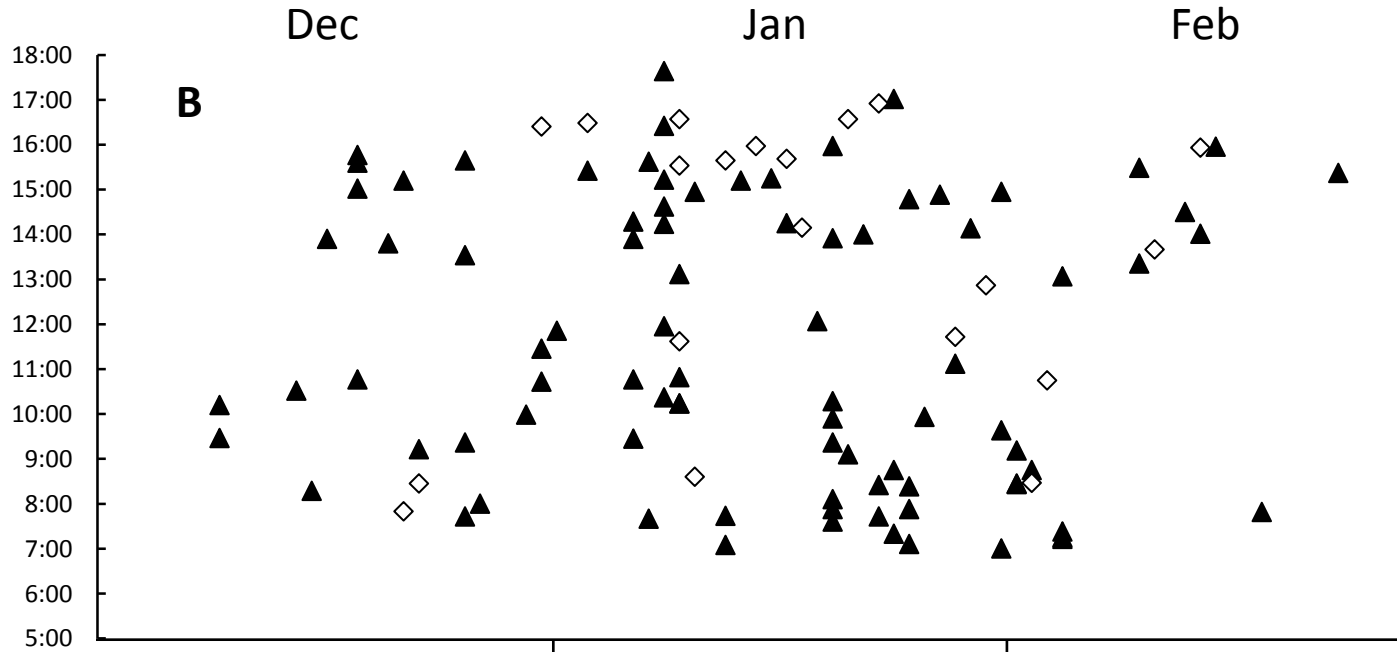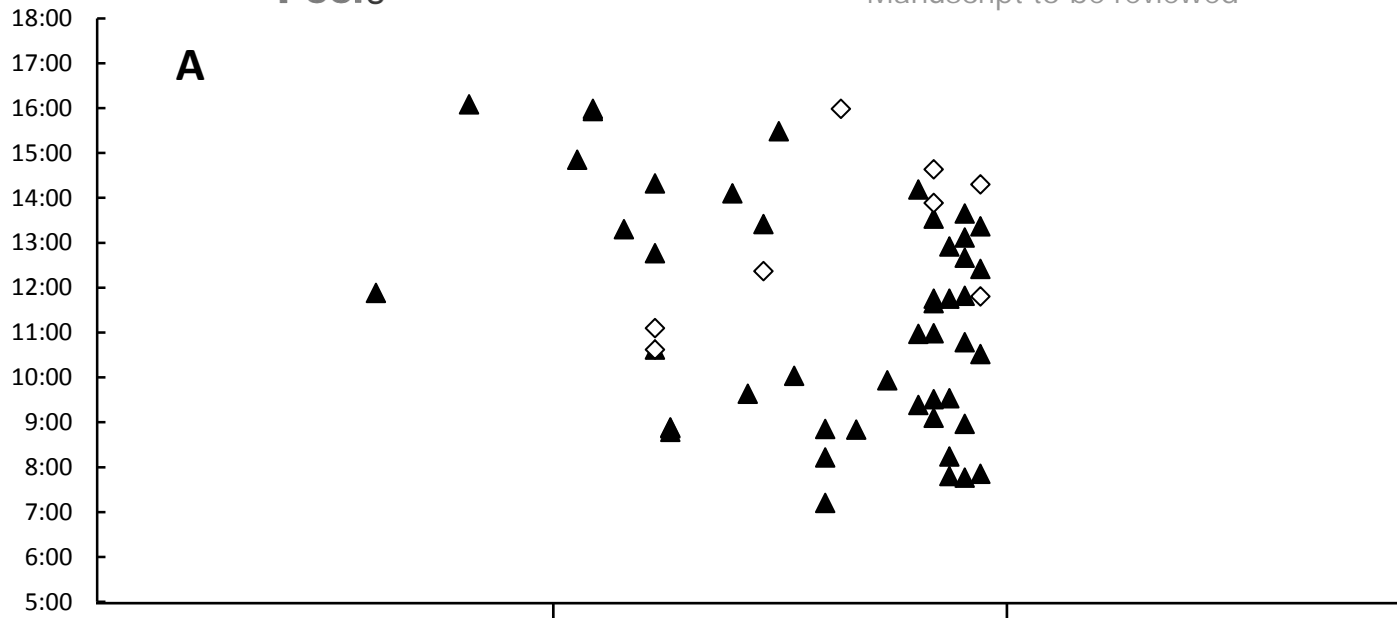
Figure 5. Plot of the number of images of goannas against time of day

The number of images of goannas taken by camera traps set at loggerhead turtle nests at Wreck Rock beach in relation to time of day that images were recorded.
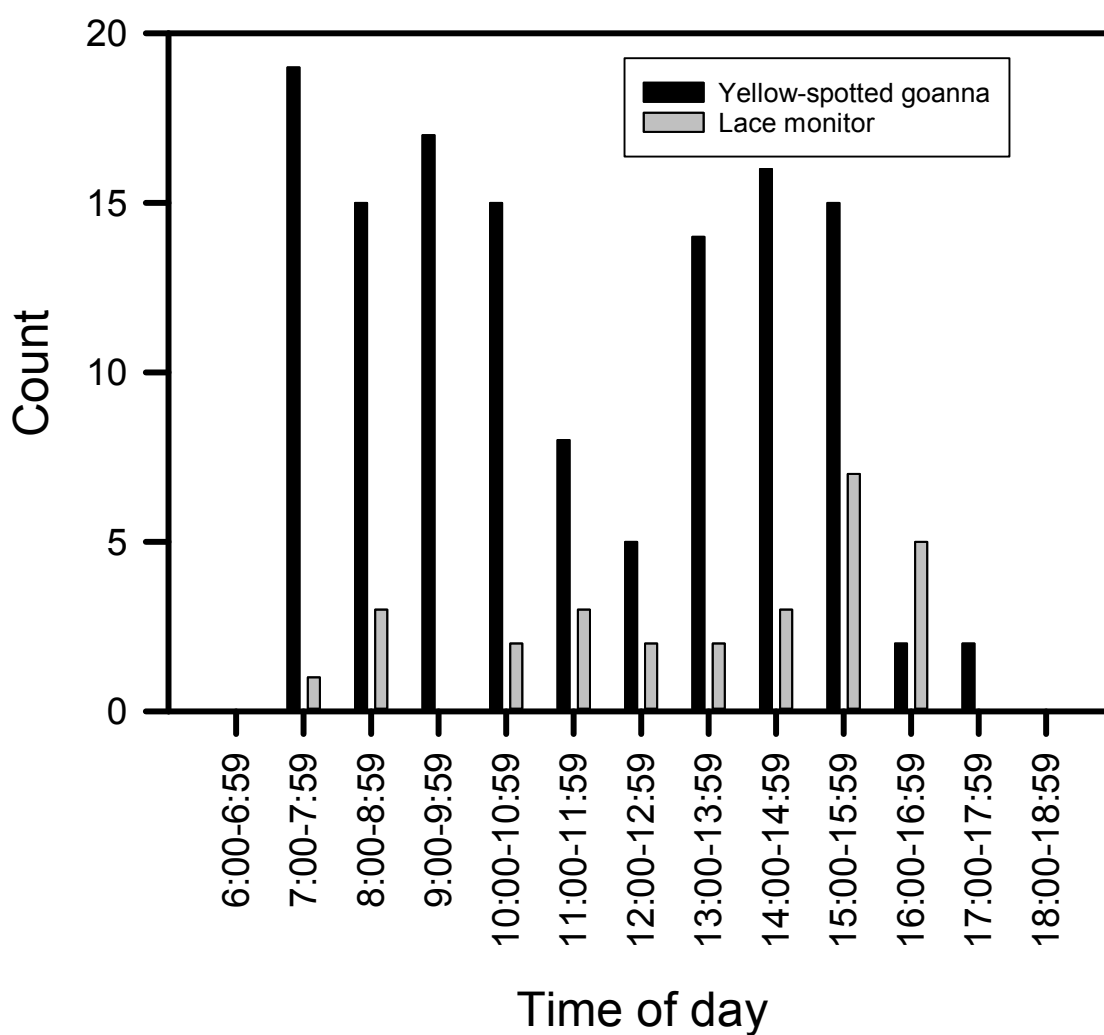
Figure 6

Figure 6. The photos of a yellow-spotted goanna opening and consuming eggs from a loggerhead turtle nest

A Yellow-spotted goanna opening and consuming eggs from a loggerhead turtle nest on 23-Jan-2015. Photos were captured by a camera trap. a. Start of digging, b & c, removal and consumption of the first egg. For full sequence, see video in the supplementary information.

2015-01-23 2:11:55 PM   M 1/5   ○ 35°C

a

HC600 COVERT
2015-01-23 2:27:59 PM   M 1/5   ○ 39°C

b

HC600 COVERT
2015-01-23 2:28:05 PM   M 4/5   ○ 39°C

c

HC600 COVERT