Development of light-weight video-tracking technology for use in wildlife research: A case study on kangaroos

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Abstract

There have been significant advances in the development of animal-borne sensor technologies, or biologgers, in recent years. This has resulted in tremendous capacity for wildlife researchers to remotely collect physiological, behavioural and social data from wildlife in circumstances that were unthinkable just decades ago. While this technology can provide us with a unique insight into the "secret lives" of wild animals, there is a need to evaluate the utility of these new sensors versus traditional wildlife research methodologies, and to critically evaluate the integrity of the data collected by ensuring that these devices themselves do not alter the physiology or behaviour of the recipient animal. This paper reports on the development of a light weight "animal borne video and environmental data collection system" (AVED), which can be deployed on animals as small as 11 kg, whilst still meeting the desired 3% body weight threshold. This AVED (referred to as the "Kangaroo-cam") simultaneously collects video footage and GPS location data for an average of 19 h. Kangaroo-cams were deployed on seven kangaroos as a proof of concept of their potential utility for the study of location specific behaviour and diet in a medium-sized terrestrial herbivore. Following device recovery and data processing, we were able to successfully score 83 foraging events which allowed us to determine diet based on visual identification (to the family level) of plants consumed. This approach could be further broadened to include a comparison of plant species consumed versus plant species encountered to provide a novel approach to diet selection analysis. When combined with GPS mapping of foraging locations, this approach would allow researchers to address questions on diet selection at both fine (within patch) and broad (habitat) spatial scales, overcoming some of the limitations of traditional diet selection methodologies. However, animal capture and collar deployment caused a significant elevation in stress hormone concentrations within the first 24 h post-capture, which highlighted the need to incorporate a time-delay capacity into these devices.

We conclude the paper by reviewing recent advances in the development of AVED technology and providing suggestions for the improvement of this Kangaroo-cam device.

Keywords: AVED, biologger, diet selection, GPS, macropod, movement ecology, telemetry, wildlife

Introduction

Over the last decade, there have been significant advances in the development of animal-borne sensor technology. These sensors, often termed *biologgers*, provide data about an animal's movements, behaviour and/or physiology (Fehlmann and King 2016), and often facilitate the collection of multiple forms of data simultaneously from wild animals. One particular type of biologger that has seen significant technological advances recently is the "animal borne video and environmental data collection system", or AVED (Moll *et al.* 2007).

AVEDs simultaneously record fine scale geolocations and continuous video footage of the environment from the perspective of the animal (Moll *et al.* 2007), thus facilitating the process of *video-tracking* (Bluff and Rutz 2008). This combination of time-referenced location and video images allow for a greater suite of ecological questions to be answered, including understanding how animals interact with the environment or conspecifics, and developing location and time-specific behavioural budgets (Moll *et al.* 2007).

Some of the greatest scientific impacts of animal-borne loggers have been in marine mammals and birds, where direct observation is difficult or impossible (Machovsky-Capuska *et al.* 2016a; Machovsky-Capuska *et al.* 2016b; Pearson *et al.* 2017). AVEDs in particular have been deployed predominantly in large marine animals or birds, and this is partly related to the large size of these units, which limits the size of animal upon which they can be deployed, or the short-term nature of deployments in birds. For example, Fehlmann and King (2016) recently reported that 90% of papers presented at the 5th bio-logging symposium in Strasbourg in 2014 involved birds or marine mammals. As such, the development of technology for use in terrestrial mammals has arguably fallen behind, despite many of the advantages of this technology still being highly relevant to this group of animals.

Global positioning system (GPS) and other traditional telemetry technologies have been widely used to study the movement patterns of a broad range of terrestrial mammals. While telemetry units have the capacity to tell where an animal has been, they do not provide detailed information about what the animal was doing at each geographic location without the addition of other sensors (Machovsky-Capuska 2016a). This gap can be partially filled by the use of traditional behavioural observations, but it is widely accepted that it is difficult, if not impossible, to directly observe free-range behaviour of wildlife for extended periods of time without affecting their behaviour (Beringer *et al.* 2004). Hence, AVEDs have the capacity to provide an unbiased view of the complete repertoire of animal behaviour irrespective of the location of an animal. As such, their potential utility is high, even for large, relatively conspicuous, terrestrial mammal species.

In this paper, we report the development of the “Kangaroo-cam”, a biologger that simultaneously collects video footage and the GPS location in time and space. Using the eastern grey kangaroo (*Macropus giganteus*; hereafter kangaroo) as a sample medium-large herbivorous, terrestrial mammal (females 17-42 kg, males 19-85 kg; Coulson 2008), we explore their fine scale behaviour and foraging ecology. We specifically aim to: 1. establish the diel activity budgets and location-specific behaviours; and 2. identify the feeding locations and diet. Further, we wanted to explore whether the "Kangaroo-cam" collected an unbiased sample of animal behaviour, as it is important to ensure that the devices themselves do not have a welfare or behavioural impact on the animal carrying the logger (Moll *et al.* 2009; Thomson and Heithaus 2014). Hence, an additional aim of this study was to determine whether kangaroos elicited a discernible stress response to capture, restraint and device fitting, as measured by faecal glucocorticoid metabolite concentrations (FGMs), which are a proxy for circulating stress hormone concentrations (Sheriff *et al.* 2011). A noticeable stress response is likely to indicate that the animal's behaviour is altered by the deployment of the device and may not be reflective of their "normal" behavioural repertoire, thereby influencing the integrity of the results (Schulz *et al.* 2005).

Materials and methods

Study area

The study was conducted in February 2014 and 2015 at Nelson Bay Golf Course (NBGC), which is located 208 km north of Sydney, Australia (32°43'31"S, 152°8'44"E). The NBGC has a population of 100-200, individually identifiable (via ear tags), free-range kangaroos with a high level of site fidelity, making it an ideal site for testing new animal tracking technology. The golf course itself is comprised of exotic, improved pastures, and is surrounded by Tomaree National Park (TNP) to the south and east. Vegetation in the areas of TNP bordering on the golf course is predominantly comprised of "Blackbutt-Apple Open Forest on Deeper Sands" (open dry-sclerophyll forest dominated by Blackbutt, *Eucalyptus pilularis*; Sydney Red Gum, *Angophora costata*; Red Bloodwood, *Corymbia gummifera;* and Old Man Banksia, *Banksia serrata*), with intermittent patches of "Nerong Open Forest" and "Wallum Scrub-Heath" (Bell 1997).

Animal handling and collar deployment

Seven adult kangaroos (females (n=5; two with no young, one with a young-at-foot and two with pouch young; and males (n=2)) were immobilised using Zoletil (Virbac, Milperra, NSW, Australia) at a concentration of approximately 5 mg/kg body weight, delivered by either a CO_2 powered projector (X-calibre, Pneu-dart, Williamsport, PA, USA using a 1 cc 3/4" dart) or a pole syringe (1 ml drug volume with 18 G ½" needle). Each kangaroo was weighed (digital hanging scale, WS603, 150 x 0.05 kg, Wedderburn, Ingleburn, NSW, Australia), sexed and ear tagged (sheep button and/or mini tags, Allflex, Capalaba, Qld, Australia) for unique identification. Additional samples, such as blood samples, were also collected as part of other investigations on these animals. Capture, measurements, sampling and Kangaroo-cam deployment took around 20 min. Kangaroos were then left in handling bags for approximately two and a half hours to fully recover from anaesthesia prior to release. Collars were retrieved by recapture approximately seven days post-release to facilitate GPS and video data download. This study was conducted with the approval of the University of Sydney Animal Ethics Committee (N00/7-2012/3/5791) and the NSW National Parks and Wildlife Service (SL100961).

Kangaroo-cam devices

We combined a miniaturised camera (previoulsy incorporated into other species-specific designs, see: Machovsky-Capuska *et al.* 2016b, Bombara *et al.* 2017, Pearson *et al.* 2017) with a GPS transmitter to develop video-tracking smart collars (Kangaroo-cam) (Fig. 1). The miniaturised-video-camera (U10 AU HD USB Flash Drive DVR Camera DV, Taiwan; see Machovsky-Capuska et al. 2016b for more details) and GPS logger (GT-730FL-S, Canmore, Taiwan) were powered by two 3400 mAh lithium polymer batteries (Table 1). Two 3D-printed plastic cases covered with water-resistant paint were used to enclose the miniature camera and GPS logger (L: 89 x W: 50 x H:37 mm) and the batteries (L: 83 x W: 48 x H:45 mm). Both cases were attached to a medium dog collar (Fig. 2) and secured to the neck of the kangaroos (Nexaband liquid tissue adhesive) to reduce movement. The collars recorded approximately 20 h of continuous video footage with a 36° field of view at 30 frames per second (720 x 480 HD) and latitute and longitude data for up to two days (1 s intervals). The smart collars weighed 330 g, which was < 3% of the weight of the kangaroo adult body mass (mean ± s.e.m. female weight = 27.5 ± 1.5 kg (n = 5, range 22.5 - 30.3 kg); male weights 46.7 kg and 61.9 kg). The camera was mounted on the side of the collar (Fig. 2), which represented a compromise between having a viewing angle which permitted us to determine when an animal was actively chewing, versus a better camera placement for a wider angle of view, which may have made it difficult to tell whether the animal was actively chewing.

Kangaroo behaviours

Kangaroo-cams enabled us to extract fine scale detailed behaviours. We determined the amount of time that animals undertook each of the following behaviours (to the nearest second): i) resting: the animal was lying down and not feeding, sometimes sleeping; ii) feeding: the animal had its head towards the ground and started nosing different foods until it raised its head again (Garnick *et al.* 2010), including chewing and foraging at the same time; iii) grooming: the animal was either scratching, self-cleaning, wetting forearms/inner thighs; iv) hopping: the animal was in a bipedal motion; vi) standing: the animal was upright and stationary and not actively feeding or chewing. These behavioural categories were mutually exclusive. Because we were predominantly interested in exploring feeding behaviour, this category took precedence over the other categories, and may include an animal that was simultaneously lying or standing and feeding.

Feeding behaviour

Feeding events were identified from the videos as those where the animal could be seen to scan available forage (usually depicted by the animal nosing different plants in the environment) and select plant material, followed by short up-and-down head movements (discernible from the movement of the camera or in some cases the animals jaw could be seen moving) that were defined as chewing. The combination of these behaviours was considered as a feeding event. Feeding events separated by less than 1 min were treated as a single feeding event regardless of the behaviour displayed in the intervening time to ensure that each feeding event was independent and involved separate forage selection. For each feeding event, the plants that were consumed were identified to Family based on visual characteristics. In some cases, identification to species level was possible when the plant displayed unique characteristics or displayed reproductive characters to confidently allow identification to that level. All identifications were verified using PlantNet NSW Flora Online descriptions and distribution data (National Herbarium of New South Wales).

Video-tracking technique

The internal GPS clock and the camera clock were synchonised after recovery. The GPS clock was set to Australian Eastern Daylight Savings time (AEDT) and the camera clock recorded the time that had elapsed since it started recording video. As both devices were turned on simultaneously, the starting time for both could be ascertained and "*common times*" recorded for both as either AEDT or time (in seconds) relative to deployment. Once behavioural events were identified by the video analysis, they were assigned to the GPS location with the same common time within ArcGIS 3.2. When the behavioural event occurred at a time with no exact coincident position, it was assigned to the position closest in time, within a tolerance range of

30 s. According to the average speed reported for these animals (6 km/h, Garnick *et al.* 2010), this is a very conservative and accurate criterion to geographically locate behaviours. Following this procedure, a total of 87 behavioural events were identified and classified as one of three distinctive behavioural states (see below) and each assigned to a geographic location. Behavioural states with "*common times*" greater than 30 s to the closest position were discarded from further analysis.

Using the above-mentioned video-tracking technique, we established the spatio-temporal scale of three distinctive behavioural states: i) feeding, ii) resting and iii) moving. Kernel areas (50 (core), 60, 70, 80, 90 and 95%) were calculated for each animal using the adaptive Kernel method (Worton 1989) using the Home Range Tools extension in ArcGIS 9.8. Finally, these behavioural states were plotted on a map, along with movement tracks and Kernel areas to give a map of behavioural activities at different locations.

Faecal glucocorticoid metabolite assay

The physiological response to collar deployment was determined by measuring faecal glucocorticoid metabolites (FGMs) in an additional subset of animals carrying collars that were of similar weights to the devices used in the study, but minus the camera lens, as it was not possible to collect samples at the time of the initial deployment. Stress hormone concentrations were determined by measuring FGMs at 0, 24 and 48 h post-capture and collar deployment in six animals (four females and two males), compared with the response to the same capture, handling and release (without collar deployment) in eight control animals (four males and four females). The females in the collar group had pouch young (PY) that were 10 d and 161 d, while the remaining two had no PY. The control (capture only) females had PY that were 10 d, 62 d, 86 d and the remaining female had no PY. Circulating stress hormones (glucocorticoids, predominantly cortisol) are metabolised in the liver and secreted in faeces following a lag time, which is equivalent to 24 h in this species (Fanson *et al.* 2017). Hence, FGM concentrations at 0 h represent the baseline, pre-capture circulating stress hormone concentration, with 24 h samples being indicative of the time of capture and 48 h samples representing one day post capture and collar fitting.

Faecal samples were collected when voided at the time of capture and immobilisation and at other times by searching the golf course for the collared or control individuals 24 and 48 h post capture. All animals have a unique ear tag colour and number combination, which can be readily discerned from distances in excess of 50 m with binoculars (Nikon, 10 x 50, Monarch 5, M511) or a spotting scope (Nikon, Prostaff 5, 20-60 x). Once a collared animal was identified, its ear tag number was recorded and the animal was observed from a distance until it defecated. Once defecation occurred, the faecal sample was visually located and collected in a zip-lock bag, and stored on ice for up to 4 h before being placed in long-term storage at -20° C for subsequent enzyme immune-assay to determine FGM concentrations.

FGMs were extracted from 0.5 g (± 0.01 g) thawed wet faeces with 5 ml of 80% methanol, following the method described by Fanson *et al.* (2017). The EIA used an antibody raised in rabbits against the FGM 3β,5α-tetrahydrocorticosterone (37e; Touma *et al.* 2003), and has previously been validated in eastern grey kangaroos (Fanson *et al.* 2017) by demonstrating an increase in FGM 24 h post adrenocorticotropic hormone (ACTH) challenge. The assay was run as described in Fanson *et al.* (2017). Briefly, 0.05 ml of standard, diluted faecal extract, or control were added to duplicate wells of a pre-coated 96-well plate, followed by 0.1 ml biotinylated steroid (working dilution 1:15,000) and 0.1 ml of primary antibody (working dilution 1:15,000). Plates were incubated overnight at 4° C and then washed 3 times before

0.25 ml streptavidin-peroxidase was added to each well. After 45 min incubation at 4° C, plates were washed 6 times and 0.25 ml TMB substrate was added. The reaction was stopped with 0.05 ml H_2SO_4 and optical density measured at 450 nm using a Dynex MRX Revelation plate reader (after Fanson *et al.* 2017). The intra-assay coefficient was calculated from repeated measures of 10 – 20 replicates of a single sample on one plate at 12.0%. Likewise, the inter-assay coefficients were calculated for low (7.7%) and high (12.9%) controls. The assay sensitivity was 0.02 ng/ml.

Data analyses

To assess the differences in food consumption in relation to geographic location and food type we used generalised linear models (GLMs). The first GLM was specified with a binary response denoting whether or not an observed feeding event occurred within the NBGC (0) or TNP (1). A second model depicted whether the kangaroos consumed native (0) vs non-native (1) plants. The third model tested whether foraging location (NBGC vs TNP) influenced the consumption of the different plant groups.

FGM concentrations were compared between collared and non-collared animals at 0, 24 and 48 h post-immobilisation, using the general linear model (repeated measures) function, the model being y = treatment, time, treatment × time, with time as the repeated subject. Results are presented as mean ± s.e.m. All analyses were performed using the software SPSS (IBM, SPSS Statistics, version 24; Chicago, IL)

Results

Camera deployments

We collected 130 h of video footage from the seven kangaroos fitted with “Kangaroo-cams”, with an average recording duration of 18.6 ± 1.6 h per animal. This included periods of day and night for each animal (Table 2).

Kangaroo behaviour and diel activity patterns

For each kangaroo, an average of 99.9% of the post-release, day-time video footage was able to be characterised into the different behavioural states, ranging from 97.5 - 100% (Table 2). Overall, kangaroos spent the majority of their daytime hours standing or feeding (Fig. 3).

Feeding behaviour

A total of 83 feeding events were recorded and scored from the video footage (12 ± 4 per animal). Of the total observed feeding events, 57% (n=47) occurred on the golf course whereas 35 (n=36) were within the national park (Wald test, $z = 12.18$, $df = 1$, $P < 0.0001$). Kangaroos consumed significantly more non-native (76%), than native plants (24%) (Wald test, $z = 41.10$, $df = 1$, $P < 0.0001$).

A total of nine plant families were identified in foraging events (Fig. 4), but over 50% of their forage intake was from the Family Poaceae (grasses) and 22% from Cyperaceae (perennial or annual herbs) (Fig. 4). Consumption of plants in the family Poaceae and Haloragaceae was positively associated with foraging on the golf course rather than the national park (Poaceae: Wald test, $z = 7.46$, $df = 1$, $P < 0.0001$; Haloragaceae: Wald test, $z = 6.48$, $df = 1$, $P < 0.01$). However, no significant differences in foraging locations were observed for the other plant families.

Behaviour and habitat use

A total of 87 behavioural events identified by the cameras were assigned to a geographic location, and the two most frequent behaviours (resting and feeding) were plotted onto maps depicting habitat use areas (50-95% kernels) and movement trajectories for each individual. Four examples are given in Fig. 6. The small sample-size means that statistical analyses were not warranted, and the following account provides an exploratory, qualitative analysis only. Fine scale movement showed by GPS tracks overlapped with behaviour locations revealed a constant pattern for all animals, in which a large area of the golf course was explored with no particular behaviour displayed other than moving. Only one smaller area was used for feeding or resting by each kangaroo during the observation period (Fig 6a-c). The only exception was animal K230 (Fig. 6d), who used three small areas for these behaviours, but still reduced areas in comparison to total area visited and distance travelled.

Almost all feeding and resting behaviours were located within core areas (50% kernel), with some of them located within 70-90% Kernel areas. No animal rested or fed beyond the general use area (95% Kernel), with the exception of the animal K230 (Fig. 6d), who showed three resting events outside of the 95% Kernel area. Despite this concentration of main activities within core areas, all animals had at least one core area in which they did not feed or rest during the recording period. Although activity was centred within the golf course, most animals had some core-use areas outside of the golf course, as noted above for feeding behaviour.

Stress response to capture and collar deployment

There was a significant difference in the stress response of control and collared animals (Fig. 7), with both the “time” and the “treatment x time” interaction being significant ($P < 0.05$ for both). FGMs were not significantly different between groups at the time of capture, but were significantly elevated in collared animals compared to uncollared controls (collar = 157 ± 21 ng/g; control = 91 ± 18 ng/g; p = 0.035) at time 24 h. By 48 h post capture, FGM concentrations were indistinguishable between the two groups (Fig. 7). There was no correlation between change in FGMs and reproductive status for females.

Discussion

In this study we have successfully developed a biologging device for kangaroos (the so-called "Kangaroo-cam") which can simultaneously log animal movements using GPS and capture video footage from a "kangaroo's-eye-view". We have demonstrated the capacity of these devices to collect continuous video footage for 19 h, and for that footage to be successfully scored to identify location-specific animal behaviour, feeding locations and diet in this grazing herbivore. Animal capture and collar deployment caused a significant elevation in stress hormone concentrations within the first 24 h post-capture, coinciding with the time of video-recording. As such, the behaviours reported here may be biased by stress-induced behaviour in the time period immediately following collar deployment. Hence, the significance of our research lies not so much in the biological findings, but rather as a demonstration of the potential utility of this video-tracking technology in a medium-sized, terrestrial mammalian herbivore, a group of animals that have previously been under-represented in the use of this type of technology.

Deployment of kangaroo-cam units on seven kangaroos resulted in the successful scoring of 83 foraging events (an average of 12 per animal), highlighting the potential strengths of AVED technology for determining diet in mammalian herbivores. Furthermore, this technology has the capacity to be utilised in diet selection studies. Diet selection, or preference, is defined as an animal's choice of specific food(s) from those that are available, and therefore requires a quantitative comparison of what is ingested by an animal versus what is available to that animal at a given place and time (Norbury and Sanson 1992). As such, still frames from the video footage of foraging events can be used to identify the plants immediately available to an animal, versus those actively consumed, in a foraging event. This has the capacity to overcome many of the current limitations with diet selection studies, which is the ability to look at diet selection at different temporal and spatial scales. At a broader scale, GPS tracking data can be used to ascertain the broader habitat utilisation choice through the analysis of home range location. At a finer scale, foraging locations within a home range can be mapped by utilising the combined video and GPS data. At an even finer scale again, preferred plants within those feeding areas can also be determined. Other methodological approaches for measuring diet selection tend to focus on one or other of these spatial and temporal scales (summarised in Table 3), thereby limiting the scale at which statements about diet selection can be made and the ecological questions that can be answered (Norbury and Sanson 1992). As such, one of the real advantages of incorporating AVED technology into diet selection studies is the capacity to measure diet selection across a range of spatial scales, using the one sampling approach to determine what foods the animals encounter (i.e. availability) and what they ingest (i.e. select), regardless of where they eat it. This removes any potential location sampling bias, as animals are sampled irrespective of their location rather than the researcher choosing where they sample. It also ensures there is not a mismatch between the scale at which food availability and selection are assessed as both can be measured simultaneously within video frames. It also allows both fine-scale, within patch selection to be measured as well a broader-scale habitat selection within an animal’s home-range. For example, in the current study we could determine exactly where an animal was foraging within its home range (Fig. 6), as well as what individual plants animals were consuming or avoiding within patches (Fig. 5).

The potential utility of AVEDs for providing unbiased behavioural sampling is demonstrated by the amount of time that kangaroos spent both on and off the golf course. While some individual animals spent almost all of their time on the golf course, others spent little, if any, time there (e.g. see Figs 6a and 6c for two extremes). Overall, kangaroos spent 43% of their time foraging away from the course. Traditional behavioural observations of foraging would have been limited to the golf course area, where the vegetation is open and the kangaroos are highly habituated to people, allowing individual animals to be unobtrusively observed with relative ease. However, the area surrounding the golf course is dominated by open dry-sclerophyll forest on sandy soils, an environment in which it is difficult to see animals, let alone unobtrusively observe them. As such, traditional behavioural observation studies would be biased towards the activities of animals in a limited proportion of their core area. This would result in the loss of data relating to foraging activities in forested habitats, thereby inflating the importance of some plant families, notably Poaceae (which was predominantly associated with the Golf Course), at the expense of almost all other family groups. This again highlights the importance of considering the spatial and temporal scale of diet selection studies.

Whilst the discussion above has focussed predominantly on some of the advantages of this approach, a more detailed description of the advantages, disadvantages and inherent biases of different diet selection methodologies is provided in Table 3. The key disadvantage of using AVEDs to study diet selection lies in the laborious nature of scoring the videos, and the high cost of the units themselves, which limits sample size. It is clear from the comparisons in Table 3 that all of the different methods have some disadvantages and biases. What is important is that these limitations are recognised and that the most suitable methodology is chosen to meet the objectives of any given diet selection study and the degree of accuracy required (Norbury and Sanson 1992). It is our contention that the use of AVEDs, such as the Kangaroo-cam, has the capacity to overcome some of the limitations of other approaches, but that the added time and cost associated with AVED use may not be justified for some research questions. They are merely another tool available to researchers interested in these types of research questions.

This paper has deliberately focused on the potential utility of AVED technology for behavioural investigations, with a focus on diet selection, rather than the biological outcomes of the research for this species. This is for two important reasons. Firstly, this type of technology has rarely been employed for the study of behaviour and diet in medium-sized, terrestrial herbivores, with previous studies focusing on larger marine mammals or birds (Fehlmann and King 2016). Hence, we wanted to demonstrate that advances in this technology mean that it is now more accessible for a broader range of species, and is equally amenable to the study of species with herbivorous diets. Even for species which are seemingly easy to study in the field, such as kangaroos, AVEDs have the capacity to provide additional insights into their behaviour in less accessible areas of their range. Secondly, the outcomes of this study highlight the need to consider whether the device itself has the capacity to change natural behaviours as a result of device- or capture- induced stress on the recipient animal.

AVED's are not necessarily a new technology in wildlife investigations. The first iterations date back to the use of the early National Geographic CRITTERCAM (Marshall 1998) on loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles, but these devices were large, cumbersome and heavy (> 2 kg), and therefore not suited to many animals (Bicknell *et al.* 2016). The Kangaroo-cam presented here is one example of how such limitations are now being overcome. Table 4 compares the weight and technical specifications of the Kangaroo-cam to a sample of historic and more recent innovative AVEDs reported in the literature. This table highlights the dramatic reductions in weight of devices, with seemingly simultaneous increases in recording times. As one example, the Kangaroo-cam could potentially be deployed on animals as small as 11 kg, whilst still meeting the desired 3% body weight threshold (and still obtaining approximately 19 h of video footage).

The capture of kangaroos and fitting of Kangaroo-cam devices resulted in a transient increase in FGM concentrations, which is indicative of a physiological stress response (Sheriff *et al.* 2011). This increase was not seen in control animals, which were captured and handled but did not have collars fitted, suggesting that the collar itself is inducing a stress response, independent of the capture process. These results are similar to those reported for white-tailed deer (*Odocoileus virginianus*) fitted with AVEDs (Moll *et al.* 2009) and Dickcissels (*Spiza americana*) fitted with radio-transmitters (Wells *et al.* 2003). Although Moll *et al.* (2009) reported no difference between AVED and control deer over an extended period of time, closer scrutiny of their data shows a transient increase in FGM in the acute period post collar fitting. In all studies, this transient elevation in FGMs had diminished within 24 h. As such, it is unlikely that this acute physiological response is detrimental to the welfare of the animal (Wells *et al.* 2003). These findings are relevant, however, to the question of the integrity of the data collected and point towards the need to exclude data collected during the first 1-2 d after collar deployment, as it may not reflect the “normal” behaviour of the animals. In the case of AVEDs, where battery life is so limited, this highlights the need to incorporate a time-delay option for the commencement of recording, as has been incorporated into other devices (e.g. Beringer *et al.* 2004; Bluff and Rutz 2008; Table 4).

The video-recording timeframe for the units developed in this study (approximately 19 h) represents one of the longest recording timeframes reported (Table 4), and highlights the recent advances in battery efficiency. However, the current study did not effectively utilise this entire timeframe, as the camera was recording continuously from the time of deployment, including anaesthetic recovery and night time when videos were un-scorable. As such, the benefits of this enhanced battery life were not fully realised in this study. Further modifications to the devices, such as addition of programable recording intervals (e.g. Nifong *et al.* 2013; Nifong *et al.* 2014; Table 4) or a light-activated time-delay switch (Beringer *et al.* 2004; Table 4), would ensure that the benefits of enhanced battery life are fully realised in the future.

In this paper, we have discussed the advantages of this approach for diet selection studies in kangaroos, and other terrestrial herbivores more generally (see Table 3 for a summary). However, AVEDs have the capacity to study other aspects of the biology of wild animals, including social interactions. For example, a study employing a similar device on domestic dogs was used to establish contact rates between con-specific animals (Bombara *et al.* 2017). In the current study we were surprised by how few social interactions we observed between conspecific kangaroos, especially since this species is highly gregarious and feeds in large groups (or mobs) out in the open (Coulson 2008). This failure to observe close social interactions is likely to be a result of the camera placement on the collar, rather than the absence of such behavioural interactions. Mounting the camera on the side of the collar to maximise our observations of feeding behaviour reduced the angle of view, which probably accounts for the lack of social observations. Moreover, we found it difficult to find a robust way of affixing the camera to the head of the animal (which would facilitate a broader view), whilst still maintaining the cables between the battery unit and recording unit.

In conclusion, this study has demonstrated the potential utility of AVEDs for studying diet selection in a medium-sized, terrestrial herbivore. Whilst the technology is not without its limitations, modifications to the existing "Kangaroo-cam" and the addition of other sensors, has the capacity to further enhance the utility of this behavioural sampling approach.

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Table 1. Video-tracking collar components, specifications, and approximate costs.

Component	**Dimensions (LxWxH (mm), weight (g))**	**Model and manufacturer**	**Approximate unit cost (USD)**
Waterproof housing (camera/GPS)	89 x 37 x 50 (83g)	Custom-made, University of Sydney	$40
Waterproof housing (battery pack)	83 x 48 x 45 (72g)	Custom-made, University of Sydney	$60
Video camera	108 x 27 x 27 (68g)	Custom-made, University of Sydney	$1750
GPS data logger	77 x 28 x 18 (15g)	GT-730FL-S, Canmore (Hsinchu County 30274, Taiwan)	$50

Table 2. Duration of simultaneous video recording and GPS data collection for each of seven kangaroos in the study. The footage scored (%) reflects the percentage of post-recovery day-time footage that was able to be categorised into the different behaviours. Reproductive status of females: YAF, young-at-foot; PY, pouch young; NPY, no pouch young. The PY were ~75 and 124 days for 207 and 230 respectively.

Kangaroo ID	Sex	Reproductive status (females)	Footage collected (h)			Footage scored (%)
			Day	Night	Total	
003	F	YAF	9.7	0.3	10.0	100.0
022	M	-	10.6	5.9	16.5	100.0
001	F	NPY	6.8	13.7	20.5	97.5
031	M	-	5.8	12.2	18.0	98.3
207	F	PY	13.5	8.0	21.5	100.0
230	F	PY	14.8	8.2	23.0	100.0
261	F	NPY	12.3	8.2	20.5	100.0

Table 3. Summary of the characteristics of commonly used methods for measuring diet selection in terrestrial, mammalian herbivores.
Information presented in the table is based in large part on an historic review by Norbury and Sanson (1992), with the addition of new and emerging techniques, such as the use of AVEDs (this paper) and the use of DNA barcoding of plant species in faeces (Guo *et al.* 2018).

Technique	**Description**	**Temporal link between habitat/patch utilisation and diet selection?***	**Lethal / Non-lethal**	**Advantages**	**Disadvantages**	**Spatio-temporal scale**
Mouth contents	Animal shot and mouth contents identified	Yes	Lethal	Easy to identify ingested material. Quantification of different species possible.	Small sample of ingesta, over small timeframe, meaning large sample sizes needed. Limited spatial and temporal range. Biased towards sampling locations. Limited to common animals and ethical concerns associated with lethality.	Small
Stomach contents	Animals shot and stomach contents identified, usually by microscopic analysis of plant fragments in comparison to reference library.	Yes	Lethal	Easier to identify ingested material than using faeces. Larger sample of ingested material than mouth contents. Quantification of different species possible.	Microscopic analysis of contents may be necessary. Limited to common animals and ethical concerns associated with lethality.	Small
Faecal contents - microscopic identification	Faecal samples collected and undigested plant fragments microscopically identified in comparison to a reference library	No	Non-lethal	Minimal disturbance to animals. Covers a broader spatial and temporal range. Quantification of different species possible. Not biased by sampling location.	Biased by differential digestion of plant species. Difficult to compare food availability to food ingested due to lag between ingestion and excretion. Difficult to identify to genus and species. Significant time and expertise required.	Broad
Observation	Observation of feeding animals and identification of plants ingested	Yes	Non-lethal	Minimal disturbance to animals. Easy to identify food if close enough. Quantification of different species possible.	Difficult for wild herbivores that are unapproachable or in vegetation types where observation is difficult. Quantification of species may be more difficult than for mouth, stomach or faecal contents.	Small (possibly broad depending on time invested and observability)

Technique	Description	Temporal link between habitat/patch utilisation and diet selection?*	Lethal / Non-lethal	Advantages	Disadvantages	Spatio-temporal scale
				Minimal preparation and equipment.	Biased towards sampling locations.	
Faecal contents – DNA barcoding	Faecal samples collected and molecular identification of undigested material (via sequencing) using universal plant primers and reference sequences	No	Non-lethal	Minimal disturbance to animals. Covers a broader spatial and temporal range. Potentially possible to identify to higher taxonomic level. Not biased by sampling location.	Difficult to compare food availability to food ingested due to lag between ingestion and excretion. Very high level of expertise and cost. Limited availability of reference sequences for some plants/regions	Broad
Observation using AVED	Identification of plants ingested based on video-recordings taken from devices mounted on the animals	Yes	Non-lethal	Minimal disturbance to animal (once acclimated to device). Easy to identify food. Quantification of different species possible. Combines fine and broad scale assessment of diet selection. Not biased by sampling location.	Quantification of species may be more difficult than for mouth, stomach or faecal contents. Expensive technology and time-consuming to analyse videos. Limited to medium-large animals with current technology.	Small-Broad (depending on recording time)

* A spatio-temporal link between habitat/patch utilisation and food selection basically means they are sampled at the location they are foraging, thereby allowing for a direct measurement of food availability and selection at the same time (i.e. simultaneous sampling of available vs ingested food).

Table 4. Technical specifications of historic and recent AVEDs, highlighting differences in the size, weight and features offered by devices. Note: this table is not an exhaustive list of AVEDs, but has been developed to highlight the changes in size over time and the taxonomic groups studied, as well as other features that are desirable in AVED devices

Device	**Species**	**Weight (% body weight)**	**Size (mm)**	**GPS (Y/N)**	**Time**	**Data storage/ retrieval**	**Video**	**Other features**	**Attachment**	**Reference**
Crittercam	Harbour seal (*Phoca vituline*)	2000 g (1.8%)	?	N	3h (10 min bursts every 45 min)	Store on board (3 h video tape)		Water temperature and depth, salt water switch (to prevent recording out of water)	Epoxy attachment between shoulder blades	[1]
Crittercam	American alligator (*Alligator mississippiensis*)	1000 g (~1.9%)	32x 10x 7.5	N?	6-8h[*1]	Store on board	1080 HD LED lights	Acceleration, depth, temperature sensors. Programmable recording intervals (time or sensor characteristics)	Harness	[2,3]
DCVS (Data-collecting video camera system)	White-tailed deer (*Odocoileus virginianus*)	?	?	N	?	UHF wireless transmission		Light-activated time delay relay	Antler or collar	[4]
Terrestrial AVED	White-tailed deer (*Odocoileus virginianus*)	1500 g (3-5%)	16.2 x 12.1 x 5.4	Y (1 min continuous every 5 min)	12.2, 12.3, 30.3, 41.6 h (4 animals)	Store on board	5 fps 176 x 144 pixels[*2]	Acceleration (2D), air pressure, temperature sensors. Remote collar release. Programmable recording intervals.	Collar	[5]
KittyCam	Domestic cat (*Felis catus*)	70 g (<3%)	75 x 50 x 25	N	10-12h	Store on board, VHF for retrieval	LED lights	Motion sensor activated	Break-away collar	[6]
(Custom)	New Caledonian crows *Corvus moneduloides*	13.6 g (4.3%)		N	Up to 94 min	Store on board, VHF for retrieval	640 × 480 pixels and 19·7 fps	Time-depth recorder. Programmable recording intervals.	Tail mounted with deflated rubber balloon	[7]

Device	**Species**	**Weight (% body weight)**	**Size (mm)**	**GPS (Y/N)**	**Time**	**Data storage/ retrieval**	**Video**	**Other features**	**Attachment**	**Reference**
C-VISS (cetacean-borne video camera and integrated sensor system)	Dusky dolphins (*Lagenorhynchus obscurus*)	342 g (~0.5%)	175 × 110 × 20	N (satellite transmitter)	67 min (9 – 284 min)	Store on board, VHF retrieval	30fps, 720 x 480HD		Suction cup mounted	[8]
(Custom)	Masked booby (*Sula dactylatra tasmani*)	70 g	60 × 60 × 15	N	?	Store on board, retrieved on return to nest	30fps, 720 x 480HD		Mounted on tail feathers	[9]
(Custom)	Domestic dog (*Canis familiaris*)	313 g (<3%)	90 x 30 x 20	Y	19 h	Store on board	30fps, 720 x 480HD		Collar mounted	[10]
Kangaroo-cam	Eastern grey kangaroo (*Macropus giganteus*)	330 g (0.5-1.4%)	8.9 x 5 x 3.7 and 8.3 x 4.8 x 4.5	Y	19 h	Store on board	30fps, 720 x 480HD		Collar mounted	[11]

References: [1] Bowen *et al.* 2002; [2] Nifong *et al.* 2013; [3] Nifong *et al.* 2014; [4] Beringer *et al.* 2004; [5] Moll *et al.* 2009; [6] Loyd *et al.* 2013; [7] Rutz and Bluff 2008; [8] Pearson *et al.* 2017; [9] Machovsky-Capuska *et al.* 2016; [10] Bombara *et al.* 2017; [11] This study

Figure 1. Individual components of the kangaroo-cam units, which were incorporated into one of two cases – the battery case or the component case (Shown as External lens in pod in this figure). Details of the specific components, size, suppliers and cost are shown in Table 1.

Figure 2. Eastern grey kangaroo (female) carrying the Kangaroo-cam device. The Kangaroo-cam is oriented pointing forwards from its location, which means it is pointed directly forward in this image .

Figure 3. Proportion of time (as a percentage of total scorable recording time) that kangaroos spent in each behavioural state during daylight hours, as determined by scoring videos recorded by Kangaroo-cam units. Note that all states are mutually exclusive and that feeding took precedence over other activities (see methods section).

Figure 4. Proportion (as a percentage) of foraging events in which different plant families were consumed by seven kangaroos.

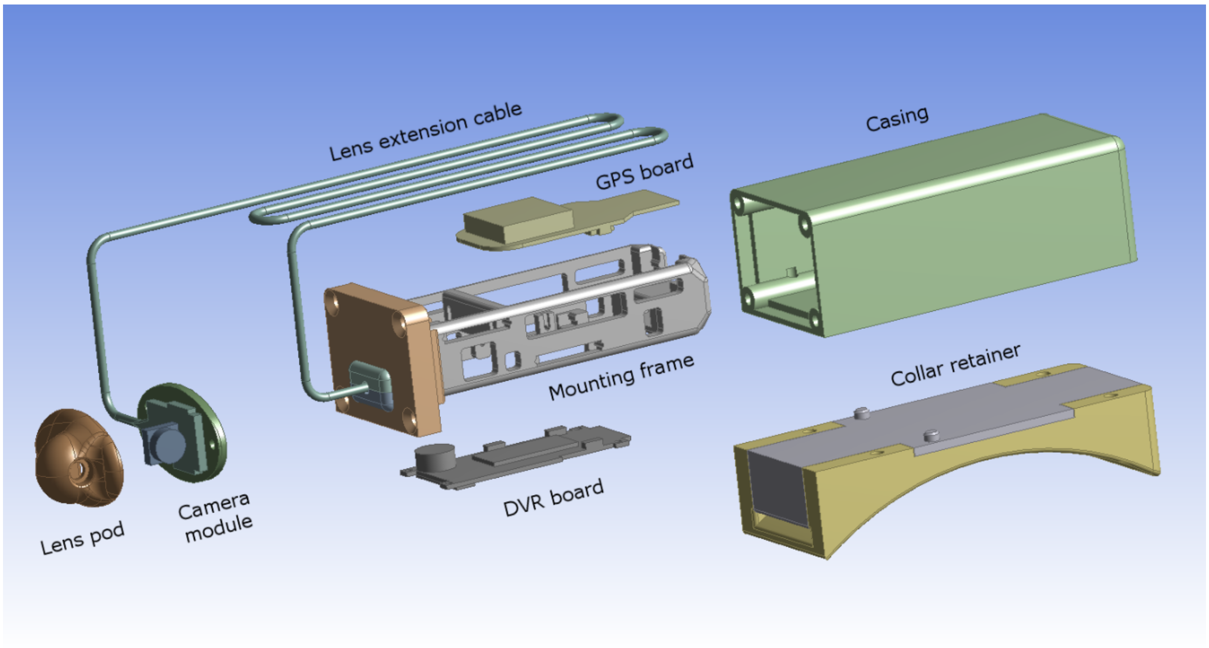
Figure 5. Still frames of images taken by the Kangaroo-cam units, showing the identification of plants consumed versus those available during foraging events in kangaroos. This highlights the potential utility of this approach for diet selection studies in herbivores.

Figure 6. GPS movement tracks and core use areas, with behavioural categories superimposed for four individuals: (a) animal 022 (male), (b) animal 261 (female); (c) animal 207 (female), and (d) animal 230 (female). Squares indicate feeding sites and pentagons indicate resting sites, while lines indicate movement trajectories. Shading represents the 50-95% kernel for core and

general animal use as follows: Red (50%), dark orange (60%), light orange (70%), yellow (80%), light green (90%) and dark green (95%).

Figure 7. Mean ± s.e.m. faecal glucocorticoid concentrations at 0, 24 and 48 h post capture in GPS collared (black line, closed circles; n = 6) and non-collared animals (grey line, open circles; n = 8) animals immobilised at time zero. Concentrations are significantly different between groups at 24 h.

EXTERNAL LENS IN POD



BATTERY CASE

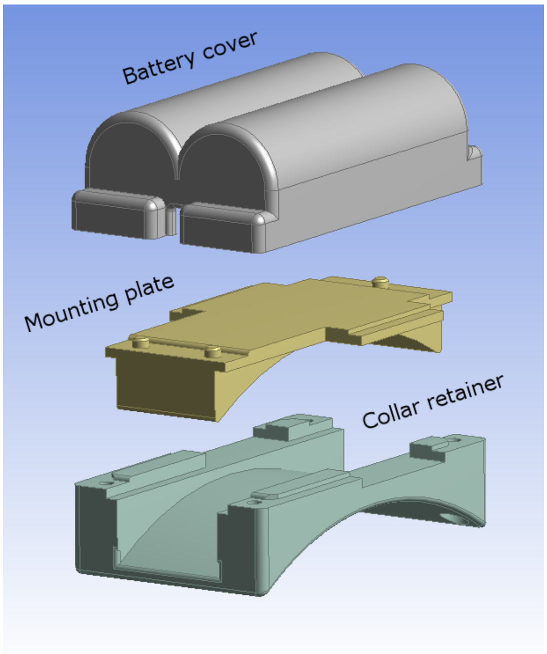


Fig. 1

Fig. 2

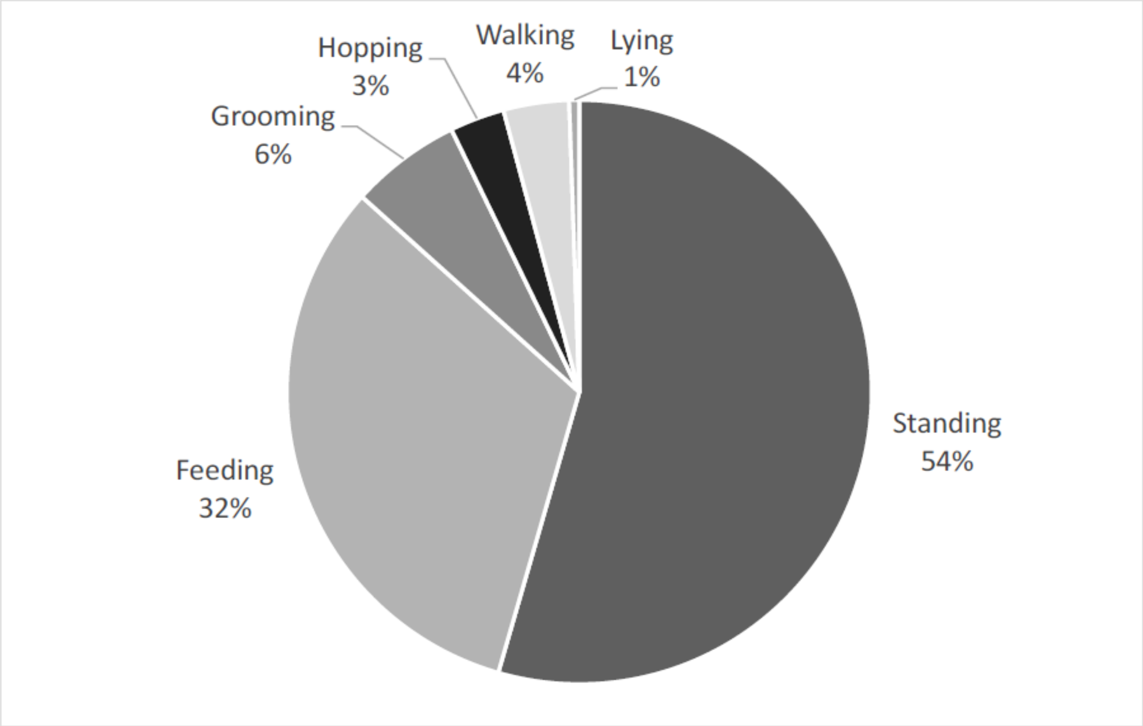

Hopping 3%
Walking 4%
Lying 1%
Grooming 6%
Standing 54%
Feeding 32%

Fig. 3

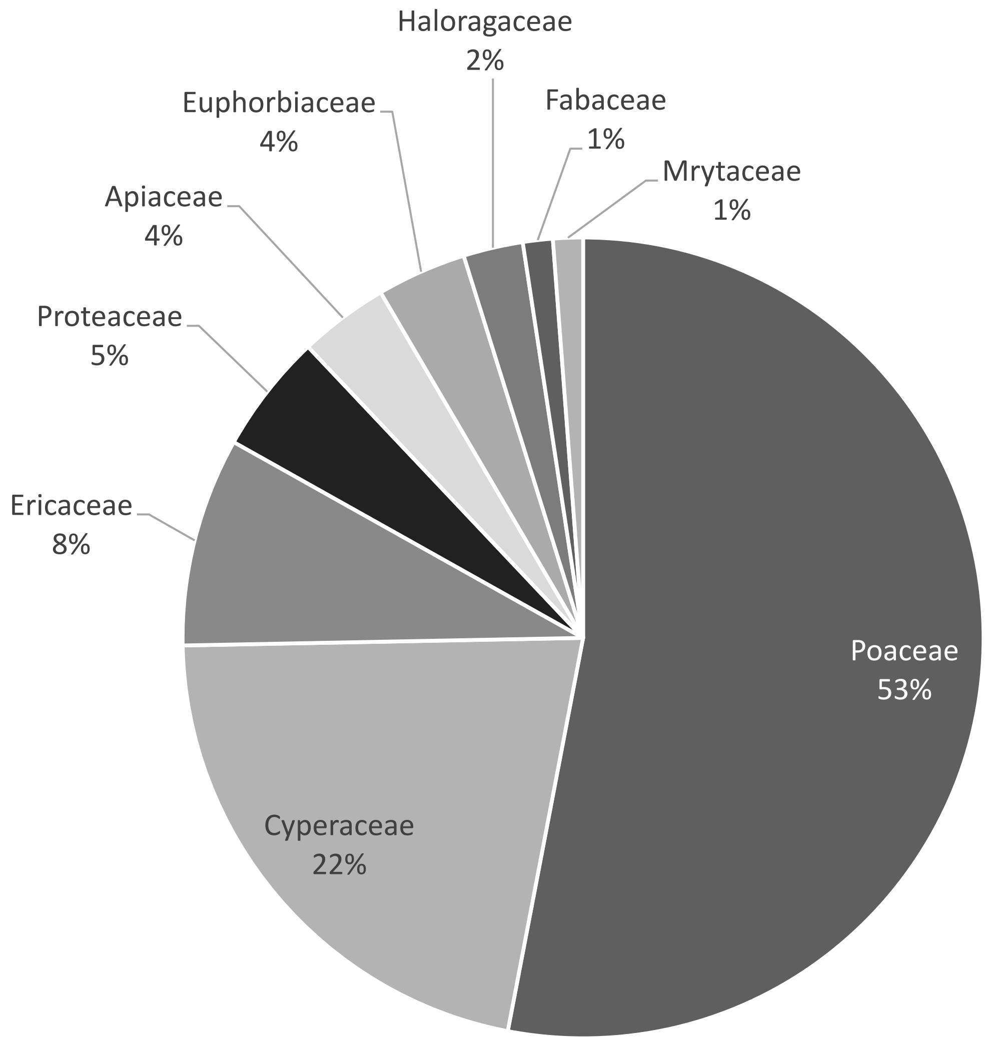

Haloragaceae
2%
Euphorbiaceae
4%
Fabaceae
1%
Mrytaceae
1%
Apiaceae
4%
Proteaceae
5%
Ericaceae
8%
Poaceae
53%
Cyperaceae
22%

Fig 4

Selected plants

Ricinocarpus spp. *Platysace spp.* *Lomatia spp.* Reed

Non-selected plants

Actinotus spp. *Banksia spp.* *Bracken spp.* *Hydrocotyle spp.*

Fig. 5

Fig. 6

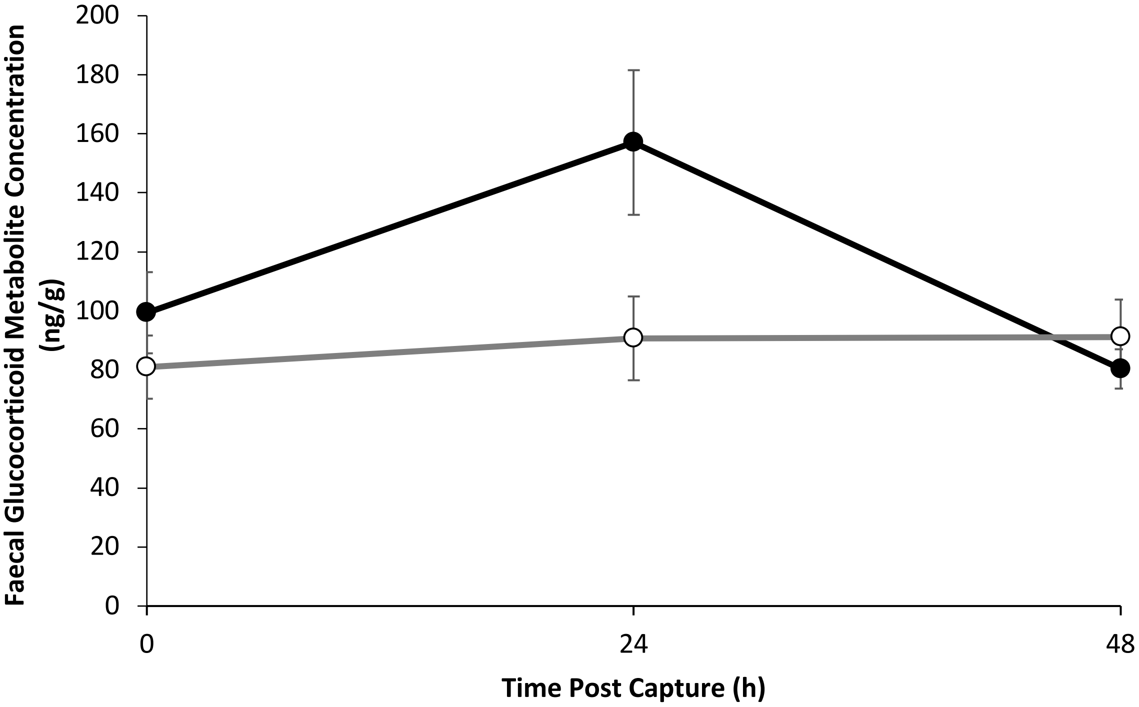

Faecal Glucocorticoid Metabolite Concentration (ng/g)
200
180
160
140
120
100
80
60
40
20
0
0
24
48
Time Post Capture (h)

Fig. 7