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Territoriality and Seasonality in the Home Range of Adult Male Free-ranging Lace Monitors (*Varanus varius*) in South-eastern Australia

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***Abstract*.—The Lace Monitor (*Varanus varius*) is a large terrestrial opportunistic carnivore of eastern Australia. The home range and movement patterns of any species are critical to understanding their ecology, however, very few home range studies investigate reptiles. To address this knowledge gap, we undertook an investigation of the home range of *V. varius* using GPS data loggers. The monitors that we tracked, males greater than 5 kg, had a mean home range (95% MCP) of 65.5 ± (SE) 10.0 ha respectively. We found that the core home range of our study animals displayed almost no overlap, consistent with dominant males defending a territory. However, anecdotal observations suggest that large monitors will tolerate smaller individuals within their home range. Our study animals also displayed seasonal variation in their movement patterns. As expected, winter movements were greatly reduced, however, animals did make infrequent forays between favored roost and feeding locations during even the coldest months.**

Key Words.—GPS; kernel density estimate; minimum convex polygon; Varanidae

Introduction

The Lace Monitor (*Varanus varius*; Fig. 1) is one of the largest terrestrial predators in eastern Australia, growing to 14 kg and reaching 2 m in length (Weavers 1988; Cogger 2018). *Varanus varius* is an opportunistic feeder and Pascoe et al. (2012) described high diet overlap between this monitor and wild dogs (*Canis lupus dingo* and *Canis lupus*), a sympatric apex predator. Guarino (2001) also described a high proportion of carrion in the diet of *V. varius*, which was supplemented by medium sized mammal prey.

Describing patterns of movement for any population of wild animals is critical to understanding the ecology of the species, and radio telemetry has enabled ecologists to more adequately describe home range and movements of varanids (Ibrahim 2002; Bolton and Moseby 2004; Ciofi et al. 2007; Imansyah et al. 2008; Smith and Griffiths 2009). More recently, there has been rapid development and use of modern GPS technology in home range studies. GPS data loggers have been used for home range studies of reptiles (e.g., Price-Rees et al. 2014), including varanids (Lei et al. 2017; Lei and Booth 2018a, Lei and Booth 2018b); however, these are relatively few when compared with the high number of studies investigating mammals. In a review of Australian home range studies, Goldingay (2015) found that only 19% of home range studies focused on reptiles, relatively few considering that reptiles make up 39% of the terrestrial fauna in Australia. In this study we present an investigation of home range and movement patterns of large male *V. varius* using GPS data loggers.

Materials and Methods

***Study site*.**—We conducted this study in the Burragorang Valley in New South Wales, Australia, located within the Greater Blue Mountains World Heritage Area (Fig. 2). The site is adjacent to the Warragamba Dam, which provides most of Sydney's water storage. In this study site, free-ranging sympatric predator and prey species provide frequent scavenging and predation opportunities for *V. varius*. Until the mid-1990s, the Burragorang Valley was actively used by grazing mammals. The study site is bisected by the Wollondilly River and is bordered to the east by the Warragamba Dam. Devonian sediments deposited during Permian and Triassic periods form the general soil types (Bannerman and Hazelton 1990; King 1994). The study site contains several vegetation communities, including regenerating ex-pastoral lands, dry open forest, and riparian woodlands (Fig. 2).

***Capture and restraint techniques*.**—We trapped for *V. varius* March 2008 to March 2009. We captured animals using cage traps (Model 48F large dog/coyote;

Figure 1. Lace Monitor (*Varanus varius*) resting in a cave in the Burragorang Valley, New South Wales, Australia. (Photographed by Michael Duncan).

Tru-Catch Traps, Belle Fourche, South Dakota, USA) approximately 120 × 50 × 65 cm (length × width × height) in size, which we baited with rabbit or fox carrion using the method described by Flesch et al. (2009). We placed cage traps where we observed high levels of *V. varius* activity. We closed cage traps after each capture, but we trapped at each location multiple times to recapture study animals for data logger retrieval and to allow opportunities for other large monitors to be captured in the same location. After capture, we weighed each animal in a porous nylon bag by hooking the bag onto a hand-held spring balance. We then attached a custom-made GPS data logger incorporating a single stage VHF transmitter within the 150–151 MHz band (manufactured by Sirtrack Scientific and Industrial Research, Havelock North, New Zealand) to each large (> 5 kg) *V. varius* using the method described by Flesch et al. (2009). Data loggers weighed approximately 240 g (accounting for < 5% of animal body mass in line with ethical considerations). Some individual *V. varius* had multiple data loggers fitted over the course of the study. In the literature we have found no evidence of an individual female *V. varius* with a mass > 3.5 kg whereas male *V. varius* are regularly > 5 kg (Carter 1992; Guarino 2002; Lei and Booth 2018a), therefore we consider our study animals to be male.

Home range.—We programed each GPS data logger to log the position of the animal every hour between 0600 and 1800 daily to detect movements during the most active time of each 24-h period. We removed position fixes with a Horizontal Dilution of Precision (HDOP) value > 5 from the analysis due to reduced spatial accuracy, which is consistent with approaches described in similar studies (Price-Rees et al. 2014). For each GPS data logger, we calculated a 100%, 95%, and 50% minimum convex polygon (MCP) and a 95%, 90%, and 50% kernel density estimate (KDE). To select a smoothing parameter (h), we simulated a suitable

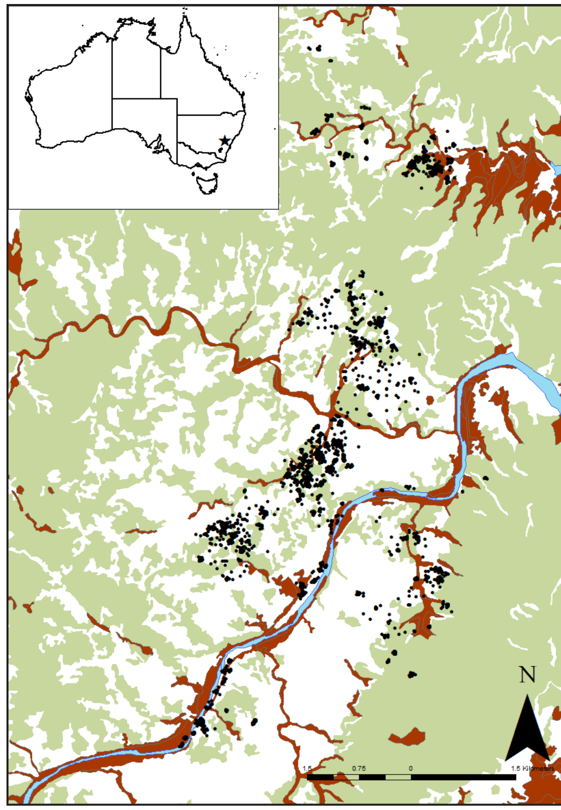

Figure 2. Location of the study site (star) in New South Wales, Australia (Inset). All position fixes for Lace Monitors (*Varanus varius*; black dots), the Wollondilly River (blue), and the major vegetation types (cleared land (white) woodland (green) and dry open forest (brown) in the Burragorang Valley.

utilization distribution (UD) of the data under a range of biologically relevant h values to identify the most robust choice of smoothing parameter for the creation of KDEs. We discounted least-squares cross-validation (LSCV), which is among the most frequently used methods for estimating h as this method is known to perform poorly when data are highly auto correlated (Worton 1989; Seaman and Powell 1996; Row and Blouin-Demers 2006). Auto correlation is common in herpetofauna studies due to the frequent use by species of confined areas within their home range (e.g., favorite retreat sites; Row and Blouin-Demers 2006). We created both MCP and KDE by using the Home Range Tools package (Rodgers, A.R., J.G. Kie, D. Wright, H.L. Beyer, and A.P. Carr. 2015. HRT: Home Range Tools for ArcGIS 10. Ontario Ministry of Natural Resources, Centre for Northern Forest Ecosystem Research, Thunder Bay, Ontario, Canada. Available from http://flash.lakeheadu.ca/~arodgers/hre/ [Accessed 25 November 2017]) in ArcMap 10.4.0.5524.

To determine if data loggers were recording position fixes for long enough to comprehensively measure the home range of each animal, we calculated the mean 95% MCP of all data loggers cumulatively for every

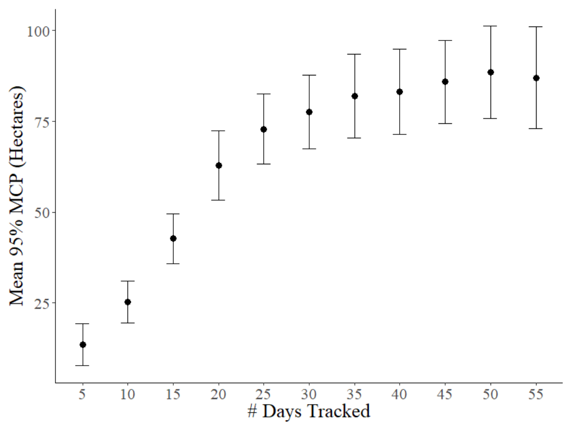

Figure 3. Mean 95% minimum convex polygon (MCP) for all data loggers, plotted against the number of days that data logger were recording postion fixes for Lace Monitors (*Varanus varius*).

5-d period. We then plotted this data series against the number of days of data logger deployment and assessed when this curve reached asymptote (Fig. 3). We considered any data logger that was recording position fixes for equal to or more than the point identified to be an adequate representation of home range.

Seasonality.—Given the strong seasonality of *V. varius* movements (Guarino 2002), we divided data points by the following seasons: summer (December, January, and February), autumn (March, April, and May), winter (June, July, and August), and spring (September, October, and November). We only included data from data loggers that were active for more than 35 d (identified in Fig. 3 as an adequate period to represent home range) within each calendar season for seasonal analysis. We measured daily movements by calculating the total distance between successive fixes for each day of tracking by using the Home Range Tools package (Rodgers et al., *op. cit.*) in ArcMap 10.4.0.5524.

We used a chi-square analysis to determine seasonal differences in home range size and we assessed differences in mean daily movements for each calendar season using Kruskal-Wallis rank sum test due to low sample sizes within seasons. If there was a significant difference in mean daily movements between seasons, we used Dunn's post hoc test to make pair-wise comparisons. We used RStudio (RStudio Team 2016) for all statistical analyses and $\alpha = 0.05$ was for all tests.

Results

We captured nine free-ranging adult *V. varius* with a mass > 5 kg, which we fitted with GPS data loggers. We fitted two of those animals (animals #1 and #3) with multiple data loggers over the course of the study. The animals that we fitted with a data logger had a mean mass of 6.8 kg ± (SE) 0.6 kg, mean snout-vent length (SVL) measured 74 cm ± 7 cm, and total length was 170 cm ± 14 cm. On average the data loggers recorded position fixes for 143.4 d ± 22.2 d (Table 1). We recorded and analyzed 6,704 acceptable position fixes, and each data logger collected on average 559 ± 103.9 acceptable position fixes. We deployed all our data loggers for more than 35 d, which was the minimum period that it took for the mean 95% MCP to reach asymptote (Fig. 3).

Mean 100% MCP for all *V. varius* in the study was 93.8 ha ± 14.7. Mean 95% KDE and MCPs for *V. varius* were 78.0 ± 14.9 and 65.5 ± 10.0, respectively (Table 1). Estimates for 50% KDE and MPCs were 11.5 ± 2.8 and 13.0 ± 4.1, respectively (Table 1). All home range estimates included significant areas without position

Table 1. Identification number (ID) of Lace Monitors (*Varanus varius*), number of useable fixes (UF), start and end dates for data recording, and number of days the data logger was active for a study in the Burragorang Valley in New South Wales, Australia. Home range estimates (50% and 95% minimum convex polygon [MCP] and kernel density estimator [KDE], in ha) for all *V. varius* in this study.

ID	UF	Start	End	Days	50% KDE	50% MCP	95% KDE	95% MCP
1	458	12 March 2008	13 September 2008	185	3.68	6.85	20.34	12.87
1	505	2 October 2008	24 December 2008	83	15.96	15.54	81.12	77.61
1	1251	9 March 2009	6 December 2009	272	3.62	5.12	49.14	33.29
2	309	12 March 2008	6 May 2008	55	13.59	12.99	92.97	92.22
3	698	12 March 2008	27 August 2008	168	3.62	13.99	87.79	97.24
3	304	2 December 2008	8 March 2009	96	22.56	33.71	94.74	78.07
4	1199	13 March 2008	2 October 2008	203	1.45	2.12	16.69	23.77
5	127	12 April 2008	1 August 2008	111	10.19	7.80	46.33	30.38
6	424	28 August 2008	7 January 2009	132	23.91	47.90	148.68	117.58
7	688	2 December 2008	10 March 2009	98	4.33	3.01	55.21	61.75
8	165	12 March 2009	26 April 2009	46	29.28	4.40	194.86	105.04
9	576	12 March 2009	7 December 2009	271	5.27	2.72	48.01	55.53
			Mean	143.4	11.46	13.01	77.99	65.45

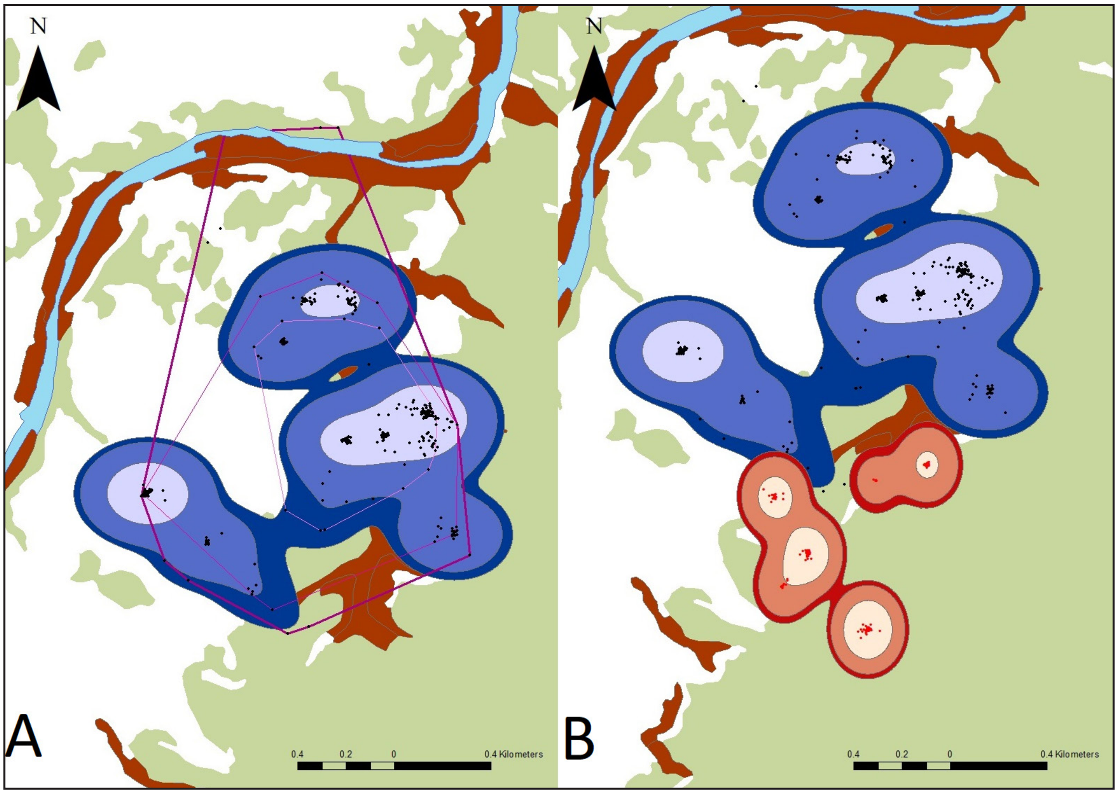

Figure 4. **A)** 95% (dark blue), 90% (pale blue), and 50% (grey) kernel density estimator (KDE) data, and 100%, (dark purple line), 95% (light purple), and 50% (grey) minimum convex polygon (MCP) data for Lace Monitor (*Varanus varius*) #6. **B)** Home range estimates for *V. varius* #6 (blue) and animal # 5 (red) showing 95%, 90%, and 50% KDE. Habitat depicted as cleared land (white), woodland (green), and dry open forest (brown).

fixes for each of the study animals, especially in 95% Kernels and 100% MCPs due to the high levels of spatial autocorrelation displayed by each of the animals (Fig. 4a.). We did, however, find both KDEs and MCPs useful for describing aspects of *V. varius* home range. The 50% KDE best represented how *V. varius* reused both refuge and feeding sites (Fig. 4b) and the 95% MCP appears to describe the exclusive territory held by each large *V. varius* in our study (Fig. 5a).

We examined home range overlap of 95% MCPs, and only two animals (#4 and #6) displayed home range overlap representing 0.8 ha (2.43% and 0.39%, respectively) of each 95% MCP (Fig. 5a). We observed no overlap in the core area (50% MCP) of any large *V. varius* during the study (Fig. 5a). We fitted several animals with replacement data loggers over the course of the study. These animals used different refuges on a temporal scale, but largely used the same territory (Fig. 5b).

The animals that we tracked throughout this study demonstrated large variation in daily movements. The largest daily movement of any animal was 2.0 km. Lizards regularly moved several hundred meters on average each day throughout summer, autumn, and spring, with movements appearing to be more sporadic and shorter throughout the winter months (Fig. 6). The largest daily movement of any individual throughout winter (0.8 km) was half that of either summer, autumn and spring (1.6 km, 2.0 km, and 1.7 km, respectively). Mean daily movements differed significantly between seasons (H = 10.27, df = 3, P = 0.016). Mean daily movements differed significantly between winter and spring (Dunn's test, P = 0.017), winter and summer (Dunn's test, P = 0.0106) and winter and autumn (Dunn's test, P = 0.022).

Discussion

Home range.—In this study, large male *V. varius* displayed home ranges that were characterized by high spatial autocorrelation. Favorite refuge and feeding sites were visited regularly and other location fixes largely represented movements between these locales. We regularly radio-tracked study animals to verify that data loggers were still attached, and we subsequently observed that retreat sites were often caves and tree hollows, and feeding locations were generally the remains of deceased macropods or other carrion. Pascoe et al. (2012) described the diet of *V. varius* in the region and reported that more than 50% of scats contained

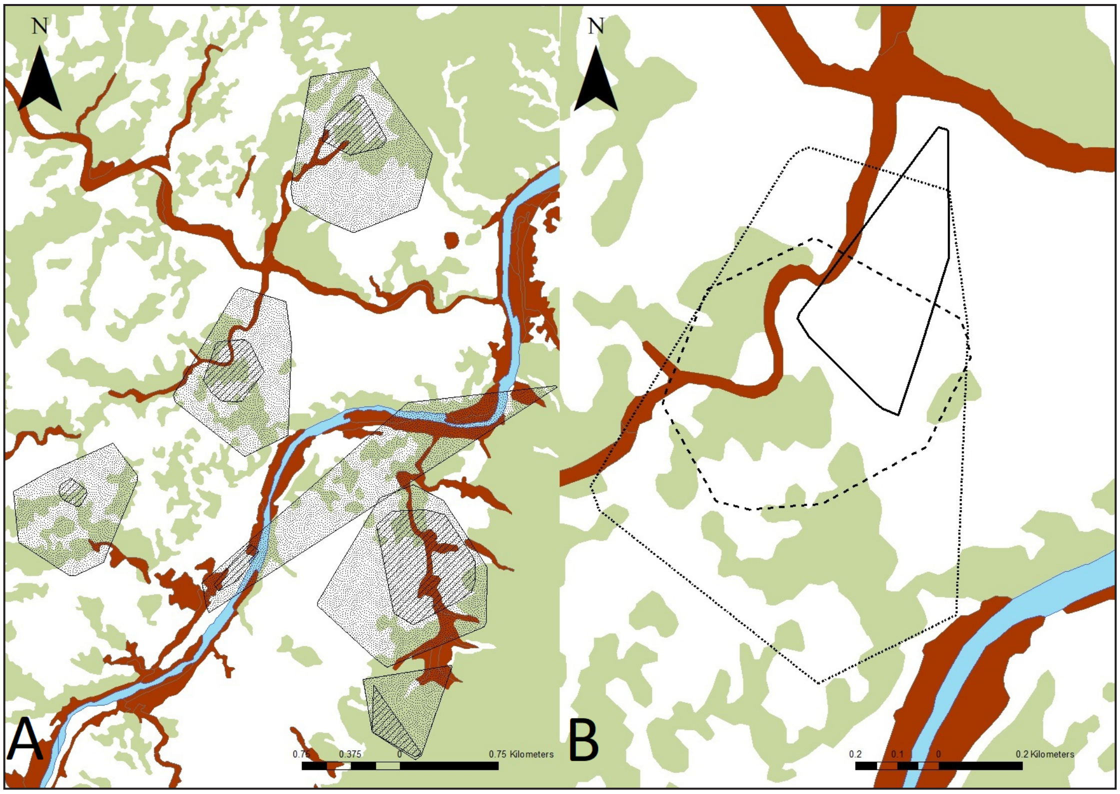

Figure 5. **A)** Spatial organization of 95% minimum convex polygon (MCP; dotted) and 50% MCP (striped) for Lace Monitors (*Varanus varius*) #1, 3, 5, 6, 7, and 8 along the Wollondilly River (blue) in cleared land (clear), woodland (green), and open forest (brown). **B)** Calculated 95% MCP for multiple data loggers deployed on *V. varius* #1 deployed on 3 December 2008 (solid), 10 February 2008 (dotted), and 3 September 2009 (dashed).

macropods. This result suggested that a large portion of *V. varius* diet at our study site is made up from the carrion, which is consistent with other diet studies (Weavers 1989; Guarino 2001), and that these opportunities were likely a result of an abundant macropod population that provided ample hunting opportunities for resident wild dogs. This is further corroborated by Pascoe et al. (2012), who reported high dietary overlap between *V. varius* and *C. lupus* and by previous studies, which reported high levels of opportunistic scavenging in *V. varius* (Weavers 1989; Guarino 2001; Jessop et al. 2010). Given the high site return rate for animals in this study, we consider that KDEs are a better spatial representation of the use of multiple core areas by *V. varius* than MCPs. We consider MCP a better method for describing the extent of the home range, however, because it did not exclude the most peripheral observations, unlike the KDE methodology. We used MCPs to compare with previous radiotelemetry studies of *V. varius*. Weavers (1993) and Guarino (2002) reported large variability in the home range estimates they calculated using the 100% MCP method. The mean home range size in those studies were 65 ha and 184.5 ha, respectively. In our study we determined a mean 100% MCP of 93.8 ha.

Our study site occurred in a typical example ex-pastoral eastern Australia, as did the study by Weavers (1993). He also studied exclusively male monitors, which may explain the similarity in home range estimates. The smaller animals that Weavers (1993) included and the dramatically smaller number of position fixes (mean = 19.94) collected in that study likely accounts for the slightly smaller MCP observed.

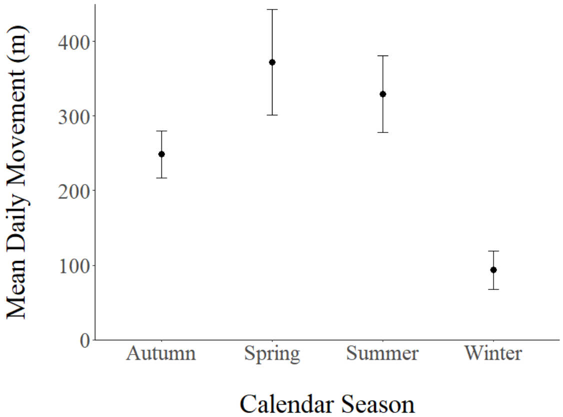

Figure 6. Mean (± SE) daily movements (m) of Lace Monitors (*Varanus varius*) during summer (two lizards), autumn (six lizards), winter (four lizards) and spring (four lizards).

In comparison with our study, Guarnio (2002) recorded a much larger home range. We think this may be due to the difference in habitat. Woodlands and forests dominated the Guarino (2002) study site, while regenerating pastoral lands dominated the matrix in our study area. The denser vegetation of the Guarino (2002) study probably favored fewer large macropods and this reduced scavenging opportunities. Pascoe et al. (2012) recorded carrion in more than 60% of dietary samples in our study site, whereas carrion occurred in fewer than 50% of samples in a study by Guarino (2001). We conclude that the small home range for *V. varius* in our study when compared with Guarino (2002) is the result of the likely abundance of scavenging opportunities within our study site due to frequent predation of macropods by wild dogs (Purcell 2010) that we think occurred at our site.

A recent study by Lei and Booth (2018a) measured male *V. varius* home range to be approximately 100 ha, while the home range for females was on average 2.5 times larger using the 95% MCP method to describe home range size. We recorded significantly smaller home ranges in our study, recording a mean 65 ha home range using the same methods of calculation. We believe that this is likely also to be a function of the different habitat types present in the two studies. Lei and Booth (2018a) undertook their study in a coastal dune system adjacent to open woodlands, while ours was a very different system. Lei and Booth (2018a) also described two major home range patterns for their study animals: clumped and linear (mostly in female monitors). While most of our study animals displayed clumped home ranges, one certainly had a linear home range, characterized by large movements. This individual regularly traversed the Wollondilly River but never crossed into the home range of other study animals who had clumped home range patterns on either side of the river.

Territoriality.—In this study we showed that large male *V. varius* did not display MCP overlap even though home ranges were directly adjacent to another study animal in most instances. Our trapping design does not rule out the possibility of bias towards animals living too far from each other that there was limited opportunity for home range overlap. Given the proximity of trapping locations, however, and the fact that we re-trapped the same locations and never captured a second monitor whose mass exceeded 5 kg, we consider it possible that this pattern represents territoriality and is likely to be a feature of large male varanids in the Burragorang Valley as they compete with other *V. varius* for resources. We hypothesize that this is unlikely to be competition over food resources due to the high availability of carrion at our study site and is therefore more likely to be competition for mates.

This is not consistent with studies of *V. varius* by Guarino (2002) and Lei and Booth (2018a), which both showed high levels of home range overlap. In the studies by Guarino (2002) and Lei and Booth (2018a), study animals were considerably smaller on average (mean mass 4,650 g and 3,000 g, respectively) than those that we studied (mean weight 6,800 g). Therefore, the studies probably included non-dominant *V. varius* who do not hold a territory. Small monitors are likely, given high population density, to overlap with the home ranges of other *V. varius* as was shown by Guarino (2002). On several occasions in our study, small *V. varius* were trapped (but excluded from this study) within the territory of larger animals, which tended to support the hypothesis that dominant *V. varius* tolerated the presence of smaller *V. varius* (Pers. obs.).

GPS technology continues to develop rapidly, leading to significant improvements in battery life and reductions in data logger weight. Although the attachment method used in this study (Flesch et al. 2009) allowed for the use of a relatively large GPS unit, technological advances have now made it possible to track far smaller animals without impeding their natural behaviors. Future studies that incorporate these new GPS units will allow for home-range and movement data to be collected across the size spectrum of individuals and act to reinforce or refute the size-mediated territoriality of male *V. varius* proposed by this study

Seasonality.—In the current study, there was a strong seasonal influence on average daily movements for *V. varius*, which is consistent with other studies of movements in Varanids (e.g., Guarino 2002; Ibrahim 2002). The size of daily movements of *V. varius* peaked in spring and reduced considerably in winter; however, animals did traverse the distance between refuge sites in all seasons, with the largest winter home range measured at more than 5 ha. These refuge sites were often caves and hollow logs where the animals spent periods of inactivity. This result suggested that *V. varius* do not hibernate during winter, consistent with Guarino (2002) who also reported winter movements, although these were very modest. Our study shows that GPS technology is more likely to pick up these more infrequent winter movements than radio-telemetry studies.

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Jason Flesch is a Lecturer in Animal Science at the University of Western Sydney, Australia. He completed a Ph.D. in 2001 on the biology, nutritional requirements and reproductive performance of Fallow Deer (*Cervus dama*), and has since undertaken research on a wide range of domestic and free ranging animals, recently focusing on reptiles. Current research includes the ecology of Varanus varius in the Blue Mountains World Heritage Area, Australia, and the nutrition, feeding behavior, and reproductive activity of captive Australian pythons. (Photographed by Michael Duncan).

Michael Duncan is a Research Assistant with the Centre for Plants and the Environment (CPE) at the University of Western Sydney, Hawkesbury, Australia. He completed a Bachelor of Science degree with honours in 1997. His main areas of research are honeybee behavior and pests, and in more recent times, herpetology. Michael is also the current secretary of the Australian Herpetological Society. (Photographed by Jason Flesch).

Mark Le Pla completed his Bachelor of Science (Ecology and Conservation Biology) with Honours at Griffith University, Gold Coast, Australia, in 2012. Where he studied the relative influence of plant composition and structure upon the bird assemblage of a eucalypt woodland in south-east Queensland, Australia. His current research interests include threatened species recovery programs, reintroductions, spatial ecology and invasive predator management. Currently Mark work as an Ecologist with the Conservation Ecology Centre, Cape Otway, Victoria, Australia, where he works on the Threatened Species Program. (Photographed by Ellie Kirke).

Robert Mulley is a Professor of Animal Science at the University of Western Sydney, Australia. Key areas of interest include husbandry and management of domesticated production animals, particularly deer. Other research areas include management of free ranging wildlife populations, meat quality assurance, and monitoring of dust and bioaerosols in industry settings. Recent research has focused on the role that Dingoes (*Canis lupus dingo*) and other predators play as keystone species in the Blue Mountains World Heritage Area, Australia, and sympatric relationships between native and exotic carnivores in the same ecosystem. (Photographed by Sue Cusbert).