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Wildlife Research

Supplementary Material

Drone thermal imaging technology provides a cost-effective tool for landscape-scale monitoring of a cryptic forest-dwelling species across all population densities

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Methods S1. Meta-review of koala population density approach, including word-search terms, databases accessed and identified studies.

We conducted a meta-review of peer-reviewed scientific literature which reports koala population density. We conducted a word-search of English language scientific literature across Google Scholar, Web of Science and Science Direct between August 2019 and January 2021. The word-search terms were selected to identify peer-reviewed empirical studies reporting koala population density (koalas per hectare) and are available in **Table S1**. Identified studies were read by two researchers to determine suitability and relevance to the study. We only included peer-reviewed studies which reported population density values for koala populations (this included mainly journal articles and book chapters; however, since koalas are monitored by diverse multi-sector stakeholders, we expanded criteria to include peer reviewed government research papers, academic theses and conference proceedings). While we believe this method uncovered the greater majority of studies containing koala population densities, we accept that some papers may have gone undetected. To maximise identification of relevant papers potentially missed by the word-search we also used the reference lists of identified papers to discover other potentially relevant studies. We established a database in Microsoft® Excel (16.45) of relevant studies. For each study we extracted the year of publication, Australian state where the koala population exists and the density estimate (koalas/ha). Private reports (including environmental consultancy) were not included in the meta-review due to a lack of a peer-review process and poor clarity around experimental design. The studies identified in this meta-review and used in the cost modelling presented in this investigation are shown in **Table S2**.

Table S1. Keywords, word-search terms and Boolean operator combinations used in our meta-review of koala population density

Word-search terms for meta-review of koala population density **** we also employed Boolean operators to narrow search results. A list of keyword and Boolean operator combinations are also shown. Note: we conducted our word-search of each database using the original listed key-words as well as the Boolean operator combinations.**	
Keywords and phrases	**Boolean operator combinations of keywords and phrases**
Koala/s population density	(Koala/s OR "*Phascolarctos cinereus"*) AND "population density"
Koala/s density	(Koala/s OR "*Phascolarctos cinereus"*) AND density
Koala/s hectare/s	(Koala/s OR "*Phascolarctos cinereus"*) AND (hectare/s OR "ha")
Koala/s monitoring	(Koala/s OR "*Phascolarctos cinereus"*) AND ("population density" OR density)
Koala/s population monitoring	(Koala/s OR "*Phascolarctos cinereus"*) AND ("population density" AND hectare/s OR "ha")
Phascolarctos cinereus population density	(Koala/s OR "*Phascolarctos cinereus"*) AND (density AND hectare/s OR "ha")
Phascolarctos cinereus density	(Koala/s OR "*Phascolarctos cinereus"*) AND ("population density" OR density AND hectare/s OR "ha")
Phascolarctos cinereus hectare/s	(Koala/s OR "*Phascolarctos cinereus"*) AND monitoring
Phascolarctos cinereus monitoring	(Koala/s OR "*Phascolarctos cinereus"*) AND "population monitoring"
Phascolarctos cinereus population monitoring	(Koala/s OR "*Phascolarctos cinereus"*) AND (monitoring or "population monitoring")
	Koala/s monitoring AND "population density"
	Koala/s monitoring AND density
	Koala/s monitoring AND (hectare/s OR "ha")
	Koala/s monitoring AND ("population density" OR density)
	Koala/s monitoring AND ("population density" AND hectare/s OR "ha")
	Koala/s monitoring AND (density AND hectare/s OR "ha")
	Koala/s monitoring AND ("population density" OR density AND hectare/s OR "ha")
	Koala/s population monitoring AND "population density"
	Koala/s population monitoring AND density
	Koala/s population monitoring AND (hectare/s OR "ha")
	Koala/s population monitoring AND ("population density" OR density)
	Koala/s population monitoring AND ("population density" AND hectare/s OR "ha")
	Koala/s population monitoring AND (density AND hectare/s OR "ha")
	Koala/s population monitoring AND ("population density" OR density AND hectare/s OR "ha")
	"Phascolarctos cinereus" monitoring AND "population density"
	"Phascolarctos cinereus" monitoring AND density
	"Phascolarctos cinereus" monitoring AND (hectare/s OR "ha")
	"Phascolarctos cinereus" monitoring AND ("population density" OR density)

	"Phascolarctos cinereus" monitoring AND ("population density" AND hectare/s OR "ha") *"Phascolarctos cinereus"* monitoring AND (density AND hectare/s OR 'ha") *"Phascolarctos cinereus"* monitoring AND ("population density" OR density AND hectare/s OR "ha") *"Phascolarctos cinereus"* population monitoring AND "population density" *"Phascolarctos cinereus"* population monitoring AND density *"Phascolarctos cinereus"* population monitoring AND (hectare/s OR "ha") *"Phascolarctos cinereus"* population monitoring AND ("population density" OR density) *"Phascolarctos cinereus"* population monitoring AND ("population density" AND hectare/s OR "ha") *"Phascolarctos cinereus"* population monitoring AND (density AND hectare/s OR "ha") *"Phascolarctos cinereus"* population monitoring AND ("population density" OR density AND hectare/s OR "ha")

Table S2. Studies containing density estimates for koala populations uncovered by the meta-review. For all studies we report the state, year of publication, density estimate/s in koalas/ha and the reference. Note: when using these density values to generate the ascending order scale of density estimates for modelling, we calculated the mid-range value for density estimates that were reported as a lower and higher range (e.g. 6 - 8.9 koalas/ha would be 7.45 koalas/ha)

Density Estimate (koalas/ha)	**State**	**Year**	**Reference**
0.006	NSW	1997	(Jurskis and Potter 1997)
0.013, 0.071, 0.12	NSW	2004	(Smith 2004)
4.0-8.0	NSW	1980	(Gall 1980)
5.6	NSW	1990	(Faulks 1990)
0.05	NSW	1995	(Leathley *et al.* 1995)
0.037	NSW	2020	(Witt *et al.* 2020)
0.01	QLD	1994	(Melzer and Lamb 1994)
0.01-0.02, 0.02-0.04, 0.03-1.3, 0.06-1.8, 0.002-1.85,	QLD	2011	(Seabrook *et al.* 2011)
0.19, 0-1.2, 0-1.3, 0.29, 0.24, 1.32, 1.16, 0.84, 0.56, 0.42, 0.43, 0.10, 0.31, 0.26, 0.18, 0.05, 0.17, 0.41, 0.15, 0.10, 0.13, 0.64, 0.19, 0.16, 0.36, 0.57, 0.18, 0.15, 0, 0.15, 0.20, 0.29, 0.34, 0.27, 0.13, 0.14, 0.17, 0.15, 0.30, 0.15, 0, 0.23, 1.09, 0.08	QLD	2001	(Dique *et al.* 2001)
0.2, 0.2-0.6, 0.6, 1.2	QLD	2013	(Ellis *et al.* 2013)
0-0.4	QLD	2013	(McGregor *et al.* 2013)
0.4	QLD	1991	(White and Kunst 1991)
0.4, 0-2.51	QLD	2004	(Sullivan *et al.* 2004)
0.02-0.4	QLD	1995	(Melzer 1995)
0.06-0.42, 0.64, 0-0.76	QLD	2003	(Dique *et al.* 2003)
0.02-1.26	QLD	2004	(Dique *et al.* 2004)
0.7-1.6, 6-8.9	QLD	1984	(Hindell 1984)
0.1-2.0, 1.0-3.0	QLD	1990	(Gordon *et al.* 1990b)
1.0-3.0, 1.9-2.5	QLD	1995	(Hasegawa 1995)
0.25	QLD	1994	(White 1994)
0.6-1.5, 1.0-2.5	QLD	1990	(Gordon *et al.* 1990a)
0-1.32	QLD	2001	(Thompson 2001)
0.3	QLD	2019	(Gentle *et al.* 2019)
0.95-1.8, 1.2-1.9, 5.3-7.3	VIC	1986	(Every 1986)
0.001-8.9, 8.6-8.9, 2.2-6.6, 7.5	VIC	1990	(Mitchell and Martin 1990)
12, 16	VIC	2013	(Ryan *et al.* 2013)
0.7-3.0	VIC	1985	(Martin 1985)
6.7	VIC	2019	(Watchorn and Whisson 2019)
0.25, 0.3, 0.3, 0.69, 0.97, 1.00, 1.13, 3.0, 7.19	VIC	2018	(Hagens *et al.* 2018)
0.66, 0.68, 0.74, 0.85, 2.89, 4.32	VIC	2020	(Ashman *et al.* 2020)
1.9	VIC	2014	(Barker *et al.* 2014)
10.1, 14.2, 18.4	VIC	2016	(Whisson *et al.* 2016)

8.62, 8.85	VIC	1997	(Downes *et al.* 1997)
0.3	VIC	1988	(Mitchell *et al.* 1988)
3.9-8.9	VIC	1990	(Mitchell 1990)
5	SA	2004	(Masters *et al.* 2004)
0.13, 0.3, 0.4, 0.5, 0.6	SA	2012	(Whisson *et al.* 2012)
1.0, 3.0, 13	SA	2010	(Whisson and Carlyon 2010)
1.97, 3.57, 10.9, 3.1, 7.1,	SA	2005	(Duka and Masters 2005)
0.2, 0.4	SA	1989	(Robinson *et al.* 1989)
1.5-3.0	SA	1972	(Eberhard 1972)

Methods S2. Detailed itemised costs and cost sources used to conduct cost comparisons of Spotlight, RPAS thermal imaging and SAT surveys under three main cost groupings.

For *Cost comparison of survey methods*:

Equipment costs include all equipment and consumables required to perform surveys with each survey method across all reported survey sites. Spotlight surveys required up to 6 headtorches (LED Lenser H14R) as well as up to 6 handheld GPS (Garmin Etrex). SAT surveys also required up to 6 handheld GPS (Garmin Etrex). RPAS thermal imaging surveys required a quadcopter drone (DJI Matrice 200 v2) equipped with various add-ons including a Zenmuse XT2 integrated 3-axis gimbal, with a Zenmuse XT2 camera with dual sensors: a FLIR longwave thermal camera (Tau2) and a 4K visual (RGB) camera. RPAS thermal imaging surveys also required up to two headtorches (LED Lenser H14R) as well as one handheld GPS (Garmin Etrex). RPAS thermal imaging surveys also required a Samsung Galaxy S4 Tablet (to program flights using DJI Pilot), as well as a boom lift (a Genie TZ-34/20 modelled here as a rented 10.6m Trailer Mounted Boom Hybrid with similar reported capability due to data availability at an A$262.88 daily rate; https://www.coateshire.com.au/trailer-mounted-boom-10-0m-11-0m-electric/petrol/diesel-hire). Visual line of sight must be maintained with the RPAS therefore a boom lift was used to maintain sight of the RPAS beyond an obstructive tree canopy. The boom lift was a required cost for the RPAS thermal imaging surveys modelled here under Australian Government Civil Aviation Safety Authority (CASA) relevant legislation (https://www.legislation.gov.au/Details/F2020C00608). To model the increased cost-efficiency of RPAS thermal imaging surveys conducted with beyond visual line of site certification (no boom lift), we have also modelled RPAS thermal imaging surveys with boom lift costs removed. We modelled RPAS licensing and training as a necessary start-up cost for RPAS thermal imaging surveys based on quotes sourced from the CASA approved ACEAVIATION Aerospace Academy (https://aaa.edu.au/courses/newcastle-repl-training/). This licensing and training is assumed to involve obtaining various licenses (e.g., Remote Pilot's Licence, RePL, and Aeronautical Radio Licence, AROC) as well as compulsory 5 hours of flight training under CASA's compulsory requirements.

Labour and personnel costs were calculated using detailed records of person minutes (of paid surveyors and volunteers) recorded for each survey method across all survey sites. We calculated labour costs using person minutes for surveying (actual survey effort) and for additional on-site time (all preparatory and concluding tasks either side of the actual survey effort for each survey method; ± 30 minutes). Costs were calculated for all personnel using a theoretical assumed minimum hourly rate of A$40. The decision to use a consistent hourly rate for the three survey methods was to provide a standardised comparison of relative efficiency and costs of survey effort. The decision-making tool provided in **Fig. 3** provides a means to compare survey effort costs with custom hourly rates for each survey method. Personnel numbers reflect the minimum personnel required to safely survey all sites (2 persons per transect) (Beranek *et al.* 2021; Witt *et al.* 2020).

Travel costs were modelled using the University of Newcastle's vehicle hire charge (A$0.77 per km) to transport personnel to and from sites using two vehicles, as well as user-pays fuel costs using the Australian Institute of Petroleum's NSW weekly average price of diesel fuel for the week ending Sunday 3rd November 2019 (149.6 c/l) (https://www.aip.com.au/pricing/new-south-walesact-retail-diesel-prices) and assuming a fuel efficiency of 11.1L/100km (2018 model Toyota Hilux; https://www.finder.com.au/toyota-hilux-review) for the total estimated kilometres travelled to and from each Port Stephens survey site and the University of Newcastle's Callaghan Campus for all surveys (**Table S3**).

Note: The cost comparisons and modelling in this investigation does not account for variation in operating costs that may occur across different bodies (e.g., institutions or departments), which may differ based on work health and safety protocols or minimum staffing numbers. The cost comparisons and modelling in this investigation also do not account for potential equipment replacement costs, including for theoretical long-term monitoring costs.

Table S3. Costs (A$) and cost sources for all components used in the comparison of costs required to conduct surveys of a low-density koala population (Port Stephens; 0.037 koalas/ha) using systematic spotlighting (Spotlight), remotely piloted aircraft system thermal imaging (RPAS thermal imaging) and the refined diurnal radial search component of the spot assessment technique (SAT) presented in **Table 1**. All costs are presented in A$ (2020)

Survey Method	**Cost Category**	**Component/Item**	**Cost ($A)**	**Source**
Spotlight	Equipment	Headtorch Led Lenser H14R	A$284.95 per unit	https://ledlenser.com.au/products/h14r-2-headlamp
		GPS (Garmen Etrex)	A$159 per unit	https://www.mountaindesigns.com/equipment/electronics-navigation/compasses-handheld-gps/garmin-etrex-10-handheld-gps/90034940?gclid=Cj0KCQiA88X_BRDUARIsACVMYD8WPAYIIncvTy_PwHGmgvD6uX_mTsvx-uWz5_7yenDykUUSXgBrZqQaAhIoEALw_wcB&gclsrc=aw.ds
	Travel	Fuel/Petrol	149.6c/l	https://www.aip.com.au/pricing/new-south-walesact-retail-diesel-prices
SAT	Equipment	GPS (Garmen Etrex)	A$159 per unit	https://www.mountaindesigns.com/equipment/electronics-navigation/compasses-handheld-gps/garmin-etrex-10-handheld-gps/90034940?gclid=Cj0KCQiA88X_BRDUARIsACVMYD8WPAYIIncvTy_PwHGmgvD6uX_mTsvx-uWz5_7yenDykUUSXgBrZqQaAhIoEALw_wcB&gclsrc=aw.ds
	Travel	Fuel/Petrol	149.6c/l	https://www.aip.com.au/pricing/new-south-walesact-retail-diesel-prices
RPAS thermal imaging	Equipment	DJI Matrice 200 v2 + Zenmuse XT2 Package	A$33,105	https://www.riseabove.com.au/dji-matrice-200-v2-dji-zenmuse-xt2-thermal-package
		10.6m Trailer Mounted Boom Hybrid	A$262.88 per day	https://www.coateshire.com.au/trailer-mounted-boom-10-0m-11-0m-electric/petrol/diesel-hire
		Licensing and Training	A$4,295	https://aaa.edu.au/courses/newcastle-repl-training/
		Samsung Galaxy S4 Tablet	A$999	https://www.thegoodguys.com.au/samsung-galaxy-tab-s4
		Headtorch Led Lenser H14R	A$284.95 per unit	https://ledlenser.com.au/products/h14r-2-headlamp
		GPS (Garmen Etrex)	A$159 per unit	https://www.mountaindesigns.com/equipment/electronics-navigation/compasses-handheld-gps/garmin-etrex-10-handheld-gps/90034940?gclid=Cj0KCQiA88X_BRDUARIsACVMYD8WPAYIIncvTy_PwHGmgvD6uX_mTsvx-uWz5_7yenDykUUSXgBrZqQaAhIoEALw_wcB&gclsrc=aw.ds
	Travel	Fuel/Petrol	149.6c/l	https://www.aip.com.au/pricing/new-south-walesact-retail-diesel-prices

Table S4. Data used to calculate travel costs for the cost comparison presented in **Table 1**. Includes total estimated kilometres (km) travelled to and from each Port Stephens survey site and the University of Newcastle's Callaghan Campus

Site Location	**Days travelled to and from for surveys**	**Distance (km) to and from site to the University of Newcastle**	**Total km travelled per vehicle**
Tiligery Habitat/Caswell Reserve	2	84km	168km
Stoney Ridge Reserve	2	104km	208km
Gurumbit National park	2	86km	172km
Ringwood Ferodale	2	58km	116km
Anna Bay	4	100km	400km

Methods S3. Assumptions and values used in various economic comparisons, including cost-effectiveness, costs across landscapes scales and per hectare costs, as well as modelling of detection costs across population density

For *Average per hectare survey costs*:

We estimated $A\$ha$ using survey effort (person hours) to monitor koalas with each survey method based on mean survey effort, estimated labour costs and known hectares six survey sites in Port Stephens presented in Beranek *et al*. (2021) and Witt *et al.* (2020). Survey sites were chosen in the original study based on various selection criteria as reported in Witt *et al*. 2020, including recently reported activity of koalas, an abundance of primary feed trees and accessibility. Only sites considered preferred or supplementary koala habitat were selected as per Lunney *et al*. (1998). Specific sites were chosen for the cost analysis based on detection of at least one koala with at least one of the three survey methods compared. Values for $A\$ha$ represent a theoretical minimum estimate and do not account for changes in terrain, weather and other logistical factors characteristic of different habitat areas and landscapes. Estimates also do not account for potential travel costs. The size in hectares for the six Port Stephens sites used in this investigation were 57ha, 73ha, 47ha, 47ha, 28ha, 28ha.

***For theoretical accumulating cost model to forecast potential costs of long-term (10-year) monitoring*:**

To project estimated koala monitoring costs using Spotlight, RPAS thermal imaging or refined SAT surveys over time we generated an accumulating cost model for the long-term (10-year) monitoring of koalas in the case study population in Port Stephens (using the itemised costs described above for labour and equipment). We compared fixed year 1 start-up costs as well as recurring labour costs required for a theoretical 17-week period of koala surveying annually using each survey method (representing 1/3 of the working year and comprising the core cooler survey months leading into and including winter; May through August). We applied an assumed ongoing inflation rate of 2.7% to costs which accumulated annually across the 10-year period (based on publicly available recent average Australian inflation rates https://tradingeconomics.com/australia/inflation-cpi). We provide the overall total and annual program costs required using different survey methods as well as the potential hectares surveyed using average per hectare costs calculated in this investigation. We do not include travel costs. Another limitation, as noted above, is we have not included equipment replacement costs for any survey method. These may be considerable for RPAS thermal imaging surveys depending on replacement frequency. User-data (e.g., on maintenance costs, replacement frequency, usage and longevity, e.g., lifespan in hours, hectares or years) from drone practitioners could be used to apply appropriate on-going and/or recuring maintenance costs to modelled long-term costs for RPAS thermal imaging. The same approach could be applied to equipment required for other survey methods (Spotlight and refined SAT surveys).

Table S5. Values used in comparing cost-effectiveness, and in density modelling for Spotlight, RPAS thermal imaging and SAT for the detection of koalas in Port Stephens. The surveys modelled here were first reported in (Witt *et al.* 2020). Note: In the original surveys, successful koala detections (physical sightings) were reported as on-ground visual confirmation of koalas during Spotlight or refined SAT surveys, or validation of RPAS thermal imaging detections by either on-ground observer or RPAS thermal imaging derived 4K footage review (Beranek *et al.* 2021; Witt *et al.* 2020). All costs are presented in A$ (2020)

Survey Method	**Average koala detections per site**	**Average effort in person hours per site**	**Average cost of effort per site**	**Detectability ratio: average effort in person hours required until one koala is successfully detected**
Spotlight	0.833	7.103	A$284.10	8.523
RPAS thermal imaging	2.00	4.49	A$179.43	2.243
SAT	0.167	5.87	A$234.74	35.211

Methods S4. Log transformations of survey effort for successful koala detection (*n* = 1) across available koala population densities used to derive survey method selection decision making tool shown in Fig. 3.

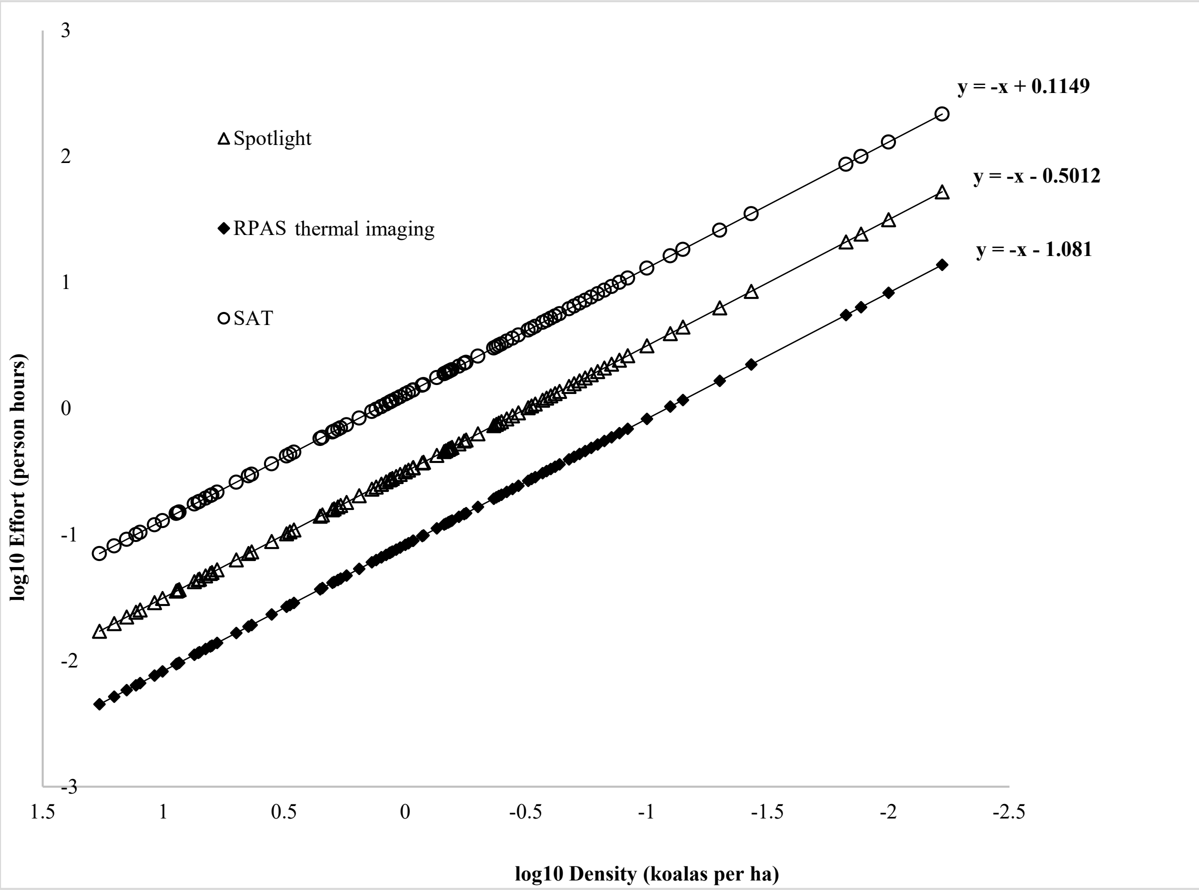

Fig. S1. Correlation between koala population density (koalas per hectare) and mean survey effort in person hours required for successful koala detection (*n* = 1) using systematic spotlighting (Spotlight), remotely piloted aircraft system thermal imaging (RPAS thermal imaging) and the refined diurnal radial search component of the spot assessment technique (SAT). All data is log transformed and both axis are presented in log10 to show linear equations used to derive survey method selection decision making tools (**Fig. 3**). y-axis values are based on an ascending order scale of publicly available koala population density values between 0.006 and 18 koalas per hectare (**Table S2**). x-axis values reflect effort in person hours required for successful koala detection (*n* = 1) adjusted for all density values on the ascending order scale using known reference values (effort) for the Port Stephens population (Port Stephens; 0.037 koalas/ha).

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