Executive Summary

This report presents findings from analysis of movement data from 13 koalas translocated from the Upper Nepean State Conservation Area to the South East Forests National Park in March/April 2025. Using continuous-time movement modelling approaches, two complementary analyses were conducted: behavioural change point analysis to identify discrete phases in post-translocation movement, and sliding window diffusion rate analysis to quantify temporal changes in daily movement rates.

Individual koalas exhibited highly variable post-translocation trajectories with no consistent temporal pattern across the cohort. While some individuals showed discrete behavioural phases that could be interpreted as exploration followed by potential settlement, others displayed variable movement patterns throughout their tracking periods. Movement phase durations ranged from 1-25 days, with root mean squared speeds varying between 3-63 m/hr and movement persistence timescales ranging from effectively zero to 2.71 hours. Similarly, sliding window diffusion rate analyses revealed substantial heterogeneity in movement rates over time. Some koalas exhibited pronounced peaks in diffusion rates whereas others showed more gradual patterns or sustained moderate rates of movement throughout their tracking periods. Critically, neither analytical approach provided reliable early-warning indicators of declining animal welfare.

The high individual variation in post-translocation behaviour indicates there are few generalisable patterns in post-translocation koala movement behaviour for this study area and that movement-based metrics alone are likely insufficient for accurately assessing individual animal welfare status. Results from this analysis suggest future translocation efforts would benefit from monitoring approaches that integrate additional datastreams (e.g. accelerometer or temperature loggers) and collect location information more frequently (30-60 minute intervals) to better match the episodic nature of koala movement ecology. Whilst a more frequent fix interval would reduce overall battery life, the data derived from such a regime would provide a more robust foundation for monitoring the welfare of translocated koalas during the initial post-release phase wherein monitoring is most crucial.

Behavioural change point analysis of translocated koalas

Behavioural change point analysis of translocated koala movement data was applied using correlated velocity models (CVMs) as implemented in the *smoove* package (Gurarie *et al.* 2017) in the R programming environment. CVMs are continuous-time stochastic models that characterise animal movement through biologically meaningful parameters that are independent of sampling scale or regularity.

The CVM framework models animal movement as an integrated Ornstein-Uhlenbeck (OU) velocity process, where velocity (rather than position) is the fundamental unit being modelled. Two candidate models within the CVM family of relevance for koala movements were used:

- **Unbiased CVM (UCVM):** Random movement with no directional bias
- **Advective CVM (ACVM):** Movement with a consistent directional component

A likelihood-based sliding window change point analysis was implemented following Gurarie *et al.* (2017). This procedure can be broken down into four distinct steps:

Step 1 – Window Sweep: A sliding window of fixed duration moved through each individual's trajectory at defined step intervals. Within each window, candidate CVM model parameters are estimated using maximum likelihood estimation.

Step 2 – Change Point Identification: For each window position, the most likely change point (MLCP, i.e. the time within the window where fitting separate models before and after maximised the combined likelihood) was identified. This process was repeated across all window positions.

Step 3 – Clustering: Initial change point candidates occurring within a defined cluster width were merged to avoid artificially fragmenting gradual behavioural transitions into multiple discrete events.

Step 4 – Model Selection: For each candidate change point, Bayesian Information Criterion (BIC) was used to assess support among three competing scenarios:

- A single homogenous model across the entire segment
- Two different parameter values of the same model type (e.g. UCVM or ACVM) before and after the change point
- Two fundamentally different model types (e.g. UCVM before, ACVM after)

Change points were retained only when the two-phase model showed substantial improvement (ΔBIC > 2) over the single-phase model. This BIC-based model selection simultaneously determines whether a behavioural change occurred and which CVM models best characterised movement before and after the transition.

Following Gurarie *et al.'s* (2017) guidelines and based on koala movement ecology, the following values were selected for this analysis:

- **Window size:** 120 hours
- **Window step:** 2 hours
- **Cluster Width:** 36 hours
- **Candidate models:** UCVM and ACVM

Window size selection balanced competing considerations: windows must be large enough to contain sufficient data points for reliable parameter estimation (Gurarie *et al.* recommend at least 25-50 locations per window), yet small enough to detect relatively rapid behavioural changes. Given the GPS collars used in this translocation program were scheduled to collect fixes at a 2-hourly interval, a window size of 120 hours (~ 5 days) represents the finest resolution available for this kind of analysis (e.g. 60 fixes per window assuming all fixes are successfully collected throughout the entire collar deployment). Additionally, this analysis describes and detects changes between relatively coarse

movement behaviours that are sustained over multiple days (e.g. exploratory ranging through an unfamiliar environment in the initial days post-release through to home range establishment), rather than fine-scale behaviours such as resting vs active foraging, making larger windows such as 120-hours appropriate.

Behavioural change point analysis is particularly well-suited for investigating post-translocation koala movement for several reasons. First, this method is an objective and data-driven approach to segmenting movement trajectories into biologically relevant phases. Traditional approaches rely on subjective assessment (i.e. the animal appears settled) or arbitrary time thresholds (i.e. animals are considered settled 30 days post-release). CVM change point analysis provides statistically rigorous, likelihood-based identification of these behavioural transitions grounded in quantifiable changes in movement parameters agnostic of different GPS fix schedules or manufacture units. This method also does not require researchers to pre-specify expected post-translocation behavioural sequences, their typical durations, or movement characteristics associated with specific behaviours. This is crucial when translocation outcomes are uncertain and where animals may display highly variable post-translocation movement behaviours. Additionally, by estimating the root mean speed (RMS) of the movement process and autocorrelation timescales (Tau), results from continuous-time behavioural change point analysis can be interpreted within broader movement ecology frameworks and can be meaningfully compared across different translocation studies, species and systems. Unlike derived metrics such as step lengths or residence times, these parameters have a consistent and biologically relevant meaning.

Sliding window analysis of koala diffusion rates

To further examine how koala movement rates changed over time following translocation, a sliding window analysis of daily diffusion rates approach using continuous-time movement models was applied to translocated koala GPS datasets using the *ctmm* R package (Calabrese *et al.* 2016; Fleming and Calabrese, 2025). This approach is intended to be complimentary to the CVM change point methods described above, providing a continuous measure of koala movement rates through time rather than separating telemetry datasets into distinct yet discrete phases. Limited daily sample sizes (~ 12 locations at best) precluded estimation of daily diffusion rates. To overcome this limitation, a moving-window approach that fitted movement models to successive overlapping time periods (windows) throughout each koala's tracking period was used.

Specifically, each koala's GPS trajectory was divided into overlapping 5-day windows (to maintain consistency with the change point analysis described above), advancing by 1-day increments. Diffusion rate – a measure of how rapidly an animal spreads out across the landscape over time (the variance in locations per unit of time, DeNicola *et al.* 2025) – was estimated for each window. Diffusion rates, expressed in hectares per day, provide an intuitive metric of space use intensity: higher values indicate more extensive ranging behavior, while lower values suggest more localised movements within a smaller area. As there was no data available that would allow for the calibration of error introduced by the observation process (e.g. the number of satellites used to estimate location, horizontal dilution or precision etc.), a consistent GPS error of ~10m was assumed. This is a value typically used when calibration data is unavailable for GPS telemetry data (Noonan *et al.* 2019; Fleming *et al.* 2020). For comparative purposes, this process was then replicated for GPS collared koalas with suitable datasets (n = 8) from the source population (Upper Nepean State Conservation Area, hereafter 'UNSCA') who were tracked during the same period (March – May 2025). Whilst these animals had more coarse fix schedules during this time (6-hourly) and fewer locations per animal, a window size of 5 days was sufficiently large to allow for estimation of diffusion rates.

Changes in diffusion rates over time can reveal important biological processes following translocation. For example, elevated diffusion rates immediately post-release may indicate exploratory behaviour as koalas assess their new environment and search for suitable habitat. Conversely, declining diffusion

rates may suggest koalas are restricting movements to a more defined area that could indicate home range establishment or declining health status.

This analysis aims to address four key questions:

1.) Are there distinct post-translocation phases (e.g. exploratory, settling, established) that are identifiable across individuals?
2.) What are the typical timeframes for behavioural transitions from release through to potential settlement and home range establishment?
3.) Are there movement patterns that may predict translocation success?
4.) Can movement data be used as an early indicator of welfare status of translocated koalas?

To date, application of continuous-time movement models to koala movement datasets is rare despite the substantial advantages methods rooted in this paradigm provide (e.g. Fleming *et al.* 2016; Fleming *et al.* 2018; Noonan *et al.* 2019). These insights will inform interpretation of translocation outcomes and can be used to refine future translocation protocols.

Results

Behavioural change point analysis

Behavioural change point analysis was successfully conducted for 11 of 13 animals in the translocation cohort. Model fitting failed for two individuals (UN70 and UN83) and was likely

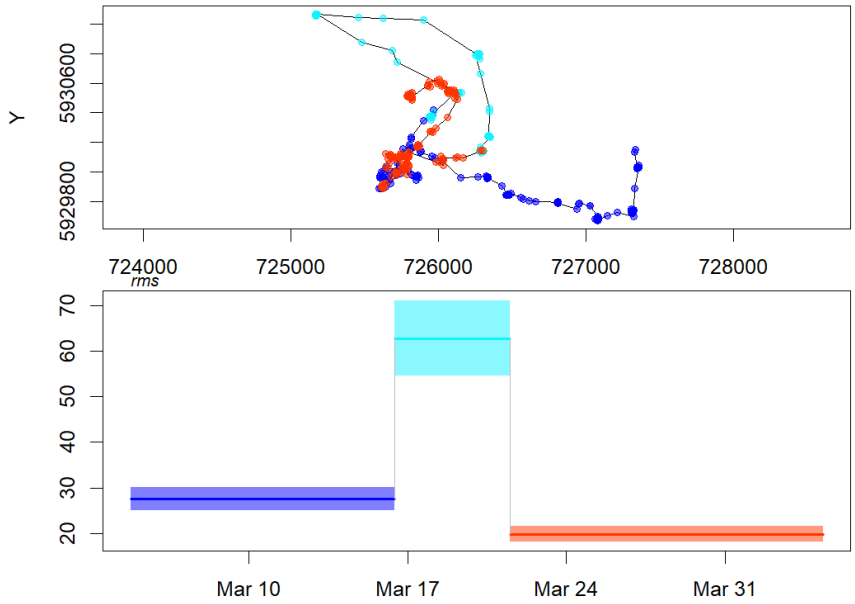
associated with the small duration of their collaring datasets (both animals were recaptured shortly after release, X and X days respectively). A brief description of the discrete movement phases and their underlying parameter estimates is provided below:

UN21 (Female, 3.5 – 5.5 yrs, deceased)

For the first twelve days after release, UN21's movement behaviour was characterised by relatively slow speeds (28 m/hr) that were generally persistent for over an hour (Tau = 1.25 hours) before changing course. Around March 16th, the root mean speed of the movement process more than doubled (63 m/hr), and movements became highly erratic and randomly maintained in time (Tau: 0.00 hours). This phase indicated movements during this time were highly "stuttered" – the koala made frequent movement bouts interspersed with extended rest periods, repeatedly starting and stopping with little consistent direction between bouts. By March 21st, the speed of the movement process returned to similar levels to that observed in the first fortnight post-release (20 m/hr) and this phase was maintained for 14 days before this animal was found deceased, with no indication of changes in movement behavior (e.g. reduced movements) in the last few days of GPS tracking.

Table 1. Estimated movement phases of koala UN21 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	4/3	16/3	12	UCVM	1.25	28
2	16/3	21/3	5	UCVM	0.00	63
3	21/3	4/4	14	UCVM	0.04	20



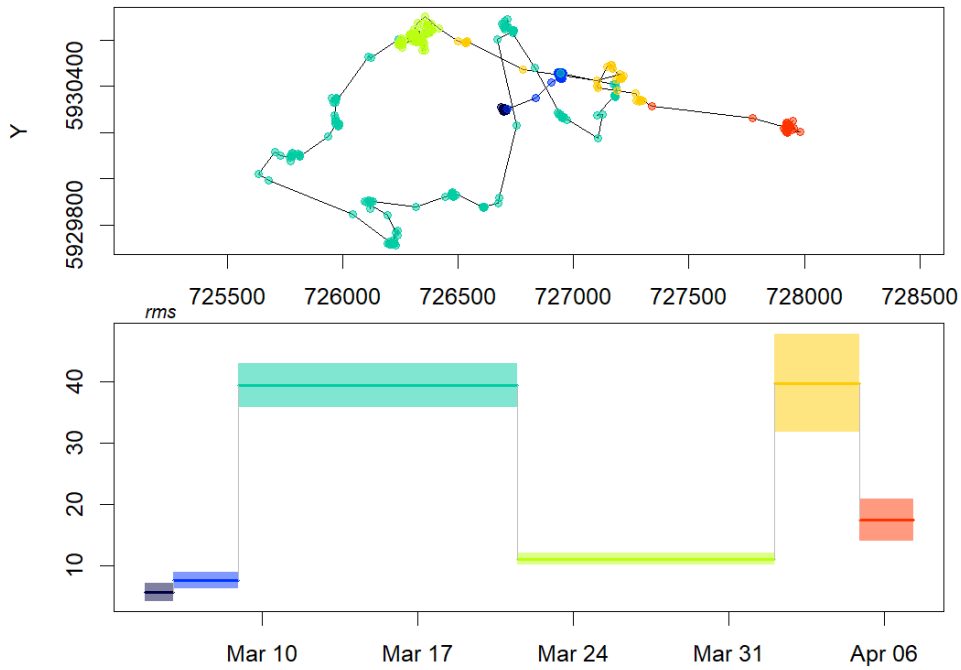
UN24 (Female, 5.5 – 6.5 yrs, Deceased)

For the first four days after release, UN24's movement behaviour was characterised by small-scale movements interspersed with extended periods in what was likely a single tree or a small stand of trees close together. Around March 8th, the movement behaviour of this koala changed: the root mean speed of the movement process increased four-fold (39 m/hr), movement was maintained for relatively long periods (1.77 hours), and the distance between successive steps increased. This behaviour was maintained for 13 days and likely represents a period of exploratory movements in search of food and/or shelter. Following this phase, this animal then spent close to a fortnight in a

small area (~ 2 ha), with limited movements and a generally slow movement process speed (11 m/hr). Beginning on 2 April, this animal then departed this area and moved similarly to phase 3 (described above), with even longer periods of sustained movement (2.71 hours) and similar speeds (40 m/hr). The final three days of this animals' movement trajectory was characterised by moderate speeds (17 m/hr) with similar velocity persistence to other more active phases.

Table 2. Estimated movement phases of koala UN24 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	4/3	5/3	1	UCVM	0.14	6
2	5/3	8/3	3	UCVM	2.48	8
3	8/3	21/3	13	UCVM	1.77	39
4	21/3	2/4	12	UCVM	0.04	11
5	2/4	5/4	3	UCVM	2.71	40
6	5/4	8/4	3	UCVM	1.45	17

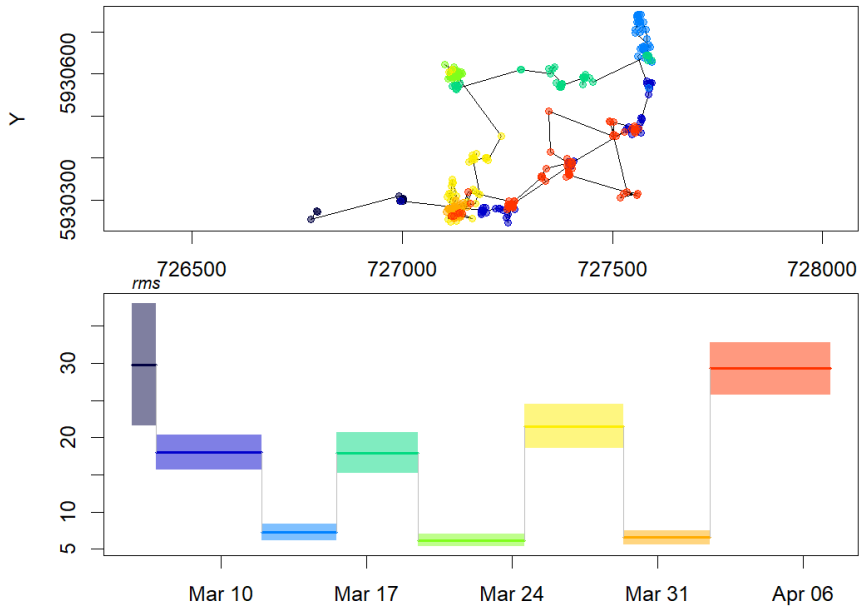


UN25 (Male, 1.25 – 3.5 yrs, Euthanased)

In the first evening post-release, this animal moved 200m east from the initial release site. Following this initial movement, this animals' movement process tended to oscillate every 4-5 days between bouts of moderate movements (phases 2, 4, 6 and 8) and short periods of restricted activity and movements (phases 3, 5 and 7) (Table 3). Movement persistence was short in all phases (Tau range: 0 – 0.09 hours), indicating movements were generally short-term in nature and directed.

Table 3. Estimated movement phases of koala UN25 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	5/3	6/3	1	UCVM	0.02	30
2	6/3	11/3	5	UCVM	0.08	18
3	11/3	15/3	4	UCVM	0.04	7
4	15/3	19/3	4	UCVM	0.01	18
5	19/3	24/3	5	UCVM	0.09	6
6	24/3	29/3	5	UCVM	0.00	22
7	29/3	2/4	3	UCVM	0.01	7
8	2/4	8/4	6	UCVM	0.00	29

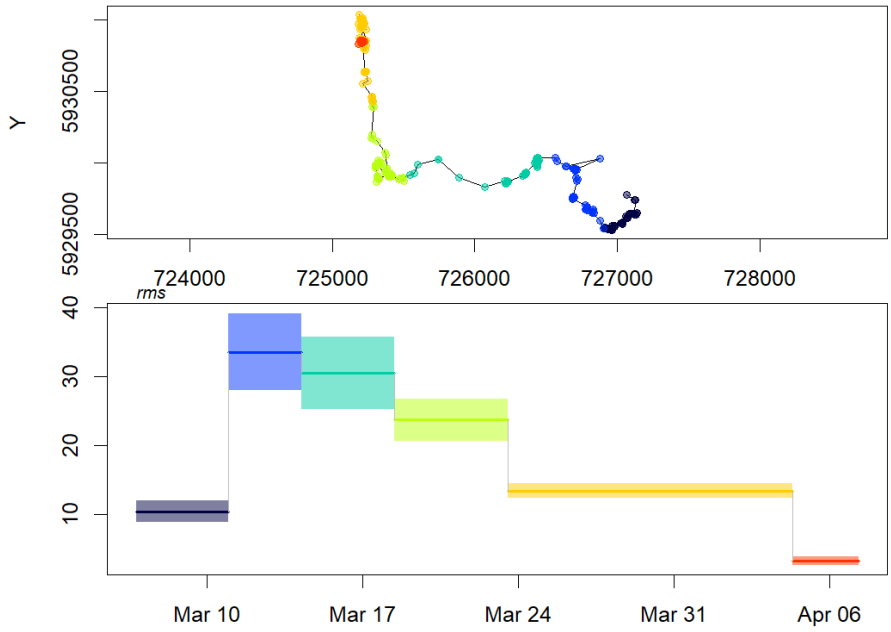


UN32 (Male, 1.25 – 3.5 yrs, Released)

After an initial phase of 4 days wherein UN32 moved slowly south-west from its release location (10 m/hr) with limited motion persistence (Tau = 0.1 hours), its movement behaviour transitioned into a series of broadly similar phases with gradually decreasing movement process speeds (Table 4). Of note is phase 3, which involved more sustained periods of movement relative to other phases. That is, whilst the RMS speeds of phases 2,3 and 4 were broadly similar, movements in phase 3 tended to be more directional (cyan) and maintained for longer periods (1.89 hours) relative to other phases. After approximately 13 days of elevated movements, UN32 then spent the next 12 days moving more slowly northwards with brief periods of movement interspersed with long periods of effective stationarity. The final phase of UN32's movements was associated with a RMS that was largely equivalent to that expected by GPS error, suggesting it likely spent this period in a single tree before being recaptured.

Table 4. Estimated movement phases of koala UN32 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	6/3	10/3	4	UCVM	0.10	10
2	10/3	14/3	4	UCVM	0.01	34
3	14/3	18/3	4	UCVM	1.89	31
4	18/3	23/3	5	UCVM	0.00	24
5	23/3	5/4	12	UCVM	0.00	13
6	5/4	8/4	3	UCVM	0.76	3

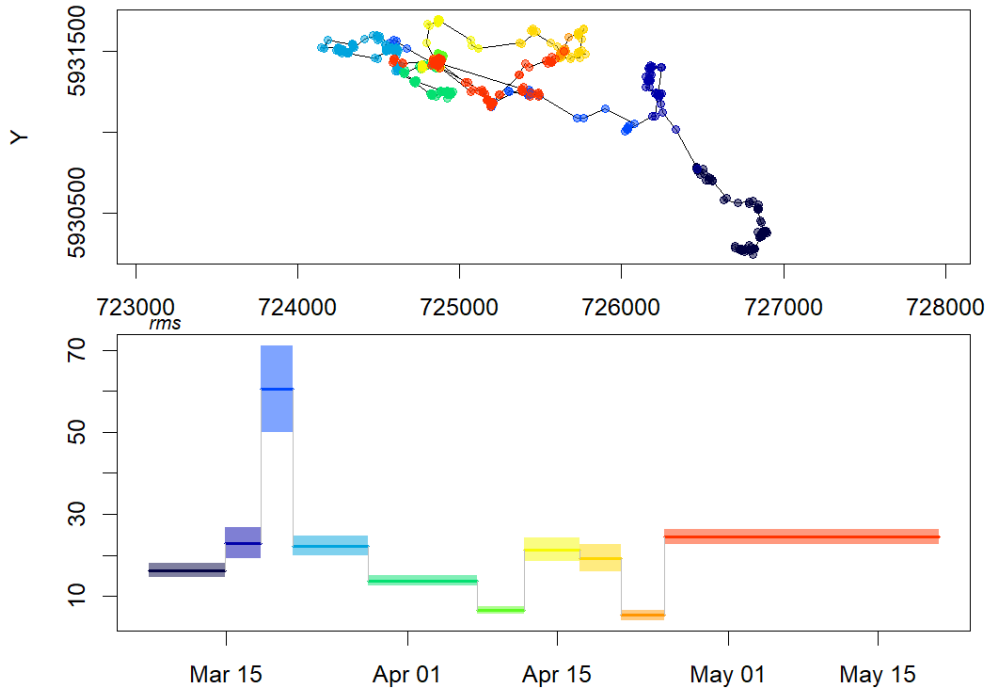


UN42 (Female, 1.25 – 3.5 yrs, Deceased)

The movement behaviour of UN42 for first eleven days post release was characterised by slow meandering movements away from its release location. However, beginning on the 18th of March, UN42 then made large and directed movements westward over a 3-day period, with the speed of the movement process tripling during this time (61 m/hr). Following this foray, UN42's movement behaviour was generally homogenous except for two apparent "rest" phases (phase 6 and 9) wherein the animal was effectively stationary for several days. Similar to UN21, there was no indication that the movement behaviour of the animal fundamentally changed in the days prior to being found moribund on the ground.

Table 5. Estimated movement phases of koala UN42 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	7/3	14/3	7	UCVM	0.05	16
2	14/3	18/3	4	UCVM	0.00	23
3	18/3	21/3	3	UCVM	0.00	61
4	21/3	28/3	7	UCVM	0.00	22
5	28/3	7/4	9	UCVM	0.06	14
6	7/4	11/4	4	UCVM	0.02	7
7	11/4	17/4	6	UCVM	0.98	21
8	17/4	20/4	3	UCVM	1.29	19
9	20/4	25/4	5	UCVM	0.05	5
10	25/4	20/5	25	UCVM	0.03	24

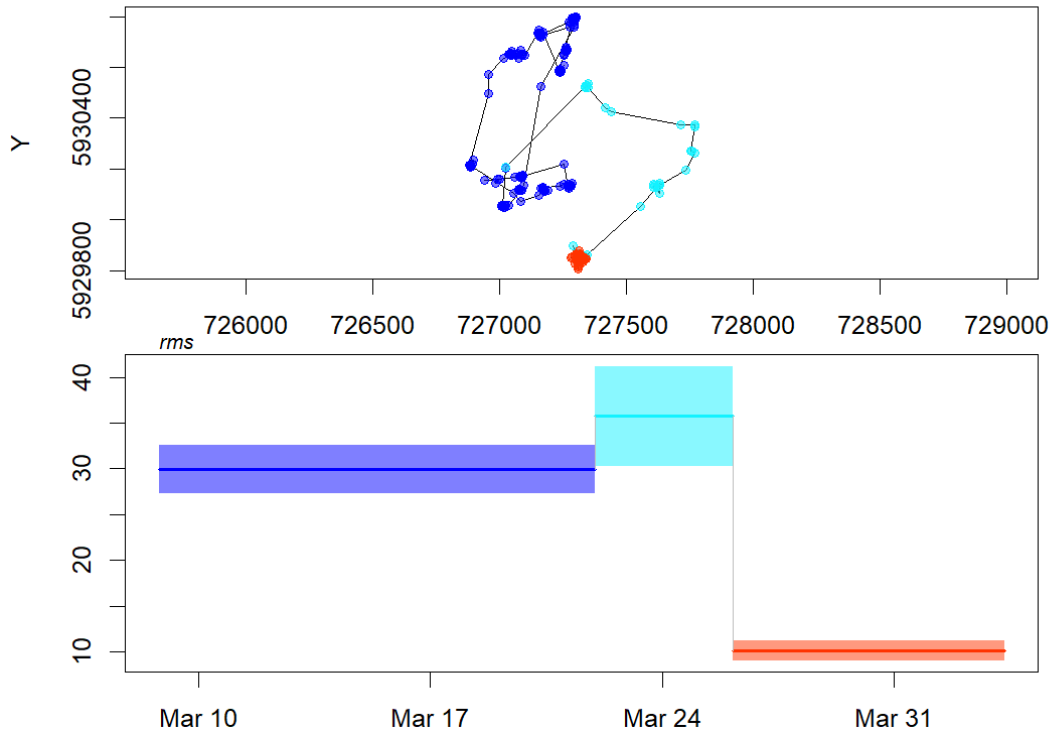


UN47 (Male, 5.5 - 6.5 yrs, Deceased)

The movement behaviour of UN47 was largely homogenous, with moderate speeds (30 m/hr) and relatively long velocity persistence in phase 1 (1.48 hours). After 21 March, the movement process changed slightly and became more “stuttered” - the koala made frequent movement bouts interspersed with extended rest periods, repeatedly starting and stopping with little consistent direction between bouts (Tau = 0.00). The final phase of UN47’s movement process was effectively stationary. This animal was tracked via on-ground tracking on the 27th of March but was unable to be visually located. It was then found heavily decomposed on the ground on 3 April. Given the speed of the movement process for this phase was close to that expected by GPS error, it is likely the movement data included in this phase includes GPS fixes collected after the animal had died and should be interpreted with this in mind.

Table 6. Estimated movement phases of koala UN47 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	8/3	21/3	13	UCVM	1.48	30
2	21/3	26/3	5	UCVM	0.00	36
3	26/3	3/4	7	UCVM	0.08	10

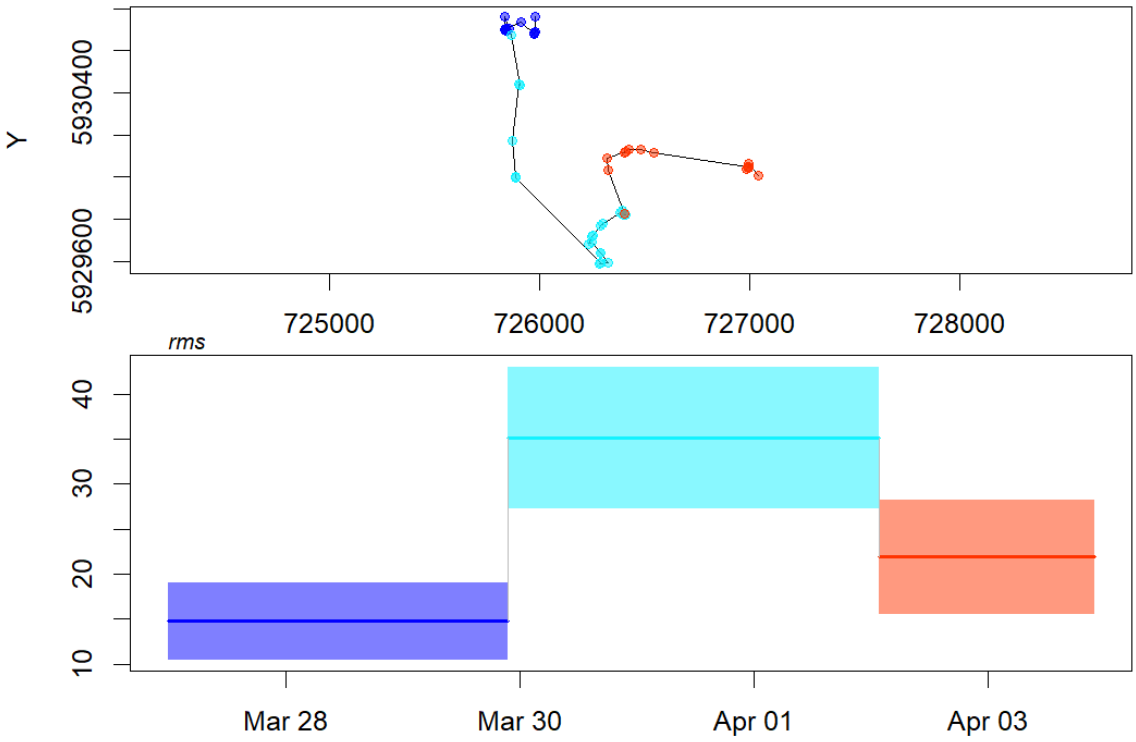


UN51 (Male, 1.25 – 3.5 yrs, Euthanased)

The first three days of UN51's movement behaviour involved slow and diffusive movements west from his release site. Beginning on 29 March, the speed of UN42's movement process doubled (RMS: 35.15 m/hr) and he made a southward journey of approximately 1.1 km over the course of two nights. The final phase of UN42's movement behaviour was characterised by slower yet more persistent motion (Tau: 1.75 hrs) eastward (Table 7). He was then found moribund on 4 March, taken into care and euthanased.

Table 7. Estimated movement phases of koala UN51 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	26/3	29/3	3	UCVM	0.01	14.76
2	29/3	2/4	4	UCVM	0.00	35.15
3	2/4	3/4	1	UCVM	1.75	21.89

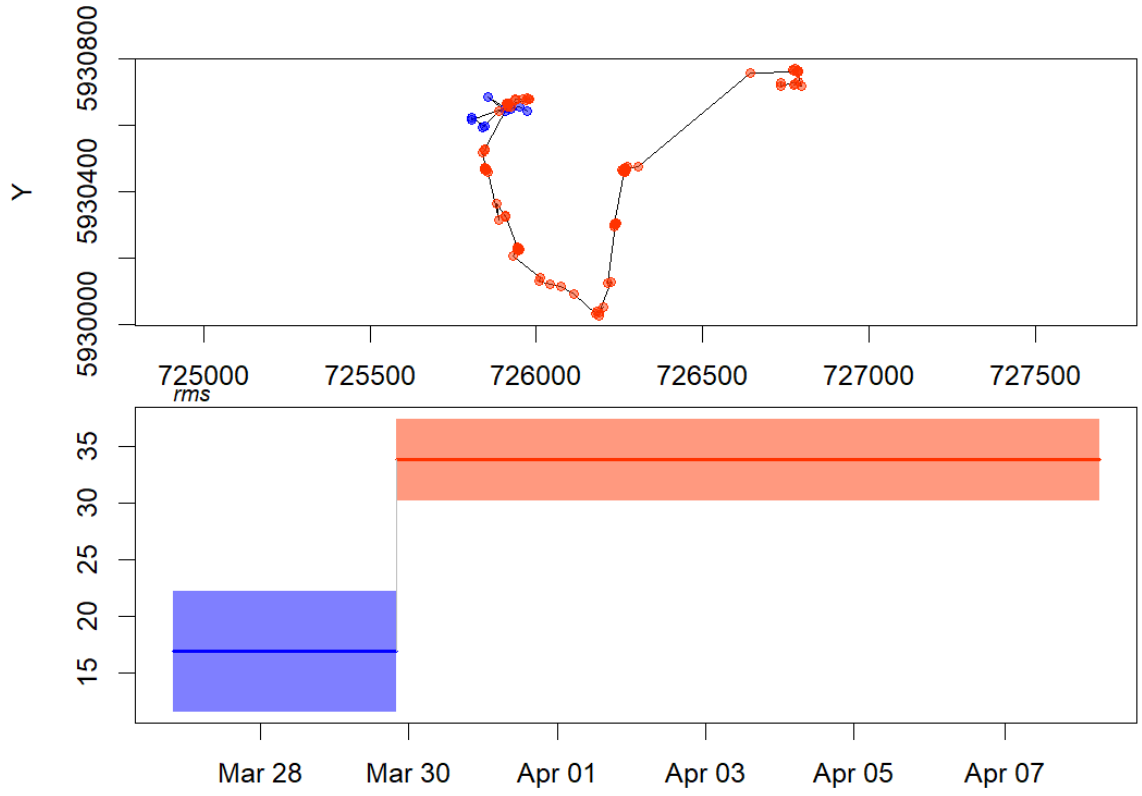


UN53 (Female, 3.5 – 5.5 yrs, Released)

After an initial phase of slow and undirected movement in the first three days after release, UN53 began a rapid journey south (~ 1000 m over four nights), then north (~440 m over two nights) and finally north-east (~650 m in a single night). This second phase was characterised by both moderate speeds (RMS: 33.78 m/hr) and motion persistence (Tau: 1.04 hrs) (Table 8).

Table 8. Estimated movement phases of koala UN53 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	26/3	29/3	3	UCVM	0.02	16.90
2	29/3	8/4	10	UCVM	1.04	33.78

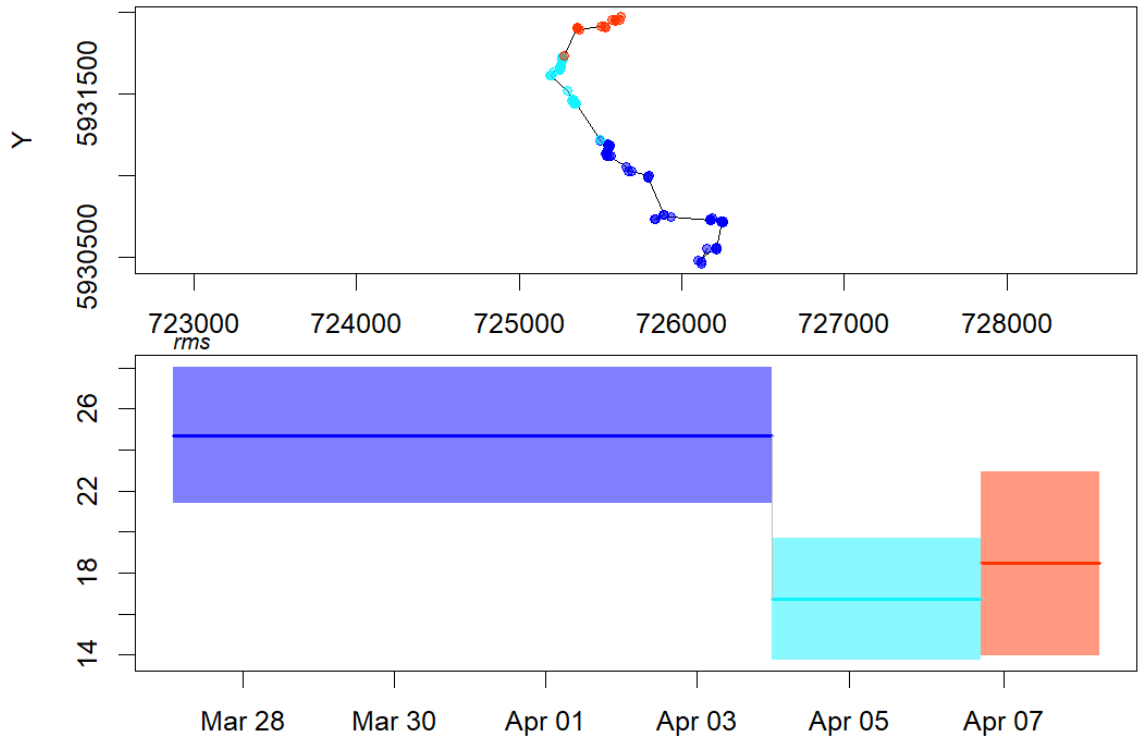


UN73 (Male, 3.5 – 5.5 yrs, Released)

The first phase of UN73's movement process was characterised by diffuse movements of a moderate speed (RMS: 24.72 m/hr) and short-term directional persistence in movements (Tau: 0.61 hours) (Table 9). Beginning on the 3rd of April and continuing until recapture, UN73 exhibited slower speeds (RMS: 16.72 and 18.46 m/hr for phase 2 and 3 respectively) and more stuttered movement (Tau: 0.00 hours) until he was recaptured and removed from the study region.

Table 9. Estimated movement phases of koala UN73 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	27/3	3/4	6	UCVM	0.61	24.72
2	3/4	6/4	3	UCVM	0.00	16.72
3	6/4	8/4	2	UCVM	0.00	18.46

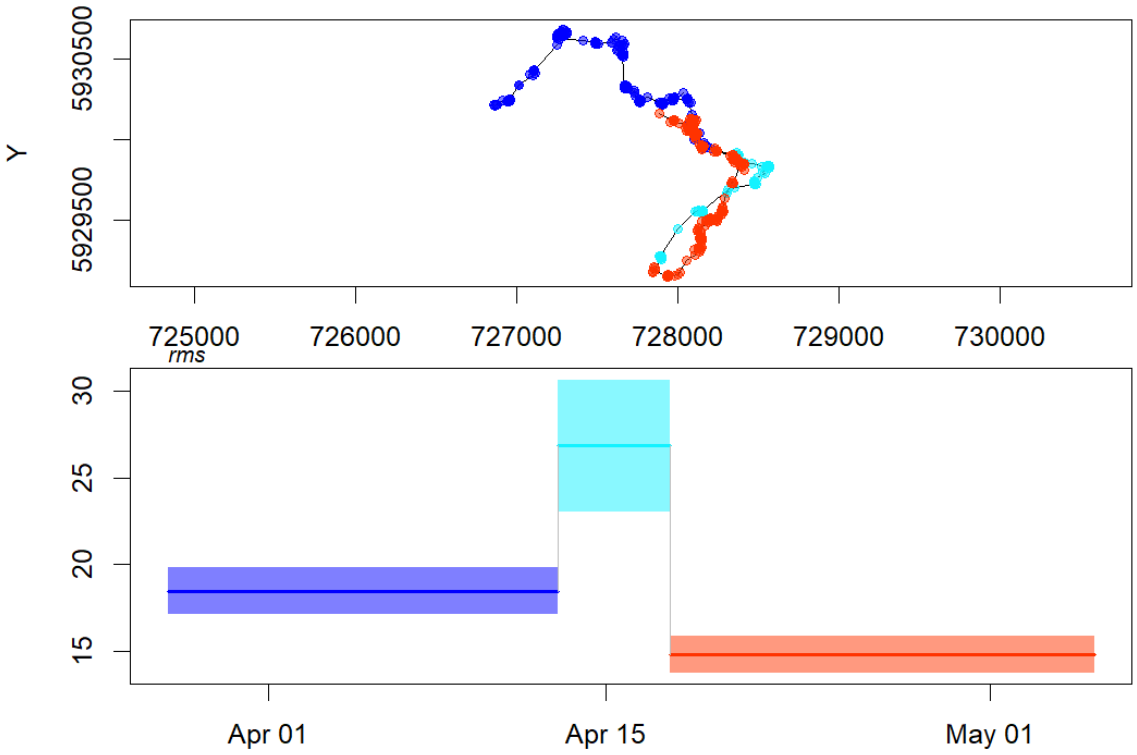


UN77 (Female, 5.5 – 6.5 yrs, Deceased)

The first phase of UN77's movement process was characterised by slow-moderate movement speeds (RMS: 18.46 m/hr) and moderate motion persistence (Tau: 0.44 hours) for seventeen days (Table 10). Beginning on 13 April, she then made more directed (Tau: 1.31 hours) and faster movements (26.83 m/hr) for four days moving north-east. After this brief phase, she then reverted to similar movement behaviour as she displayed post-release for the final 18 days of her collar deployment. That is, slow-moderate speeds (RMS: 14.78 m/hr) albeit with little persistence in motion (Tau: 0.00 hours). She was observed sitting unusually low in a tree during routine tracking on 5 May, recaptured and transferred to care and eventually found dead in her enclosure on 14 May.

Table 10. Estimated movement phases of koala UN77 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	27/3	13/4	17	UCVM	0.44	18.46
2	13/4	17/4	4	UCVM	1.31	26.83
3	17/4	5/5	18	UCVM	0.00	14.78

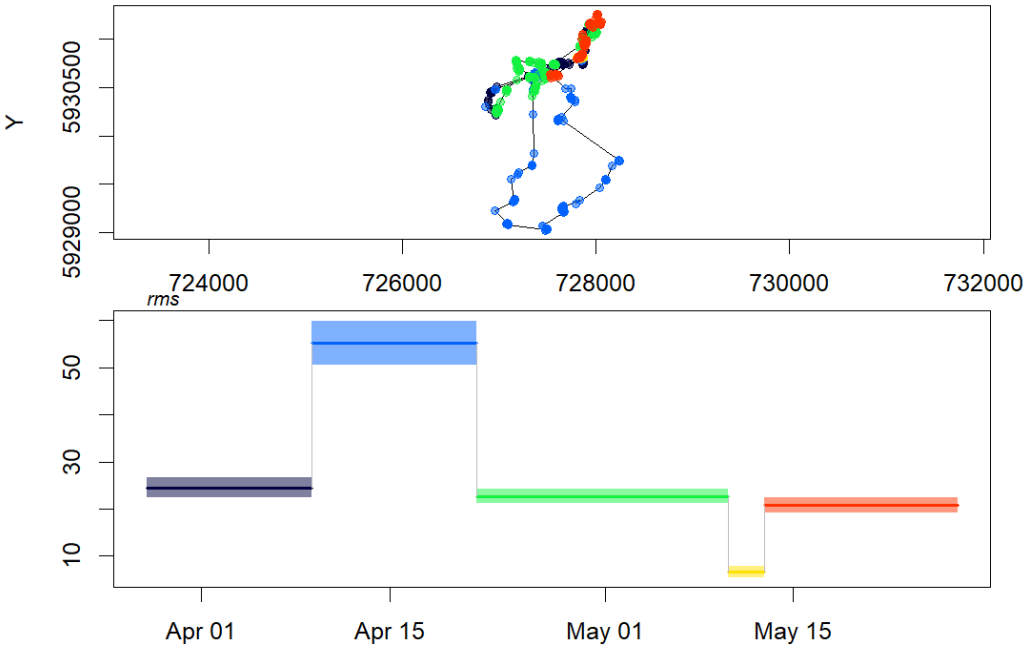


UN81 (Female, 1.25 – 3.5 yrs, Released)

The initial phase of UN81's movement behaviour was characterised by moderate speeds (24.51 m/hr) and moderate directional persistence in motion (Tau: 0.90 hours) and was maintained for 12 days after release post-translocation (Table 11). Beginning on 9 April, she then made a looping journey south, moving twice as fast as her initial phase (RMS: 55.29 m/hr) with stuttered and irregular directional persistence (Tau: 0.00 hours). At the completion of this phase, she returned to the same area she utilised post-release. Her movement behaviour returned to that she displayed during the initial fortnight post-release – moderate speeds and moderate directional persistence (Table 11). This behaviour was largely homogenous for the remainder of her collar deployment with a brief two-day period wherein she was effectively stationary or moved briefly between a small number of trees close to each other (RMS: 6.66 m/hr). She was then recaptured on 27 May, taken to care and then eventually released back to her source location in the Upper Nepean SCA on 8 June.

Table 11. Estimated movement phases of koala UN81 as predicted by behavioural change point analysis and fitted CVM models. Days = the length (in days) of the movement phase; Model = the type of CVM that best describes the movement phase (UCVM or ACVM); Tau = the timescale over which velocity is maintained (in hours); RMS = the root mean squared speed of the movement process (in meters/hour).

Phase	Start	End	Days	Model	Tau	RMS
1	27/3	9/4	13	UCVM	0.90	24.51
2	9/4	21/4	12	UCVM	0.00	55.29
3	21/4	10/5	19	UCVM	0.92	22.67
4	10/5	12/5	2	UCVM	0.00	6.66
5	12/5	27/5	15	UCVM	0.69	20.77



Sliding window analysis of koala diffusion rates

There was sufficient data to estimate mean diffusion rate within 5-day windows for 12 of the 13 translocated koalas. Translocated koalas exhibited considerable individual variation in the temporal dynamics of their diffusion rates following release (Figure 1). Several koalas displayed pronounced peaks in diffusion rates at different time periods during their tracking periods. For example, UN21 maintained relatively low diffusion rates (< 2 ha/day) for approximately two weeks post-release before exhibiting a sharp peak in diffusion rates to approximately 15 ha/day around mid-March, followed by a rapid decline back to baseline levels. Indeed, several translocated animals released in the first cohort displayed similar spikes in movement during the same time, albeit with some degree of differences in the timing of these peaks.

The sliding window analysis revealed no consistent temporal pattern of diffusion rates shared across all individuals. In contrast to the initial expectation that translocated koalas might uniformly exhibit initial exploratory movements (high diffusion) followed by a progressive decline in daily diffusion rates to relatively stable movements as animals became more familiar with their environment, translocated koalas displayed idiosyncratic trajectories. Some individuals showed early peaks in diffusion rates (UN32, UN42); others displayed delayed increases (UN21, UN47, UN83), while others exhibited relatively stable or gradually changing patterns throughout their tracking periods (UN53, UN73). This heterogeneity in post-translocation movement dynamics suggests that factors such as physiological condition, age, habitat quality, or personality traits may play important roles in driving post-release movement behaviour.

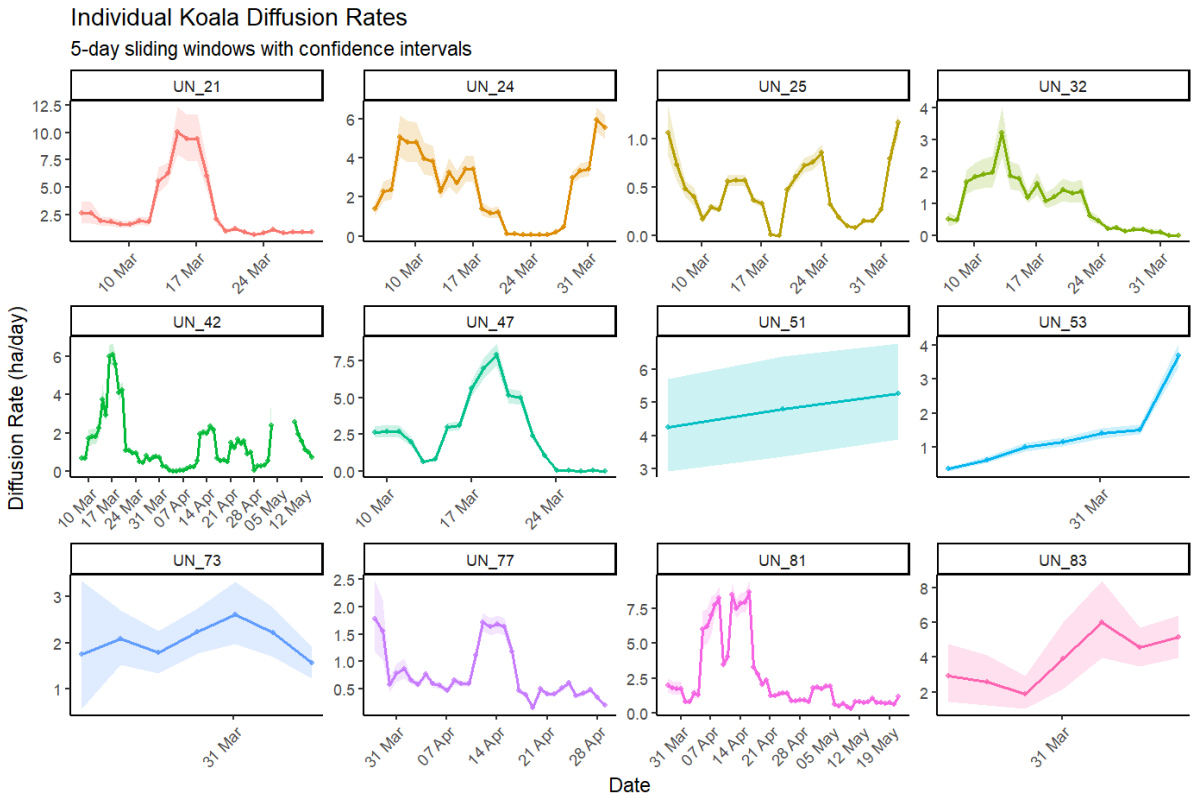


Figure 1. Temporal dynamics of diffusion rates for translocated koalas estimated by sliding window analysis. Each panel shows diffusion rates (hectares/day) for individual koalas, estimated from 5-day sliding windows advanced at 1-day increments throughout the tracking period. Solid lines represent point estimates and shaded ribbons indicate 95% confidence intervals. Note that the vertical axis scales differ among individuals to emphasise within-individual temporal patterns. Koalas displayed highly variable post-translocation diffusion trajectories, with some individuals exhibiting distinct peaks in movement intensity (e.g. UN21, UN42, UN47), while others showed more sustained or gradually changing patterns (e.g. UN51, UN53, UN73, UN81).

There were six koalas from the source population (UNSCA) with sufficient data during the study period (March – May 2025) to estimate diffusion rates for comparative purposes: five females and one male (SW-STL-035). Similar to the translocated koalas, temporal patterns in diffusion rate were highly variable through time (Figure 2) with both extended periods of little to no movement (e.g. SW-STL-035, SW-STL-049, SW-STL-050) and short-term spikes in diffusion rate (e.g. SW-STL-042, SW-STL-048) observed. All koalas survived their entire GPS-collar deployments (May 2024 – May 2025).

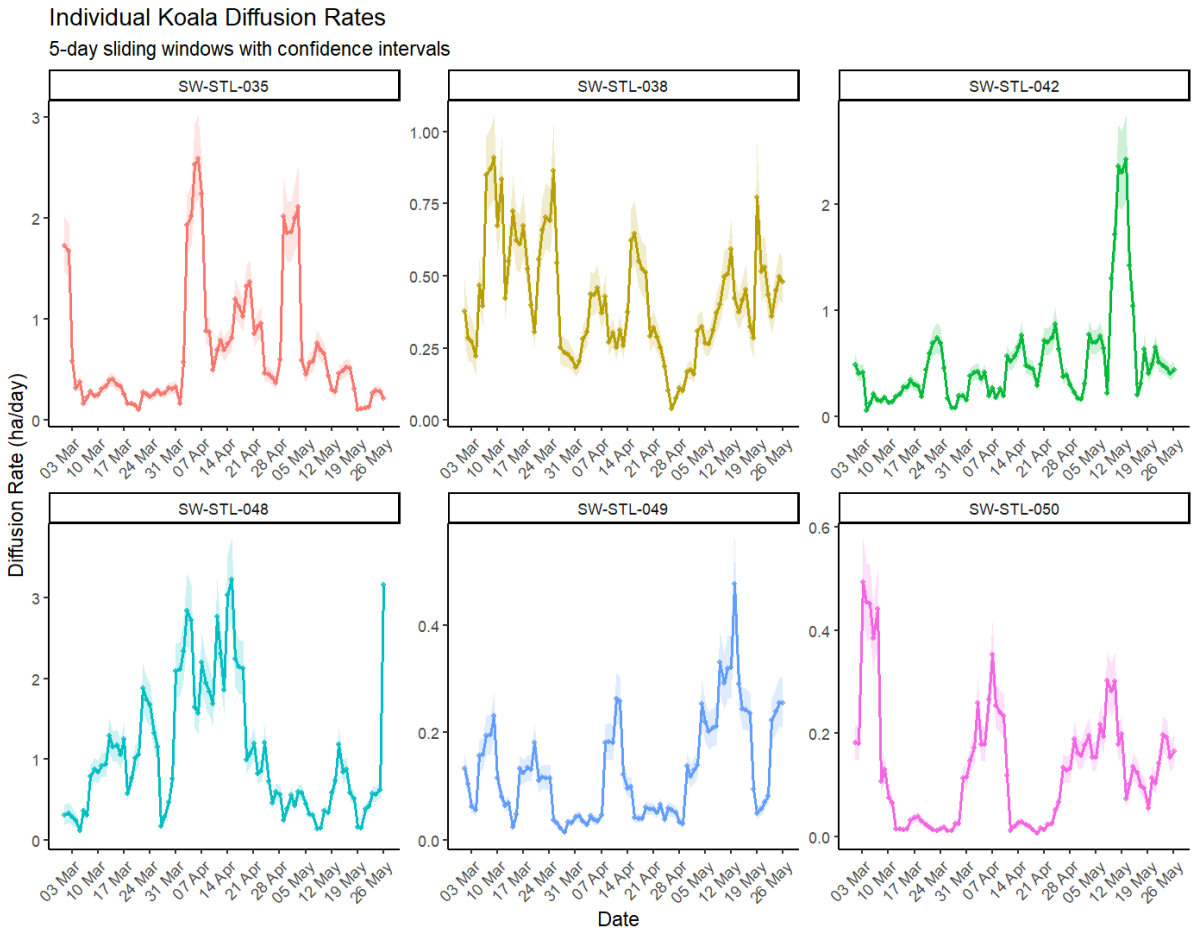


Figure 2. Temporal dynamics of diffusion rates for UNSCA koalas estimated by sliding window analysis. Each panel shows diffusion rates (hectares/day) for individual koalas, estimated from 5-day sliding windows advanced at 1-day increments throughout the tracking period. Solid lines represent point estimates and shaded ribbons indicate 95% confidence intervals. Note that the vertical axis scales differ among individuals to emphasise within-individual temporal patterns. All koalas are females except for SW-STL-035.

Discussion

Both the behavioural change point analysis and sliding window diffusion estimates revealed substantial individual variation in post-translocation movement patterns, with little evidence of a consistent temporal trajectory shared across the cohort. While some koalas exhibited discrete behavioural transitions that could be interpreted as phases of exploration followed by settlement (e.g. UN32, UN81), others displayed erratic or fluctuating patterns throughout their tracking periods (e.g. UN24, UN25), and several individuals showed sustained moderate movement rates without clear evidence of stabilisation (e.g. UN53, UN73). This heterogeneity suggests that both intrinsic (individual traits) and extrinsic (environmental factors) may be influential in the movement behaviour of koalas post-translocation. Importantly, this same temporal heterogeneity in diffusion rates was observed in range-resident koalas from the source population (UNSCA – Figure 2) and has been observed in other koala populations monitored throughout NSW as part of the Sentinel program (Le Pla *et al.* Unpublished data). Consequently, population-level generalisations about “typical” post-translocation movement behaviours or timeframes for settlement may be inappropriate for koalas, and management approaches that rely on rigid time-based monitoring schedules (e.g. assuming animals are settled after a predetermined time period) can risk mischaracterising individual outcomes.

Critically, neither analytical approach provided clear early-warning indicators that could have reliably identified animals requiring intervention or in declining health prior to mortality. Several koalas that ultimately died in-situ or required euthanasia (e.g. UN21, UN47, UN77) maintained moderate diffusion rates and exhibited no dramatic changes in movement behaviour in the days immediately preceding their decline. Conversely, some animals that displayed apparent systemic declines in movement rate after a brief period of exploratory movements that one may think is indicative of declining health or welfare status (e.g. UN32 and UN81) were recaptured with relatively minor loss in body weight and were successfully released back into the source location. Similarly, most koalas from the source population who were GPS tracked during the study period exhibited extended periods of little to no movement interspersed by infrequent bouts of more moderate movements (Figure 2). This finding challenges the assumption that movement-based metrics (e.g. low movements for several days) alone can serve as sensitive welfare indicators for translocated koalas.

This apparent insensitivity may be partially attributable to the fundamental movement ecology of koalas, which naturally involves extended periods of inactivity interspersed with relatively brief movement bouts. Whilst relatively frequent by GPS telemetry standards, the two-hourly fix schedule of GPS collars used in this translocation is likely too coarse to adequately characterise the short-duration movement bouts typical of koala behaviour (e.g. Marsh *et al.* 2014). Indeed, recent analysis of a state-wide koala GPS telemetry dataset indicates that GPS fix schedules of half-hourly to hourly are required to adequately resolve velocity in koala movements (Le Pla *et al.* unpublished data). Consequently, distinguishing between “normal” sedentary behaviour and pathological inactivity associated with declining health requires either very high-resolution data that can better characterise fine-scale activity patterns, or the integration of movement data with other remotely-sensed physiological or activity indicators (e.g. accelerometers).

A significant rainfall event during the study period (late March) may have temporarily suppressed koala movements. However, there was little evidence that this resulted in consistent and fundamental changes to the movement process or diffusion rate of translocated koalas. Whilst koala movements were generally low during this time, many individuals had similar low movements during more benign conditions wherein wind and rain was not a factor (e.g.UN21, UN25, UN42) or were already moving little in the days prior to the weather event occurred (e.g. UN24, UN32) (Figure 1). Directly attributing this weather event to koala movement patterns is challenging due to the small sample sizes of koala locations on any given day (~ 12 at best) and the scale at which koala movements likely respond to such a stochastic event (minutes – hours). As a moving window of 5-days was used in both the behavioural change point analysis and diffusion rate estimation, estimates of movement properties (e.g. RMS or diffusion rate) from these approaches represent an average across the entire window. Consequently, whilst there was little evidence that sustained periods of high rainfall and wind suppressed koala movements at this temporal scale, this does not necessarily preclude fine-scale suppression of movement and feeding behaviour that may have further challenged translocated koalas

The limitations of movement-based monitoring must be acknowledged in the broader context of translocation welfare assessment. In this program, the translocation team implemented frequent on-ground visual assessments of koalas through the post-release period, yet these field observations alongside frequent assessment of real-time movement data still failed to reliably identify animals in decline prior to mortality or critical intervention points. Translocated koalas were confirmed to be feeding and did not display overtly obvious visual indicators of body condition loss during field observations preceding their decline. This outcome highlights a fundamental challenge in koala welfare assessment: the species’ cryptic nature, relatively subtle external indicators of declining health, and capacity to maintain apparently normal behaviours (including feeding and movement) even when physiologically compromised can combine to make accurate welfare assessment of koalas without physically capturing animals immensely challenging.

These findings have important implications for the design of future translocation monitoring programs utilising GPS telemetry. The high individual variation in post-translocation movement trajectories suggest that monitoring protocols should emphasise individual-level tracking with adaptive intervention criteria that account for both recent movement patterns and other welfare indicators. While broad-scale movement patterns may lack sensitivity as welfare indicators, certain specific movement patterns may nonetheless warrant heightened scrutiny. For instance, sustained directed nightly movements of 300-400 m or more for multiple consecutive evenings are likely to incur significant energetic costs for koalas, particularly if these movements occur in unfamiliar environments that are topographically complex and where knowledge of key resources to capable of replenishing said energetic stores is lacking. Such movement patterns could be used as additional triggers for intensifying monitoring efforts at an individual level.

Future translocation programs aiming to characterise fine-scale movement behaviour of koalas would benefit from GPS collars with a higher fix-rate (e.g. 15–30-minute intervals) despite the associated trade-offs in battery longevity and data storage. This finer temporal resolution would be better matched to the episodic nature of koala movement behaviour and allow for additional analytical approaches that can discern distinct behavioural states that may be informative for dynamic welfare assessment of translocated koalas (e.g. Hidden Markov Model behavioural state assignment, McClintock and Michelot, 2018). Whilst a reduced GPS battery life would preclude the collection of location information at a high frequency over longer time scales, this limitation would not necessarily compromise objectives such as a home range estimation and survival due to the highly autocorrelated nature of koala movement data (Le Pla *et al.* In prep). Indeed, combining short-medium term GPS tracking with monitoring approaches that still allow for the infrequent collection of location information (e.g. VHF tracking) over a longer period would allow both short-term and long-term monitoring objectives to be met.

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