

Supplement to: Movement Tools (amt): R Package for Managing Tracking Data and Conducting Habitat Selection Analyses

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Supplement S1

Source code to reproduce the two examples.

Example 1: One animal

```
library(raster)
library(lubridate)
library(amt)
library(tidyverse)
set.seed(123)

dat <- read_csv("data/Martes pennanti LaPoint New York.csv") %>%
  filter(!is.na('location-lat')) %>%
  select(x = 'location-long', y = 'location-lat',
         t = 'timestamp', id = 'tag-local-identifier') %>%
  filter(id %in% c(1465, 1466, 1072, 1078, 1016, 1469)) # for example 2
dat_1 <- dat %>% filter(id == 1016)

dat_1 <- amt::make_track(dat_1, x, y, t, crs = sp::CRS("+init=epsg:4326")) %>%
  amt::transform_coords(sp::CRS("+init=epsg:5070"))

summarize_sampling_rate(dat_1)

stps <- amt::track_resample(dat_1, rate = minutes(10), tolerance = minutes(1)) %>%
  filter_min_n_burst(min_n = 3) %>% steps_by_burst() %>%
  time_of_day(include.crepuscule = FALSE)

str(stps, width = 80, strict.width = "no", nchar.max = 80, give.attr = FALSE)
```

```

35
36
37 land_use <- raster("data/landuse_study_area.tif")
38 wet <- land_use == 90
39 names(wet) <- "wet"
40
41 eda1 <- stps %>% extract_covariates(wet, where = "start") %>%
42   mutate(landuse = factor(wet, levels = c(0, 1), labels = c("other", "forested wetland")))
43
44 # Plot 1 -----
45
46 p1 <- eda1 %>% select(landuse, tod = tod_end_, sl_, ta_) %>%
47   gather(key, val, -landuse, -tod) %>%
48   filter(key == "sl_") %>%
49   ggplot(., aes(val, group = tod, fill = tod)) + geom_density(alpha = 0.5) +
50   facet_wrap(~ landuse, nrow = 2) +
51   xlab("Step length [m]") + theme_light() +
52   ylab("Density") +
53   theme(legend.title = element_blank())
54
55 p2 <- eda1 %>% select(landuse, tod = tod_end_, sl_, ta_) %>%
56   gather(key, val, -landuse, -tod) %>%
57   filter(key == "ta_") %>%
58   ggplot(., aes(val, group = tod, fill = tod)) + geom_density(alpha = 0.5) +
59   facet_wrap(~ landuse, nrow = 2) +
60   xlab("Turn angle") + theme_light() +
61   theme(legend.title = element_blank(),
62         axis.title.y = element_blank())
63
64 library(cowplot)
65 pg1 <- plot_grid(
66   p1 + theme(legend.position = "none"),
67   p2 + theme(legend.position = "none"), rel_widths = c(1, 1)
68 )
69
70 leg <- get_legend(p1)
71 plot_grid(pg1, leg, rel_widths = c(1, 0.1))
72
73 ggsave("fig_eda_1_animal.pdf", width = 20, height = 18, units = "cm")
74
75 #####
76
77 # fit the model
78 m1 <- stps %>% amt::random_steps(n = 9) %>%
79   amt::extract_covariates(wet) %>%
80   amt::time_of_day(include.crepuscule = FALSE) %>%
81   mutate(log_sl_ = log(sl_)) -> d1
82
83 m1 <- d1 %>% amt::fit_issf(case_ ~ wet + sl_ + wet:tod_end_ + sl_:tod_end_ + strata(step_id_))
84 m1 <- d1 %>% amt::fit_issf(case_ ~ wet + log_sl_ + wet:tod_end_ + log_sl_:tod_end_ + strata(step_id_))
85 m1 <- d1 %>% amt::fit_issf(case_ ~ wet + log_sl_ + sl_ + wet:tod_end_ + log_sl_:tod_end_ + sl_:tod_end_ + strata(s
86
87 AIC(m1$model)
88 summary(m1)
89
90 s <- summary(m1$model)$coefficients

```

```

91 s
92 print(xtable::xtable(s, digits = 4,
93                       type = "latex",
94                       caption.placement = "top"))
95
96 shape <- sl_shape(m1)
97 scale <- sl_scale(m1)
98
99 shape_adj_day <- amt::adjust_shape(shape, coef(m1)["log_sl_"])
100 shape_adj_night <- amt::adjust_shape(shape, coef(m1)["log_sl_"] +
101   coef(m1)["log_sl_:tod_end_night"])
102
103 scale_adj_day <- amt::adjust_scale(scale, coef(m1)["sl_"])
104 scale_adj_night <- amt::adjust_scale(scale, coef(m1)["sl_"] +
105   coef(m1)["sl_:tod_end_night"])
106
107 # speed
108 speed_day <- shape * scale_adj_day
109 speed_night <- shape * scale_adj_night
110
111 speed_day <- shape_adj_day * scale
112 speed_night <- shape_adj_night * scale
113
114 speed_day <- shape_adj_day * scale_adj_day
115 speed_night <- shape_adj_night * scale_adj_night
116
117 scale
118 shape
119
120 shape_adj_day
121 shape_adj_night
122
123 x <- seq(1, 500, 1)
124 plot(x, dgamma(x, shape = shape_adj_night, scale = scale_adj_night), type = "l")
125 lines(x, dgamma(x, shape = shape_adj_day, scale = scale_adj_day), type = "l")
126
127
128 # Bootstrap everything
129 mod_data <- stps %>% amt::random_steps(n = 9) %>%
130   amt::extract_covariates(wet, where = "end") %>%
131   amt::time_of_day(include.crepuscule = FALSE) %>%
132   mutate(log_sl_ = log(sl_), cos_ta_ = cos(as_rad(ta_)))
133
134 strata <- unique(mod_data$step_id_)
135 n <- length(strata)
136
137 bt <- replicate(1000, {
138   m_boot <- mod_data[mod_data$step_id_ %in% sample(strata, n, TRUE), ] %>%
139     amt::fit_clogit(case_ ~ wet + log_sl_ + sl_ + wet:tod_end_ +
140       sl_:tod_end_ + log_sl_:tod_end_ + strata(step_id_))
141
142   scale_adj_day <- amt::adjust_scale(shape, coef(m_boot)["sl_"])
143   scale_adj_night <- amt::adjust_scale(shape, coef(m_boot)["sl_"] +
144     coef(m_boot)["sl_:tod_end_night"])
145
146   shape_adj_day <- amt::adjust_shape(shape, coef(m_boot)["log_sl_"])

```

```

147   shape_adj_night <- amt::adjust_shape(shape, coef(m_boot)["log_sl_"] +
148     coef(m_boot)["log_sl_:tod_end_night"])
149
150   ## speed
151   c(shape_adj_day * scale_adj_day,
152     shape_adj_night * scale_adj_night)
153 })
154
155 bt2 <- data_frame(
156   rep = 1:ncol(bt),
157   day = bt[1, ],
158   night = bt[2, ]
159 ) %>% gather(key, val, -rep)
160
161
162 bt2 %>% group_by(key) %>% summarise(lq = quantile(val, 0.025),
163                                     me = median(val),
164                                     mean = mean(val),
165                                     uq = quantile(val, 0.975))
166
167 # m/min
168 bt2 %>% group_by(key) %>% summarise(lq = quantile(val, 0.025) / 10,
169                                     me = median(val) / 10,
170                                     mean = mean(val) / 10,
171                                     uq = quantile(val, 0.975) / 10)
172
173 ## Simulate ud
174 wet_c <- crop(wet, amt::bbox(dat_1, spatial = TRUE, buff = 1e3))
175
176 mk <- amt::movement_kernel(scale, shape_adj_day, wet_c)
177 hk <- amt::habitat_kernel(list(wet = coef(m1)["wet"]), wet_c)
178
179
180 system.time(ssud_day <- amt::simulate_ud(
181   mk, hk,
182   as.numeric(stps[1, c("x1_", "y1_")]),
183   n = 1e7))
184 plot(ssud_day)
185
186 system.time(tud_day <- amt::simulate_tud(mk, hk, as.numeric(stps[1501, c("x1_", "y1_")]), n = 72, n_rep = 5e3))
187 plot(tud_day)
188
189
190 # night
191 mk <- amt::movement_kernel(scale, shape_adj_night, wet_c)
192 hk <- amt::habitat_kernel(list(wet = coef(m1)["wet"] +
193                               coef(m1)["wet:tod_end_night"]), wet_c)
194
195 system.time(ssud_night <- amt::simulate_ud(
196   mk, hk, as.numeric(stps[1, c("x1_", "y1_")]), n = 1e7))
197 plot(ssud_night)
198
199 system.time(tud_night <- amt::simulate_tud(mk, hk, as.numeric(stps[1501, c("x1_", "y1_")]), n = 72, n_rep = 5e3))
200 plot(tud_night)
201 plot(tud1 <- crop(tud_day, extent(c(1778000, 1782000, 2412000, 2415000))))
202 plot(tud2 <- crop(tud_night, extent(c(1778000, 1782000, 2412000, 2415000))))

```

```

203
204
205 plog <- list(
206   geom_raster(),
207   coord_equal(),
208   scale_fill_continuous(low = "white", high = "red",
209                         tran = "log10", na.value = "white"),
210   scale_y_continuous(expand = c(0, 0)),
211   scale_x_continuous(expand = c(0, 0)),
212   theme_light(),
213   theme(legend.position = "none"))
214
215 p1 <- list(
216   geom_raster(),
217   coord_equal(),
218   scale_fill_continuous(low = "white", high = "red", na.value = "white"),
219   scale_y_continuous(expand = c(0, 0)),
220   scale_x_continuous(expand = c(0, 0)),
221   theme_light(),
222   theme(legend.position = "none"))
223
224 r1 <- data.frame(rasterToPoints(mk))
225 p1 <- ggplot(r1, aes(x, y, fill = d)) + plog + ggtitle("Movement kernel (night)")
226
227 r2 <- data.frame(rasterToPoints(hk))
228 p2 <- ggplot(r2, aes(x, y, fill = layer)) + p1 + ggtitle("Habitat kernel (night)")
229
230
231 r1 <- data.frame(rasterToPoints(tud1))
232 p3 <- ggplot(r1, aes(x, y, fill = layer)) + plog + ggtitle("Transient UD (day)")
233
234 r2 <- data.frame(rasterToPoints(tud2))
235 p4 <- ggplot(r2, aes(x, y, fill = layer)) + plog + ggtitle("Transient UD (night)")
236
237
238 r1 <- data.frame(rasterToPoints(ssud_day))
239 p5 <- ggplot(r1, aes(x, y, fill = layer)) + p1 + ggtitle("Steady state UD (day)")
240
241 r2 <- data.frame(rasterToPoints(ssud_night))
242 p6 <- ggplot(r2, aes(x, y, fill = layer)) + p1 + ggtitle("Steady state UD (night)")
243
244 cowplot::plot_grid(p1, p2, p3, p5, p4, p6, ncol = 2, labels = "AUTO")
245
246
247
248 ggsave("img/fig_one_animal1.pdf", height = 20, width = 24, units = "cm")

```

249 Example 2: Many animals

```

250 library(ggplot2)
251 library(raster)
252 library(lubridate)
253 library(amt)
254 library(parallel)
255
256

```

```

257 dat <- read_csv("data/Martes pennanti LaPoint New York.csv") %>%
258   filter(!is.na('location-lat')) %>%
259   select(x = 'location-long', y = 'location-lat',
260          t = 'timestamp', id = 'tag-local-identifier') %>%
261   filter(id %in% c(1465, 1466, 1072, 1078, 1016, 1469))
262
263 dat_all <- dat %>% nest(-id)
264 dat_all$sex <- c("f", "f", "f", "m", "m", "m")
265 dat_all <- dat_all %>%
266   mutate(trk = map(data, function(d) {
267     amt::make_track(d, x, y, t, crs = sp::CRS("+init=epsg:4326")) %>%
268     amt::transform_coords(sp::CRS("+init=epsg:5070"))
269   }))
270 dat_all %>% mutate(sr = lapply(trk, summarize_sampling_rate)) %>%
271   select(id, sr) %>% unnest
272
273 land_use <- raster("data/landuse_study_area.tif")
274 rcl <- cbind(c(11, 12, 21:24, 31, 41:43, 51:52, 71:74, 81:82, 90, 95),
275             c(1, 1, 2, 3, 3, 3, 2, 5, 5, 5, 5, 5, 5, 5, 5, 8, 8, 1, 1))
276 # water, dev open, dev, barren, forest, shrub and herb, crops, wetlands
277 # 1: water, wetlands
278 # 2: developed (open)
279 # 3: developed (other)
280 # 5: forest, herbaceous
281 # 8: crops
282 lu <- reclassify(land_use, rcl, right = NA)
283 names(lu) <- "landuse"
284
285 m1 <- dat_all %>%
286   mutate(steps = map(trk, function(x) {
287     x %>% amt::track_resample(rate = minutes(10), tolerance = seconds(120)) %>%
288     amt::filter_min_n_burst() %>%
289     amt::steps_by_burst() %>% amt::random_steps() %>%
290     amt::extract_covariates(lu, where = "both") %>%
291     mutate(landuse_end = factor(landuse_end))
292   }))
293
294
295 m1 <- m1 %>% mutate(fit = map(steps, ~ amt::fit_issf(., case_ ~ landuse_end +
296                                                     strata(step_id))))
297
298
299 d2 <- m1 %>% mutate(coef = map(fit, ~ broom::tidy(.x$model))) %>%
300   select(id, sex, coef) %>% unnest %>%
301   mutate(id = factor(id)) %>% group_by(term) %>%
302   summarize(
303     mean = mean(estimate),
304     ymin = mean - 1.96 * sd(estimate),
305     ymax = mean + 1.96 * sd(estimate)
306   )
307
308 d2$x <- 1:nrow(d2)
309
310
311 p1 <- m1 %>% mutate(coef = map(fit, ~ broom::tidy(.x$model))) %>%
312   select(id, sex, coef) %>% unnest %>%

```

```

313 mutate(id = factor(id)) %>%
314 ggplot(., aes(x = term, y = estimate, group = id, col = id, pch = sex)) +
315 geom_rect(mapping = aes(xmin = x - .4, xmax = x + .4, ymin = ymin,
316                        ymax = ymax), data = d2, inherit.aes = FALSE,
317           fill = "grey90") +
318 geom_segment(mapping = aes(x = x - .4, xend = x + .4,
319                          y = mean, yend = mean), data = d2, inherit.aes = FALSE,
320             size = 1) +
321 geom_pointrange(aes(ymin = conf.low, ymax = conf.high),
322               position = position_dodge(width = 0.7), size = 0.8) +
323 geom_hline(yintercept = 0, lty = 2) +
324 labs(x = "Habitat", y = "Relative Selection Strength") +
325 theme_light() +
326 scale_x_discrete(labels = c("Developed (open)", "Developed (other)", "Natural", "Crops"))
327
328 p1
329
330 ggsave("img/fig_all_animals.pdf", width = 24, height = 12, units = "cm")

```

331 **Supplement S2**

332 The likelihood of the parameters, $\boldsymbol{\beta}$, given the data, \mathbf{X} :

$$L(\boldsymbol{\beta}|\mathbf{X}) = \prod_{i=1}^n \frac{\exp(\text{wet}_i(\beta_1 + \beta_2 \text{tod}_i) + \log_sl_i(\beta_3 + \beta_4 \text{tod}_i))}{\sum_{j=0}^R \exp(\text{wet}_{ij}(\beta_1 + \beta_2 \text{tod}_i) + \log_sl_{ij}(\beta_3 + \beta_4 \text{tod}_i))}$$

333 Where $\beta_1, \beta_2, \beta_3, \beta_4$ are the parameters (the components of $\boldsymbol{\beta}$), whereas tod_i, \log_sl_i
 334 are the covariates for step i (the components of \mathbf{X}). Each step i is coupled with
 335 R random steps; steps that the animal could have taken, but did not. Together
 336 with the observed step ($j = 0$), these random steps comprise the contrast set in the
 337 denominator.