

## Supporting Information (SI): Characterization of Movement Phenomena in Light of the Conceptual Framework

We analyzed 32 sets of answers to a questionnaire (Table S1) distributed among authors of the Special Feature and their students, each of whom independently evaluated the relevance of 23 *mechanistic attributes*, representing the four components of the proposed theoretical framework for each of eight *movement phenomena* that have often been described in the literature (foraging, dispersal by animals, dispersal by plants, one-way migration, two-way migration, irruption, nomadism and accidental displacement). In a second part of the questionnaire, the authors were asked to evaluate the relevance of 14 *pattern attributes*, representing general patterns of movement in space and time for each of the movement phenomenon. All attributes and phenomena are defined and illustrated in Table S1.

The relevance of each attribute for each movement phenomenon was expressed by a score ranging from 0 (not relevant) to 4 (highly relevant). The results revealed highly diverse opinions concerning the relevance of both the mechanistic and the pattern attributes to the selected movement phenomena (Table S2). The diversity of opinions, quantified by the complement of Simpson's index (1-D; the probability that two randomly-chosen authors provided a different answer to a specific question) was  $0.66 \pm 0.11$  (mean  $\pm$  SD) for questions about relationships between movement phenomena and mechanistic attributes, and  $0.68 \pm 0.11$  for movement phenomena and pattern attributes, with a range of 0.18-0.82 in both cases. This diversity of opinion might reflect ambiguous definition of some attributes and/or variation among authors in their knowledge and experience with different movement types.

Nevertheless, a principal component analysis (PCA) performed on the mean ranks of the mechanistic attributes and pattern attributes (Table S3) revealed clear patterns of relationships among the eight movement phenomena and between movement phenomena and the two types of attributes (Fig. S1, Fig. S2). We highlighted some relationships among movement phenomena in the main text of the manuscript, and here we summarize the relationships found between movement phenomena and the attributes.

The first and second axes of a PCA biplot of the mechanistic attributes explained 61% and 16% of the total variance, respectively (Fig. S1). Axis 1 distinguished accidental displacement and plant dispersal associated with passive motion and lack of particular motivation, from foraging and two-way migration associated with active motion guided either by gradient cues in search for local resources to gain energy (foraging) or by global cues in search of seasonal remote resources (two-way migration). Axis 2 further distinguished two-way migration associated with the use of genetically-coded memory to seek safety or reproduce, from nomadism and foraging associated with elements of pure search for ephemeral resources. Irruption, dispersal of animals and one-way migration were not strongly distinguished by the first two axes.

The first and second axes of a PCA biplot of the pattern attributes explained 44% and 31% of the total variance, respectively (Fig. S2). Here, axis 1 distinguished two-way migration (and to a lesser extent one-way migration), interpreted as an annual activity, in which individual organisms move rapidly along relatively straight lines and across large distances, from foraging, interpreted as a diel activity in which organisms exhibit high velocity variance in movements confined to the breeding habitat. Axis 2 highlights commonalties between two-way migration and foraging, based on similar roundtrip patterns, intermittency (foraging) and consistent use of the same track (two-way migration), both distinguished from accidental displacement, characterized as an uncommon activity completed within a single generation. Nomadism, irruption, dispersal of plant and animals were not strongly distinguished by the first two axes.

**Table S1:** Definitions of mechanistic and pattern attributes of eight movement phenomena. To assess the relevance of each attribute to each movement phenomenon, authors were asked to mark if the statements defined below can be considered always true (4), usually true (3), sometimes true (2), rarely true (1) or always false (0).

| <b>Table S1: mechanistic attributes</b> |                              |  |
|---|------------------------------|--|
| <b>Component</b>                        | <b>Mechanistic attribute</b> | <b>Statement definition</b>  |
| internal                                | no motivation                | this type of movement is not driven by any internal motivation   |
| internal                                | energy                       | this type of movement is driven mostly to gain energy  |
| internal                                | safety                       | this type of movement is driven mostly to gain safety (moving from high to low risk areas)   |
| internal                                | learning                     | this type of movement is driven mostly to gain experience and learn  |
| internal                                | reproduction                 | this type of movement is driven mostly to reproduce or related activities such as care of young, etc.  |
| motion                                  | passive                      | commonly involves passive (vector-mediated) transport  |
| motion                                  | active                       | commonly involves active (self-propelled) motion   |
| motion                                  | ground (walk, run, etc.)     | commonly involves organisms that are being transported, walk, run, etc on the ground   |
| motion                                  | air (fly, glid, etc.)        | commonly involves organisms that are being transported, fly, glide, etc on air   |
| motion                                  | water (swim, sail, etc.)     | commonly involves organisms that are being transported, swim, float etc on water   |
| navigation                              | pure search                  | commonly involves pure search (no previous information, no cues)   |
| navigation                              | direct recognition of target | commonly involves direct recognition of the target   |
| navigation                              | gradient cues                | commonly involves the use of gradient cues (e.g., chemical gradient, resources density gradient, etc)  |
| navigation                              | global cues                  | commonly involves the use of global cues (e.g. geomagnetic field, sun, stars, etc)   |
| navigation                              | learned spatial memory       | commonly involves learning of explicit locations   |
| navigation                              | genetically-coded memory     | commonly involves movements that can only be explained by some genetically-coded information   |
| navigation                              | cue-free navigation          | commonly involves cue-free navigation (e.g. path integration) NOTE: THIS VARIABLE WAS EXCLUDED FROM ANALYSIS BECAUSE THIS EXPLANATION WAS UNCLEAR TO MANY AUTHORS. |
| external                                | local resources              | movement is strongly affected by local (same habitat or home range) resources (energy, shelter, mates)   |
| external                                | remote resources             | movement is strongly affected by remote (other habitat/region or outside home range) resources   |
| external                                | seasonal resources           | movement is strongly affected by predictable seasonal variation in resource quality/availability   |
| external                                | ephemeral resources          | movement is strongly affected by unpredictable interannual variation in resource quality/availability  |
| external                                | conspecifics                 | movement is strongly affected by conspecifics (including positive and negative effects)  |
| external                                | competitors                  | movement is strongly affected by interspecific competitors   |
| external                                | predators                    | movement is strongly affected by predators   |

**Table S1 (continued): pattern attributes**

| <b>Component</b> | <b>(b) Pattern attribute</b> | <b>Statement definition</b>   |
|------------------|------------------------------|---|
| movement         | one generation               | completed within one generation; ; may or may not be repeated in the next generations                         |
| movement         | diel                         | completed within one day (or less); may or may not be repeated in the following days                          |
| movement         | seasonal                     | completed approximately within one season; may or may not be repeated in the following seasons                |
| movement         | annual                       | completed approximately within one year; may or may not be repeated in the following years                    |
| movement         | common (re lifetime track)   | covers a significant proportion (in terms of length) of the organism lifetime track                           |
| movement         | breeding home range          | occurs mostly within a relatively restricted area (local habitat, home range) in which the organism reproduce |
| movement         | large-scale                  | occurs mostly within a relatively large (continental, global) much larger than the breeding home range        |
| movement         | return (round-trip)          | typically a round-trip movement   |
| movement         | track use consistency        | the organism typically follows the same track each movement event   |
| movement         | ceases in target encounter   | ceases when the organism encounter a target that fulfills its movement goal                                   |
| movement         | Intermittency                | involves continuous (short/long) moves, typically interrupted (for various reasons), thus includes many stops |
| movement         | path straightness            | movement is highly directional  |
| movement         | high mean velocity           | typical velocity is faster than that of most other types of movement the organism performs                    |
| movement         | high velocity variance       | typical velocity is more variable compared to most other types of movement the organism performs              |

**Table S1: examples of movement phenomena**

| <b>Movement phenomenon</b> | <b>Examples</b>  |
|----------------------------|--|
| Foraging                   | ant trails, vulture search for carrion, cheetah hunting  |
| Dispersal (plants)         | dandelion seeds by wind, fruits by frugivores  |
| Dispersal (animals)        | breeding and natal dispersal in birds and mammals  |
| One-way migration          | aphids, ballooning spiders and many other insects, marine larvae   |
| Two-way migration          | the relatively large-scale movements of arctic terns, sea turtles and monarch butterflies (but not vertical migration of plankton) |
| Irruption                  | the irregular movements of lemmings, migratory locusts and crossbills  |
| Nomadism                   | the relatively prolonged movement of wildebeest, blind army ants, polar bears, some kangaroos                                      |
| Accidental displacement    | vagrant/accidental birds   |

**Table S2.** Diversity of opinions on the relevance of mechanistic and pattern attributes for eight movement phenomena (columns), estimated by the complement of Simpson's index (1-D; the probability that two randomly-chosen authors will provide a different answer). For each column, the highest (greatest divergence) and the lowest (greatest consensus) values are highlighted in *bold italics* and underline, respectively.

| <b>Table S2: mechanistic attributes</b> |  |                 |                               |                                |                              |                              |                  |                 |                                    |
|---|--|-----------------|-------------------------------|--------------------------------|------------------------------|------------------------------|------------------|-----------------|------------------------------------|
| <b>Component</b>                        | <b>Movement phenomenon<br/>Mechanistic attribute</b> | <b>Foraging</b> | <b>Dispersal<br/>(plants)</b> | <b>Dispersal<br/>(animals)</b> | <b>One-way<br/>migration</b> | <b>Two-way<br/>migration</b> | <b>Irruption</b> | <b>Nomadism</b> | <b>Accidental<br/>displacement</b> |
| internal                                | no motivation  | <u>0.23</u>     | 0.75                          | 0.52                           | <u>0.52</u>                  | <u>0.40</u>                  | 0.56             | 0.58            | 0.65                               |
| internal                                | energy   | 0.39            | 0.73                          | 0.72                           | 0.69                         | 0.73                         | 0.77             | 0.68            | 0.64                               |
| internal                                | safety   | 0.71            | 0.77                          | 0.66                           | 0.70                         | 0.76                         | 0.73             | 0.62            | 0.61                               |
| internal                                | learning   | <b>0.77</b>     | <u>0.18</u>                   | 0.75                           | 0.66                         | 0.80                         | 0.57             | 0.74            | 0.50                               |
| internal                                | reproduction   | 0.74            | 0.72                          | 0.73                           | 0.70                         | 0.65                         | 0.78             | 0.66            | 0.42                               |
| motion                                  | passive  | 0.57            | 0.63                          | <u>0.50</u>                    | 0.68                         | 0.50                         | 0.64             | 0.62            | 0.71                               |
| motion                                  | active   | 0.58            | 0.57                          | 0.54                           | 0.75                         | 0.67                         | 0.70             | 0.70            | 0.71                               |
| motion                                  | ground (walk, run, etc.)                             | 0.59            | 0.73                          | 0.66                           | 0.66                         | 0.56                         | 0.57             | 0.61            | 0.68                               |
| motion                                  | air (fly, glid, etc.)                                | 0.54            | 0.64                          | 0.62                           | 0.61                         | 0.62                         | 0.55             | 0.59            | 0.67                               |
| motion                                  | water (swim, sail, etc.)                             | 0.50            | 0.58                          | 0.55                           | 0.56                         | 0.58                         | <u>0.54</u>      | <u>0.54</u>     | 0.61                               |
| navigation                              | pure search  | 0.67            | 0.76                          | 0.68                           | 0.76                         | 0.67                         | 0.76             | 0.75            | <b>0.81</b>                        |
| navigation                              | direct recognition of target                         | 0.64            | 0.57                          | 0.69                           | 0.77                         | 0.80                         | 0.65             | 0.76            | 0.45                               |
| navigation                              | gradient cues  | 0.57            | 0.61                          | 0.61                           | 0.65                         | 0.69                         | 0.72             | 0.64            | 0.53                               |
| navigation                              | global cues  | 0.70            | 0.59                          | 0.68                           | 0.77                         | 0.69                         | 0.77             | 0.71            | 0.57                               |
| navigation                              | learned spatial memory                               | 0.55            | 0.18                          | 0.75                           | 0.63                         | 0.61                         | 0.66             | 0.72            | <u>0.38</u>                        |
| navigation                              | genetically-coded memory                             | 0.74            | 0.75                          | 0.72                           | 0.78                         | 0.67                         | <b>0.82</b>      | <b>0.79</b>     | 0.49                               |
| external                                | local resources                                      | 0.56            | 0.77                          | 0.60                           | <b>0.80</b>                  | <b>0.80</b>                  | 0.67             | 0.69            | 0.66                               |
| external                                | remote resources                                     | 0.75            | 0.72                          | 0.68                           | 0.72                         | 0.64                         | 0.78             | 0.67            | 0.57                               |
| external                                | seasonal resources                                   | 0.64            | 0.74                          | 0.73                           | 0.75                         | 0.59                         | 0.72             | 0.78            | 0.68                               |
| external                                | ephemeral resources                                  | 0.72            | 0.78                          | 0.74                           | 0.72                         | 0.74                         | 0.74             | 0.65            | 0.70                               |
| external                                | conspecifics   | 0.68            | <b>0.78</b>                   | 0.59                           | 0.69                         | 0.71                         | 0.67             | 0.65            | 0.64                               |
| external                                | competitors  | 0.66            | 0.78                          | 0.75                           | 0.74                         | 0.76                         | 0.75             | 0.70            | 0.55                               |
| external                                | predators  | 0.66            | 0.78                          | <b>0.75</b>                    | 0.74                         | 0.77                         | 0.70             | 0.73            | 0.66                               |

| <b>Table S2 (continued): pattern attributes</b> |  |                 |                               |                                |                              |                              |                  |                 |                                    |
|---|--|-----------------|-------------------------------|--------------------------------|------------------------------|------------------------------|------------------|-----------------|------------------------------------|
| <b>Component</b>                                | <b>Movement phenomenon<br/>Pattern attribute</b> | <b>Foraging</b> | <b>Dispersal<br/>(plants)</b> | <b>Dispersal<br/>(animals)</b> | <b>One-way<br/>migration</b> | <b>Two-way<br/>migration</b> | <b>Irruption</b> | <b>Nomadism</b> | <b>Accidental<br/>displacement</b> |
| movement  | one generation                                   | 0.69            | 0.65                          | 0.73                           | 0.77                         | <b>0.80</b>                  | 0.77             | <b>0.78</b>     | <b>0.81</b>                        |
| movement  | diel   | 0.62            | 0.79                          | 0.65                           | 0.62                         | 0.67                         | 0.60             | 0.74            | 0.75                               |
| movement  | seasonal   | <b>0.81</b>     | 0.80                          | 0.68                           | 0.68                         | 0.76                         | 0.74             | 0.77            | 0.77                               |
| movement  | annual   | 0.73            | 0.81                          | <b>0.80</b>                    | <b>0.79</b>                  | 0.60                         | 0.78             | 0.72            | 0.76                               |
| movement  | common (re lifetime track)                       | 0.79            | 0.77                          | 0.77                           | 0.74                         | 0.68                         | <b>0.79</b>      | 0.69            | 0.76                               |
| movement  | breeding home range                              | 0.65            | 0.72                          | 0.70                           | <u>0.57</u>                  | <u>0.50</u>                  | <u>0.56</u>      | 0.66            | 0.42                               |
| movement  | large-scale                                      | 0.72            | 0.67                          | 0.58                           | 0.69                         | 0.62                         | 0.71             | 0.72            | 0.73                               |
| movement  | return (round-trip)                              | 0.63            | <u>0.18</u>                   | 0.64                           | (0.00)*                      | (0.00)*                      | 0.60             | 0.78            | 0.51                               |
| movement  | track use consistency                            | 0.61            | 0.33                          | <u>0.57</u>                    | 0.71                         | 0.53                         | 0.58             | 0.73            | <u>0.23</u>                        |
| movement  | ceases in target encounter                       | 0.71            | <b>0.82</b>                   | 0.73                           | 0.70                         | 0.60                         | 0.76             | 0.74            | 0.58                               |
| movement  | intermittency                                    | 0.68            | 0.70                          | 0.61                           | 0.76                         | 0.76                         | 0.72             | 0.69            | 0.79                               |
| movement  | path straightness                                | 0.67            | 0.74                          | 0.58                           | 0.67                         | 0.61                         | 0.64             | 0.65            | 0.74                               |
| movement  | high mean velocity                               | 0.69            | 0.77                          | 0.61                           | 0.64                         | 0.58                         | 0.60             | <u>0.60</u>     | 0.72                               |
| movement  | high velocity variance                           | <u>0.61</u>     | 0.82                          | 0.71                           | 0.59                         | 0.65                         | 0.72             | 0.65            | 0.71                               |

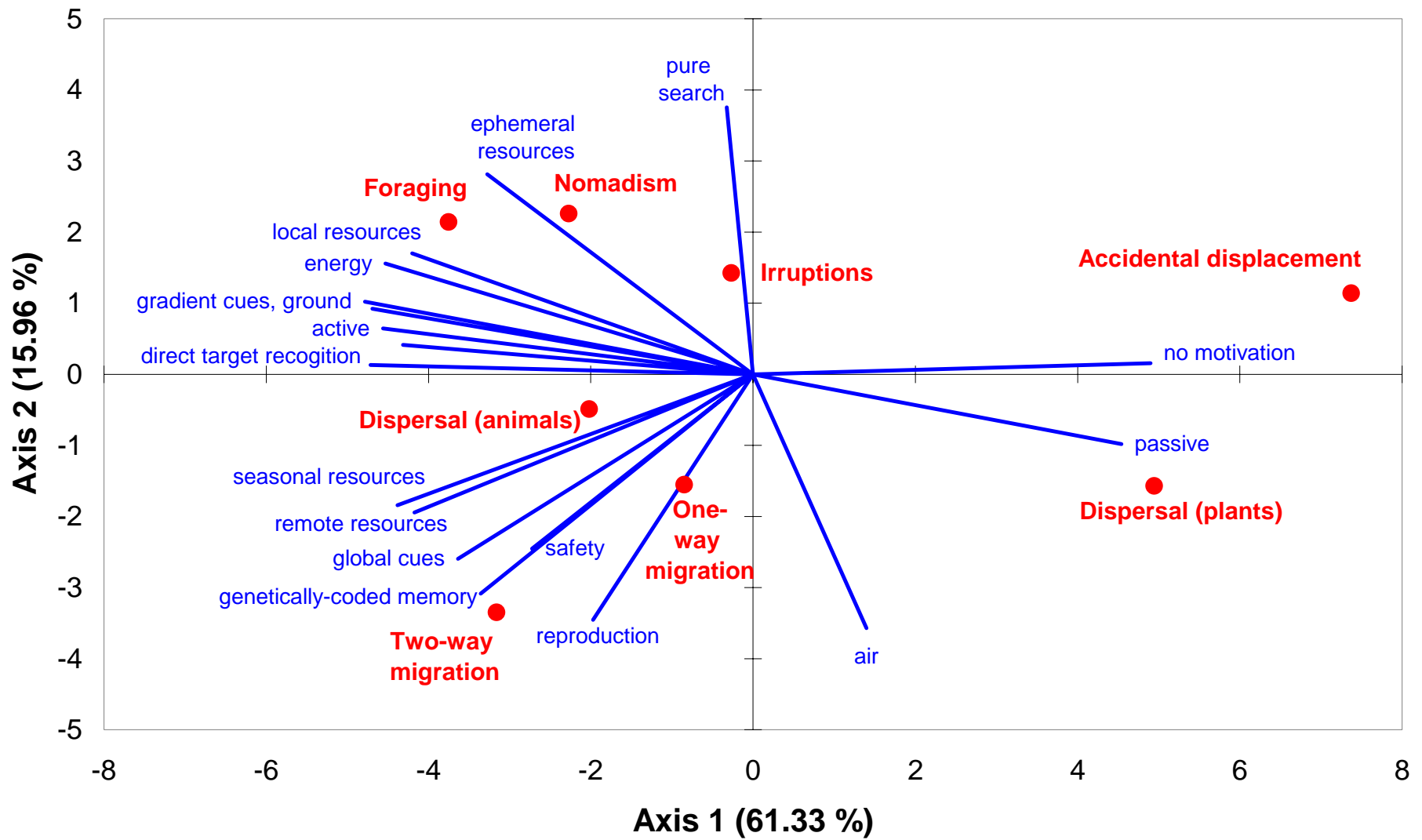
\*The two values in parentheses were fixed because they are true or false by definition.

**Table S3.** Mean opinion of 32 authors of this Special Feature and their students on the relevance of mechanistic and pattern attributes for eight movement phenomena (columns). Relevance was expressed by a score ranging from 0 (not relevant) to 4 (highly relevant).

| <b>Table S3: mechanistic attributes</b> |  |                 |                               |                                |                              |                              |                  |                 |                                    |
|---|--|-----------------|-------------------------------|--------------------------------|------------------------------|------------------------------|------------------|-----------------|------------------------------------|
| <b>Component</b>                        | <b>Movement phenomenon<br/>Mechanistic attribute</b> | <b>Foraging</b> | <b>Dispersal<br/>(plants)</b> | <b>Dispersal<br/>(animals)</b> | <b>One-way<br/>migration</b> | <b>Two-way<br/>migration</b> | <b>Irruption</b> | <b>Nomadism</b> | <b>Accidental<br/>displacement</b> |
| internal                                | no motivation  | 0.13            | 2.13                          | 0.47                           | 0.47                         | 0.31                         | 0.56             | 0.59            | 2.97                               |
| internal                                | energy   | 3.75            | 1.19                          | 2.09                           | 2.19                         | 2.56                         | 2.34             | 3.03            | 0.78                               |
| internal                                | safety   | 1.13            | 1.53                          | 1.97                           | 1.72                         | 1.66                         | 1.16             | 1.69            | 0.69                               |
| internal                                | learning   | 1.78            | 0.22                          | 1.34                           | 0.78                         | 1.56                         | 0.63             | 1.59            | 0.50                               |
| internal                                | reproduction   | 1.28            | 2.59                          | 2.78                           | 2.44                         | 2.50                         | 1.63             | 1.81            | 0.44                               |
| motion                                  | passive  | 0.97            | 3.38                          | 1.72                           | 2.09                         | 0.84                         | 1.31             | 0.94            | 3.00                               |
| motion                                  | active   | 3.41            | 1.19                          | 3.22                           | 2.78                         | 3.59                         | 3.13             | 3.31            | 1.88                               |
| motion                                  | ground (walk, run, etc.)                             | 2.38            | 2.78                          | 2.34                           | 2.41                         | 2.53                         | 2.22             | 1.88            | 2.28                               |
| motion                                  | air (fly, glid, etc.)                                | 2.59            | 1.31                          | 2.53                           | 2.28                         | 2.44                         | 2.28             | 2.50            | 1.59                               |
| motion                                  | water (swim, sail, etc.)                             | 2.41            | 2.00                          | 2.41                           | 2.41                         | 2.44                         | 1.94             | 1.94            | 2.06                               |
| navigation                              | pure search  | 2.16            | 1.72                          | 2.31                           | 1.88                         | 0.81                         | 1.91             | 2.34            | 1.81                               |
| navigation                              | direct recognition of target                         | 2.69            | 0.53                          | 1.75                           | 1.72                         | 2.13                         | 1.25             | 1.69            | 0.38                               |
| navigation                              | gradient cues  | 2.47            | 0.63                          | 2.16                           | 2.09                         | 1.94                         | 2.06             | 2.28            | 0.53                               |
| navigation                              | global cues  | 1.31            | 0.63                          | 1.69                           | 2.19                         | 2.88                         | 1.59             | 1.53            | 0.66                               |
| navigation                              | learned spatial memory                               | 2.88            | 0.13                          | 1.28                           | 0.75                         | 2.81                         | 0.88             | 1.69            | 0.31                               |
| navigation                              | genetically-coded memory                             | 1.25            | 1.29                          | 1.72                           | 2.13                         | 2.59                         | 1.88             | 1.50            | 0.53                               |
| external                                | local resources                                      | 3.50            | 1.72                          | 2.50                           | 2.34                         | 2.06                         | 2.81             | 2.59            | 0.84                               |
| external                                | remote resources                                     | 1.69            | 1.13                          | 2.38                           | 2.44                         | 3.00                         | 1.75             | 2.47            | 0.69                               |
| external                                | seasonal resources                                   | 2.63            | 1.88                          | 2.22                           | 2.31                         | 3.31                         | 2.00             | 2.47            | 0.88                               |
| external                                | ephemeral resources                                  | 2.25            | 1.41                          | 1.91                           | 1.72                         | 1.66                         | 2.69             | 2.78            | 1.09                               |
| external                                | conspecifics   | 2.78            | 1.72                          | 2.69                           | 2.25                         | 2.41                         | 2.78             | 2.47            | 0.78                               |
| external                                | competitors  | 2.84            | 1.59                          | 2.47                           | 1.97                         | 1.84                         | 1.78             | 2.03            | 0.53                               |
| external                                | Predators  | 2.75            | 1.75                          | 2.25                           | 1.94                         | 1.78                         | 1.56             | 2.06            | 0.78                               |

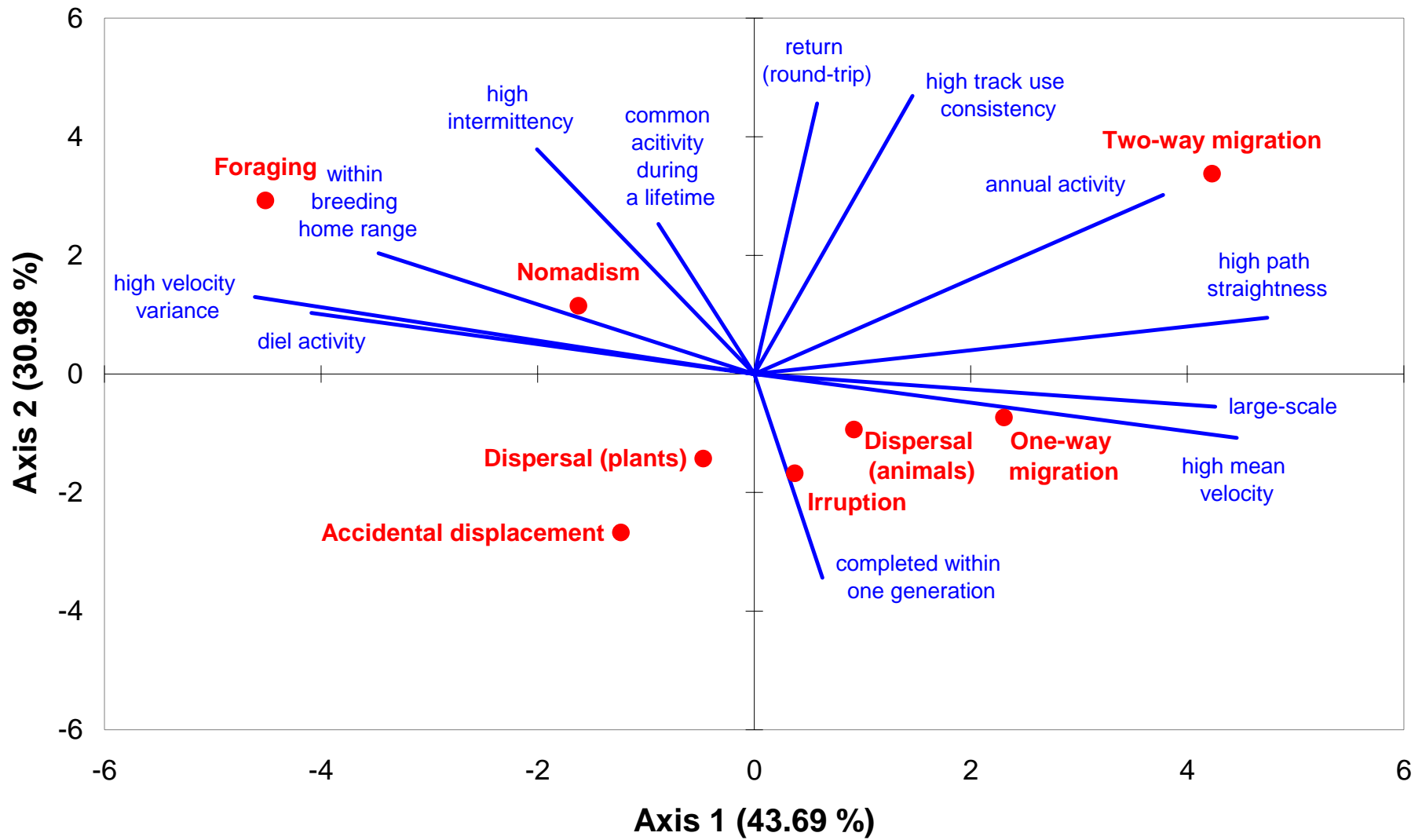
| <b>Table S3 (continued): pattern attributes</b> |  |                 |                               |                                |                              |                              |                  |                 |                                    |
|---|--|-----------------|-------------------------------|--------------------------------|------------------------------|------------------------------|------------------|-----------------|------------------------------------|
| <b>Component</b>                                | <b>Movement phenomenon<br/>(b) Pattern attribute</b> | <b>Foraging</b> | <b>Dispersal<br/>(plants)</b> | <b>Dispersal<br/>(animals)</b> | <b>One-way<br/>migration</b> | <b>Two-way<br/>migration</b> | <b>Irruption</b> | <b>Nomadism</b> | <b>Accidental<br/>displacement</b> |
| movement  | one generation                                       | 2.09            | 2.97                          | 2.78                           | 2.56                         | 2.03                         | 2.56             | 2.22            | 2.28                               |
| movement  | Diel   | 1.94            | 2.28                          | 2.53                           | 2.63                         | 2.50                         | 1.84             | 2.00            | 1.59                               |
| movement  | seasonal   | 1.66            | 2.00                          | 2.03                           | 2.13                         | 3.22                         | 1.81             | 2.13            | 1.41                               |
| movement  | Annual   | 2.53            | 2.53                          | 1.81                           | 1.97                         | 2.41                         | 1.66             | 2.63            | 1.38                               |
| movement  | common (re lifetime track)                           | 2.69            | 1.52                          | 1.09                           | 0.53                         | 0.47                         | 0.50             | 0.78            | 0.34                               |
| movement  | breeding home range                                  | 2.91            | 1.91                          | 1.44                           | 1.03                         | 0.84                         | 0.88             | 1.22            | 1.59                               |
| movement  | large-scale  | 1.13            | 1.75                          | 2.34                           | 2.78                         | 3.22                         | 2.53             | 2.38            | 2.63                               |
| movement  | return (round-trip)                                  | 2.53            | 0.13                          | 0.69                           | (0.00)*                      | (4.00)*                      | 0.66             | 1.72            | 0.44                               |
| movement  | track use consistency                                | 1.84            | 0.23                          | 0.68                           | 1.03                         | 2.88                         | 0.56             | 1.13            | 0.16                               |
| movement  | ceases in target encounter                           | 2.22            | 2.06                          | 2.88                           | 3.03                         | 3.28                         | 1.81             | 1.63            | 0.63                               |
| movement  | intermittency  | 2.72            | 1.22                          | 1.69                           | 1.75                         | 2.13                         | 1.94             | 2.47            | 1.66                               |
| movement  | path straightness                                    | 1.41            | 2.06                          | 2.09                           | 2.44                         | 3.03                         | 1.97             | 1.50            | 1.69                               |
| movement  | high mean velocity                                   | 1.09            | 2.61                          | 2.25                           | 2.47                         | 2.97                         | 2.41             | 1.41            | 1.97                               |
| movement  | high velocity variance                               | 2.53            | 2.06                          | 1.69                           | 1.50                         | 1.47                         | 1.75             | 2.34            | 1.84                               |

\*The two values in parentheses were fixed because they are true or false by definition.



**Figure S1:** Principal Components Analysis (PCA) biplot for movement phenomena (red circles) and their association with 23 mechanistic attributes related to the movement ecology framework (blue lines). The factor loadings are scaled by a vector of 5 to match the scores of the movement phenomena.





**Figure S2:** Principal Components Analysis (PCA) biplot for movement phenomena (red circles) and their association with 14 pattern attributes (blue lines). The factor loadings are scaled by a vector of 5 to match the scores of the movement phenomena.