Ecography

ECOG-05047
Fedriani, J. M., Ayllón, D., Wiegand, T. and Grimm, V. 2020. Intertwined effects of defaunation, increased tree mortality, and density compensation on seed dispersal. – Ecography doi: 10.1111/ecog.05047

Supplementary material

Appendix 1: Detailed description of the study area and study system.

Appendix 2: Delta ODD-description of DisPear model (Version 11/10/2019).

Appendix 3: Reasoning of dispersers' spatial behaviour and habitat use.

Appendix 4: Isolated impact of increased tree mortality on overall and habitat-specific seed dispersal.

Appendix 1: Detailed description of the study area and study system.

Our study site is located within the Doñana World Biosphere Reserve, SW Spain (elevation 0-80 m, Fig. A1). The climate is Mediterranean sub-humid, characterized by dry, hot, long summers (June-September) and mild, wet winters (November-February). The landscape is comprised by ten habitat types differing in vegetation cover, presence of *P. bourgaenea*, and level of human interferences (Fedriani et al. 1999; Fig. A1). Nonetheless, for the purpose of this study, they have been grouped into four main habitat types: *i*) the Mediterranean scrubland is mainly formed by *Pistacia lentiscus* shrubs with variable brush of *H. halimifolium* and *C. humilis*, with scattered *Q. suber* and *Pinus pinea* trees (this habitat holds most adult and juvenile *Pyrus bourgaeana*), *ii*) an old-field that was used during decades for intensive cattle grazing and currently is an open area of *Juncus* spp. with some *Halimium halimifolium* and *Staracanthus genistoides* bushes, and scattered *Quercus suber* and *Olea europaea*. *Pyrus bourgaeana* is rapidly recolonizing this habitat, where many saplings and some reproductive trees have been recorded, *iii*) the marshes are open areas flowed in winter and thus unsuitable for most terrestrial plants (e.g. *P. bourgaeana* has never been observed within this habitat), and *iv*) 'other habitats' comprising patches of praire, pine, ash and *Eucaliptus* spp. forests, and cultivations. Though most of these habitats are suitable for *P. bourgaeana*, its density is very low due to human activities (logging, fires, etc.).

Pyrus bourgaeana Decne (Rosaceae) is a small (3-6 m height) deciduous tree endemic to the Iberian Peninsula and North Africa (Morocco). In the Doñana area, the species exhibits a highly fragmented distribution, with trees occurring in low densities (generally < 1 individual/ha) across several Mediterranean scrubland patches that are isolated from each other by natural and human barriers such as marshes, towns or cultivations (Fedriani et al. 2010). Such reduced and fragmented distribution resulted from large suitable areas being historically transformed into farmlands, pasturelands, and *Eucaliptus* spp. timber forests

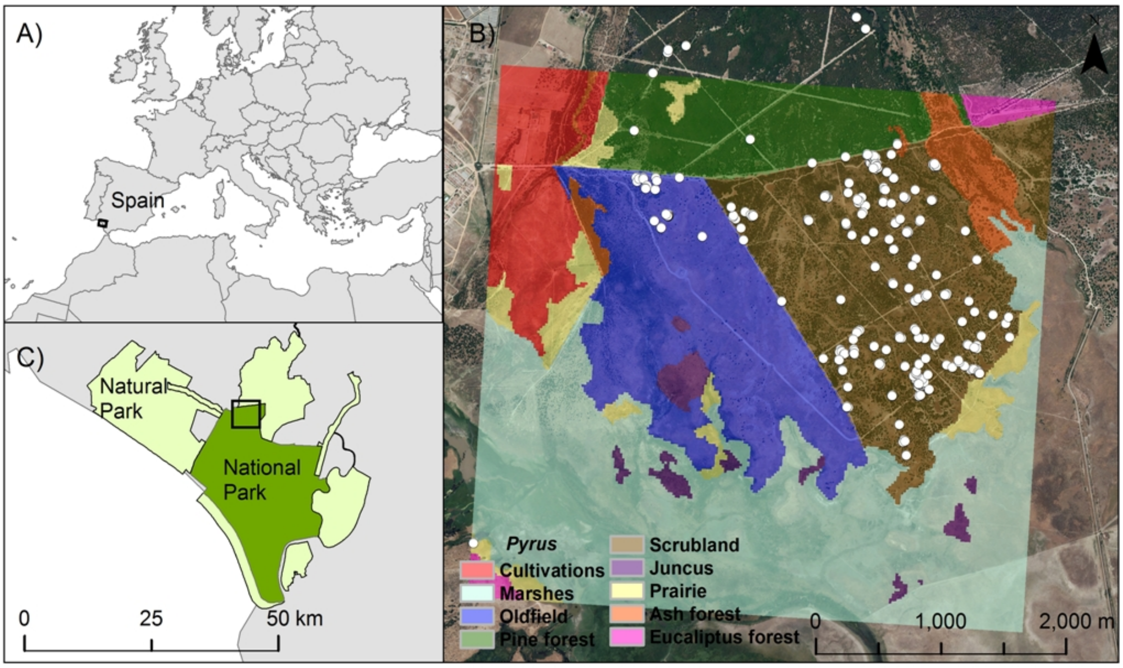
(Granados et al. 1988, Fedriani et al. 2019). The Doñana population experiences high levels of adult mortality mostly due to summer droughts and windy storms (Zywiec et al. 2017, Authors *unpublished data*).

Each tree usually produces yearly between 200-700 fruits. After ripening, they drop to the ground from September to December and are harvested by a diverse assemblage of frugivores (Fedriani and Delibes 2013). Local effective seed dispersers are mostly intermediate-sized mammalian carnivores (badger and red fox; Fedriani and Delibes 2013), which occur in low densities (Fedriani et al. 1999). Seedlings emerging from seeds dispersed by carnivores are often observed in field (Fedriani and Delibes 2009b). Seedlings emerge from winter to early spring, and undergo extensive mortality during the first year due to summer droughts, herbivory, and fungal infection (Fedriani et al., 2012, Authors *unpublished data*).The population shows also a limited reproduction and regeneration ability (Fedriani et al. 2010, 2012) and a marked left-skewed demographic structure, with many individuals in older age classes, few juveniles, and even fewer seedlings and saplings (Fedriani et al. 2019).

The current seed dispersal guild of this tree is very limited compared with one with which it evolved in the western Mediterranean basin. For instance, from the Pleistocene until a few decades ago, probable seed dispersers such as the Barbary macaque (*Macaca sylvanus*), the brown bear (*Ursus arctos*), and the wolf (*Canis lupus*) have become extinct in the Doñana area (Fedriani et al. 2010, Fedriani and Delibes 2011, Garrote et al. 2018). Furthermore, even extant *P. bourgaeana* seed dispersers, the Eurasian badger *Meles meles* and the red fox *Vulpes vulpes*, have and continue experiencing intensive human-related mortality due to poachers, road kills, etc (Fedriani 1997, Revilla et al. 2001, Authors *unpublished data*). As a consequence, the populations experience strong dispersal limitation which leads to its strongly clustered spatial distribution in Doñana (Fedriani et al. 2010, Fedriani and Wiegand 2014).

Habitat usage and movements of both foxes (n = 31) and badgers (n = 17) has been studied in detail at our study site by telemetry (e.g. 24-h periods, with dispersers being located at 1-h intervals; Fedriani et al. 1999, Revilla and Palomares 2002). In general, during daytime both foxes and badgers are inactive hidden in their den at the Mediterranean scrubland, while during sunset they tend to move towards open habitats such as the oldfield and the marshes where they remain active during most nighttime. Since both carnivores intensively feed on Iberian pear fruits during the autumn and early winter, they disperse seeds into different habitat types (Fedriani and Wiegand 2014) where seedlings often emerge.

Figure A1: Study site showing (a) location of the Doñana National Park (DNP) in southwestern Spain, (b) location of our study site within the DNP and (c) detailed view (including habitat types) within the DNP. The white disks represent the reproductive *Pyrus bourgaenea* trees.



References

Fedriani JM 1997. Relaciones interespecíficas entre el lince Ibérico, *Lynx pardinus*, el zorro, *Vulpes vulpes*, y el tejón, *Meles meles*, en el Parque Nacional de Doñana. PhD Thesis. Universidad de Sevilla, Seville, Spain.

Fedriani, J.M., Ferreras, P., Delibes, M. 1998. Dietary response of the eurasian badger, Meles meles, to a decline of its main prey in the Doñana National Park. J. Zool 245: 214-218.

Fedriani, J.M., Palomares F., and Delibes, M. 1999. Niche relations among three sympatric Mediterranean carnivores. Oecologia 121: 138-148.

Fedriani JM and M. Delibes 2009a. *Seed dispersal in the Iberian pear* Pyrus bourgaeana*: a role for infrequent mutualists.* Ecoscience 16: 311-321.

Fedriani JM and M. Delibes (2009b). Functional diversity in fruit-frugivore interactions: a field experiment with Mediterranean mammals. *Ecography,* 32, 983-992.

Fedriani JM, Wiegand T. and M. Delibes. 2010. Spatial pattern of adult trees and the mammal-generated seed rain in the Iberian pear. Ecography 33:445-455.

Fedriani JM, Zywiec M and M Delibes. 2012. Thieves or mutualists? Pulp feeders enhance local endozoochore recruitment. Ecology. 93:575–587.

Fedriani JM and M Delibes. 2013. *Pulp feeders alter plant interactions with subsequent animal associates.* Journal of Ecology 101: 1581-1588.

Fedriani JM and T. Wiegand. 2014. Hierarchical mechanisms of spatially contagious seed dispersal in complex seed-disperser networks. Ecology 95:514–526.

Fedriani, J. M., García, L., Sanchéz, M., Calderon, J., & Ramo, C. (2017). Long-term impact of protected colonial birds on a jeopardized cork oak population: Conservation bias leads to restoration failure. *Journal of Applied Ecology*, 54, 450–458.

Fedriani JM, T Wiegand, D Ayllón, F Palomares, A Suárez-Esteban and V. Grimm. 2018. Assisting seed dispersers to restore old-fields: an individual-based model of the interactions among badgers, foxes, and Iberian pear trees. Journal of Applied Ecology 55: 600–611.

Garrote P, G Calvo, M Żywiec, M Delibes, A Suárez-Esteban, and JM Fedriani. 2018. Strong among population variation in frugivory strength by functional diverse frugivores: a 'reciprocal translocation' experiment. Oecologia 187: 143-154.

Granados, M., Martín, A., & García Novo, F. (1988). Long-term vegetation changes on the stabilized dunes of Doñana National Park (SW Spain). Plant Ecology, 75, 73–80.

Revilla E , F Palomares, M Delibes. 2001. Edge-Core Effects and the Effectiveness of Traditional Reserves in Conservation: Eurasian Badgers in Doñana National Park. Conservation Biology 15: 148-158

Żywiec M, Muter E, Zielonka T, Delibes M, Calvo G, and JM Fedriani. 2017. Long-term effect of temperature and precipitation on radial growth in a threatened thermo-Mediterranean tree population. Trees - Structure and Function 31: 491-501.

Appendix 2: ODD-description of *DisPear* model (Version 11/10/2019)**.**

Fedriani JM, D. Ayllón, T. Wiegand, and V. Grimm. *Submitted.* Intertwined effects of defaunation, increased tree mortality, and density compensation on seed dispersal.

Model description

This model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual-based models (Grimm et al. 2006, 2010, 2020; Railsback and Grimm 2019). We provide a "delta-ODD" (Grimm et al. 2020) that identifies the ODD elements that have changed from the original model description (M1; Fedriani et al. 2018) and includes new description for those elements (M2). The new additions are marked in red, elements that apply only to the original model M1 are in blue, and common descriptions remain in black. The model is implemented in NetLogo (version 5.2.0; Wilensky 1999). We therefore use NetLogo conventions such as variable names, parameters and procedures. The design and parameterization of this model relies on a comprehensive knowledge of the study system accumulated during the last two decades (e.g. Fedriani 1997; Fedriani et al. 1999, 2010, 2012, 2015, 2018, 2019; Fedriani and Wiegand 2014).

1. Purpose and patterns

M1: The model illustrates the potential of combining long-term comprehensive field studies with individual-based, spatially explicit simulation models (hereafter SEIBM) to identify the effectiveness of contrasting tree planting strategies in enhancing oldfield restoration. To this end, we model Iberian pear *Pyrus bourgaeana* seed dispersal by red foxes *Vulpes vulpes* and badgers *Meles meles* under different restoration scenarios (i.e. density and distribution of planted trees) and analyze their influence on three main aspects of oldfield recolonization: 1) the total number of oldfield cells receiving seeds, 2) the number of oldfield cells receiving seeds from isolated and aggregated trees, and 3) the number of fox-dispersed and badger-dispersed seeds arriving into the oldfields.

M2: The model simulates the emergence of *P. bourgaeana* seed dispersal kernels and habitat-specific seed arrival from the interaction between the physiological traits, habitat use and foraging behavior of its mammalian seed dispersers, red fox *V. vulpes* and badger *M. meles*, and the abundance and spatial distribution of fruiting trees in a heterogeneous landscape. We analyze how the seed arrival is altered by the combined effect of two global change components (1) selective defaunation of disperser species, and (2) augmented *P. bourgaeana* tree mortality. In addition, we evaluated the extent to which density compensation of the defauned species by the other disperser species palliates the combined impact of defaunation and tree mortality on dispersal kernels. To this end, we quantify the effect of those factors on the number of fox-dispersed and badger-dispersed seeds arriving into each of the four habitat types (Mediterranean scrubland, oldfield, marshes, 'other habitats') comprising our focal heterogeneous landscape.

To consider our model realistic enough for its purpose, we used for its design patterns in dispersers' movement (patterns regarding the propensity of individuals of each species to travel longer or shorter distances depending on the period of the circadian cycle) and habitat use (patterns describing the changes in species-specific relative use of habitat types over the circadian cycle), and species-specific patterns of feces abundance, spatial distribution and clustering. All these patterns are based on extensive field and experimental data collected over two decades.

2. Entities, state variables, and scales

The model has six kinds of entities: *i*) dispersers that move across the landscape; they are either foxes or badgers. The disperser movements are characterized by species-specific mean movement distances and habitat selection which depend on the circadian cycle (see below); ii) spatial-groups represent the spatial area where the different social groups of dispersers centre their activities (movements, foraging, resting, etc); *iii*) spatial units referred to as patches (or cells) of 20 x 20 m² that represent different habitat types (see below for details); *iv*) fruiting *P. bourgaenea* trees (in M2 trees are modeled as individual entities, while in M1 are a special type of patches); *v*) fruits produced by *P. bourgaenea* trees that fall to the ground when ripe and thus become available to seed dispersers; and *vi*) disperser feces delivered by dispersers containing dispersed seeds. The state variables of the entities are described in Table A1.

Table A1: Entities included in *DisPear*, their state variables, and corresponding units or values.

Entity	State variable	Description	Unit or Values
Dispersers	species	Disperser species	fox/badger
	group	Social group to which the disperser belongs	northern/southern
	habitat-ini	Habitat where each disperser is initialized	10/9 categories
	den	Patch where dispersers set their den	patch coordinates
	previous-patch	Patch visited in the previous time step	patch coordinates
	pot-visited-patches	Patches that can be potentially visited during movement	List
	disperser-fruits	Set of fruits in the disperser's stomach	List
Spatial-groups	Group	Northern or Southern	Northern or Southern
	group-members	Agentset comprising the dispersers belonging to the spatial group	List
	Home-Range	Agentset comprising the patches that belong to the home range of the spatial group	List
Fruits	status	Either available to dispersers, eaten, or unavailable (e.g. rotten)	3 categories
	age	After falling, fruits are available for three days	ticks (= h)
	time-in-disperser	After certain time in disperser's stomach fruits are delivered	Ticks
	mother-patch	It is the tree-patch from where fruits are removed by dispersers	patch coordinates
	defecation-time	Time from fruit ingestion to delivery (within feces)	Ticks

	Sp	Species of disperser that ate the fruit	fox/badger
	fruits-hab	Habitat type where the dispersed fruits are delivered	10/9 categories
Feces	fruits-in-feces	Set of fruits within feces	List
	species	Species of the disperser that delivered the feces	fox/badger
	feces-hab	Habitat type where feces are dropped	10/9 categories
	neighbours	Number of conspecific feces within distance of 2 patches	discrete number
Patches	habitat	Classification based on vegetation composition	10/9 categories
	n-trees	Number of trees in a patch	discrete number (1-8)
	patch-total-n-fruits	Total number of fruits within the patch	discrete number
	patch-fruits	Set of fruits within a patch	List
	patch-feces	Set of feces within a patch	List
Trees	crop-size	Number of fruits each tree produces each season (estimated empirically)	discrete number
	total-n-fruits	Total number of fruits in a tree	discrete number

The landscape is comprised by ten habitat types differing in vegetation cover, presence of *P. bourgaenea*, and level of human and top-predator interferences. Because of these differences, and because foxes and badgers differ in their pattern of habitat usage, habitat is critical for seed disperser movements and thus for the seed rain they generate. Represented habitats include:

a) Old-field: Before 1979 this area (~ 310 ha) was a Mediterranean scrubland (as described below). Then, the private owners mechanically removed all shrubs and most trees, resulting in a continuum of open grasslands with minimum understory of Mediterranean scrubs. The area was used for intensive cattle grazing until 1996, when the land was expropriated, protected, and managed by the Spanish National Park Service. Managers removed all cows from the old-field. Currently, it is an open area of *Juncus* spp., *Silene laeta* and *Gaudinia fragilis* but with some *Halimium halimifolium* brushes and scattered *Quercus suber* and *Olea europaea*. Moreover, since livestock removal, the area is being recolonized by *P. bourgaeana* and other mammal-dispersed shrubs (e.g. *Chamaerops humilis*).

b) Scrubland: the Mediterranean scrubland is mainly formed by *Pistacia lentiscus* shrubs with variable brush of *H. halimifolium* and *C. humilis*, with scattered *Q. suber* and *Pinus pinea* trees.

c) Fruiting-trees: adult *P. bourgaeana* trees (n = 328) are located in 208 patches, all within the Mediterraean scrubland. Each patch of this habitat type has assigned a number of reproductive fruiting trees (ranging 1-8) representing the observed local distribution of trees. Each tree is assigned a crop size attained from an empirically-estimated Poisson distribution.

d) Praire: this habitat type mainly surrounds the Mediterranean scrubland and the old-field, and includes some patches of variable size dominated by *Asphodelus ramosus* and *Armeria gaditana*.

e) Juncus: These are small patches (< 1ha) dominated by *Juncus* spp. that are located also in the ecotone between the scrubland or the old-field and the marshes.

f) Pine forest: these are comprised of *Pinus pinea* with a shrubby understory of *P. lenticus*.

g) *Eucalyptus* spp. forest.

h) Marshes: open areas where trees and shrubs are practically absent.

i) Ash forest: these are patches of *Fraxinus angustifolia* along natural streams.

j) Cultivations.

M2: To calculate the number of seeds that arrive to each habitat, for the sake of simplicity, we grouped the above ten habitats into four habitat types (Mediterranean scrubland, oldfield, marshes, 'other habitats').

The model is spatially explicit and its spatial extent is a rectangular landscape of 221 × 208 patches (total area is ~1840 ha). This spatial resolution was chosen to account for the small scale of aggregation of *P. bourgaeana* (Fedriani et al. 2010), the responses of dispersers to such aggregated food resource, as well as to encompass disperser typical home range sizes (Fedriani et al. 1999). The model space is represented as bounded, as opposed to toroidal, such that seed dispersers at one edge of the space are "reflected" and cannot jump to patches on the opposite edge.

The model runs with hourly time steps. Because disperser activity and habitat use markedly varies along the circadian cycle (Fedriani et al. 1999), we identify five periods: sunrise (05:00-08 h), daytime (09:00-18 h), sunset (19-21 h), night1 (22-01 h), night2 (02-04 h). Dispersers can potentially harvest *P. bourgaenea* fruit at any time, though it is less likely during daytime because they are less active.

M1: Each simulation lasts 1800 time steps (75 days x 24h). The time period modeled (75 days) represents the 'dispersal season', i.e. when ripe *P. bourgaenea* fruits are available to dispersers (mid September to the end of November).

M2: Each simulation lasts 45000 time steps (25 fruiting seasons x 75 days x 24h). The time period modeled (25 years) represents 25 consecutive 'dispersal seasons', i.e. when ripe *P. bourgaenea* fruits are available to dispersers (mid September to the end of November).

3. Process overview and scheduling

The model considers six main processes: two involving fruiting trees (fruit dropping, and mortality), one involving fruits (status and age updating), and three performed by dispersers (movement, fruit uptake, and fruit delivery). Patches and feces do not perform any active process. All processes take place with hourly time step except processes performed by trees: fruit dropping occurs only at the beginning of the day (i.e. once every 24 time steps), and tree mortality takes place once per fruiting season (i.e. once every 1800 time steps). The different model entities execute the following actions within one hour in the same predetermined order (but entities are processed in a randomized sequence):

1. Fruiting trees drop ripe fruits.

2. Fruits update their status (available, eaten, in-feces) and age.

3. Dispersers move, eat, and defecate. Dispersers carry out three processes:

3.1. They move, depending on the circadian cycle and species, over a certain distance and in a certain direction. A corridor is placed along the straight line connecting the initial and final position, representing the potentially visited habitat patches during the movement.

3.2. Whenever there are available fruiting trees within the corridor, they feed on them.

3.3. Dispersers drop feces containing seeds into randomly selected cells of the corridor, according to empirically estimated gut-retention-time distributions for foxes and badgers (Authors *unpublished data*).

4. Observer update counters, plots model graphical outputs and writes model output files.

5. Move to next fruiting season: when the fruiting season is over, a proportion of fruiting trees die, alive fruiting trees set their new initial crop, and existing fallen fruits and defecated feces from the previous season are removed from the simulation.

4. Design concepts

This section describes the model at a conceptual level, using the design concepts identified by the ODD protocol, except for the *Objectives* (see *Adaptation*), and *Learning* concepts, which do not apply to this IBM.

Basic principles

M1: The model explores the effectiveness of contrasting tree planting strategies in enhancing oldfield restoration by a tree dispersed by two frugivorous mammals, which differ in their activity, habitat use, and level of frugivory. Oldfields are lands that have been abandoned by humans and thus represent vacant habitats for native (and exotic) plant species. Old-field attraction to seed dispersers can be altered by, for example, adding critical resources (food, dens) for foxes and badgers. The model focuses on the first critical stage of plant recolonization (seed arrival) and its driving process (seed dispersal). The model addresses important questions to natural restoration of abandoned lands, such as (i) what combination of density and spatial distribution of planted trees (i.e. aggregated, regular, random) is most effective in oldfield restoration?, (ii) how could managers maximize the seed rain generated by vertebrate frugivores into oldfields by planting fruiting trees of target species?

M2: This model version aims to understand whether and how global change can disrupt ecosystem functioning and in particular the seed dispersal service provided by vertebrate frugivores. More specifically, we investigate the combined effects seed disperser defaunation and increased tree mortality on the dispersal kernel of a threaten tree population as well as the extent to which density-compensation could palliate the impact of such global change components.

Collectives

Red foxes and, especially, Eurasian badgers live in social (or spatial) groups comprised by several adult and subadult individuals (as well as the pups of each year). Individuals belonging to the same group share a home range. In the model the spatial groups to which seed dispersers belong are represented as a collective. These "spatial-groups" is a breed characterized by three state variables: *i*) "group" ("northern" or "southern"), *ii*) "group-members" (agentset comprising the dispersers belonging to the spatial group) and *iii*) "Home-Range" (comprising the patches that belong to the home range of the spatial group). The spatial groups do not perform any active action but at initialization when they define their home range (see *Initialization* element). Then, every time-step they ask the individuals that belong to them to perform all disperser actions. Yet belonging to either one spatial group or the other only affects dispersers in their movement action. Dispersers know to which spatial group they belong and thus direct their movements within their home range (see *Sensing* concept). However, this does not prevent dispersers from occasionally moving out of their respective home range, a pattern that is consistent with field knowledge. The home ranges of the two spatial groups are represented as ellipses, which coarsely resemble the shape of these carnivore home ranges, being the same for both disperser species. Dispersers do not change their spatial group over time

Emergence

M1: The emerged seed rain into the oldfield is affected by the density and spatial distribution of planted trees as well as by the oldfield attraction level and the activity of the dispersers. The oldfield attraction level determines in the first place the time dispersers spend on the oldfield and on other habitat types (e.g. scrubland, where most fruiting trees are), thus the intensity of the seed rain (i.e. number of arrived seeds), and eventually the speed of the oldfield recolonization. Nevertheless, how changes in restoration strategies and in the level of attraction to the oldfield interact in producing the spatial patterns of seed rain is difficult to forecast because several counteracting effects may occur.

M2: The number and spatial distribution of dispersed seeds emerge from the interaction of fruiting trees and dispersers and thus depend on the number and location of trees (which is affected by tree mortality) and the number of individuals of each disperser species (which is affected by defaunation and density compensation), which differ in their habitat use and movement behavior, and hence in their probability of finding existing trees.

Adaptation

Behavior of the seed dispersers is imposed via empirical rules; they do not make adaptive decisions. Adaptation is to some degree reflected in the different rules for movement in different habitat types and at different times of the day. Fitness-seeking is thus implicit in our model. For the purpose of our model, we considered representing adaptive decision making of disperses not necessary.

Sensing

The disperser species represented in the model are highly mobile mammals with high cognitive abilities and memory. We thus assume that they know where different habitats are located. As a result, they tend to show directionality in their movements towards their preferred habitats within the home range of their respective spatial group according to the observed circadian cycle: they tend to move towards the oldfield during sunset and towards the scrubland during sunrise. Dispersers are classified into two spatial groups depending on their position at the simulation initialization, i.e. individuals belonging to the southern spatial group and individuals belonging to the northern spatial group. Individuals belonging to the southern group do not tend to move to the northern portion of the study area and vice versa.

Interaction

The model relies on endozoochory, a worldwide pervasive plant-animal interaction where frugivores ingest fruits and then often disperse their seeds away from the mother plant. Trees and dispersers interact in the sense that dispersers eat fruits and thereby change their gut content. We assumed no direct intra- or interspecific interactions among dispersers. However, dispersers of each species belong to two spatial or social groups. Under field conditions, the ranges used by carnivore spatial groups are usually defended from conspecifics belonging to other groups, usually by fecal marking behavior. Therefore, by distinguishing two spatial groups, the model implicitly represents such intraspecific interactions. An explicit but indirect interaction between dispersers is via exploitative competition for fruits because fruits ingestion could potentially limit the amount of available fruits for other dispersers at later time steps.

Stochasticity

Stochasticity is first used in initializing the model (see below), to assign each disperser their initial home patch (also called 'den'; which will determine the spatial group dispersers belong to), and to assign a crop size to each tree. The crop size of each *P. bourgaeana* is randomly drawn from an empirically-estimated Poisson distribution (with mean equal to 505; Fedriani et al. 2015). Moreover, each fruiting tree drops every 24 hours a random number of fruits, ranging from 2 to 4 (Authors *unpublished data*). Every fruiting season, a defined number of trees die, the choice of dead trees being random.

Each hour of each circadian cycle period, foxes and badgers move a distance randomly drawn from empirically-estimated distributions. During sunset, dispersers can either do short-distance (1 patch) movements around their dens or move far away from the den. The choice between these two movement types is randomly set with a probability given by the old-field attraction level. During late night (night2) and sunrise, dispersers can either move in direction to their dens or to somewhere else. Choosing between these two movement types is randomly set with probabilities of moving to their dens of 0.99 and 0.90 for late night and sunrise, respectively.

Whether a disperser eats during a time step (subject to fruits being available within the movement corridor) is also modeled as a Bernoulli trial (stochastic true-or-false event) using a species-specific probability. The number of fruits eaten by dispersers during a feeding bout is a random number between zero and a species-specific parameter.

The timing of seed delivering by seed dispersers is also stochastic; while the probability of a digested fruit to be delivered is calculated through a deterministic logistic function, whether it is finally delivered or not is a stochastic event. When fruit delivery occurs, the precise location of delivered feces (fruits and seeds within feces) by each disperser is randomly chosen within half patch (i.e. 10m) of the current disperser position.

Observation

Graphical output on the NetLogo interface shows the habitat type of each patch, via patch color. Trees (red patches), feces containing dispersed fruits (and seeds), and disperser locations are also shown. Each day, the model displays a trace on the movements of all foxes and badgers so that their movements can be observed for a 24-h cycle.

To allow the observation of mammal-generated seed rains and thus to address the question the model was designed for, summary statistics on the dispersal kernel are provided via reporters and plots on the interface and output files. The model provides graphical display of several model outputs: distribution of seed dispersal distances from mother tree, distribution of distances for each dispersed fruit to the nearest tree (i.e. minimal dispersal distance), distribution of distances from each feces to nearest fecal sample (i.e. index of fecal aggregation), as well as the use of main habitat types (i.e. old-field, marshes, and scrubland) for foxes and badger during each of the 5 different periods of the circadian cycle. Habitat-use graphs display for each habitat type, circadian period, and disperser species, two bars: one (on the left) corresponding to the observed value estimated by telemetry and one (on the right) that corresponds to the model-simulated values.

The following model outputs can be recorded at the population level: 1) Summary on use of each of the ten habitat types by each disperser species during each circadian period (*habitat-use* file); 2) Summary on disperser statistics (*distance-moved-dispersers-Pop* file), including the mean and standard deviation of distance moved by each disperser species during each circadian period; 3) Summary on feces statistics (*feces-dispersion-aggregation-Pop* file), including the mean and standard deviation of distance to closest tree-patch and number of neighboring feces (within a user-defined radius) of all feces and of feces located within a 'experimental plot' (see Model Validation). In this latter case, both distance and feces aggregation is referred to tree-patches and feces located within the *experimental plot*. The experimental plot is a 72-ha parcel within the study area where previous empirical studies (Fedriani et al. 2010) have generated relevant data that can be used to assess the accuracy of simulated patterns; 4) Summary of fruits statistics (*fruits-dispersion-Pop* file), including the mean and standard deviation of distance to mother tree-patch, and distance to closest tree-patch of all fruits and of fruits located within the experimental plot. The user defines whether these output files are written or not through the interface's switch *Population-outputFiles?*

The model also allows the possibility of recording dispersal and aggregation features of feces at the individual level (*feces-dispersion-aggregation-Ind* file): it records the coordinates, habitat type, disperser's species, distance to closest tree-patch and number of neighboring feces of all individual feces and of all feces within the experimental plot. Likewise, the model records in the *fruits-dispersion-Ind* file the distance to mother tree-patch, and distance to closest tree-patch of all fruits and of fruits located within the experimental plot. The user defines whether these output files are written or not through the interface's switch *Individual-outputFiles?* Finally, the model allows the possibility of recording movement distances and habitat use of individual dispersers (*hourly-distances* file) on an hourly basis by means of the interface's switch *hourly-habitat-output?*

5. Initialization

First, habitats are assigned to patches according to an input file representing the study area and the observed distribution of trees. Each patch creates a number of trees indicated by the input file. In the first model version M1, 328 individual trees are produced (only 176 patches of Mediterranean scrubland have trees). M2 includes also some trees present in other habitat types, which were georeferenced during a new survey in December 2018. Overall, 328 individual trees are produced by the model (277 in Mediterranean scrubland [in 176 patches], 34 in the oldfield [21 patches], and 17 in the pine forest [9 patches]). Patches included in the experimental plot are identified. The model starts at 12hs, when dispersers are usually in the scrubland. Besides, the crop size of each *P. bourgaeana* tree is randomly drawn from a Poisson distribution (mean 505 fruits per tree; Table A2) parameterized based on observed field data. In M1, the total number of fruits in a patch is estimated as the sum of the individual crop sizes of trees within the patch.

Then, the dispersers spatial groups are defined, their associated home range being delineated as an ellipse, which is characterized by four parameters: its centre, the most eastern point in the major axis, angle, and eccentricity (Table A2). These parameters are specific for each spatial group, but do not differ between disperser species. All patches in and within the ellipse belong to the home range of the spatial group.

Finally, the dispersers are initialized by setting the total number of dispersers (*number-dispersers* global parameter) and the proportion of foxes vs. badgers by means of the parameter *dispersers-proportion*. Each disperser is randomly given an initial home patch (called den), typically (80% and 90%, for badgers and foxes, respectively) within the scrubland, on a buffer area (width defined through the parameter *buffer-den*) along the border between the scrubland and the oldfield. This area of den-initialization includes also a small "peninsula" of the scrubland southwestern portion which is very close (but not directly bordering) with the oldfield. In the remaining 20 and 10% of the cases, the initial home patch of each disperser (the den) is assigned randomly, with each patch having an equal probability of selection (irrespective of whether another disperser has been assigned to the same patch), but limited to open habitats (oldfield, marshes, juncus and prairie) within the area defined by the two spatial groups (northern or southern). In this way, foxes and badgers are usually initialized in the scrubland, which is in accordance with our telemetry data. These rules are based on empirical data indicating that most dispersers locate their dens in such portion of the study area. The initial position defines to which spatial group the disperser belongs (see Sensing concept), so that dispersers with an initial y-coordinate over the parameter *limit-social-groups* belong to the northern spatial group, and vice versa. Since the home ranges of the spatial groups overlap, this limit is defined as the average value of the y-coordinates of the most southern patch of the buffer area of the northern spatial group and the most northern buffer-patch of the southern group.

M2: When defaunation is modeled, the number of dispersers of each species is first calculated as described above (through the parameters *number-dispersers* and *dispersers-proportion*). Then, a number of individuals of the defauned species (defined by the parameter *selective-defaunation*; Table A2) is removed and a fraction of the removed individuals is replaced by individuals of the other disperser species (defined by the parameter *compensation-strength*). Finally, the resulting numbers of dispersers of each species are placed in their initial home patch following rules described above.

Table A2: Global parameter values for initialization, dispersers (foxes and badgers), Iberian pear tree, and fruits rules.

Parameter	Definition (units)	Value	Source
Initialization			
number-dispersers	Number of dispersers	10	Own Data[1]
fox-prop	Proportion of fox individuals	0.5	Own Data[1]
defauned-species	Defauned species	Fox/Badger	Scenario analysis
selective-defaunation	Proportion of defauned individuals	0-1	Scenario analysis
compensation-strength	Proportion of defauned individuals compensated by the other species	0-1	Scenario analysis
buffer-den	Corridor width where dens are placed at model initialization (cells)	42	Calibrated
den-location-probability	The probability that foxes are not initiated in the buffer-den	0.1	Expert knowledge
den-location-probability	The probability that badgers are not initiated in the buffer-den	0.2	Expert knowledge
limit-social-groups	y-coordinate used to discriminate the social group of dispersers	116	Expert knowledge
Ellipse-Xc(S/N)	X-coordinate of the center of the ellipse defining the southern/northern spatial groups	110/80	Expert knowledge
Ellipse-Yc(S/N)	Y-coordinate of the center of the ellipse defining the southern/northern spatial group	75/135	Expert knowledge
Xa(S/N)	X-coordinate of the eastern axis point of the ellipse defining the southern/northern spatial group	185/160	Expert knowledge
Angle(S/N)	Angle of the ellipse defining the southern/northern spatial group	25/15	Expert knowledge

Ecc(S/N)	Eccentricity of the ellipse defining the southern/northern spatial group	0.75/0.75	Expert knowledge
Dispersers			
mean-mov-dist-sunset-fox *sd-mov-dist-sunset-fox*	Mean (±1SD) distance travelled by foxes during sunset (cells)	24.93 (±23.37)	Own data[1]
mean-mov-dist-night1-fox *sd-mov-dist-night1-fox*	Mean (±1SD) distance travelled by foxes during night1 (cells)	22.56 (±23.19)	Own data[1]
mean-mov-dist-night2-fox *sd-mov-dist-night2-fox*	Mean (±1SD) distance travelled by foxes during night2 (cells)	24.07 (±23.16)	Own data[1]
mean-mov-dist-sunrise-fox *sd-mov-dist-sunrise-fox*	Mean (±1SD) distance travelled by foxes during sunrise (cells)	17.19 (±22.24)	Own data[1]
mean-mov-dist-day-fox *sd-mov-dist-day-fox*	Mean (±1SD) distance travelled by badgers during daytime (cells)	8.53 (±17.66)	Own data[1,2]
mean-mov-dist-sunset-badger *sd-mov-dist-sunset-badger*	Mean (±1SD) distance travelled by badgers during sunset (cells)	15.94 (±20.46)	Own data[1,2]
mean-mov-dist-night1-badger *sd-mov-dist-night1-badger*	Mean (±1SD) distance travelled by badgers during night1 (cells)	26.61 (±25.73)	Own data[1,2]
mean-mov-dist-night2-badger *sd-mov-dist-night2-badger*	Mean (±1SD) distance travelled by badgers during night2 (cells)	27.27 (±29.39)	Own data[1,2]
mean-mov-dist-sunrise-badger	Mean (±1SD) distance travelled by badgers during sunrise (cells)	16.61 (±24.54)	Own data[1,2]
mean-mov-dist-day-badger *sd-mov-dist-day-badger*	Mean (±1SD) distance travelled by badgers during daytime (cells)	2.66 (±8.47)	Own data[1,2]
prob-den-night2-fox	Probability of not facing the den by foxes at night2	0.99	Expert knowledge
prob-den-sunrise-fox	Probability of not facing the den by foxes at sunrise	0.1	Expert knowledge
prob-den-night2-badger	Probability of not facing the den by badgers at night2	0.99	Expert knowledge
prob-den-sunrise-badger	Probability of not facing the den by badgers at sunrise	0.1	Expert knowledge
max-distance-to-den-fox	Distance from the den below which foxes stop moving during daytime	2	Calibrated
max-distance-to-den-badger	Distance from the den below which badgers stop moving during daytime	5	Calibrated
oldfield-attraction	Probability of dispersers being attracted to the oldfield at sunset	0.95	Expert knowledge

movement-corridor	Corridor width defining the patches potentially visited by each disperser during their movement (patches)	5	Calibration
tree-attraction	Attraction of dispersers to tree patches based on the level of tree aggregation	0.5-2	Scenario analysis
max-fruits-stomach-eat-fox	Maximum number of fruits a fox can keep in its stomach	2	Expert knowledge
max-fruits-stomach-eat-badger	Maximum number of fruits a badger can keep in its stomach	2	Expert knowledge
max-n-fruits-to-eat	Maximum number of fruits the disperser can eat during a feeding bout	2	Own data[3,4]
time-between-eating-fox	Probability that foxes eat fruits in a time step	0.1	Calibrated
time-between-eating-badger	Probability that badgers eat fruits in a time step	0.15	Calibrated
Fox-RetentionTime1	Retention time at which fox defecating probability is 10% (hours)	6.352	Own data[5]
Fox-RetentionTime9	Retention time at which fox defecating probability is 90% (hours)	40.418	Own data[5]
Badger-RetentionTime1	Retention time at which badger defecating probability is 10% (hours)	3.232	Own data[5]
Badger-RetentionTime9	Retention time at which badger defecating probability is 90% (hours)	28.69	Own data[5]
Trees			
mean-crop-size	Mean of a Poisson distribution describing the number of fruits produced per tree	505	Own data[6]
mean-fall-fruit	Mean number of fruit fallen per day	2	Own data[6]
var-fall-fruit	Variance in the mean number of fruit fallen per day	3	Own data[6]
freq-large-fruit-fall-event	Frequency (in days) of large fall-fruit events (LFFE)	4	Own data[6]
prop-fallen-fruits-LFFE	Proportion of fallen fruits during LFFE in relation to the standing crop	0.45	Own data[6]
Mort-%-trees	Proportion of trees that die every fruiting season (%)	0.5	Own data[5]
Fruits			
time-available	Number of hours fallen fruits are available to dispersers	72	Own data[3,4]

Notes: [1]Fedriani et al. (1999), [2]Revilla and Palomares (2002), [3]Fedriani and Delibes (2009), [4]Fedriani and Delibes (2013), [5]Authors (*unpublished data*), [6]Fedriani et al. (2015).

6. Input data

The model does not include any input time series of environmental drivers.

7. Submodels

1. Fruit falling (procedure *fall-fruits;* patch procedure in M1, tree procedure in M2):

At the beginning of a day, i.e. once every 24 time steps, each fruiting tree drops a random number (between 2-4) of ripe fruits that become available to seed dispersers. Also, because large fractions of the fruit crops often fall down during heavy winter/fall storms (Authors *unpublished data*), four large fruit-fall episodes (each corresponding to 45% of the standing fruit crop) occur every dispersal season in randomly selected days.

The fruits' variables are initialized: time having been available, time in disperser guts, time when defecated, and distance to mother tree are set to zero; the current patch is set as the "mother patch" and the species of disperser is set to "none". Once the crop size of a fruiting tree has been depleted (i.e. all fruit have matured and fallen down beneath the tree), the tree will not produce more fruit until the next dispersal season.

2. Fallen fruits update their status and age (fruit procedure):

Fallen fruits available to dispersers update their *time-available* state variable. After three days being available, fruits become "unavailable" to dispersers (e.g. because they are harvested by seed predators or rot) and thus disappear from the model. Fruits previously ingested by dispersers (status equal to "eaten") increase their ingestion time (*time-in-disperser* state variable).

3. Disperser movement, foraging and feces delivery (disperser procedure *walk-eat-defecate*):

3.1. Disperser movement (procedure *disperser-walk*):

The movement model is based on observed hourly straight-line distances moved by dispersers and the directionality of such movements. Data concerning dispersers' movements come from telemetry studies, through which dispersers were located at 1-h intervals during 24-h periods (Fedriani et al. 1999). This approach allowed us to estimate the initial and final disperser locations for each hour of the circadian cycle and, thus, the straight-line distance moved as well as the directionality and habitat usage of such movements (Fig. A2). Therefore, in the model, dispersers "jump" from their initial position to the calculated final position. However, it can be assumed that, despite of having a preferred main movement direction, along their way dispersers sense fruits near to their linear path, and might also decide to defecate, depending on the gut retention times represented in the model. Therefore, for each "jump" a corridor whose width is defined through the parameter *movement-corridor* is calculated (procedure *define-pot-visited-patches*). Based on probabilities described below, dispersers will eat fruits if there are any available in the corridor, or defecate at a randomly chosen patch within the corridor. Dispersers eat and defecate just once within each movement (i.e. one hour).

The disperser first chooses a direction of movement towards a certain habitat, and then moves a distance randomly drawn from a normal distribution defined through its mean and standard deviation. Dispersers only move towards habitats within the limits of their spatial group, which are defined through global parameters (see Table A2); however, since they move a random distance, they can end up their movement outside the area of its spatial group. The observed movement distributions and interaction patterns vary with daytime and disperser species, as detailed below and in Table A3.

In the next description, NetLogo procedures implementing the corresponding activities are given in parentheses; “pxcor” and “pycor” refer to the patch coordinates of the landscape of 221 x 208 patches with the lower left corner having the coordinates (0, 0). The rationale underlying model rules concerning disperser movements during each period of the circadian cycle defined is detailed in Appendix A3.

During sunset (*disperser-towards-oldfield*), dispersers perform either short-distance (1 patch) movements around their dens or move far away from their dens (a random distance set from the specific normal distribution). Choosing between these two movement types is randomly set with a probability given by the old-field attraction level. Foxes moving away from their dens will move towards open habitats within the western part of their spatial range. Badgers moving away from their dens and belonging to the southern group will move towards any marsh or scrubland patch whereas badgers belonging to the northern group will move towards any marsh or scrubland patch.

Early at nighttime (*disperser-in-oldfield1*), dispersers from the southern and northern groups move towards a randomly chosen patch from the habitats prairie, marshes, scrubland, or cultivations within their respective ranges.

During late night (*disperser-in-oldfield2*) dispersers tend to start moving back to their dens. They move either towards their dens or to any open habitat but avoiding the most western portion of the study area, away from their dens. Choosing between these two movement types is randomly set by the probability of moving to their dens (only 1%). Most of the times (99%), dispersers move towards habitats (old-field, prairie, juncus, marshes, scrubland, cultivations) within their spatial group ranges.

At sunrise (*disperser-towards-scrubland*), dispersers move either towards their dens (90% of cases) or towards any scrubland patch within their spatial group ranges (10%).

During daytime (*disperser-in-scrubland*), dispersers do almost not move when they are close (<5 patches) to their den, otherwise they make short approaches to their den. Both disperser species, but more often foxes, make marked changes of den location within their spatial group range every few days. In the model this process is executed at 12pm every 5 (foxes) or 15 (badgers) days, when disperser dens are relocated within the same buffer area in the scrubland defined in the initialization section above (*redefine-den-movement* procedure).

3.2. Disperser ingestion of fruits (procedure *disperser-eat*): Whenever there is a patch with trees within the corridor connecting the dispersers' initial and final positions, they will eat a random number (between 1-2) of fruits if the disperser is not satiated, that is: (1) the number of fruits in the stomach of the disperser is below its maximum capacity (set by the species-specific parameter *max-fruits-stomach-eat)*, and (2) the disperser is not satiated by other food types (a random number drawn from a uniform distribution between zero and one is lower than the species-specific parameter *time-between-eating*). Ingested fruits switch then their status to "eaten", the time-in-disperser is set to 0, and the disperser species (fox or badger) and their mother-patch are also set. Ingested fruits become part of the disperser's fruit-set and are removed from the patch's set of fruits (*remove-eaten-fruits* patch procedure). In M1, the disperser chooses where to feed based on a certain probability that changes depending on the level of aggregation of trees in the patch (i.e., on the number of trees in the patch) controlled by the global parameter *tree-attraction*: (i) if *tree-attraction* is 1, then dispersers visit aggregated and isolated trees with the same probability, (ii) if the value is 0.5, the probability to visit isolated trees was double than for aggregated ones, and (iii) if the value is 2, the probability to visit aggregated trees was double than for isolated ones.

3.3. Disperser defecation (procedure *disperser-defecate*): This procedure determines which ingested fruits (and their seeds) are delivered within feces following a two-step process: first, the probability of being delivered is calculated for each ingested fruit as a function of the time passed since it was ingested by the disperser (*time-in-disperser* state variable); second, it is determined, stochastically, whether the fruit is defecated by comparing a random number drawn from a uniform distribution between zero and one and the estimated probability. If the random number is lower than the probability of delivery, then the fruit is defecated. The probability of delivery is estimated through species-specific logistic functions fit to empirical distributions of fruit retention times within the disperser guts (Authors *unpublished data*). In the model, logistic functions are defined via parameters that specify the predictor values at which the survival probability value equals 0.1 and 0.9. The logistic functions are defined as:

$S = e^{Z} / (1 + e^{Z})$

where

$Z = LogistA + (LogistB \times time\text{-}in\text{-}disperser)$,

$LogistA = LogistC - (LogistB \times RetentionTime1)$,

$LogistB = (LogistC - LogistD) / (RetentionTime1 - RetentionTime9)$,

$LogistC = \ln(0.1/0.9)$, and

$LogistD = \ln(0.9/0.1)$.

Feces with fruits are dropped either on a randomly chosen patch (foxes) or, if exists, on a patch previously used for defecation (badger) within the corridor. For each feces, the habitat of deposition, number of neighboring feces within a specified radius (*feces-aggregation-radius* global parameter), and distance (in meters) to nearest tree are set. To account for small-scale disperser movements during defecation, the precise coordinates of each feces are randomly changed within 10m (0.5 patches) from its initial deposition place. Besides, for each fruit within feces, its status (in-feces), dispersal distance from mother tree (in meters), habitat of delivery, defecation time, and feces ID are set. For both feces and fruits defecated within the experimental plot, the distance to the nearest tree within the experimental plot is calculated. Likewise, the number of neighboring feces on the experimental plot that are within the specified radius is calculated for all feces within the experimental plot. Finally, the fruits that have been delivered within feces are removed from the disperser-fruit sets.

4. Move to next fruiting season (procedure *pass-to-next-season*):

At the end of a fruiting season, i.e. once every 1800 time steps (75 days x 24 hours), a proportion of alive fruiting trees (set by the parameter *Mort-%-trees*) die. Dead trees are chosen randomly. Alive fruiting trees set their new initial crop as described in initialization. Existing fallen fruits and defecated feces from the previous season are removed from the simulation. Dispersers and their dens remain at the same location.

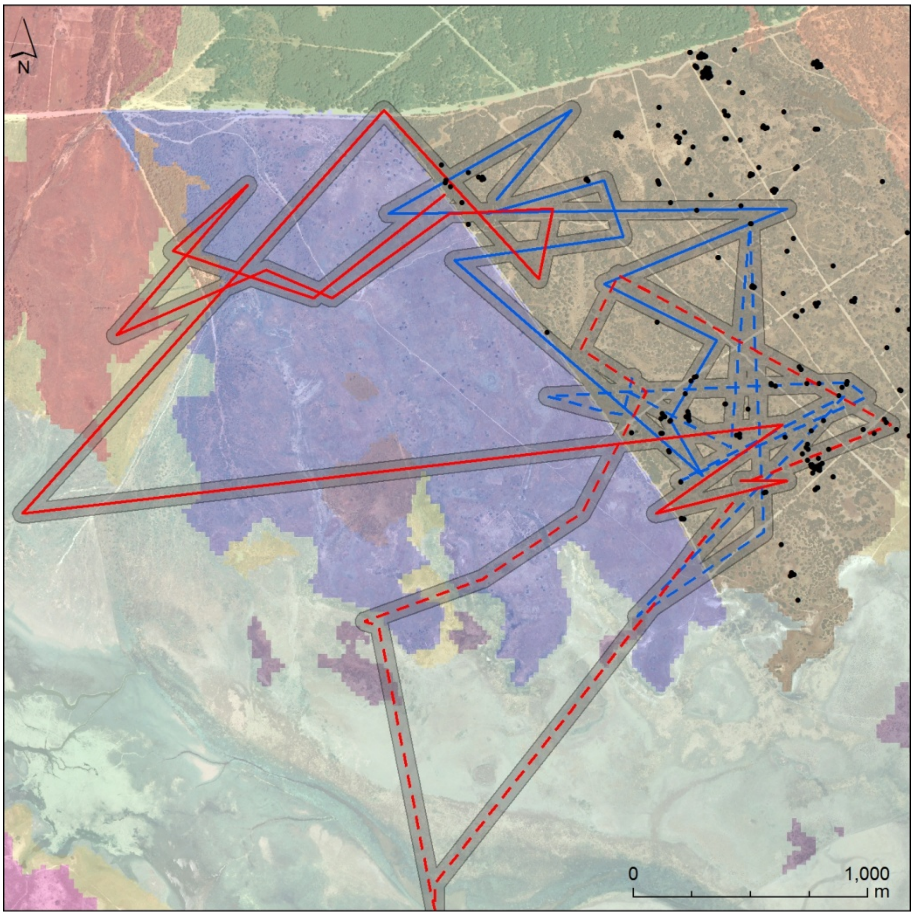


Figure A2: Examples of the 24h movements of two foxes (in red) and two badgers (blue). Continuous and discontinuous lines correspond to northern and southern spatial groups, respectively. The corridor width defining the patches potentially visited by each disperser during their movements (5patches) is represented by the shaded area at each side of the lines.

References

Fedriani JM 1997. Relaciones interespecíficas entre el lince Ibérico, *Lynx pardinus*, el zorro, *Vulpes vulpes*, y el tejón, *Meles meles*, en el Parque Nacional de Doñana. PhD Thesis. Universidad de Sevilla, Seville, Spain.

Fedriani JM and T. Wiegand. 2014. Hierarchical mechanisms of spatially contagious seed dispersal in complex seed-disperser networks. Ecology. doi: 10.1890/13-0718.1

Fedriani, J.M., Palomares F., and Delibes, M. 1999. Niche relations among three sympatric Mediterranean carnivores. Oecologia 121: 138-148

Fedriani JM, Zywiec M and M Delibes. 2012. Thieves or mutualists? Pulp feeders enhance local endozoochore recruitment. Ecology. 93:575–587.

Fedriani JM, Wiegand T. and M. Delibes. 2010. Spatial pattern of adult trees and the mammal-generated seed rain in the Iberian pear. Ecography 33:445-455.

Fedriani JM, T Wiegand, G Calvo, A Suárez-Esteban, M Jácome, M Żywiec, and Miguel Delibes. 2015. Unraveling density and distance dependence of plant reproduction using a spatially explicit framework. Journal of Ecology 5: 1344–1353.

Fedriani JM, T Wiegand, D Ayllón, F Palomares, A Suárez-Esteban and V. Grimm. 2018. *Assisting seed dispersers to restore old-fields: an individual-based model of the interactions among badgers, foxes, and Iberian pear trees.* Journal of Applied Ecology 55: 600–611.

Fedriani JM, PJ Garrote , G Calvo, M Delibes, AR Castilla and M Żywiec . 2019. *Combined effects of seed provenance, plant facilitation, and restoration site on revegetation success*. Journal of Applied Ecology 56: 996-1006.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., et al., 2006. A standard protocol for describing individual-based and agent-based models. Ecol. Model. 198, 115–296.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, G., Giske, J., Railsback, S.F., 2010. The ODD protocol: a review and first update. Ecol. Model. 221, 2760–2768.

Grimm, ,V., Railsback, S.F., Vincenot, C.E., Berger, U., Gallagher, C., DeAngelis, D.L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A.S.A., Milles, A., Nabe-Nielsen, J., Polhill, J.G., Radchuk, V., Rohwäder, M.S., Stillman, R.A., Thiele, J.C., Ayllón, C. 2020. The ODD protocol for describing agent-based and other simulation models: a second update to improve clarity, replication, and structural realism. Journal of Artificial Sociecities and Social Simulation. 23 (2) 7. http://jasss.soc.surrey.ac.uk/23/2/7.html

Railsback, S. F., Grimm, V. (2019). Agent-based and individual-based modeling: a practical introduction. 2nd edition. Princeton University Press.

Rey-Benayas, J. M., Bullock, J. M., and Newton, A. C. (2008). Creating woodland islets to reconcile ecological restoration, conservation, and agricultural land use. Frontiers in Ecology and the Environment 6: 329-336.

Wilensky, U., 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Appendix A3: Reasoning of disperser's spatial behavior.

Table A3: Reasoning of the commands used to simulate fox and badger spatial behavior during different periods of the circadian cycle. References: a, Fedriani JM (1997); b, Fedriani et al. (1999); c, Murray et al. (1995); d, Kruuk (1989); e, Macdonald (1987).

Submodel	Command short description	Rationale	References
disperser-towards-oldfield	Short-distance movements around dens at sunset	Both foxes and badgers are typically organized in spatial or social groups with somewhat exclusive home ranges. Based on our telemetry data, in the model we identify two spatial groups (i.e. southern or northern) both for foxes and badgers. Therefore, here and in subsequent submodels, dispersers are asked to move towards patches within the range of their corresponding spatial group. This does not prevent that individuals sometimes move out from their ranges either within the home range of the opposite social group or somewhere else. At sunset dispersers can make two distinct sorts of movements: 1) Prior to moving to foraging habitats (e.g. oldfield), both foxes and badgers usually explore the immediate vicinity of their dens. These small movements are thought to be related to territorial marking (feces, urine) as well as to the assessment and prevention of possible risks (e.g. predation, competitors).	a-b
	Movements towards foraging habitats	2) Foxes tend to forage on open habitats (marshes, oldfield) located on the western part of their spatial range, i.e. at the east of the center of their corresponding ellipse, and thus they are asked to orientate towards those habitats. These open habitats are preferred because: 1) of high abundance of diverse food items that comprise fox diet (rabbits, insects, carrion, etc), 2) they facilitate	a-e

		the typical foraging behavior of canids (i.e. chase their mobile prey). Badgers, however, forage on both close (scrubland) and open (e.g. marshes, oldfield) habitats. Badgers are therefore asked to orientate towards scrubland or towards the marshes within their spatial range. By orientating part of their movements towards the marshes, badgers also do use other open habitats that are in their way such as the oldfield and the prairie. This is largely because they are harvesters rather than hunters and base their diet on barely mobile prey (e.g. baby rabbits excavated from their dens), which are abundant in both open and close habitats.	
disperser-in-oldfield1	Keep moving within foraging habitats early at night	Early at night, foxes usually forage in open habitats though they also do some use of the scrubland. Thus, they are asked to orientate towards scrubland or towards the most western open habitats (marshes, cultivations, and prairie) although in the way they also use the oldfield. Badgers tend to orientate their movements towards both open (prairie, cultivations) and close habitats (scrubland).	a-b
disperser-in-oldfield2	Keep foraging and start to approach dens late at night	Late at night, dispersers keep active in their typical foraging habitats though sometimes move towards their dens (i.e. they avoid moving to the western part of their corresponding spatial range).	a-b
disperser-towards-scrubland	Moving towards dens at sunrise	At sunrise, both foxes and badgers most often move towards their dens or towards the scrubland where their dens are located.	a-b
disperser-in-scrubland	Stay or approach the den during daytime	During daytime both foxes and badgers virtually do no move if there already are in or very close to their den. Otherwise, they move towards their den.	a-b

References

Fedriani JM 1997. Relaciones interespecíficas entre el lince Ibérico, *Lynx pardinus*, el zorro, *Vulpes vulpes*, y el tejón, *Meles meles*, en el Parque Nacional de Doñana. PhD Thesis. Universidad de Sevilla, Seville, Spain.

Fedriani, J.M., Palomares F., and Delibes, M. 1999. Niche relations among three sympatric Mediterranean carnivores. Oecologia 121: 138-148.

Kruuk, H. (1989). The social badger: ecology and behavior of a group-living carnivore (*Meles meles*). Oxford University Press.

Macdonald, D. W. (1987). Running with the fox. New York: Facts on File Publications.

Murray DL, Boutin S, O'Donoghue M, Nams VO (1995) Hunting behaviour of a sympatric felid and canid in relation to vegetation cover. Anim Behav 50:1203-1210.

Appendix 4: Isolated impact of increased *Pyrus bourgaeana* tree mortality on (A) overall and habitat-specific seed dispersal accumulated during 25 years; and (B) overall accumulated number of produced fruits.