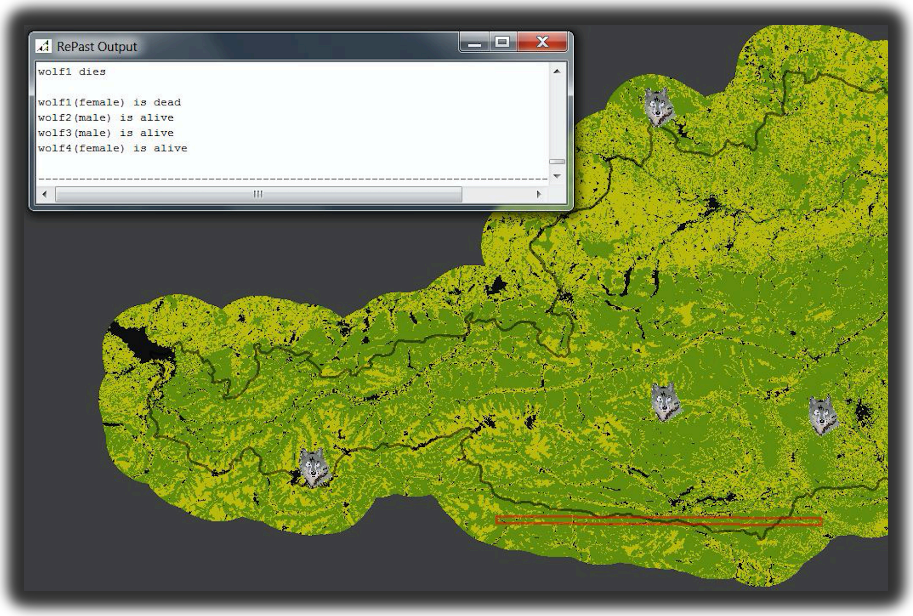
Developing a Human-Environment Agent Based Model to Assess Carnivore Recolonization Scenarios in Austria



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Summer 2015

Abstract

Austria is one of the last countries in Europe that has not been recolonized with stable populations of large carnivores (bear, wolves, and lynx), yet many dispersing individuals have been observed. Understanding the spatial and temporal patterns of the recolonization process can help prepare management agencies for conflict that may arise and allow for adaptive management, yet characterizations of the recolonization process are lacking in most areas where it is occuring. Here, a geospatial application of an agent-based model was explored as a potential tool in characterizing the spatial and temporal patterns of wolf recolonization in Austria. Submodels for wolf appearance in Austria, dispersal through a habitat suitability model, mating, pack formation, and death were developed in the RePast/Agent Analyst programming environment. The model was parameterized with a range of literature-derived values and validated using expert estimates of wolf population. Model outputs included the total wolf agent number, wolf agent presence locations, and the number and location of wolf packs that formed. Throughout model runs, wolf agent locations were predictably focused near where wolves appeared from neighboring populations; yet different parameterizations resulted in varied larger-scale movement patterns. About half of all model runs resulted in wolf pack formation, predominantly near the Slovenian and Italian borders, indicating that the model predicts recolonization is likely overall. Though this type of modeling involves several limitations, it can lend insight into the recolonization process that can be improved through the collection of more empirical data and greater understanding of carnivore decision-making in the literature.

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Chapter 1. Introduction

The combination of agent based modeling (ABM) and geographic information systems (GIS) allows the exploration of complex real world systems in a novel, process-based way (Macal and North, 2009). Using the potential of these technological frameworks together, physical, biological, and social variables can be integrated to derive insight into the space-time dynamics of environmental problems and to inform management decision making (An et al., 2015). Here, an ABM within the GIS framework is developed and demonstrated using an important and timely environmental issue in Austria with marked potential for human conflict: the recolonization of wolves into areas where they have been extinct for over a hundred years. Modeling the processes of wolf movement in Austria can give early insight into areas that might be priorities for environmental managers, allow the exploration of different potential scenarios for the recolonization process, and perhaps most importantly, create a framework that can be refined and expanded as more data become available and more is known about the recolonization process.

1.1 Large carnivore recolonization in Europe

Historically, humans have had a contentious relationship with large carnivores such as wolves, bears, and lynx (Kellert et al., 1996). Species that were once widespread throughout Europe and North America disappeared throughout much of their ranges by the early 20^{th} of century (Oakleaf et al., 2006;

Zeiler et al., 1999). Starting in the mid-1900s, attitudes toward large carnivores began to change positively in most developed countries, resulting in public and government support for the establishment of laws protecting them from hunting (Crook, 2012; Zeiler et al., 1999). In Europe, these changes have resulted in the expansion of species' ranges and increases in overall populations (IUCN, 2015). Sweden, Germany, Switzerland, and France, for example, have recently seen the formation of their first wolf packs in nearly a century (Enserink and Vogel, 2006). The importance of the return of large carnivores has been argued for aesthetic and ethical reasons (e.g. they deserve to be here and their existence adds to the human experience), scientific reasons (e.g. trophic cascades: a functional ecosystem requires top predators to be complete), and due to the idea that these charismatic species can attract funding and support for conservation on a larger scale (Barua, 2011; Linnell et al., 2005; Soulé and Terborgh, 1999).

However, there are many policy and management challenges inherent in negotiating the return of wolves, especially in the human dominated landscapes of Europe. In most areas, population expansion is occurring in areas of substantial livestock production, giving rise to conflict between government agencies, conservationists, and residents fearing for their livelihoods (Enserink and Vogel, 2006). In addition, many people still consider these predators a risk to human safety and as competitors for finite prey populations that hunters value (Bisi et al., 2010; Enserink and Vogel, 2006).

These points of conflict and misunderstanding have caused humans to persist as the primary threat to carnivore populations: for instance, one study tracking dispersing wolves in Spain identified illegal hunting and automobile strikes as the cause of twelve out of thirteen wolf deaths (Blanco and Cortés, 2007). Predicting the dynamics of range expansion and recolonization can help in addressing some of these issues, allowing for management plans that are prepared to deal with conflict (Marucco and McIntire, 2010). Specifically, agent based models incorporating behaviors at the individual level through both space and time have been identified as key in exploring policy scenarios and designing effective adaptive management plans (Chapron and Arlettaz, 2006).

1.2 Agent based modeling for dispersal and range extension

Agent based modeling (ABM) and simulation, also called individual-based modeling in the ecological modeling literature, is a relatively new, rapidly growing field of research within geoinformatics that consists of modeling individual autonomous agents' interactions over space and through time based on predetermined parameters and programmed rule sets (Macal and North, 2009). Human-environment systems are ideal for evaluating the potential of ABM simulation models in integrating multiple systems due to their inherent complexity features and because different parts of the system generally operate at different temporal and spatial scales (An and Crook, In press). In these cases, ABMs consist of representations of the individual components of the parts of the system (such as individual animals, humans, defined habitat/landscape areas) that interact over time based on goals, rule-sets, feedbacks, and learning that are all programmed into the model using an object oriented programming language (Parker et al., 2003).

ABMs have been shown to reliably represent behavioral ecology through the modeling of a species' habitat-selection and movement (Pitt et al., 2003; Rabinowitz and Zeller, 2010; Semeniuk et al., 2011). After the construction of the computational model, it can be used in the analysis of the potential implementation of policies that could affect the trajectory of the human-environment system (Watkins et al., 2011). For example, Marucco et al (2010) use agent based modeling to predict wolf recolonization over a 5-15 year time span in the French-Italian border region by incorporating data on social structure, dispersal, habitat selection, reproduction, and mortality. They extend this model to investigate wolf depredation (livestock consumption) risks over space. In another example, Watkins et al. (2011) analyze the efficacy of different habitat corridor designs for jaguars in Belize using a least cost approach for simulating jaguar movement.

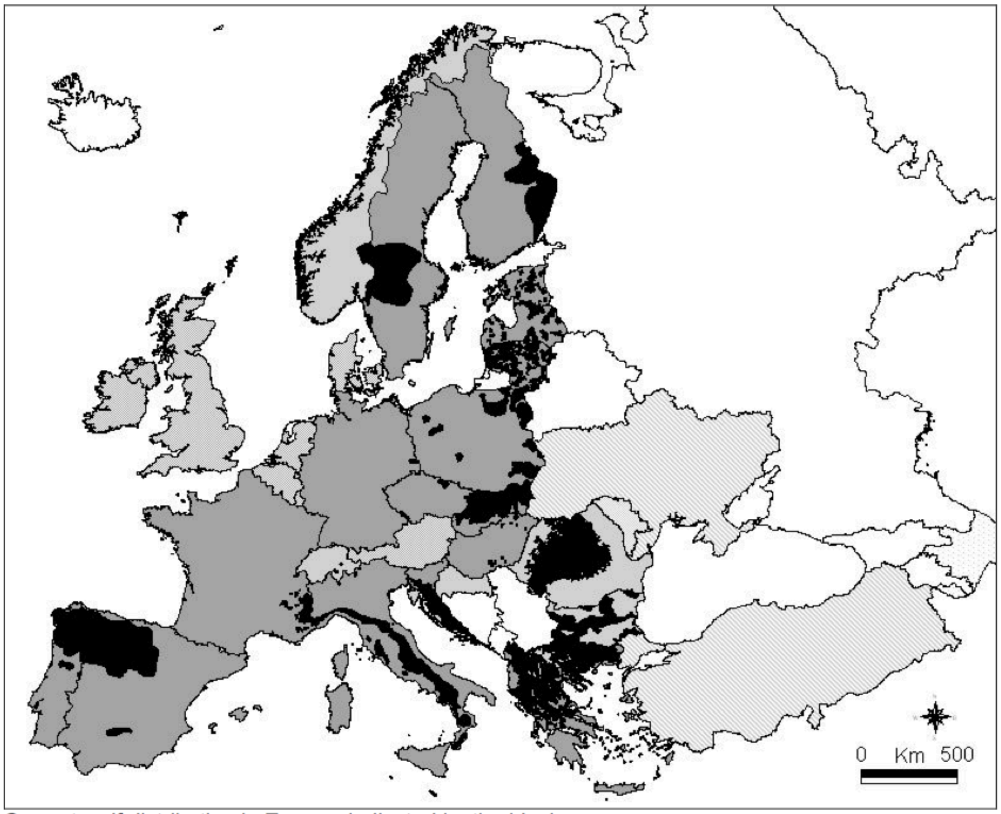
1.3 Current research

The current research seeks to use an agent based model to predict the spatio-temporal patterns of wolf recolonization in Austria. The goal is to recreate the current situation by using theoretical parameters for wolf presence, movement, and behavior derived from the literature. Over several runs, the number of packs formed, the number of wolves present, and the average number of wolves existing at a given time over a five-year period can be modeled. Additionally, we can predict the possible spatial configuration of dispersal and new pack formation in Austria. Then, the model can be used to explore different scenarios (wolf reintroduction, improvement of attitudes, etc). Ultimately, such models can inform management planning and preparation of local populations for wolf recolonization at suitable spatial and temporal scales.

1.4 Study area

Austria is a landlocked country in central Europe with a population of about 8 million and a total area of 83,871 square kilometers (CIA, 2015). It is located at an important geographic crossroads, straddling both sides of the alps in the West and containing gently sloping plains in the North and East. Nearly half of the country (47.2%) is covered in forest (CIA, 2015).

Austria was historically home to healthy populations of wolves, however by 1882 all breeding populations were hunted, poisoned, and trapped to local extinction by humans (Dungler, 2008). During the 20th century, fewer than two dozen wolves were observed, all of which were thought to have been immigrating from neighboring countries (Schafer, 2012). Starting in the second half of the 20th century, wolf populations all over Europe have been strengthening and expanding (Figure 1).



Current wolf distribution in Europe, indicated by the black areas.

Legend

- Countries with recorded wolf presence, not included in the EU, that have ratified the Bern Convention.
- Countries with recorded wolf presence, included in the EU, that have ratified the Bern Convention.
- Countries with recorded wolf presence, not included in the EU, that have ratified the Bern Convention, for which a map was not available.
- Countries not included in the EU, that have ratified the Bern Convention, not included in the present report.
- EU countries where wolf is absent.
- Countries not included in the EU, and that have not ratified the Bern Convention.

Figure 1 – Wolf distribution in Europe in 2005, with Austria standing out as being wolf-free (from Salvatori and Linnell, 2005).

These expanding wolf populations have resulted in a substantial increase in the number of wolf encounters in Austria since the late 1990s (Figure 2). It is estimated that between 2009 and 2011 there were between two and eight wolves at any given time within Austria (Schafer, 2012).

Figure 2 – Photograph from camera trap of escaped wolf “Fritzi” in Styria (Photo from Kleinzeitung, 2015)

Genetic evidence has helped in identifying the source populations of the solitary dispersers that have been observed, indicating that they have arrived from the Balkan, Carpathian, and Appenine/Western Alps populations (Figure 3; Schafer, 2012). Despite an increase in dispersing individuals, pack establishment has not yet occurred in Austria. For pack establishment, the coincidence of a number of different phenomenon needs to occur: the meeting of more than one wolf, the presence of suitable habitat, and the existence of favorable policies/management plan that ensures protection in the face of poaching, automobile strikes, and retaliatory killings.

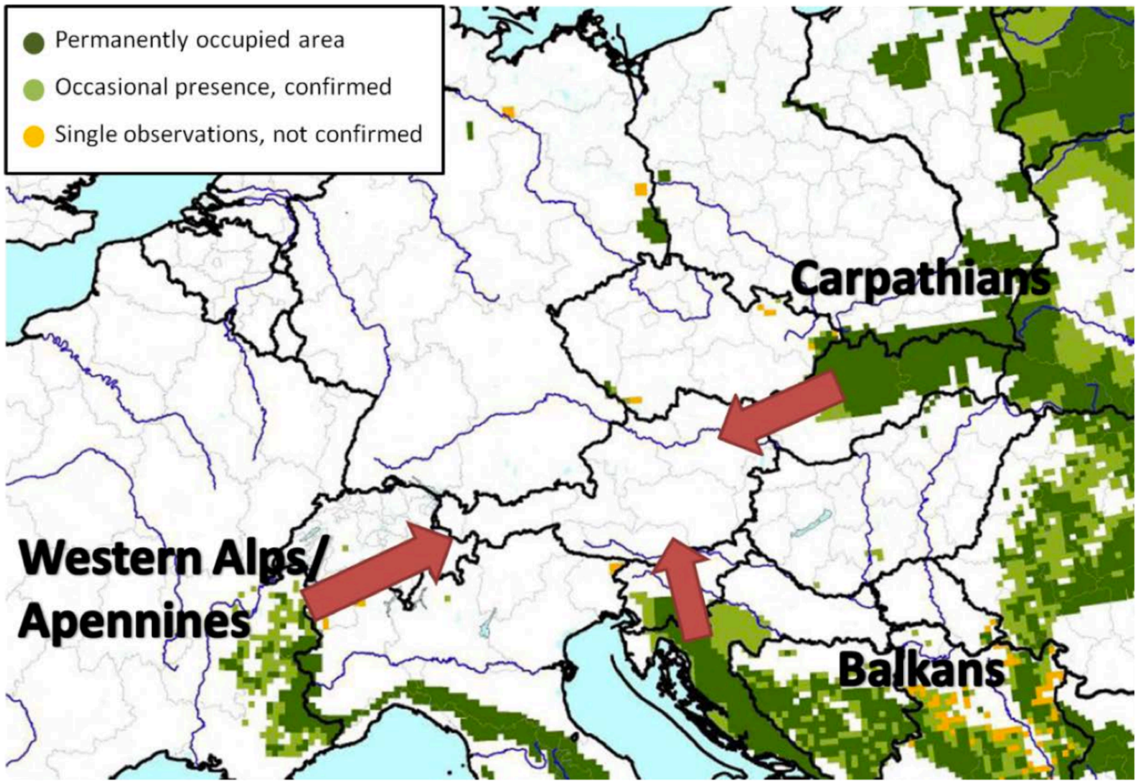


Figure 3 – Source populations for wolves migrating into Austria (From Schafer, 2012; KORA/LCIE, 2007; Rauer, 2010)

Chapter 2. Methods and Model Overview, Design, and Details (ODD)

2.1 Habitat Suitability

European Union Corine land cover datasets were used to derive rudimentary habitat suitability for wolves (Figures 4 and 5). The 44 Corine land cover classes were reclassified into either 1) low, 2) medium, or 3) high suitability as wolf habitat. These groupings represent land cover types a wolf might 1) avoid, 2) consider suitable for transit, 3) consider suitable as core habitat.

The Corine Level 1 land cover classification consists of five high level classes: artificial surfaces (class 1), agricultural areas (class 2), forests and semi-natural areas (class 3), wetlands (class 4), and water bodies (class 5). Artificial surfaces, urban areas, wetlands, water bodies, and some of the "forests and semi-natural areas" (e.g. glaciers and perpetual snow) were classified as low suitability habitat. Agricultural areas made up the medium suitability class. Most of the forests and semi-natural areas subgroups (apart from those listed above) were classified as high suitability habitat.

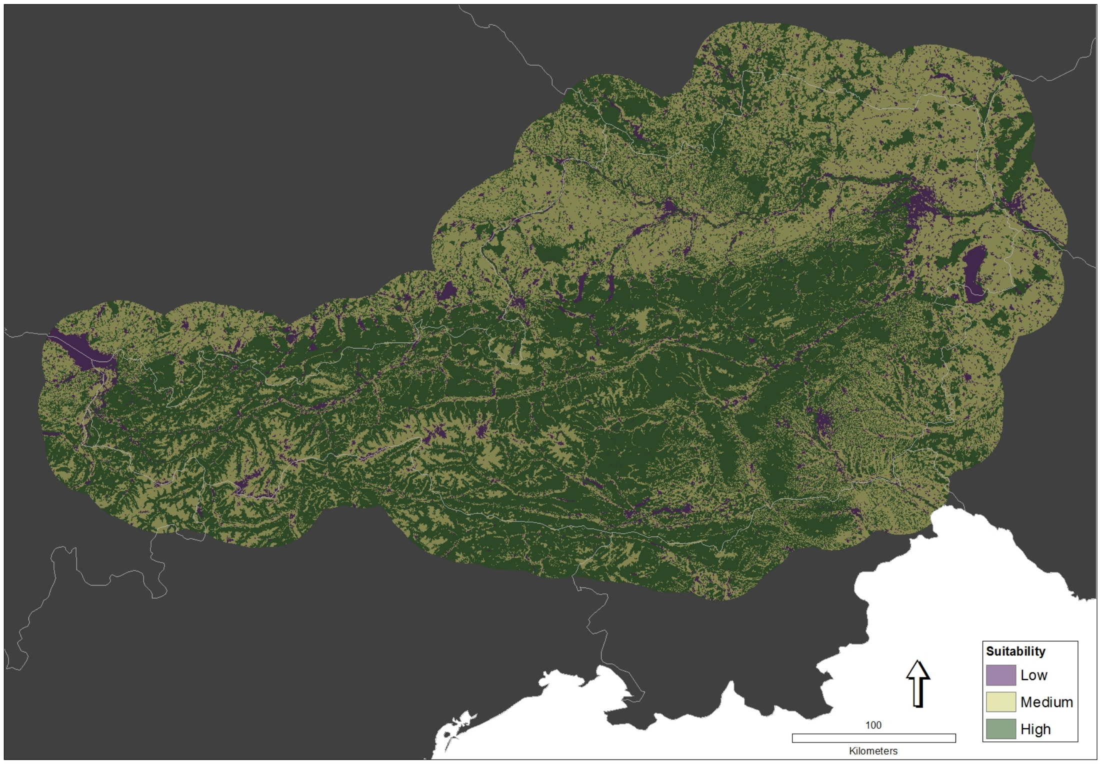


Figure 4 –Habitat suitability map of the entire study area

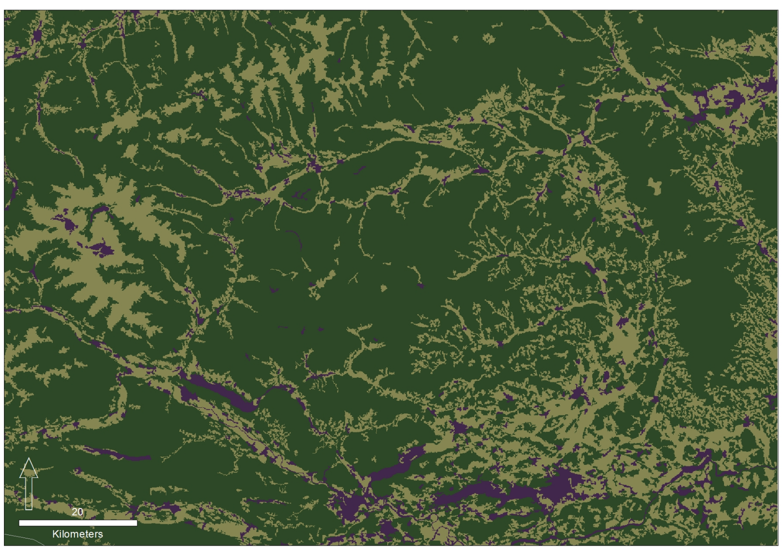


Figure 5 – Large scale habitat suitability example – south-central Carinthia.

2.2 Agent Analyst

The programming of rule-sets and wolf agent attributes was implemented using Agent Analyst, an open source extension to the ArcGIS GIS software suite. Agent Analyst combines the strengths of the well-established Recursive Porous Agent Simulation Toolkit (Repast) ABM software with the spatial database and display functionalities of ArcGIS (North et al., 2006). It works by linking and integrating the two programs: ArcGIS provides an environment for visual display of simulations, data creation, data management, and GIS analysis while Repast allows rule set programming and easy scheduling of submodels. Programming in the Agent Analyst environment uses the “Not Quite Python” programming language, which is a python-like language that enables access the Java-based libraries of Repast (Johnston et al., 2013).

2.3 ODD Protocol

The description of the methods used to construct the Austria Wolf Recolonization Model follows the ODD (Overview, Design concepts, Details) protocol that has become the standard for describing Agent Based Models (Grimm et al., 2010, 2006; Railsback and Grimm, 2012).

2.3.1 Overview

Purpose

The purpose of the model is to simulate wolf dispersal and pack formation in Austria. Once movement patterns have been established, the model is intended to assess the potential of exploring different scenarios resulting in wolf recolonization via pack formation.

Entities, state variables and scales

The model contains three entities: individual wolf agents, packs formed by multiple wolf agents, and the environment over which processes operate. Wolf agents are described by the following state variables: their name/id number, their location (x and y coordinates), whether they are alive or dead, their sex, whether they have mated, and whether they have formed a pack.

Individual wolf agents operate over an environment consisting of a rudimentary habitat suitability model (Figure 4 and Figure 5). All pixels in the study area are placed in one of three categories (0, 1, or 2) corresponding to low, medium, or high habitat suitability (see **Habitat Suitability** section above for more details). Each suitability pixel is 100 meters x 100 meters. For more information on model variables, see **Table A2 in Appendix 1.**

Packs can also be considered entities, and are formed as the outcome of a number of different decision and proximity-based rules for wolf agents. A pack is created as a two dimensional area in the “packs” raster. The spatial extent of a pack depends on the pack size input parameter.

The spatial extent of the model includes an area slightly larger than the boundaries of Austria (approximately 600 x 350 km). The habitat suitability raster was created to include a 30km buffer of Austria's national boundary. Individual wolves, however, are able to travel outside this area (though there are rules introduced that make it difficult for them to exist "alive" for very long outside of the suitability raster, simulating their migration away from the study area).

Each model time step represents two weeks of time. For the movement submodel, there are substeps in which the wolf agents decide on movement destination on an hourly basis. The model is intended to be run over moderate temporal scales and a five-year time period is demonstrated here. This corresponds to one hundred and thirty time steps.

Process Overview and Scheduling

The model proceeds in biweekly (one time step makes up two weeks) time steps as illustrated in Figure 6**.** There is an initialization step prior to each model run, in which rasters are loaded into the model and starting wolves are placed according to the number specified in model run parameters. In each of the subsequent model steps, a number of actions take place for each wolf in order of the wolf's ID number.

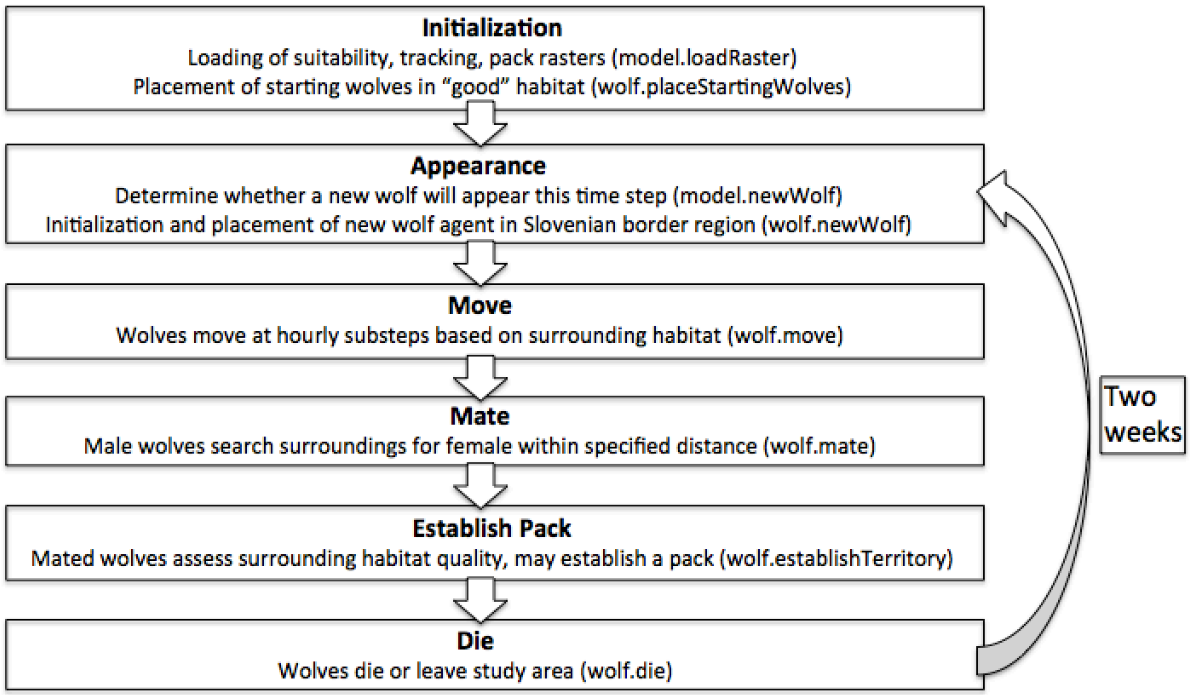


Figure 6 – Process overview and scheduling

First, new wolves appear in the model environment in the *appear* submodel. Then, the *move* submodel runs, in which wolf agent dispersal occurs at hourly substeps. Next, in the *mate* submodel, wolves search for a mate, and potentially form a pair (depending on input parameter values). If there are wolves who have formed a pair, the *establish pack* submodel determines if there is sufficient good quality habitat to support a pack (again, determined by user specified input parameters about the percentage of good habitat required). Finally, the *die* submodel results in wolf agents dying based on mortality probabilities or by leaving the study area.

2.3.2 Design Concepts

Basic Principles

The basic principle of the Austria Wolf Model is to give information to assess whether qualitatively described patterns of wolf dispersal, presence, and behavior in Austria can be used to estimate the likelihood that permanent wolf populations may be formed in the country (as wolf packs).

Emergence

The Austria Wolf Model includes the concept of emergence by capturing the system level phenomenon of wolf populations and pack formation over a large area through the decisions and movement of individuals. Formation of packs, and the number of packs formed, are wholly results of rule sets that arise from individual wolf agents' decision-making and stochasticity.

Objectives

The rule sets of the model are designed to make the establishment of a pack the ultimate objective of wolf agents.

Sensing

The model includes sensing in three ways. First, the wolf agents are able to sense the land cover type of the surrounding environment. First, as part of the move method, wolf agents move via a biased random walk by checking the environment pixel where they may move to and deciding whether or not to move there based on specified probabilities for each land cover type. Second, male wolves look around themselves at every time step to find potential mates, sensing the presence of female wolves within a specified radius. Finally, wolf agents that have found a potential mate once again sense land cover types surrounding themselves, tabulating how many nearby pixels are of suitable habitat for pack formation.

Interaction

Wolf agents may interact with each other at two points during a time step. First, wolves of opposite sex are considered potential mates based on proximity and may, based on specified probabilities, mark each other as a mate. Then, based on their assessment of surrounding habitat, they may form a pack by changing each other's establishTerritory field.

Stochasticity

The model contains a substantial amount of stochasticity in order to establish the range of possibilities inherent in different model scenarios. The distances wolves travel in a given two week period are the sum of distances randomly drawn hourly from a normal distribution based on mean wolf movement distances over longer time periods. The decision of whether or not to move to different habitat types is based on drawing from random distributions. Mortality at each step is determined by a certain probability specified in model parameters.

Furthermore, the decision to mate upon meeting a wolf of the opposite sex can be assigned a probability (though this probability is set to 1 by default).

Collectives

The model does not explicitly model collectives, but the formation of packs can be seen as the beginning of the formation of a collective. Future models should consider implementing this design concept by allowing packs to have their own decision rules.

Observation

During model runs, the spatial distribution of wolves and packs at each time step can be observed. For analysis over several model runs, the number of packs formed and the average number of wolves alive at each time step over the five-year period are compiled and reported to compare scenarios. Additionally, all of the locations wolves ended up at the end of each time step and all of the packs formed over several model runs are written to separate raster files to allow a spatial overview of movement density. Pack areas can be output to see where are likely locations of pack formation (though this was only done as an example for some model runs here because the writing of pack areas to raster is computationally intensive).

2.3.3 Details

Initialization

Prior to the first time step, the environment is loaded into the model, and "starting wolves" are placed on the landscape, representing the wolves that are already in Austria. The number of these wolves is selected by the user prior to the model run. Each starting wolf is randomly placed in "good" habitat within the national borders of Austria.

Input

The environment is based on an external data file. Corrine land cover classification data (2006) at 100m spatial resolution was adapted to create a habitat suitability model for Austria (see *Habitat Suitability* section) and a 30 km buffer around Austria (European Environment Agency).

Submodels

Each time step, the following submodels are run: *appear, move, mate, establish pack, and die* (Figure 6). The *appear* submodel requires code to be run at two levels: at the model level and the individual wolf level At the model level, at each time step, the annual rate of new wolf appearance parameter is converted to a biweekly probability using the following equation:

$$P = 1-e^{-\lambda t}$$

A random number between 0 and 1 is drawn at each time step, and if that number is smaller than the biweekly probability, a wolf agent is created Variables specifying the ID number of the next wolf in line to be activated and that there will be a wolf agent activated this time step are passed to the agent/wolf level code. While the model level code indicates that a new wolf will be created, the wolf level submodel activates the individual wolf (nextWolf), turning its “alive” variable set to 1 (alive).

A random draw determines whether the new wolf will come from the Carpathian, Alpine, or Dinaric population source according to the probabilities assigned to each in the specified parameters (default dictates a 50% chance of a wolf being from Dinaric population, and 25% chance for the Carpathian and Alpine populations). Then, the sex of the new wolf is set according to a random number draw that is compared to the input parameter for probability of new wolf agents being female (model default states that 75% of new wolves will be male, based on expert estimates). Finally, the new wolf is randomly placed within the start box of the corresponding source population (Figure 7).

Figure 7 – Start boxes for the three source populations with overlay showing previous research outlining proposed dispersal corridors (From Schafer, 2012; KORA/LCIE 2007; Rauer 2010).

The *move* submodel is run by all living wolf agents (self.alive = 1) that have not established a pack (self.establishPack = 0). In it, wolf agents move hourly based on average movement distances and surrounding habitat types. First, the daily average and standard deviations for movement (model parameters) are converted to hourly distances. For each wolf agent, 336 hourly movement decisions take place at every time step. At each of the 336 hours, X and Y distances for movement are randomly drawn from a normal distribution of hourly mean distance and hourly standard deviation variables. Direction (whether the X and Y movements are in the positive or negative directions) is chosen based on random binary draw.

While the potential movement distances and directions are established here, the wolf agent only moves after considering habitat suitability (subject to randomness), undertaking a movement trajectory that can be considered a biased random walk. The action works as follows: at each hourly time step, the wolf agent checks the suitability of the proposed cell established above. Using random number generators, the following rules are applied: if the suitability of the cell is low, the wolf agent has a 5% chance of moving to it, if the suitability is medium, the wolf agent has a 75% chance of moving to it, if the suitability is good, the wolf agent has a 95% chance of moving to it, and if the cell is out of bounds, the wolf agent has a 70% chance of moving to it. If the wolf agent moves out of bounds, there is a chance it leaves the study area completely (see the *die* submodel for more information about this decision rule).

The *mate* submodel allows wolf agents to detect other wolf agents of the opposite sex within a specified radius (model parameter). The submodel is run for all "male" wolf agents that are "alive" and have not already found a mate. Each male wolf agent calculates distance to all female wolves according to:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

If the distance between a male wolf agent and a female wolf agent is less than the parameter value for the minimum distance for detecting a mate, a random number draw takes place. If the parameter for mating probability is less than the random number draw, the wolf agents are marked as potential mates and their foundMate variable is changed to 1.

The *Establish Pack* submodel is run by all male wolf agents that have found a mate and have not already established a pack. In this submodel, the wolf agent checks surrounding territory for suitability. If it finds the requisite percentage of suitable territory (model parameter), it establishes a pack. First, bounds of the potential pack area are calculated by converting wolf location in map coordinates to wolf location on the raster grid. Minimum and maximum bounding pixels define the potential pack box based on packArea parameter (km^2). The wolf checks every pixel within the potential pack box, summing pixels of good habitat and the total pixels of pixels, ultimately coming up with a measure of the percentage of good habitat within the potential pack box. If the percentage of good habitat is greater than the percentGoodHabitatForPack parameter, the wolf establishes a pack. The wolf agent then outputs the location of the pack to raster by writing new pixel values to each pixel within the pack box (this, however, is computationally taxing and has only been demonstrated for select model runs here).

The *die* submodel is run by each living wolf agent. The annual mortality rate is converted to biweekly mortality probability (using equation 1), and a random decimal between 0 and 1 is drawn for each living wolf agent at each time step. If the random number is less than the mortality probability, the wolf agent is no longer considered alive (and therefore no longer carries out any of the submodels listed above).

In addition to death due to random probabilities, out of bounds wolf agents (found to finish the turn out of the study area during the *move* submodel) have a 25% chance of “leaving” the study area (thus no longer being considered alive). This means, however, that they have a 75% chance to remain alive, return to the study area, and persist for future time steps even if out of the study area.

Model parameters and calibration

Because wolf recolonization is poorly understood in Austria, and only fragmented data exist regarding wolf movement and presence in the country, the model was primarily parameterized using a range of literature values (Table 1). Values for specific wolf behaviors derived from the literature were related to average movement distance, average mortality, the distance wolves can detect potential mates, the area required for a pack, and the number of starting wolves in Austria. Parameters qualitatively derived from general literature review or set as placeholders pending new information on the process included the rate of new wolf appearance, the amount of good habitat required within the pack area for a pack to form, and mating probability.

Table 1 Start Parameters			
Parameter	**Estimate Range**	**Units**	**Source**
mortRate	0.44-0.76	Annual death rate	Blanco and Cortes (2007), Marucco and McIntire (2010)*
newWolfRate	~2.8	Wolves per year	
startingWolvesInAustria	2-8	Wolves	Schafer (2012)*
meanDailyDispersal	22.8-27.4	km/day	Jedrezejewski et al. (2001), Ciucci et al. (1997)*
sdDailyDispersal	~25	km/day	Mech (1970)*
mateSearchRadius	20.7-39.2	km	Hurford et al. (2006)*
mateProbability	1	unitless	Hurford et al. (2006)*
packArea	173-294	km^2	Okarma et al. (1998)*
percentGoodHabitatForPack	-	good habitat %	
probFemale	0.25		Rauer (personal communication, 2015)*
probDinaric	0.50		Rauer (personal communication, 2015)*
probCarpathian	0.25		Rauer (personal communication, 2015)*
probAlpine	0.25		Rauer (personal communication, 2015)*
	*See Appendix 2 for details		

Table 1 – Start parameters

Three different models were run ten times each to reflect the range of literature-derived parameters (Table 2). These models were meant to demonstrate the range of possible situations that may reflect the real-world system. The first model (M1) used the values which would likely lead to lower probabilities of wolf recolonization. The second model (M2) used the values which would likely lead to higher probabilities of wolf recolonization. The third model (M3) used intermediate values which would lead to moderate probabilities of wolf recolonization.

Table 2 Model Parameters

Parameter	Model #1 (Low likelihood)	Model #2 (High likelihood)	Model #3 (Middle likelihood)	Model #4 (Scenario)	Units
mortRate	0.76	0.44	0.60	0.33	Death rate per year
newWolfRate	2	3	3	4	Wolves per year
startingWolvesInAustria	2	8	5	5	Wolves
meanDailyDispersal	16.12	19.37	17.75	12.00	km/day (x and y)
sdDailyDispersal	16	19	17.50	12.00	km/day (x and y)
mateSearchRadius	20.7	39.2	30.2	30.2	km
mateProbability	1	1	1	1	unitless
packArea	234	173	204	204	km^2
percentGoodHabitatForPack	0.85	0.75	0.80	0.80	percent good habitat
probFemale	0.25	0.25	0.25	0.25	
probDinaric	0.50	0.50	0.50	0.50	
probCarpathian	0.25	0.25	0.25	0.25	
probAlpine	0.25	0.25	0.25	0.25	

*Mortality set to non-disperser level (from Marucco and McIntire, 2010; Cortez and Blanco, 2009)

Table 2 – Start parameters for different models runs

2.3.4 Model validation and Scenario Experiments

Model validation

Model validation was conducted using estimates of the average number of wolves present in Austria at a given time and based on estimates of the approximate total number of wolves that have been noted in Austria provided by an expert in Austrian wolves who has collected genetic data on wolf presence (Rauer 2015, personal communication). The four models were assessed by how closely they fit these estimates of around 5 wolves on average and 17-18 wolves total over the last five year period. Because the model is intended to predict and pack formation, which has not yet happened in the area, there is no appropriate data for spatial validation, and model outputs should be viewed as exploratory.

Scenario experiment

As ABMs are designed to allow scenario exploration, a scenario with modified start parameters (M4) was demonstrated. This scenario assumed a lower mortality rate, higher new wolf rate to simulate improved attitudes and/or friendlier policies toward wolves in Austria and surrounding countries. In addition, the mean dispersal distance was reduced to decrease the number of wolves leaving the study area. There is substantial room for further scenario development in such a model, including the ability to explore reintroduction of wolves (as demonstrated in Yellowstone National Park, USA) by specifically placing start wolves in good quality habitat, or by further increasing the new wolf rate to simulate population growth in the source populations surrounding the study area.

Chapter 3. Results: Model Output

3.1 Wolf agent survivorship

Model output included the total number of wolves that were alive in the study area over each entire model run and the average number of wolves alive at a given time step. The total number of wolves over the entire model run ranged from 8 to 27 in models M1-M3, with the averages being 11.6, 21.7, 17.4, respectively. The average number of wolves alive at a given time step ranged from .62 to 2.81 in Models M1-M3. Scenario M4 had higher total numbers of wolf agents and higher average number of wolf agents (23.5, 5.38)

Table 3 Number of wolves

	M1 Total	M1 Avg	M2 Total	M2 Avg	M3 Total	M3 Avg	M4 Total	M4 Avg
Run 1	15	2.48	20	3.32	18	2.19	24	4.02
Run 2	8	0.96	18	1.81	18	2.66	22	4.40
Run 3	10	1.30	25	3.37	12	1.20	22	5.79
Run 4	8	0.93	27	5.27	14	2.22	23	5.71
Run 5	10	1.61	19	2.02	23	2.81	28	7.18
Run 6	14	0.62	20	2.08	20	2.64	28	5.39
Run 7	11	0.80	25	5.11	19	2.43	24	4.48
Run 8	11	1.35	25	4.09	19	1.83	21	5.48
Run 9	17	1.55	22	3.42	14	1.58	21	4.66
Run 10	12	1.66	16	3.12	17	2.19	22	6.73
Average	11.60	1.33	21.70	3.36	17.40	2.18	23.50	5.38

Table 3 - Total number of wolves and average wolf population

3.2 Wolf agent movement

At each time step, wolf agent location was documented by changing the value of the underlying pixel in the *tracking* raster. Aggregate locations of each wolf at each time step over the ten runs of each model were collected for visualization through the use of kernel density estimation (KDE). Figure 8 shows KDE for the wolf agent presence locations over ten model runs, indicating hotspots of wolf presence over the course of the model runs. All models show a similar primary pattern (that could have been fairly easily predicted): that there are well-defined hotspots near wolf start locations and that presence densities generally decrease away from these areas.

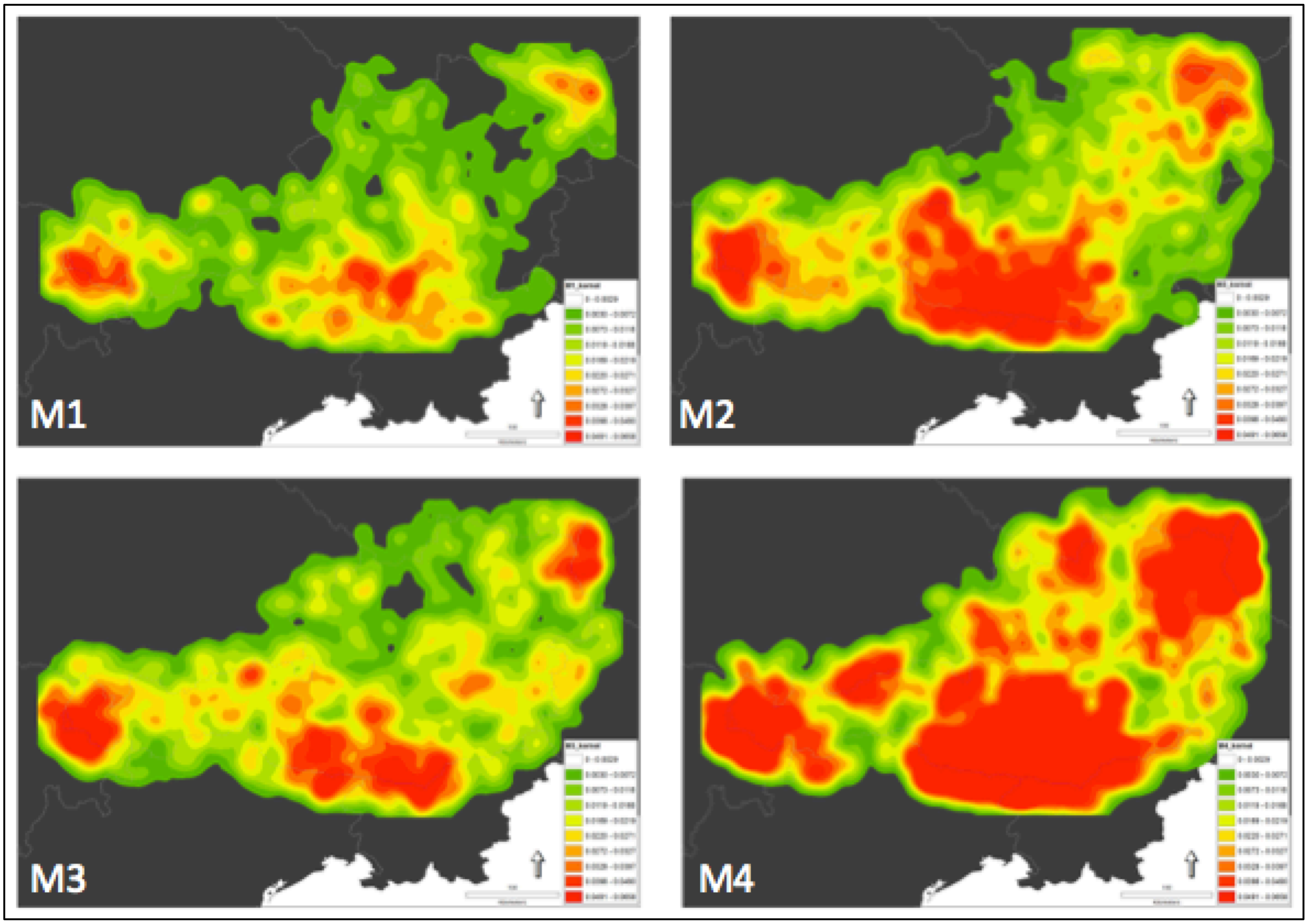


Figure 8 – Kernel Density Estimation of wolf presence locations for each model.

However, other patterns seen in these maps help identify other areas of likely wolf presence and areas that may be considered potential movement corridors. M1 appears to have low connectivity, but better connectivity between the Dinaric and Alpine start areas than the Dinaric and Carpathian start areas. M2 seems to show corridor patterns between start areas rather than well-defined hotspots. Specifically, a corridor toward the northwest part of the Dinaric start area (Western Salzburgerland) appears to be well defined. M3 has more clustered hotspots than apparent corridors: one halfway between the Dinaric and Carpathian start areas and one between the Alpine and Dinaric start areas. M4 has two well-defined hotspots: one in the north central part of the study area (an area that shows low wolf presence in other models) and between the Alpine and Dinaric start areas.

3.3 Pack formation

Individual model runs over the five year study period resulted in up to three packs being formed (Table 4). The probability of pack formation differed depending on the model used. Over ten model runs, no packs were formed using M1, between zero and three packs for M2, and between zero and two packs for M3 and M4. The average number of packs formed was 1.20 for M2, .50 for M3, and 1.10 for M4.

Table 4 Number of packs				
	M1	**M2**	**M3**	**M4**
Run 1	0	1	0	1
Run 2	0	1	0	0
Run 3	0	1	0	0
Run 4	0	1	1	1
Run 5	0	2	2	2
Run 6	0	0	0	2
Run 7	0	3	0	1
Run 8	0	1	1	2
Run 9	0	1	0	0
Run 10	0	1	1	2
Average	0.00	1.20	0.50	1.10

Table 4 – Number of packs formed for each model run

Data about the origin of wolf agents that formed packs was recorded during each model run. In all cases, wolf agents mated with a member of their own source population or with a wolf agent of unknown source location (one of the “starting” wolf agents that was placed upon initialization of the model). This means that model outputs showed no mixing of different source populations.

3.4 Pack locations

Locations of pack formation were written to the “packs” raster layer for each of the ten runs for a given model, resulting in a map showing all areas that were included in one or more packs (Results for M4 shown in Figure 7, below). In the ten runs of M4, it is clear that the majority of packs were formed near where

Austria, Slovenia, and Italy meet, along the start box for new Dinaric wolves. This makes sense given that new wolves are more likely to come from that area than the other two start areas. A number of packs, however, were formed in other areas that seem to have large amounts of good habitat further to the north and to the east of the Dinaric start box. These packs are the result of the meeting of two start wolf agents that do not have a specific origin or due to a Dinaric wolf agent meeting a starting wolf agent.

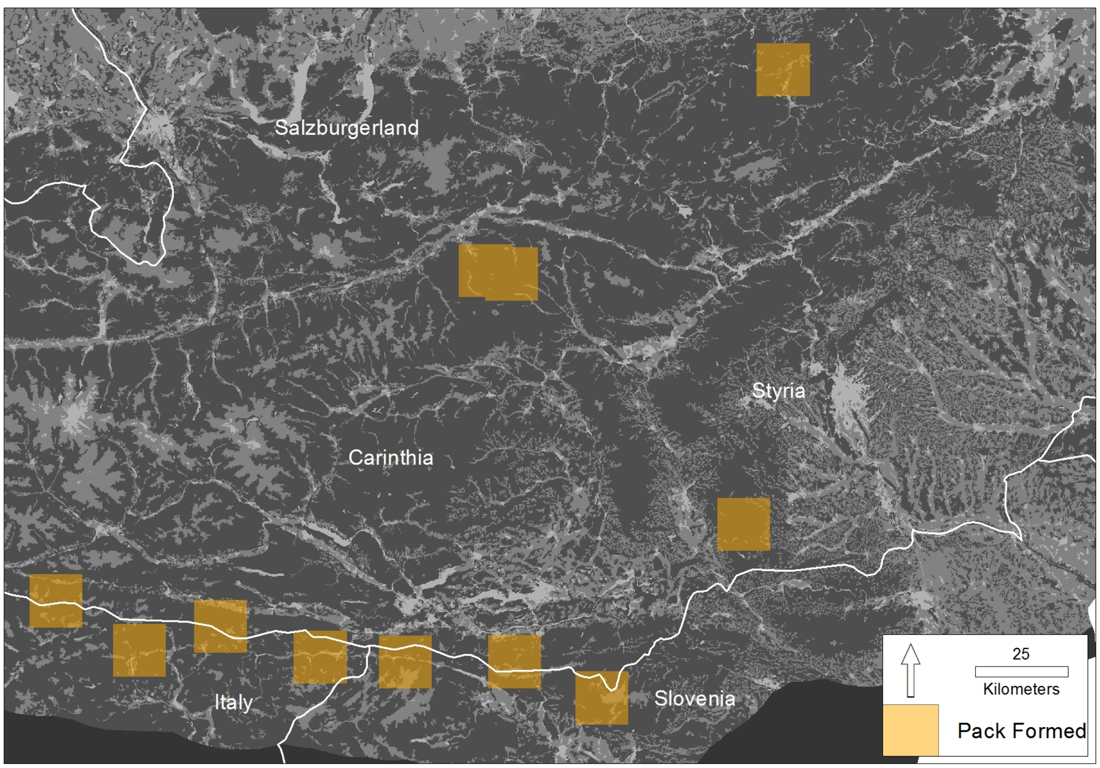


Figure 9 – Example of the locations of pack formation (showing all packs formed over the ten model runs of M4).

3.5 Pack formation timeline

Details on the time step of pack formation for the four models were compiled (Figure 9). M2 demonstrates a high degree of early pack formation, followed by few packs being formed in later time steps. Meanwhile, M3 shows the opposite trend: despite few total packs, most were formed in the second half of model runs. Finally, M4 shows a fairly uniform distribution for pack formation, with similar numbers of packs being formed in early and late time steps.

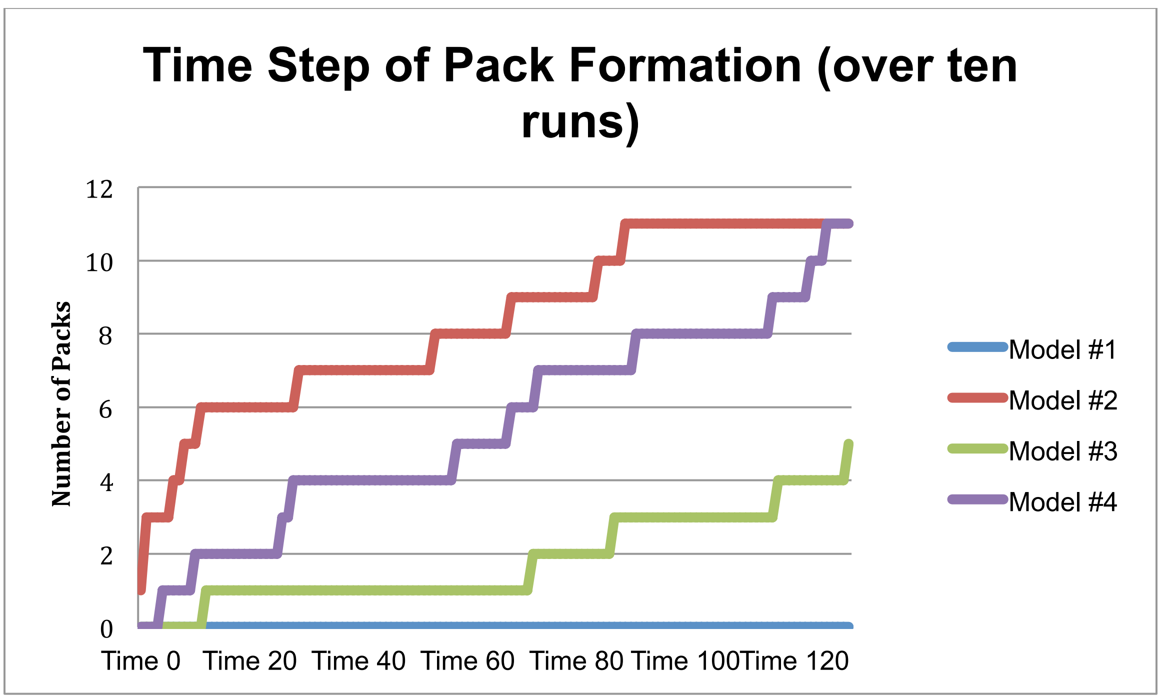


Figure 10 – Time step of pack formation over ten runs of each model.

Chapter 4. Discussion and Conclusion

4.1 Model success

The Austria Wolf Model developed here demonstrates the use of agent based modeling in describing the phenomenon of wolf recolonization in Austria using literature based values on wolf movement and behavior for model parameterization. Though there was little data for empirical validation, comparison of model output with expert knowledge about recent population and distribution of wolves in Austria indicates approximate correspondence. Model run averages for the high likelihood model (M3) indicated an average of over 3 wolves alive in Austria at a given time step while expert estimates were that there were usually around 5 wolves in the past five years (with another range of estimates given as between 2 and 8 wolves in a given year). This model also had an average total of 21.7 total wolves over a model run compared to estimates of 17-18 over the last five year period. It is apparent that minor changes to model parameters that are still within the realm of realistic values can result in outcomes even closer to estimates of reality. For instance, M4 (the improved attitudes scenario) resulted in an average of 5.38 wolves at a given time step (extremely close to the expert estimate of ~5 wolves on average in the last five years).

This model does not purport to be an accurate prediction of where and when recolonization will occur. Instead, it is a learning tool that helps in formalizing the system of interest and by demonstrating the mechanisms that will result in recolonization. Knowing the time and place of pack formation is challenging, but the model has shown that in all but the most pessimistic conceptualizations of wolf movement and survival a pack is likely to form. Of course, more data and improved understanding of the individual actions that make up each submodel would result in an improved model. For instance, wolf movement decisions are certainly more complicated than the biased random walk employed in the model, however, an attempt to truly accurately model wolf movement would require a great deal more empirical data on wolf movement as well as the integration of animal psychology literature. Any improvements in submodel formulation will undoubtedly give the model more accuracy and power. As many such improvements are possible, the model described above should be seen as a framework that can be expanded upon and developed further to result in even better understanding of the system. This assertion parallels that of Watkins et al (2011), who stated that in their ABM of Jaguar movement, framework parameters should be seen as a starting point in an iterative process that can continually be improved upon and compared with future empirical data.

The model has shown that pack formation is likely in Austria in the medium term. This sentiment was shared in the meeting with an expert on wolves in Austria, though he stressed the extreme uncertainty in predicting when and where pack formation may occur. While creating such a model may not point to precisely where and when pack formation will occur, it does help in identifying several things about the process that may be useful for management. First, the maps of likely dispersal locations and areas of pack formation give an idea of where likely areas for pack formation are (with admittedly high degrees of uncertainty), however, perhaps more importantly, these maps show specifically which areas are highly unlikely for pack formation. Secondly, the maps of wolf presence density identify potential movement corridors between source populations, which have attributes desirable for wolves and may be vital in fostering gene flow between the three distinct populations surrounding Austria. Finally, the ability to run different scenarios allows dynamic analysis of the phenomenon, allowing changes to parameter values reflecting changes in known empirical data (i.e. the model can be modified to reflect known wolf locations or Austria-specific mortality rates once these things are established).

4.2 Management implications

Knowing these outcomes can help in guiding management policy and outreach. In the several conversations about wolves I had with residents of Carinthia and Salzburgerland, it was apparent few people knew that any wolves were present in Austria at all, let alone what the implications of recolonization were for them personally. Identifying likely areas (and ruling out unlikely areas) of wolf movement and pack formation can help management agencies in being proactive in their outreach strategies, spreading information in a way that prepares stakeholder groups that may have more negative attitudes toward wolves. For instance, they could attempt to popularize husbandry practices that minimize conflict, stress the truly low levels of personal danger wolves pose to humans, and educate stakeholders about what to do in the case of conflict. Such proactive preparations have been undertaken in Weisbaden, Hesse, Germany, which has also had several transient wolves and similar near-term potential for pack formation (Klein, 2015). Their proactive management has centered on the creation of a substantial wolf management action plan that includes the creation of instructional handbooks for walkers and hikers in potential wolf areas, calls for two wolf management experts per county to handle conflict and outreach, training for farmers and shepherds in flock/herd protection, establishment of a wolf hotline (with over 100 calls in the last several years), and free access to electrified fences (Klein, 2015). Perhaps more importantly during the early stages of recolonization, establishing such a management plan draws media coverage that prepares and educates the public (as in the podcast about Weisbaden by Klein, 2015). Clearly, such proactive outreach and management is costly, but having some information about likely areas for dispersal and pack formation helps in prioritizing where such actions may be most beneficial.

4.3 Limitations

While acknowledging the overall strengths and weaknesses in the performance of such an exploratory ABM as outlined above, there are several specific areas in which the model could be improved in the short term. First, more thorough validation and calibration for each submodel would be desirable, though this would require substantial amounts of empirical data that do not yet exist yet for this research topic. Sensitivity analysis should be conducted to get a better idea of the degree to which changes in each variable can affect model outcomes. More rigorous calibration could also have been undertaken within the range of literature values used to come up with the model that most consistently followed the limited validation estimates we had. In addition, the five year time scale used is long enough to consider integrating the downstream effects and feedbacks of pack formation. Specifically, wolf agents that mate should be able to create offspring that enter into the model. Finally, the integration of the human dimension (attitude and its effect on mortality) could be spatially modeled, as initially proposed, rather than assumed to simply be an influence on mortality (as modeled in the scenario example, M4). All of these things could be reasonably accomplished with enough time and with further collection of new data.

4.4 Conclusion

This research successfully created an agent based model to assess carnivore recolonization in Austria. Using literature-derived values for wolf movement and behavior, the model delivered results not far from expert estimates of wolf presence and population in Austria. Furthermore, the demonstration of a scenario (in which parameters differed from literature values) resulted in values even closer to known values. This indicates that the ABM is a fair representation of the complex processes involved in the system at hand and should be thought of as a framework for further model refinement as more data and knowledge becomes available. Even with the uncertainties inherent in modeling such a complex, data-deficient process, the results found here have enough merit to foster further thought about the recolonization process by management bodies and should be able to improve overall understanding of the situation.

Acknowledgements

I am extremely grateful to the Austrian Marshall Plan Foundation for facilitating and funding this work. I had a tremendous experience learning about Austria (both its wolves and its culture). I also want to thank Dr. Gernot Paulus (Fachhochschule Kärnten) for his guidance, support, and enthusiasm in conducting this research, Dr. Georg Rauer (University of Veterinary Medicine, Vienna) for sharing his knowledge and expertise about the current status of wolves in Austria, and Dr. Piotr Jankowski (San Diego State University) for his help in the application process.

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Appendix 1 – Data, Fields, and Actions Dictionaries

Table A1. GIS Data Dictionary for Austria Wolf Model

Dataset	Data type	Description
hundred_wolves.shp	shapefile	Points representing wolves
aus_suitab	raster	Suitability raster
tracking	raster	Dataset that stores wolf movement
packs	raster	Dataset that stores wolf pack area

Table A2. Fields Dictionary for Austria Wolf Model

Actions	Data Type	Description	Parameter?
Wolf model			
mortRate	double	Average annual mortality rate for wolves (death/yr)	y
nextWolf	integer	Tracks which wolf to activate next	
newWolfRate	integer	Average annual rate of wolf migration into study area (wolf/yr)	y
newWolf	integer	Logs whether a new wolf agent will be activated this step	
step	integer	Tracks the step number	
startingWolvesInAustria	integer	Number of wolves randomly placed in Austria at step 0	y
meanDailyDispersal	integer	Average X and Y distance a wolf travels in a day	y
sdDailyDispersal	integer	Standard deviation of the X and Y distance a wolf travels in a day	y
mateSearchRadius	integer	Distance a wolf looks around itself for a mate	y
mateProbability	double	Probability that if a wolf of the opposite sex is found, mating occurs	y
packArea	integer	Area required for new pack establishment	y
percentGoodHabitatForPack	double	The percent of packArea that must be "good habitat" for pack to form	y
totalLiving	integer	Tracks cumulative number of living wolves at all time steps	
numPacks	integer	Tracks the number of packs that have been formed in the model run	y
probFemale	double	Probability new dispersing wolf is female	y
probDinaric	double	Probability new dispersing wolf is from Dinaric population	y
probCarpathian	double	Probability new dispersing wolf is from Carpathian population	y
probAlpine	double	Probability new dispersing wolf is from the West Alpine population	y
Wolf agent			
alive	integer	Binary variable tracking whether wolf is alive	
foundMate	integer	Binary variable tracking whether wolf has found a mate	
establishPack	integer	Binary variable tracking whether wolf has established a pack	
sex	string	Whether male or female	
outOfBounds	integer	Binary variable stating if wolf ends time step out of bounds	
mateName	string	Name of mate, if applicable	
Name	string	Name of wolf	
origin	string	Population of origin (Alpine, Carpathian, Dinaric)	

Table A3. Actions Dictionary for the Austria Wolf Model	
Actions	**Description**
Wolf model	
updateDisplay	Update ArcMap display
writeAgents	Save wolf location data to shapefile
loadRaster	Load suitability, tracking, and packs rasters
newWolf	Determine whether a new wolf will appear
step	Tracks and prints step number
printLine	Prints a line to console output
summaryStats	Outputs summary statistics at each time step
trackWolves	Ouputs wolf location to tracking raster
Wolf agent	
step	Prints wolf status
placeStartingWolves	Activates and places initial wolf agents
newWolf	Activates and places new wolf agent
move	Finds a new location and moves there (hourly substeps)
mate	Males search surroundings for females
establishTerritory	Mated males search surroundings for good habitat, may establish pack
die	Deactivates wolf agent due to mortality or leaving study area
stepEndReport	Prints wolf status

Appendix 2 – Start Parameter Details

Table A4. Start Parameters

Parameter	Estimate Range	Units	Source	
mortRate	0.44-0.76	Annual death rate	Blanco and Cortes (2007), Marucco and McIntire (2010)*	*Estimate for peripheral and disperser wolves in Spain, and estimated disperser mortality in W. Alps
newWolfRate	2.8	Wolves per year		*approximate rate for calibration of stable pop using startingWolfRate = 5 and mortRate = .44
startingWolvesInAustria	2-8	Wolves	Schafer (2012)*	*Estimates for2009-2011
meanDailyDispersal	22.8-27.4	km/day (x and y)	Jedrezejewski et al. (2001), Ciucci et al. (1997)*	*Poland and Italy study estimates of daily movement. 25.1 avg for side C, model computes sides A and B separately - pythagoran theoreom estimates
sdDailyDispersal	~25	km/day (x and y)	Mech (1970)*	*When hunting can be ~50km a day according to Mech (1970), so this minus avg dispersal is used as SD. Parameter is scaled using pythagorean theorem
mateSearchRadius	20.7-39.2	km	Hurford et al. (2006)*	* avg for side C, model computes sides A and B separately - pythagoras theoreom estimates
mateProbability	1	unitless	Hurford et al. (2006)*	
packArea	173-294	km^2	Okarma et al. (1998)*	*Poland study
percentGoodHabitatForPack	-	good habitat %		*qualitative estimate
probFemale	0.25		Rauer (personal communication, 2015)*	*estimate from personal communication
probDinaric	0.50		Rauer (personal communication, 2015)*	*estimate from personal communication
probCarpathian	0.25		Rauer (personal communication, 2015)*	*estimate from personal communication
probAlpine	0.25		Rauer (personal communication, 2015)*	*estimate from personal communication