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Predicting human-wildlife interaction in urban environments through agent-based models

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HIGHLIGHTS

- Wildlife synurbization leads to coexistence and conflict with human society.
- Agent-based models (ABM) can identify risk areas for human-wildlife interaction.
- The ABM accurately forecasted human-wild boar interactions in Barcelona (Spain).
- Anthropogenic food resources attract wild boars to urban areas generating conflict.
- The method and model can be adapted to other contexts, including epidemiology.

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ABSTRACT

Synurbic species adapt to global urbanization by increasingly inhabiting urban environments, where social and ecological factors, such as anthropogenic food resources and habitat alterations, promote close human-wildlife interactions. Ineffective management of these interactions can result in conflicts, altered animal population dynamics, and increased public and private expenditures. This study presents the Barcelona wild boar (BCNWB)-prototype model, a spatially explicit, incremental agent-based simulation that captures interactions between citizens and wild boar (*Sus scrofa*) agents in fine-scale GIS-based scenarios in Barcelona. Developed using GAMA software, the model's results were analyzed with QGIS and R software. The model aims to simulate the dynamics of the social-ecological system underlying the urban ecosystem use by synurbic wild boars and their interactions with humans in the (peri)urban area of Barcelona, Spain.

The BCNWB-prototype model demonstrated high accuracy in predicting the magnitude and location of wild boar movements (multiple-resolution-goodness-of-fit = 0.73) compared to reported wild boar presences in Barcelona. The model also forecasted 115 attack events and 1,442 direct feeding events during a one-year simulation period, as compared to the actual 150 attacks and 1,858 feeding events reported annually. The model's strong performance highlights its potential as a predictive tool for identifying priority areas for human-wild boar interactions and conflicts. Additionally, the model could be employed to assess the cost-effectiveness of management strategies and evaluate the spread, transmission risks, and public health implications of pathogens carried by wild boars.

Abbreviations: ABM, Agent-based model; BCN, Barcelona; HWI, Human-Wildlife interaction; MAB, Metropolitan Area of Barcelona; NP, Natural Park.

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1. Introduction

Urban areas continue expanding, with 56% of the human population currently living in cities (79.1% in developed countries) and it is predicted to be 68.4% by 2050 (86.6% in developed countries) (UN, 2018). One response of wildlife to global urbanization is an increase of synurbization, where the novel cityscapes are utilized by some animal species (Luniak, 2004). In recent decades, wildlife associated with rural landscapes or undeveloped wilderness is gradually colonizing cities and thriving in urban environments (Ditchkoff et al., 2006). This leads to co-inhabitation between wild animals and urban human dwellers, creating opportunities and challenges for wildlife management in cities (Luniak, 2004; Patterson et al., 2003). Urbanization changes the social context in which wildlife management and decision-making occurs, with implications for the future of wildlife institutions and policies, where science has to be integrated (Patterson et al., 2003).

Wildlife presence in cities can have negative consequences (Ditchkoff et al., 2006). The close contact between wildlife and humans in urban environments has raised human-wildlife interactions (HWIs; Conejero et al., 2019), defined as the spatial and temporal concurrence of human and wildlife activities, and conflicts where one part or both are affected (Decker et al., 2010; Patterson et al., 2003; Peterson et al., 2010). Since both social and ecological factors are involved in HWIs and conflicts, understanding the ecological role of wildlife in urban ecosystems is critical (Adams, 2005; Dearborn & Kark, 2010; Lischka et al., 2018; Magle et al., 2012).

As a generalist species, wild boar (*Sus scrofa*) abundance has increased, spreading its distribution worldwide (Massei et al., 2011). The plastic behavior of this species (Gamelon et al., 2013; Podgórski et al., 2013) and its habituation to humans have allowed wild boar to colonize and exploit a wide range of habitats, including (peri)urban environments (Cahill et al., 2012; Castillo-Contreras et al., 2018; Stillfried, Gras, Börner, et al., 2017). Wild boar finds a lack of natural predators but an abundance of anthropogenic food resources, giving urban populations an advantage over natural populations when food is a limiting factor. These differences are especially relevant during food and water scarcity periods throughout the year (i.e. summer in Mediterranean areas), changing wild boar population dynamics by reducing mortality and increasing population growth rate, body condition and fertility, and therefore boosting abundance (Cahill et al., 2012; Castillo-Contreras et al., 2021; González-Crespo et al., 2018), as described in other synurbic species (e.g., Luniak, 2004).

The presence of wild boar, attracted by anthropogenic food resources to urban environments, and the human habituation to their presence in urban areas have exacerbated the human-wild boar interactions and conflicts, such as damages in green areas and street furniture, traffic accidents, the risk of disease transmission and attacks on people and pets (Conejero et al., 2019; Kotulski & Koenig, 2008). These conflicts have consequences in the social-ecological system of HWIs (Lischka et al., 2018). In the ecological system, synurbization and the related habituation have produced changes in the wild boar population dynamics and animal behavior, and therefore an ecosystem imbalance due to overpopulation (Lischka et al., 2018; Tucker et al., 2020). In the social system, they have resulted in economic consequences such as the increase in public expenses related to restoring street furniture and green area elements, the capture of problematic individuals and police interventions, as well as private expenses related to green areas, plantations and facility restoration (Lischka et al., 2018).

The wild boar presence in urban areas also increases animal and public health concerns, such as intraspecific and interspecific (to humans and pets) disease transmission, traffic accidents and attacks on people or pets (Fernández-Aguilar et al., 2018; Meng et al., 2009; Wang et al., 2019). Moreover, the probability of cross-transmission of zoonotic agents between wild boar and humans seems to be related to the city structure, with health facilities (both human and veterinary) playing a role in the acquisition of such pathogens by wild boar (Darwich et al., 2021). Other social consequences like fear to the presence of wild boar in the streets, conflicts among neighbors related to feeding behaviors, and animal welfare issues can also appear.

The city of Barcelona (BCN) with its metropolitan area (Metropolitan Area of Barcelona, hereafter MAB) containing the 80 km^2 Natura 2000 Collserola Natural Park (NP), serves as an example of the challenge posed by the management of wild mammals in urban ecosystems. In recent years, part of the wild boar population in Collserola NP has become synurbic (Cahill et al., 2012; Castillo-Contreras et al., 2018; Hagemann et al., 2022), therefore becoming habituated to human presence and settling in the (peri)urban area of the MAB. The synurbic wild boar of the Collserola NP population form a genetically differentiated population from the nearby rural wild boar population (Hagemann et al., 2022). Similar to other European cities (e.g., Podgórski et al., 2013; Stillfried et al., 2017a), wild boars have expanded their range into BCN, attracted by anthropogenic food resources and using the urban area mostly from dusk to dawn (Castillo-Contreras et al., 2018).

Previous studies on the Collserola NP wild boar population have evaluated the factors attracting wild boar into the urban area and the spatiotemporal preferences of these synurbic individuals inside the city (Castillo-Contreras et al., 2018, 2021). The habituation of the MAB citizens to the wild boar presence in urban areas (Conejero et al., 2019), and its genetic relationship with the adjacent rural wild boar populations (Hagemann et al., 2022) have also been studied. Also, epidemiological studies have detected zoonotic pathogens in wild boar from the MAB, such as *Campylobacter* and hepatitis E virus (Castillo-Contreras, 2019; Fernández-Aguilar et al., 2018; Navarro-Gonzalez et al., 2018; Wang et al., 2019). Regarding wildlife management, a population dynamics study and Population Viability Analysis model with sensitivity tests (González-Crespo et al., 2018) pointed out that reducing the wild boar abundance and anthropogenic food resource availability in the MAB would be the best strategy for decreasing human-wild boar interactions. This reduction of the wild boar abundance could be achieved through increased mortality of young wild boar (González-Crespo et al., 2018), either by hunting or using live-capture methods, which have been assessed from in terms of efficiency, feasibility, and animal welfare (Barasona et al., 2013; Torres-Blas et al., 2020). However, previous Population Viability Analysis (González-Crespo et al., 2018) did not incorporate the spatial component of the wild boar population in either natural or urban environment.

Spatially explicit agent-based models (ABM) (Bui et al., 2008; Heppenstall et al., 2012) address this limitation by integrating the spatial complexity of social-ecological systems, allowing for more accurate evaluation of eco-epidemiological scenarios and intervention strategies. The GAMA platform, an ABM tool with Geographic Information System (GIS) capabilities (Taillandier et al., 2019) facilitates the integration of city structures at a fine-scale resolution. Utilizing an ABM approach, the model can represent wild boar in the Collserola NP population and citizens in the urban environment as individual agents, each involved in multiple activities and behaviors allowing for a more realistic and detailed representation of the system under study. This individual-level representation enables the exploration of emergent phenomena resulting from interactions between agents and their environment and assess more comprehensively the dynamics of HWIs interactions in urban settings (Amouroux, 2011; Zhang & DeAngelis, 2020). Consequently, ABM outcomes can identify areas with higher wild boar presence and human activity, leading to a better understanding of the increased risks associated with human-wild boar interactions.

The aim of this study is to develop a spatially explicit ABM, the Barcelona wild boar prototype (hereafter, BCNWB). The prototype accurately represents the utilization of urban ecosystems by synurbic wild boar and the associated HWIs in Barcelona's urban area. This model seeks to enhance the spatial, temporal, type, and numerical understanding of wild boar presence and human-wild boar interactions in the current social-ecological system in the (peri)urban regions of the MAB. To better capture reality, the model included environmental, urban infrastructure, wild boar biological and behavioral, and human social variables (Table 1). The BCNWB prototype model is intended to serve as a foundational model for population studies and epidemiological risk assessments while informing the prioritization of previously proposed mitigation and management measures (González-Crespo et al., 2018, 2023; Massei et al., 2011). Additionally, the model enables the integration of high-resolution economic assessments.

2. Material and methods

2.1. Study area

The MAB is one of the largest European metropolitan areas, occupying 636 km^2 and inhabited by 3.24 million people (population density of approx. 5,000 people per km^2) (Àrea Metropolitana de Barcelona, 2020). The Natura 2000 Collserola NP, included in the 110 km^2 Collserola massif, is a Mediterranean hilly area located within the MAB, with an altitude ranging from 60 to 512 m. The study area is composed by the Collserola NP and five out of the ten districts of the city of BCN, directly bordering Collserola NP limit (Fig. 1) (Ajuntament de Barcelona, 2020).

2.2. Model description

The model was implemented in the publicly available GAMA software, an ABM combined with GIS capabilities (Taillandier et al., 2019). A complete, detailed model description, following the ODD (Overview, Design concepts, Details) protocol (Grimm et al. 2006, 2010, 2020) is provided in Appendix A.

The basic idea underlying the BCNWB prototype is to explore the dynamics of wild boar movement within a (peri)urban ecosystem and their interactions with citizens, leading to human-wild boar interactions (HWIs). The purpose of the model is to simulate the movement of wild boar in the urban environment, assess the impact of their presence, and investigate the consequences of HWIs for both the wild boar population and the urban community. The model performance is evaluated by its capacity to replicate the documented presence of synurbic wild boar in an urban area, showing how wild boar in the (peri)urban ecosystem of Barcelona, Spain, are drawn from Collserola NP into the urban area due to the availability of anthropogenic food resources, subsequently becoming habituated to human presence.

To consider our model realistic enough for its purpose, we use the following patterns: spatially explicit data, incorporating stochasticity, and integrating ecological and social components. The model includes the following entities: Wild boar agents, Citizen agents, and Environment (wild boar interaction areas for feeding and resting). The state variables characterizing these entities are listed in Table 1. The study area (Fig. 1) spans 123.15 km2, with 110.00 km2 of natural ecosystems in the Collserola NP and 13.15 km2 of urban ecosystems in the city of BCN. The spatial resolution is based on vector layers and polygons representing the urban environment and natural resources, and the temporal resolution is set to 1-hour time steps. The model covers the (peri)urban area of Barcelona. The most important processes of the model repeated every time step, are food management process, wild boar population dynamics, wild boar agent movement, citizen agent movement, and human-wild boar interactions. The most important design concepts of the model are adaptive behavior of agents, emergence of wild boar movement patterns, and spatial heterogeneity of the urban environment. The model is initialized with real data on wild boar populations, citizen demographics, and environmental attributes. Model dynamics are driven by input data representing environmental resources, urban infrastructure, and human activities. The data sources include published research, public databases, and surveys conducted by the authors.

Key processes in the model are the wild boar agent movement and human-wild boar interactions. The wild boar agent movement involves foraging and resting activities, with agents detecting food resources and

Table 1
State variables included in the BCNWB prototype.

Variable	Description	Type	Value	Reference
Environment				
Time	Simulated time	Date	N/A	N/A
Date	Simulated date	Date	N/A	N/A
CurrentHour	Current simulated hour	Int	0–23	N/A
CurrentDay	Current simulated day	Int	1–30	N/A
CurrentMonth	Current simulated month	Int	1–12	N/A
ScarcePeriod	Period when the MaxFood of each WIA is reduced to 50%	Bool	True from May to September	Cahill et al., 2003
ReproTime	Period when reproduction can occur	Bool	True from September to May	Rosell et al., 2001
Wild boar interaction area (WIA)				
ID	Identification of the WIA agent	Int	N/A	N/A
Nature	Type: resting or feeding WIA	String	WIA-R and WIA-F	N/A
GrowingPeriod	Period when the WIA-F agent produces food	Bool	True from CurrentHour: 8 to 20	N/A
Food*	Quantity of food available in a WIA-F	Float	0-MaxFood	N/A
MaxFood	Maximum quantity of food available in a WIA-F	Float	0.1–1	Assumption
FoodProd*	Quantity of food produced in each step	Float	Urban: rnd (0.009, 0.04) Natural: rnd (0.006, 0.02)	Assumption Assumption
Building agents				
Nature	Type of building	String	Working (business), resting (residences), leisure and health care	N/A
Road network agents				
ID	Identification of the building agent	Int	N/A	N/A
Nature	Type of road network	String	Hydrological, path and street network	N/A
Wild boar agents				
ID	Identification of the wild boar agent	Int		
AgeM	Age of the wild boar agent in months	Int	0–132	Rosell et al., 2001
MortalityRate*	Wild boar agent probability of dying for each sex and age class	Float	Table 2	Assumption
ReproductionRate*	Female wild boar agent probability to reproduce for each age class	Float	Table 2	Assumption
Pregnancy	Pregnant status of the female wild boar agents	Bool	True-False	N/A

(continued on next page)

Table 1 (*continued*)

Variable	Description	Type	Value	Reference
ReproductionDist	Distance where mating events occur	Float	30 m	Assumption
GestationPeriod	Period when the female wild boar agent Pregnancy status = True	Float	114 days	Henry, 1968
LitterSize*	Number of offspring	Int	1–6	Rosell et al., 2001
SexRatio*	Sex-ratio at birth of the wild boar agents initialized during the simulation	Float	0.5	Rosell, 1998
TimeForaging	Time when the wild boar agent starts the foraging activity	Int	CurrentHour: 20	Assumption
TimeHiding	Time when the wild boar agent starts the resting activity	Int	CurrentHour: 8	Assumption
Speed*	Normal speed of the wild boar agent according to sex and age class	Float	1–10 km/h	Morelle et al., 2015
DetectionDist	Distance at which the wild boar agents can detect food	Float	1000 m	Toger et al., 2018
HabituationProb*	Probability that juvenile non-urban wild boars have to evolve to yearling synurbic wild boars	Float	0.15	Data gathered by the authors
AggressiveState	Aggressive status of the synurbic wild boar agents	Bool	True-False	N/A
AggressiveProb*	Probability of an adult synurbic wild boar to change to AggressiveState	Float	2.5% annual	Fernández-Aguilar et al., 2018, Conejero, 2022 (see Input data section C.2.)
AggressionProb	Probability of an adult synurbic wild boar to attack a citizen agent or pet	Float	Table 2	Assumption
BCN citizen agents				
Nb citizens	Initial number of citizen agents	Int	57,347	Ajuntament de Barcelona
Speed*	Normal speed of the citizen agent	Float	1–5 km/h	Assumption
TimeWork/ TimeNature*	Time when the citizen agent goes from the resting to the working assigned buildings or to the leisure destination	Int	1–12	Assumption
TimeRest*	Time when the citizen agent goes from the working to the resting assigned buildings	Int	16–23	Assumption
InteractionDist	Distance for human-wild boar interaction events to occur	Float	10 m	Assumption
FeedDist	Distance for feeding events to occur	Float	5.5 m	Assumption
FeedWbProb	Probability of a feeder citizen agent to feed a synurbic wild boar agent	Float	0.37	Conejero, 2022 (see Input data section C.2.)

* State variables including random components.

selecting destinations based on distance and availability. Human-wild boar interactions include feeding events, attacks, and the influence of citizen sub-types on the likelihood of these interactions occurring.

The model validation aimed to replicate the documented pattern of synurbic wild boar presence in an urban area using a multiple-resolution goodness-of-fit test. This test compared the model-generated raster map to the actual wild boar presence raster map from 2014 to 2022. The analysis employed R software Version 4.0.3, utilizing the mrgf function from the spdynmod library (Martínez-López et al., 2015). The test adjusted for moving windows with increasing cell numbers (100 × 100 m) from 1 to 101 and combined them into a weighted average (Costanza, 1989; Kuhnert et al., 2005). Investigating different resolutions in the validation process helps to assess the model's performance and accuracy across spatial scales. This multi-resolution approach allows for a better understanding of the model's ability to capture spatial patterns and heterogeneity in actual data, providing a comprehensive evaluation and identifying potential weaknesses or limitations. Additionally, it can reveal optimal performance at specific scales, guiding future improvements or refinements to the model.

2.3. *Input data*

To create a comprehensive and realistic model, the BCNWB prototype relies on various input data sources (Table 2) that provide the necessary information on the urban ecosystem, natural resources, wild boar populations, and citizen demographics.

Data related to the environment included information on (1) road network and building agents, obtained from the Instituto Geográfico Nacional, containing topologic information at a 1:25,000 scale; (2) land cover for natural food resources, retrieved from the Centre de Recerca Ecològica i Aplicacions Forestals and Generalitat de Catalunya; and (3) anthropogenic food resources, including direct data on stray cat colonies, waste containers, and feeding areas gathered on the field and from the Ajuntament de Barcelona, and indirect data consisting of police incidence clusters and randomly assigned waste containers in urban intersections.

Data for wild boar agents included information on (1) population dynamics, collected from previously published research (González-Crespo et al., 2018) and publicly available data (Departament d'Agricultura, Ramaderia, Pesca i Alimentació of the Generalitat de Catalunya & Minuartia, 2019); and (2) wild boar incidences and hunting data, obtained from the local police records of wild boar incidences in the urban area of BCN and hunting data from Collserola NP.

Data for citizen agents included (1) citizen demographics, obtained from publicly available information from the Ajuntament de Barcelona; and (2) surveys on citizen characteristics and past experiences with wild boar, collected by the authors through interviews with passers-by in

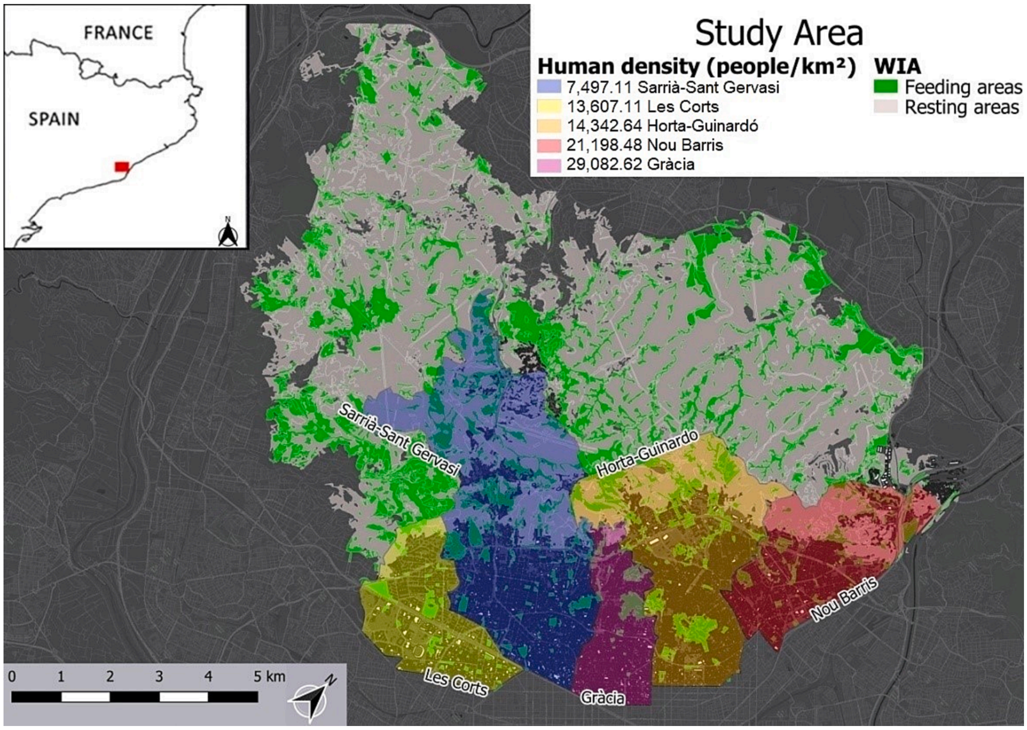


Fig. 1. Study Area. Collserola Natural Park and the five districts of Barcelona (Les Corts, Sarrià-Sant Gervasi, Gràcia, Horta-Guinardó and Nou Barris) included in the model. Human density and wild boar interaction areas (WIA, i.e., feeding and resting areas) are shown.

Barcelona (Conejero, 2022).

These input data sources contributed to the initialization of the model and drive its dynamics, enabling the simulation of wild boar movements and interactions with citizens in the urban environment of Barcelona.

Due to the importance of the activity patterns of synurbic wild boar in the urban ecosystem, both the wild boar incidences in the urban area of BCN registered by the local police and the hunting bag in Collserola NP were used as input data for initialization, calibration, and validation. The incidence database recorded the citizen phone calls related to synurbic wild boar presence in the urban area of BCN. This geolocated dataset is composed of an average of 600 incidences per year, registered from 2010 to 2022, and it is considered as a reliable proxy of the actual synurbic wild boar presence in the urban area of Barcelona (Castillo-Contreras et al., 2018). The data from 2010 were used to randomly initialize the positions of synurbic wild boar in the locations where wild boar presence had been reported to the local police. The incidence clusters from 2011 to 2013 were employed for calibrating the location of food resources in the urban area. Isolated incidents from this period, however, were not used for calibration. Finally, incidents from the period of 2014–2022 were used for validation purposes.

3. Results

The multiple-resolution-goodness-of-fit analysis demonstrated the model accuracy in predicting actual wild boar presences registered by the local police (Fig. 2), with a goodness of fit ranging from 0.7384 (cell size = 1) to 0.7129 (cell size = 101) and a 0.7293 weighted average fit (Appendix D). The results of our sensitivity and uncertainty analysis demonstrated that the model outcomes were robust across a reasonable range of parameter values, except for the wild boar abundance, as the model did not heavily rely on extreme or specific values for accurate prediction (Appendix B). The model successfully simulated the social-ecological system's impact on human-wild boar interactions in a temporal and spatial manner during the study period. This included (1) the potential use of space in the urban ecosystem by synurbic wild boar, (2) the differential effects of natural and anthropogenic food resource exploitation on the synurbization process, and (3) wild boar population dynamics in both natural and urban ecosystems. The simulation results, along with data from the BCN local police (Fig. 2), showed that synurbic individuals from the Collserola NP wild boar population infiltrate the urban area of BCN during nightly foraging activities for anthropogenic food resources, leading to human-wild boar interactions. Moreover, the model quantified, localized, and characterized such human-wild boar interactions.

The model predicted 8,680 human-wild boar interactions in the urban area, with 1,213 direct feeding events (from 1,858 citizen feeder agents offering anthropogenic food resources to synurbic wild boar agents) and 120 synurbic wild boar attack events on citizen agents (Fig. 3). The model's predictions of human-wild boar interactions aligned with the data collected by the authors through surveys (Conejero, 2022; see Input data section C.2). Citizen surveys revealed an average of 150 wild boar aggressions per year, with 3.24% of citizens identified as wild boar feeders (1,858 citizens in the modeled population) when encountering synurbic wild boar in the urban area (Conejero, 2022).

The results indicated that for a wild boar presence to be recorded by local police, the following sequence of events must happen: (1) a wild boar entered the city; (2) after five to eight presences, a human-wild boar interaction occurred (in 12.2–20.5% of predicted presences; Table 3). Then, three scenarios were possible: (3a) a citizen reported the wild boar presence to the local police in one of every ten encounters (8.4–11.9%) due to habituation to wild boar presence in urban areas; (3b) the citizen may feed the wild boar (in 14.0–17.8% of interactions); or (3c) the wild boar attacked a human (in 1.4–5.9% of human-wild boar interactions).

4. Discussion

This study showcases the suitability of ABM in developing predictive models that integrate complex social and ecological factors across time and space. Platforms like GAMA software, offer an ideal framework for

Table 2
Input data and parameterization used for the BCNWB prototype.

Variable	Description	Type	Value	Reference
Wild boar agents				
Nbwb	Initial number of wild boar agents for each sex and age class	Synurbic wild boar Male Juvenile	90	González-Crespo et al., 2018
		Synurbic wild boar Male Yearling	32	
		Synurbic wild boar Male Adult	22	
		Synurbic wild boar Female Juvenile	91	
		Synurbic wild boar Female Yearling	35	
		Synurbic wild boar Female Adult	22	
		Non-urban wild boar Male Juvenile	106	
		Non-urban wild boar Male Yearling	39	
		Non-urban wild boar Male Adult	26	
		Non-urban wild boar Female Juvenile	108	
		Non-urban wild boar Female Yearling	42	
		Non-urban wild boar Female Adult	26	
MortalityRate*	Wild boar agent annual probability to die for each sex and age class	Male Juvenile	0.30	
		Male Yearling	0.43	
		Male Adult	0.35	
		Female Juvenile	0.29	
		Female Yearling	0.35	
		Female Adult	0.39	
ReproductionRate*	Female wild boar agent annual probability to reproduce for each age class	Female Juvenile	0.15	
		Female Yearling	0.60	
		Female Adult	0.70	
AggressionProb	Probability of an adult synurbic wild boar to attack a citizen agent	To regular citizen	0.0126	Conejero, 2022
		To pet owner	0.0379	
		To feeder citizen	0.0869	
BCN citizen agents				
Nb citizens	Initial number of citizen agents for each sub-type	Regular citizen	38,823	Conejero, 2022
		Pet owner	16,648	
		Feeder citizen	1,858	

* Variables modified by random environmental variation (+/-0.15).

creating and implementing these models. The BCNWB prototype accurately reproduced wild boar presence in the urban area of BCN and associated human-wild boar interactions in space and time. The model, based on stochastic empirical data, is easy to interpret and incorporates specific urban morphology through its GIS capabilities. The calibration process, supplemented with sensitivity and uncertainty analysis, reinforced the modes robustness and credibility. This multi-pronged approach ensures that the model is not only a precise representation of observed data but also has the flexibility and robustness necessary for broader applications. There is a growing need for bottom-up approaches that account for fine-scale information in models addressing practical ecological issues, such as the emergence of spatial patterns (DeAngelis & Yurek, 2017; McLane et al., 2011). Incorporating these models offers the advantage of including various scales of resolution and mechanisms capable of simulating the emergence of patterns from small-scale processes to fundamental drivers of ecosystems (DeAngelis & Yurek, 2017; McLane et al., 2011).

By analyzing the ratios among wild boar presences predicted by the model, predicted human-wild boar interactions, actual wild boar incidences registered by the local police of BCN, and the number of predicted feeding and attack events, it was possible to estimate the magnitude of each value using the local police wild boar incidence record as the sole real proxy to date (Table 3). The discrepancy between the model's predictions and the police records is likely due to the detectability and reporting ratio of wild boar in urban areas. When a wild boar is in the urban area, the most common outcome of a human-wild boar interaction is a mere encounter between a citizen and the wild boar, more frequently than a citizen reporting the presence of the wild boar (3a), feeding the wild boar (3b), or being attacked by the wild boar (3c). The results indicate a trend in citizens' behavior following a human-wild boar interaction: feeding the wild boar is more common than reporting it to the police, probably due to citizen habituation to wild boar presence in urban areas (Conejero et al., 2019; Conejero, 2022); and attacks are the rarest event. Consequently, the actual presence of wild boar within BCN urban area could be closer to the values provided by the model. The values recorded by the local police serve as a rough, sixty-fold lower proxy, assuming that human activity and citizen habituation to wild boar presence in the urban area remain relatively constant (Conejero et al., 2019).

The spatial alignment of the BCNWB prototype with the actual wild boar presences in Barcelona's urban area underscores the significance of anthropogenic food resources in attracting and drawing wild boar into urban environments, as previously suggested. (Castillo-Contreras et al., 2018). The model's high predictive correspondence indicates that real synurbic individuals from the Collserola NP wild boar population prioritize foraging for anthropogenic resources within the urban area. This preference aligns with findings from previous studies on the same population (Cahill et al., 2012; Castillo-Contreras, 2019; Castillo-Contreras et al., 2018) or in other urban contexts, such as in Haifa, Israel (Toger et al., 2018), emphasizing the critical role of anthropogenic food resources in driving wild boar infiltration into urban areas. However, some urban wild boar populations, like those in Berlin, Germany, prioritize natural resources when available (Stillfried, Gras, Busch, et al., 2017).

Wild boar piglets learn to forage for food from the sow during weaning around three to four months of age (Chapman & Trani, 2007; Oostindjer, Bolhuis, Mendl, et al., 2011). The prioritization of anthropogenic versus natural food resources may be influenced by early learning experiences with the caregiver (mother) during the developmental sensitive period in juvenile wild boar (Worthman et al., 2010). Since piglets are born mainly in spring (Macchi et al., 2010; Mauget, 1982), in Mediterranean climates the food scarcity period occurs in summer, i.e., before the first six months of age and around the

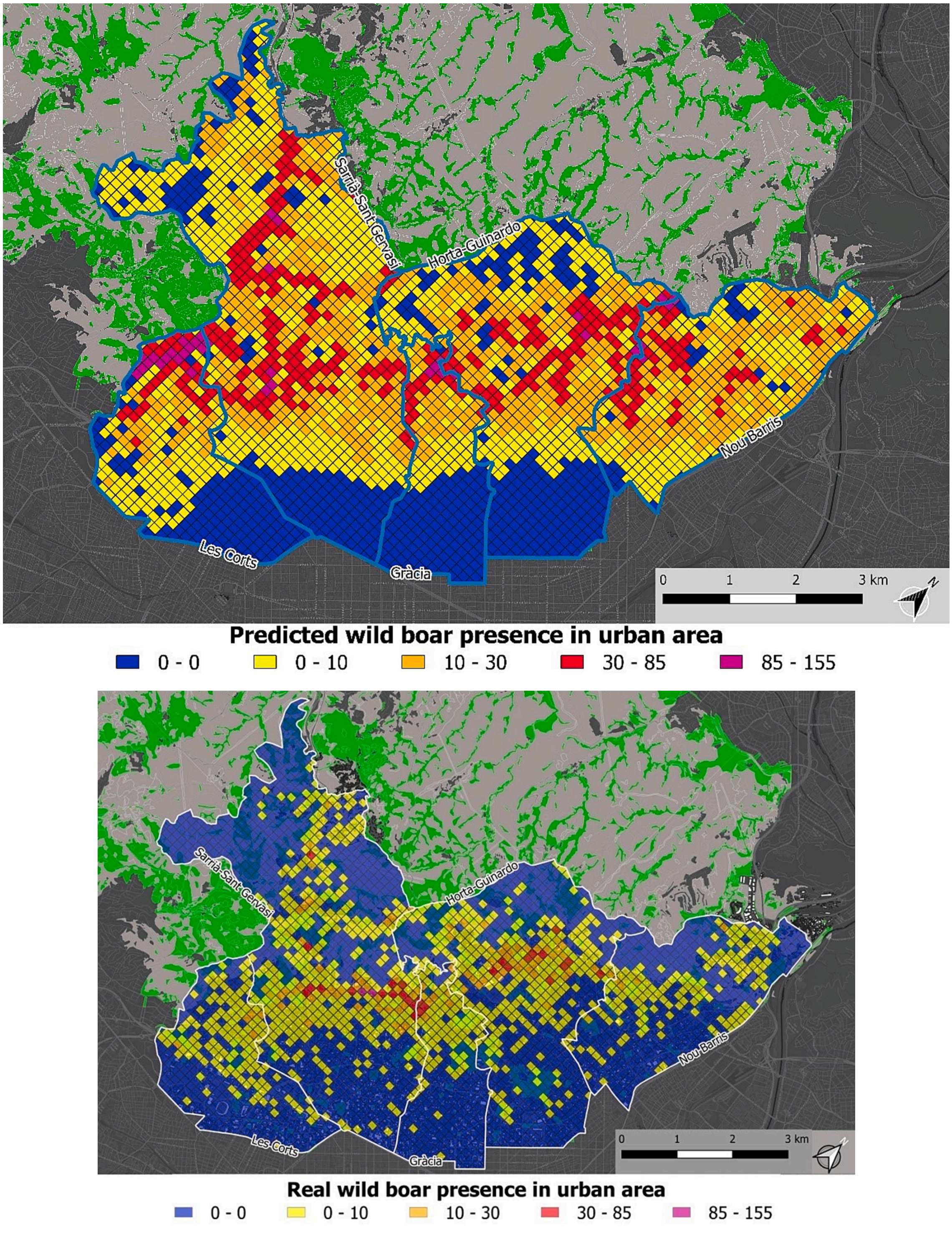
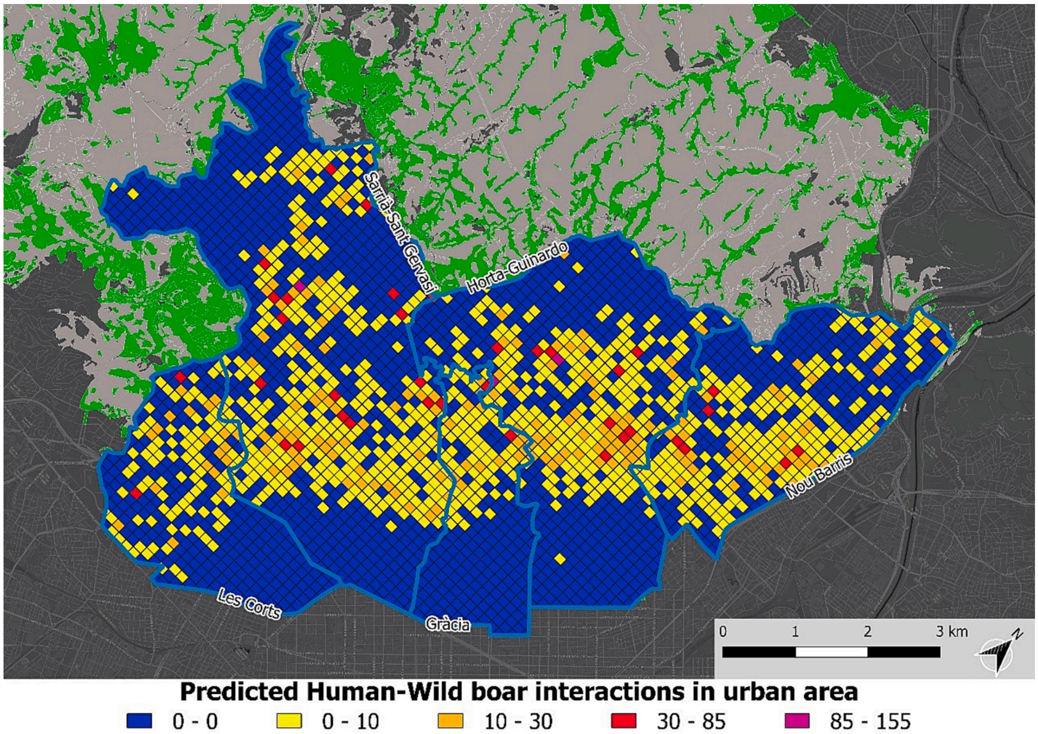


Fig. 2. Vector maps of the wild boar presence in the urban area of Barcelona within the study area, as predicted by and the BCNWB model (a) and as registered by the local police of Barcelona (b).

aforementioned sensitization period. Therefore, the juvenile wild boar will learn to select anthropogenic food resources as they are available all year-round. In contrast, in northern regions with colder continental climates the scarcity period occurs in winter, when the wild boar is older than six months and the sensitization period is over. Then, the juvenile wild boar will prioritize natural food resources and use anthropogenic resources mostly as a supplement when access to natural resources is limited. This could explain the higher consumption of anthropogenic food resources and synurbization rate, and the closer interaction with citizens of urban wild boar in Mediterranean cities compared to Central European cities (Castillo-Contreras et al., 2018, 2021; Stillfried, Gras, Busch, et al., 2017). However, both strategies involve wild boar being attracted to urban areas by anthropogenic food resources. Traditional urban wildlife management strategies often underestimate the role of anthropogenic food sources and neglect their spatial distribution, leading to unsuccessful management goals for promoting or controlling an urban population (e.g., Cahill & Llimona, 2004, Castillo-Contreras et al., 2018, 2021).



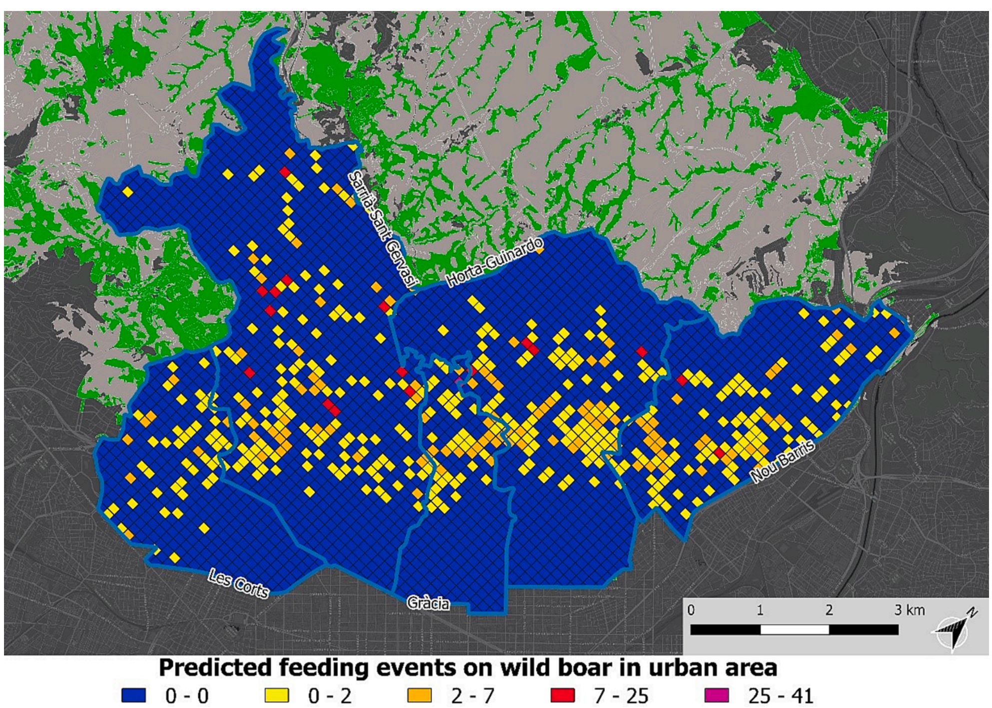


Fig. 3. Human-wild boar interaction pattern maps in the urban area of Barcelona obtained by the BCNWB prototype. a) Human-wild boar interactions; b) feeding events; c) attack events.

The model includes several assumptions, such as wild boar agents not preferring a specific type of food in a wild boar interaction area and not returning to a visited wild boar interaction area on the same day. The model also assumes that the maximum quantity of food available varies among wild boar interaction areas based on the type of resources they contain. The model also assumes that the wild boar incidences registered by the local police of Barcelona are a reliable proxy of actual wild boar presence in urban areas. However, the model has limitations, such as insufficient data on feeding event schedules, locations of wild boar interaction areas only in urban areas, and precise locations of local police incidences in non-urban areas. Furthermore, urban residents may become habituated to wild boar presence, resulting in underreported wild boar-related incidents (Conejero et al., 2019). These limitations, including lower incident reporting and the lack of data in non-urban areas, may lead to an underestimation of actual wild boar presence. Additionally, to make the model computationally feasible, the human population was scaled down by 10% to 57,347 citizen agents. This proportion aligns with the reported percentage of Barcelona citizens

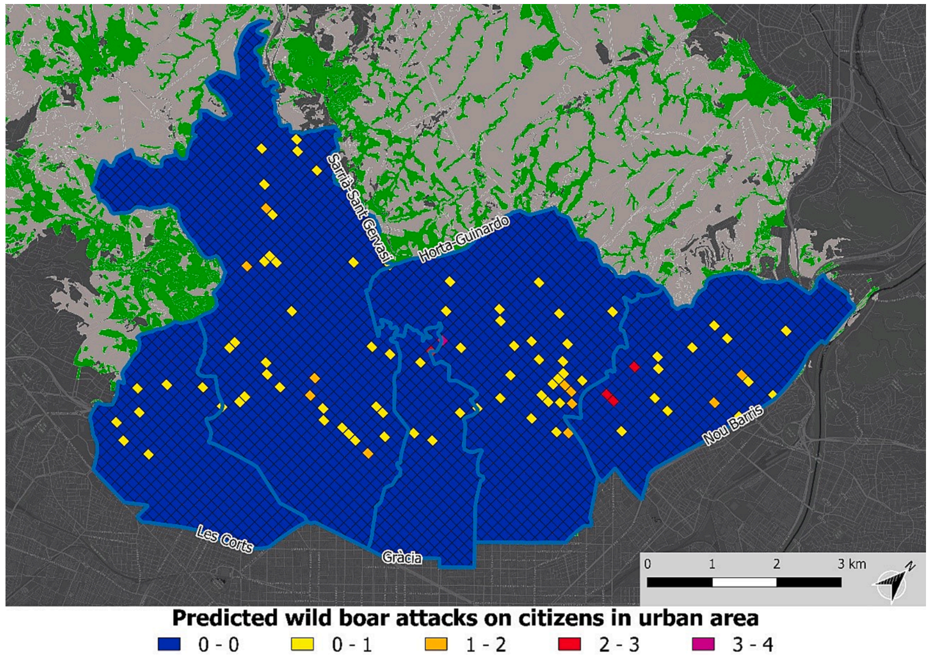


Fig. 3. (*continued*).

Table 3
Relationships among the wild boar presences predicted by the model and empirically recorded by the local police in the urban area of Barcelona and the associated interactions with humans (interactions, feeding and attack events), calculated both as the average ratios and the ratio of the averages. The values indicate the proportion of the events in a column that end up as events in a row.

	Origin	Variable type	Predicted Wild boar presence (%)	Predicted Human-Wild boar interactions (%)
Human-Wild boar interactions	Model output	Predicted by the model	12.2[a] – 20.5[b]	
Wild boar presence reports	Empirical observation	Police reports	1.6[a] – 2.4[b]	8.4[a] – 11.9[b]
Feeding events	Model output	Predicted by the model	5.7[a] – 2.9[b]	17.8[a] – 14.0[b]
Attack events	Model output	Predicted by the model	4.2[a] – 0.3[b]	5.9[a] – 1.4[b]

[a] Average of the ratios.
[b] Ratio of the averages.

using public spaces during wild boar foraging hours (8 PM to 8 AM) (Autoritat del Transport Metropolità, 2019). While the impact of tourists is important in managing urban wildlife like pigeons (González-Crespo & Lavín, 2022), their effect on wild boar in the study area was considered negligible due to limited overlap between wild boar presence and tourist locations and timings.

Despite these limitations, the model demonstrated high performance, proved useful for the study's objectives, and exhibited a strong correlation and fitness with actual data obtained from citizen reports and surveys.

In the future, the prototype model will be updated with improved data and technology. Further development will include updating wild boar and citizen agents by implementing a decision-based architecture to guide their behavior. The model performance and its ability to accurately predict wild boar presence in the urban area of Barcelona validate the prototype, making it applicable for use in other model designs. The prototype can be expanded with additional sub-models to identify priority areas for human-wild boar interactions and conflicts. Identifying these areas can serve as a scientific assessment tool for applying, predicting, and evaluating the effects of management measures to reduce habituation and urban wild boar presence. Future studies will incorporate the degradation, restoration, and elimination rates of wild boar interaction areas for feeding to account for wild boar-caused damages, City council management of green areas and street furniture, and potential wild boar feeding points. By assessing the efficacy and efficiency of management measures before implementation, the model can aid decision-making processes. Furthermore, the epidemiological sub-model expansion could help predict and evaluate the risk of pathogen spread and transmission within the wild boar population and at the human-wild boar interface, providing valuable insights into both animal and public health implications.

5. Conclusions

Overall, the BCNWB prototype accurately predicted wild boar presence in the urban area of Barcelona and associated human-wild boar conflicts, highlighting the influence of anthropogenic food resources on attracting and habituating wild boar to urban environments. The BCNWB prototype model is designed to be incremental and should be viewed as an initial step in a multidisciplinary approach to studying wildlife management in urban ecosystems.

The development and implementation of Agent-Based Models (ABMs) can offer valuable decision support tools that are easily adaptable for various animal species, contexts, and regions. These tools address a wide range of research questions and evaluate interactions, conflicts, and disease transmission potential at the wildlife-domestic-human interface.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2023.104878.

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