**Eradicating the grey squirrel Sciurus carolinensis from urban areas: an innovative decision-making approach based on lessons learnt in Italy**



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# Eradicating grey squirrel *Sciurus carolinensis* from urban areas: an innovative decision making approach based on lessons learnt in Italy

Innovative Decision Support System to eradicate grey squirrel from urban areas

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**Abstract**

BACKGROUND: Eradication of Invasive Alien Species supports the recovery of native biodiversity. In Europe, a new Regulation introduces obligations to eradicate the most harmful invasive species. However, eradications of charismatic mammals may encounter strong oppositions. Considering the case study of the Eastern grey squirrel (Sciurus carolinensis Gmelin, 1788) in central Italy, we developed a structured decision making technique, based on a Bayesian Decision Network model and explicitly considering the plurality of environmental values of invasive species management to reduce potential social conflicts.

RESULTS: The model identified priority areas for management activities. These areas corresponded to the core of the grey squirrel range, but they also included peripheral zones, where rapid eradication is fundamental to prevent the spread of squirrels. However, when the model was expanded also integrating the attitude of citizens towards the project, the intervention strategy slightly changed. In some areas, the citizens' support was limited and this resulted in a reduced overall utility of intervention.

CONCLUSION: The suggested approach extends the scientific basis for the management decisions, evaluated in terms of technical efficiency, feasibility and social impact. Here, the Bayesian Decision Network model analysed the potential technical and social consequences of management actions and it responded to the need of transparency in the decision process, but it can be easily extended to consider further issues, common in many mammal eradication programs. Thanks to its flexibility and comprehensiveness, it provides an innovative example of how to plan rapid eradication or control activities, as required by the new EU Regulation.

**Keywords**

adaptive management, Bayesian Belief Networks, Decision Support System, eradication, invasive alien species, social conflicts

## 1. INTRODUCTION

To respond to the threats posed by invasive alien species (IAS), the Convention on Biological Diversity (CBD, guiding principles adopted in 2002 with Decision VI/23) and the new European Union Regulation on the prevention and management of the introduction and spread of invasive alien species (EU Regulation No. 1143/2014) call for a hierarchical approach, giving priority to the prevention of unwanted introductions, and carrying on eradications (or permanent control when eradication is not feasible) when prevention fails.[1] Several studies have shown that successful eradications can produce significant effects in terms of recovery of native biological diversity.[2-4]

In Europe, most intentional eradications of animals have targeted invasive vertebrates.[3] Among them, mammals seem to represent particularly successful invaders compared to other vertebrates[5] because they are relatively likely to establish. The eradication of invasive mammals has progressed substantially in recent years, and a range of techniques has been developed for their removal from increasingly large areas.[6,7]

In spite of these advances, several mammal species still represent a threat to the conservation of biodiversity in Europe (e.g. Castor canadensis Kuhl, 1820; Myocastor coypus Molina, 1782; Neovison vison Schreber, 1777; Rattus norvegicus Berkenhout, 1769; Rattus rattus L.,1758; Global Invasive Species Database (http://www.iucngisdi.org)). In this respect, the Eastern grey squirrel (Sciurus carolinensis Gmelin, 1788) provides an emblematic example. Although the grey squirrel has been included in the list of 100 of the World's Worst IAS (IUCN Invasive Species Specialist Group, ISSG) because of its severe impact on the conservation of the European red squirrel (Sciurus vulgaris L., 1758)[8] and on forests in general,[9-13] attempts to eradicate it locally failed.[14-16]

In the United Kingdom, control projects aiming at the conservation of the native red squirrel typically faced resource challenges[17] and their effectiveness was reduced because of the high grey squirrel dispersal abilities, which made re-colonization likely.[18] As a consequence, the UK experience highlighted the need for wider geographical and co-ordinated systematic removal programmes to effectively manage grey squirrel populations.[17] But in this context, public support for red squirrel conservation remained high[19] and a careful, retrospectively analysis of technical, geographical and political challenges in red squirrel conservation initiatives also provided a foundation for successful intervention in part of the UK grey squirrel range.[20]

On the contrary, grey squirrel eradication attempts in Italy failed because of the strong opposition of some sectors of the society, including radical animal right groups.[16] Here, the grey squirrel is mainly perceived by the general public as an aesthetically appealing mammal and social conflicts raised in conservation programs aiming at its eradication or control,[16] because of divergences of views on the need to euthanize animals.[21] Ethical conflicts are also likely to be exacerbated because the species was introduced through pet trade and was then released in urban parks,[22-24] where it became the most visible, non-domesticated mammal, characterized by a high level of confidence, and ultimately perceived as a member of the urban community.[25]

Social conflicts were described for the management of several other taxa[26] ranging from small invertebrates such as the zebra mussel (Dreissena polymorpha Pallas, 1771) to predators in general,[27] and to large ungulates such as red deer (Cervus elaphus L., 1758).[28] In general, the conflicts are related to the lethal control. Alongside funding and planning issues, social acceptance is thus an additional key challenge for the eradication of invasive species[7,29] and the human dimension issues are generally deemed relevant for IAS management.[26]

Nevertheless, and although grey literature on this phenomenon is not scarce, a small number of peer-reviewed papers on biological invasions explicitly include the analysis of social dimensions. Structured decision making techniques should be developed to take into account the plurality of environmental values.[28] The need for a comprehensive approach to tackle the social issues raised by the introduction of the grey squirrel in particular has already been highlighted, and such an approach should include the development of specific tools aimed to involve the general public and to clarify roles and management responsibilities.[21]

A first Decision Support System (DSS) for the management of grey squirrel populations in Italy was thus developed in the framework of the LIFE EC-SQUARE Project (LIFE09 NAT/IT/000085, Eradication and control of grey squirrel: actions for preservation of forest ecosystems). This DSS was based on a decision tree approach that considered the approximate size of red and grey squirrel populations and the spatial distribution of animals, the extent of the areas, their location in relation to ecologically sensitive areas (e.g. Natura 2000 sites), and the general attitude of the public towards the eradication of animals as main factors to identify the intervention priorities (http://www.rossoscoiattolo.eu/en/life-ec-square-final-project-results). Here, we propose an extension of this approach, based on the development of an Influence Diagram (ID), a graphical model that describes the relationships between the variables of a system, and on the corresponding Bayesian Belief Network (BBN), a probabilistic model that represents random variables and their conditional dependencies. The new approach still allows the identification of intervention priorities, but it explicitly considers the uncertainty in the evaluation process. Moreover, the DSS is extended to the scientific basis of the management decisions, which are evaluated in terms of technical efficiency, feasibility and social impact. We applied such an approach to guide the management decision process in the framework of a LIFE+ Project, U-SAVEREDS (LIFE13 BIO/IT/000204, Management of grey squirrel in Umbria: conservation of red squirrel and preventing loss of biodiversity in Apennines), aimed at eradicating the grey squirrel from an area of about 50 $km^2$ in Umbria, Central Italy.

## 2. CASE STUDY

The main goal of the U-SAVEREDS Project is the conservation of the European red squirrel in the Umbria Region. Here, the red squirrel is locally at risk because of the presence of the Eastern grey squirrel, that has been accidentally introduced in the city of Perugia in the early 2000s.[30] Since then, the alien species spread to a range of at least 50 $km^2$ (Fig. 1). It occupied natural areas neighbouring Perugia and connected to other Apennines forested areas, but it also remained linked to several types of human settlements, including the Perugia city centre and several sub-urban areas with high human population density.

Conservation actions were planned to remove grey squirrels and to preserve or restore populations of the native red squirrel in the Perugia area. The removal of grey squirrels will be carried out with live-trapping and euthanasia, according to the current regulations and guidelines;[31] captures followed by surgical sterilization and release of the animals could also be implemented for a limited number of animals, determined on the basis of the availability of suitable sites for release within the project area. Management actions will be implemented within pre-defined Management Units (MUs, see Fig. 1), identified in the very early stages of the LIFE U-SAVEREDS Project by taking into account both anthropogenic and natural features of the project area, and considering the knowledge about grey squirrel local distribution. Information about forest types and management and geo-botanic features, types of urban settlements (with high/low population densities) and the presence of urban parks were also considered to identify MUs, whose boundaries were often identified along roads or forest paths.

## 3. METHODS

### 3.1 Model structure

The DSS is the last step of an overall risk analysis for the grey squirrel in Umbria. It consists of a model that can be used to inform managers about the implications of actions. As such, a DSS is typically a model where a set of management guidelines and their effects (including costs and benefits, i.e. "utilities") are explicitly represented as probabilities.[32] In our specific case study, the DSS aimed to identify the optimal strategy to maximize the utility of intervention for each MU, with the final goal to eradicate the grey squirrel population.

Since the identification of the optimal strategy requires the evaluation of a complex socio-ecological context, we adopted a modelling approach that allows achieving a clear conceptual understanding of the studied system. The modelling procedure can be divided in three main steps: (i) characterization of the studied system, identification of the main challenges for the project implementation and of the social and environmental “critical elements” to consider; (ii) identification of attributes to characterize each critical element; (iii) adoption of a specific but easy to understand language to express the system relations.[33]

To characterize the system, we revised the previous experiences of grey squirrel eradication,[9,14,34-36] with particular reference to those conducted in Italy,[16,21] but also taking into account programs carried out elsewhere.[17,20,37] We identified difficulties, considering grey squirrel presence and distribution and the ecological and human-related features of the project area, as described in the "Case study" section. We analysed this information in the light of the previous experience of the LIFE EC-SQUARE Project, which recently tackled the issues to protect the red squirrel in the North-West of Italy and to limit the spread of the grey squirrel in the rest of the country and in continental Europe. Taking into account the difficulties encountered in this and other grey squirrel removal programmes,[20,38] we noted the critical elements of each case study, finally identifying those applicable to our specific system.

We also identified specific attributes for each element (Tab. 1). While critical elements correspond to the main themes generally considered in removal programmes, the specific attributes correspond to concrete variables related to those themes (e.g. squirrel density and distribution are commonly identified as specific attributes for the critical element ‘status of squirrel populations’). Specific attributes were chosen with a preference for quantitative features. When possible and appropriate, the values of the specific variables were measured in a GIS environment (e.g. percentage of urban areas) or obtained via ad hoc data collections. This was the case for data on the status of squirrel populations, since in the early stages of the LIFE U-SAVEREDS Project we implemented specific surveys to assess the population size and distribution of both red and grey squirrels in the Perugia area (see further below, “Parameterization”, for details).

To illustrate the overall conceptual understanding of the system we adopted a graphical language to describe the most direct and relevant relationships among the model elements and their attributes. Both model elements and attributes are referred to as 'variables'. Specifically, we defined a directed acyclic graph (DAG) representing an Influence Diagram (ID, Fig. 2). The ID illustrates the causal web of the model variables and it was elicited from the experts of the technical task force of the LIFE U-SAVEREDS Project, a working group of 7 people that discussed the structure of the ID during regular project meetings. Within the ID, each node represents a random variable, while arrows connecting nodes (edges) represent potential correlations or causal relationships among variables.[39]

We then converted the ID into a Bayesian Belief Network (BBN).[40] We expressed each variable as a set of discrete, independent, mutually exclusive and exhaustive states, or classes.[39] According to their position within the network, nodes can be distinguished in exogenous/endogenous and parent/child nodes. Exogenous nodes (also called parentless nodes or input parent nodes) are simply nodes with no incoming arrows and they should represent variables for which data or any other kind of information are available to express the probability (belief) of each variable state. Nodes with both incoming and outgoing arrows are endogenous, summary child nodes; they are affected by other variables in the model and they may represent general topics, or themes, within the model framework, so that they can sometimes be referred to as 'latent variables'.[40] Nodes with no outgoing arrows are endogenous, outcome child nodes.[41] Since we designed the ID and the corresponding BBN for reasoning about decision making we also included a decision node that identifies the decision alternatives under consideration (the ‘control strategy’ node) and a ‘utility’ or value node that describes the outcomes, which are expressed as a function of the values of the parent nodes (Fig. 2). For this reason, the model can also be defined as a Bayesian Decision Network (BDN).

**3.2 Parameterization**

Once the graphical network of nodes was built, we characterized each node and relationship by a probability. For input nodes, we explicated the frequencies of the states, i.e. we specified the unconditional (prior) probability of each state. These nodes were mostly evaluated from existing data, using GIS databases when possible (see also Tab. 1). For strictly quantitative variables (e.g. the extent of MUs, the percentage of urban areas), data were extracted using a GIS, and classes were chosen according to the 1$^{st}$ and 3$^{rd}$ quartile of the distribution of attribute values. For other variables (e.g. attendance level) the only way to elicit state probabilities was to rely on the expert opinion. For the status of squirrel populations, previous data on the grey squirrel presence were used to assess, through a kernel estimator, the core area of the population range. Point transect surveys (263 points) were conducted within the core area and in neighbouring MUs adopting a distance sampling methodology.[42,43] The minimum number of individuals present in the surveyed region was obtained correcting the counts by animal detectability. Second, a monitoring protocol based on an adaptive, iterative sampling strategy was established to verify the presence of the alien grey squirrel in new areas. A random sample of MUs neighbouring the actual grey squirrel range (primary MUs) was surveyed via direct observation of the animals (collected in 281 observation points and along 47 transects) and by camera-trapping (348 trap-days), and then secondary MUs were surveyed only if adjacent to primary MUs in which the species was actually detected. Data collection was performed from March to December 2015.

We then specified the probabilities for the states of the endogenous, child nodes via conditional probability tables (CPTs, i.e. tables reporting the marginal probability of a variable with respect to others), taking into account all combinations of states of their parent nodes. As for the model structure, the parameters were elicited by the staff of the LIFE U-SAVEREDS Project. The probability elicitation was carried out by asking the staff experts questions regarding the priority and utility of intervention for different scenarios, that is for the different cells of CPTs.[44] All assessments were grouped by linear opinion pool.[45] We adopted this expert-based approach for all endogenous variables, since at the beginning of the project no data were available for measurable child nodes (e.g. 'citizens' support', Tab. 1). Communication activities to involve citizens were planned for all MUs where grey squirrels were detected. First, a letter was sent to citizens to inform about the project activities, and then the staff of the project started a 'door-to-door' campaign, recording data on citizens that granted the permission to enter their private properties to control squirrels. From February 2016 data were collected in 4 MUs.

We defined three states (e.g. small, intermediate, large) for most nodes, with a few exceptions (Table 1). The number of parental nodes and states was chosen according to the guidelines provided by Marcot et al. (2006).[40] These authors suggest that a limited number of parent nodes and the fewest discrete states necessary within any given node should be used to represent influences. Enough states should be used to ensure the precision of the model, which is also determined by the overall size of the CPTs. The choice of the number of nodes and states thus took into account the need to provide a balance between parsimony and precision and to keep the CPT tractable and understandable.[40] The analyses were carried out in R environment,[46] using the gRain package to convert the ID to the final BBN model.[47]

## 4. RESULTS

### 4.1 Model structure

The two main challenges that emerged from the analysis of previous grey squirrel eradication projects were the difficulty to identify: 1) intervention priorities, and 2) the most effective and socially acceptable management strategy essential for maximising the cost-benefit ratio (overall utility) of intervention in each MU. For the identification of intervention priorities we recognized the following critical elements (or latent variables): status of squirrel populations; ecological background; spatial issues; social background; sanitary risks (Tab. 1, Fig. 2).

The critical element 'status of squirrel populations' was characterized by 3 specific attributes (squirrel presence, grey squirrel density and grey squirrel distribution; Tab. 1). The squirrel presence variable allowed discriminating MUs with both red and grey squirrels, from MUs where only one squirrel species occurred. The approximate density (low, medium, high) and spatial distribution (scattered, clustered and homogeneous) of grey squirrels were also deemed relevant to decide where to act first.

The critical element 'spatial issues' took into account several spatial features of each MU. With the subzone attribute, we classified the MUs in 5 groups (Tab. 1). The subzones were identified as homogeneous areas, sharing important features such as the overall level of urbanization or the peripheral or central position in the project area. Some subzones (e.g. Northern Perugia) can represent ecological corridors towards the Apennines or other natural areas; this role could be reinforced in case of high ecological connectivity. Others were differentiated because they were clearly disconnected from other subzones. This was the case for Southern Perugia, which includes all the MUs located South-East of the Perugia city centre (Fig. 1).

The variables valuing the level of natural protection (measured as percentage of area included in Natura 2000 sites), the percentage of urban areas, the type of woodlands (scattered trees, fragmented or continuous forests) and the distance of each MU from red squirrel areas were included in the ID in order to characterize the MUs' 'ecological background' (Tab. 1).

The 'sanitary risks' critical element took into account both the risks of zoonosis and the risks of disease spread among squirrels, as detailed in Tab. 1. It was included in the model because data on the sanitary status of grey squirrels will be collected alongside control activities, and the reporting of legally notifiable diseases and/or Poxvirus should be obviously considered to set the intervention priorities.[48]

The 'social environment' of each MU was described by 4 specific attributes, including the presence of parks, the attendance of public green areas, and information about whether or not citizens fed grey squirrels. We also decided to consider the reporting of agricultural damage caused by grey squirrels as this factor could in turn affect the citizens' attitude towards the squirrel presence and the project activities.

For the identification of management strategies and utility maximization, additional critical elements were identified in: citizens' support; communication profile; probability of success of the control strategies; working environment (Tab. 1). As shown in Fig. 2, the 'citizens' support' and the 'communication profile' (low/intermediate/high, depending on the implemented communication activities) were conditioned by the choice of the control strategy (euthanasia/surgical sterilization), and both elements in turn affected the 'success probability' and the 'working environment', a latent variable describing the overall attitude towards the project. The 'success probability' was indeed related to both social and technical factors. In addition to the variable 'control strategy', it was related to the extent and the ecological connectivity of each MU, and to the status of squirrel populations (Tab. 1). Since social issues were also considered to potentially affect the probability of success of the management activities, the 'citizens' support' variable was included in the ID as a parental node for both the 'success probability' and the 'working environment'.

### 4.2 Priority and utility of intervention in MUs

Taking into account the model structure and the CPTs and finally entering the data (i.e. setting the evidence) for input nodes for each MU, we queried the network to obtain the conditional distribution of the priority.

For this step, the input data were represented by a table that synthetized the features of MUs with respect to the attributes of the latent variables ‘spatial issues’, ‘ecological background’, ‘social environment’, ‘sanitary risks’ and ‘status of squirrel populations’. For the latter, we used data on squirrel populations collected in 2015 (Fig. 1). A total of 209 squirrel sightings were recorded, of which 25 only referred to red squirrels. The latter were detected in 6 MUs, and most sightings were recorded in a MU at the margins of the grey squirrel range. Due to the few sightings of this species, we could only obtain an overall estimate of 112 red squirrels. On the contrary, the grey squirrel presence was detected in most MUs, and the minimum number of individuals estimated for the core area of the grey squirrel distribution and for the neighbouring MUs was 1510. More than 40% (627) of these animals were located in 4 central MUs (2.8 km$^2$). The adaptive sampling protocol allowed to verify the presence of the species in new, peripheral MUs located North-East of the Perugia city (Fig. 1).

On the basis of these data, several MUs located in the centre of the project area were classified as ‘high priority’ units (Fig. 3a). On the contrary, the priority of intervention was low or null for most peripheral MUs but the model also identified some high/intermediate priority MUs located North- and South-East of the Perugia city centre.

For high priority MUs, the chosen control strategy was the capture and subsequent euthanasia of the animals, while capture followed by surgical sterilization and release was foreseen only for intermediate/low priority MUs. Taking into account the chosen ‘control strategy’, we computed the expected utility of the management activities in each MU, defined on the basis of its parental nodes (Fig. 3b). Most of the high priority MUs were characterized by a high utility, but Fig. 3b also shows that some changes occurred in the classification of MUs when we took into account variables related to the ‘working environment’ and to the ‘success probability’ of management activities. The latter success probability largely depended on the ‘citizens’ support’ for control strategies, a model variable whose values can be dynamic, since they can be affected by project communication activities (Fig. 4). For a central MU, mostly coincident with the core area of the grey squirrel distribution, the results of the communication activities were encouraging, as we obtained the permission to enter the private properties for grey squirrel control. This MU was small (about 40 ha) but grey squirrel density was high (> 4 animals/ha), animals were almost homogeneously distributed and the level of attendance by citizens was high. Here, because of the change in the citizens’ attitude towards the project following the communication activities, the probability of high utility increased from 0.33 to 0.78 (Fig. 4a). On the contrary, in another high priority unit where access was granted to <75% of the private areas, the confidence in an intermediate utility increased, while the probability of a high/low utility decreased (Fig. 4b). In the remaining MUs concerned by the communication activities, the support of citizens stayed at an intermediate level (i.e. similar to that expected ‘a priori’) and relevant changes in the probabilities of low, intermediate and high utility did not occur.

**5. DISCUSSION AND CONCLUSIONS**

Eradication of alien species supports the recovery of biological diversity and it should be attempted[3] when prevention of invasion fails according to the new European Regulation No. 1143/2014. To put the recommendations into practice challenges may differ among species and contexts. For grey squirrel programs, issues include planning problems, often related to the identification of spatial intervention priorities and to the optimization of available financial resources. Together with the accessibility of woodlands inhabited by the invasive species, planning and funding intermittency were identified as key factors in European projects aimed at the grey squirrel local eradication.[17,20]

In Italy, the LIFE EC-SQUARE project recently tackled issues related to the presence of administrative subdivisions in the project area, a factor that could affect the coordination of management actions, and to citizen opposition towards the project.

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Learning from this experience, in the framework of another LIFE+ Project (LIFE U-SAVEREDS) we implemented a DSS aimed at identifying intervention priorities while also focusing on the human dimension of grey squirrel removal. In Italy, grey squirrel eradication programs often raised severe social conflicts[16] generally related to the divergence in ethical values regarding lethal control.[49,50] To reduce conflicts in invasive species management or, more generally, in adaptive management, several authors advocated the definition and adoption of structured decision making techniques to explicitly consider divergent values.[21,28,51]

A DSS could tackle this issue, since DSSs generally include various sorts of models that can be used to inform managers about the implications of alternative actions.[32] Indeed, DSSs were especially helpful in difficult management contexts, characterized by multiple issues, assessment criteria, stakeholders and values. They can be based on different methodologies, including simulations, decision trees, expert systems and fuzzy logic.[52-57] Here, we chose an approach based on a BDN. Some example of contexts where DSSs based on BBNs proved useful include regional and long-term natural resource planning,[39,52,58] the adaptive management of forests[51] and the determination of appropriate conservation strategies for rare species.[32]

A DSS based on a BBN model has several desirable features.[41] First, it promotes a shared conceptual understanding of the system being managed[51] facilitating the analysis of the studied system by the experts. BBNs also facilitate stakeholder participation in the decision process.[58] They are useful tools to communicate with non-experts about management decision. In spite of their mathematical complexity BBNs can be expressed in familiar terms, and through their graphical construction they provide an intuitive representation of complex relationships.[39,41] Second, a BBN approach is flexible as it has the ability to incorporate different types of data (e.g. qualitative and quantitative data) and to deal with uncertainty.[59,60] Uncertainty is effectively represented by a BBN so that it propagates throughout the network finally affecting the utility outcome in DSSs. This is of major importance because under uncertainty, the true levels of risks/utilities associated with a decision remain unknown,[59] and thus uncertainty needs to be communicated and dealt with, rather than obscured.[59,61,62]

The BBN-based DSS (or BDN) was indeed useful for the staff of the U-SAVEREDS Project. In this case, available knowledge of the studied system derived from very different sources and several interrelated issues (e.g. spatial, ecological and social issues) should be tackled at the same time. Because the whole system involved a relatively large number of variables and relationships potentially affecting the utility of intervention, the initial framework was rather confusing. The staff thus took advantage of the conceptual effort required to identify and elicit the BBN model structure. The BBN allowed a direct integration of variables of different nature (Bayesian random variables), resulting from an analysis of the system from different points of view and based on different system values. Last but not least, the possibility of using latent variables to represent the main debated themes allowed a final straightforward simplification of the whole network making it presentable to a non-expert audience. A simplified version of the LIFE U-SAVEREDS ID was indeed used to communicate with non-experts about the decision making process, and it turned out that the reasoning behind the identification of intervention priorities was understood by experts of other fields and by the general public. The BBN thus responded to the need of transparency in the management decision process, promoting trust and confidence between stakeholders and decision makers.[28]

From a practical perspective, we particularly appreciated the fact that complete and exhaustive knowledge of the values of initial parameters was not strictly necessary to run a BBN model. Preliminary analysis can be carried out, and then the outcome of interest can be easily recalculated as the knowledge of initial variable increases. Although explicitly including feedbacks in BBNs is not an easy task, in the specific case study new data gathered on squirrel populations or a detected change in the attitude of citizens towards the project was easily incorporated in the model and the evaluation of the priority and utility of intervention for each MU was updated quickly (Fig. 4). In this framework, the chosen control strategy, the communication activities and the resulting citizens' support to project activities were strictly related, and we observed that the communication profile specifically implemented for a central MU produced a positive change in the citizens' attitude. This resulted in high utility of intervention for the MU. In other cases, the communication campaign allowed to verify an inadequate support for project activities, leading to a reduction in the utility of intervention. Since carrying out control activities is not optional to reach the eradication goal, this result must be interpreted as a recommendation to revise and adapt the adopted communication profile, identifying appropriate communication tools and messages. This should be done on a MU-basis, taking into account the presence of particular stakeholder groups.

Also, new variables could be added to the model. Although we considered the most critical elements for our case study, Table 1 does not include all possible factors that could affect a grey squirrel eradication project. For example, we did not consider insufficient funding and problems related to grant schemes because we took advantage of LIFE funding, which greatly reduced the relevance of these issues. Anyway, they could be easily included in a future version of the model, e.g. by adding an additional latent variable affecting the probability of success of management activities. Thus, the BBN approach adopted to develop our DSS can be extended to address further issues and it can be applied to other contexts or regions where grey squirrels have invaded.

Working with BBNs also has some drawbacks.[63] The main difficulty we encountered concerned the elicitation of expert knowledge to parameterize the model. In this case, we adopted a rather simplified procedure by asking experts questions corresponding to different scenarios reflected by the cells of conditional probability tables.[64] Further effort will be devoted to the improvement of this parameterization step, as we are aware that robust results can be attained only via accurate elicitation. The elicitation of the model parameters (i.e. conditional probabilities) is indeed recognized as one of the most difficult steps in BBN development. Best practice to tackle this issue is based on face-to-face interviews of the experts, but such an approach may not be feasible mostly because of time and budget constraints. An alternative option is to set up an elicitation survey, which could be administered via web-based tools.[64] This will also allow an increase in the number of experts involved in the elicitation process.

In our experience, the balance between the difficulties of the BBN development and its practical and conceptual advantages was clearly shifted towards the latter. The adopted methodology allowed us to re-organize available information, to evaluate the main management issues, and to finally identify key areas for control activities aiming at the eradication of the Eastern grey squirrel in Umbria. Via the BDN, we were able to reason about management decisions and their consequences from both technical and social perspectives so that we could finally classify the grey squirrel MUs in terms of intervention priority and utility. The final model was multidisciplinary, it explicitly considered spatial, ecological, biological and social issues. We hope it can guide us to reach the goal of grey squirrel eradication in urban areas, and that it can provide an innovative example of how to face the challenges of IAS management now posed by the EU Regulation, especially for the eradication of charismatic or financially important species, which could otherwise encounter the opposition of some stakeholders.

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**References**

1. Simberloff D, Martin J-L, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E and Vilà M, Impacts of biological invasions: what's what and the way forward. *Trends Ecol Evol* **28**:58–66 (2013).
2. Simberloff D., Non-natives: 141 scientists object. *Nature* **475**:36 (2011).
3. Genovesi P., Eradications of invasive alien species in Europe: a review. *Biol Invasions* **7**:127–33 (2005).
4. Jones HP, Holmes ND, Butchart SHM, Tershy BR, Kappes PJ, Corkery I, Aguirre-Muñoz A, Armstrong DP, Bonnaud E, Burbidgek AA, Campbell K, Courchamp F, Cowan PE, Cuthbert RJ, Ebbert S, Genovesi P, Howald GE, Keitt BS, Kress SW, Miskelly CM, Oppel S, Poncet S,

Rauzon MJ, Gérard Rocamora G, Russell JC, Samaniego-Herrera A, Seddon PJ, Spatz DR, Towns DR and Croll DA, Invasive mammal eradication on islands results in substantial conservation gains. *Proc Natl Acad Sci USA* DOI: 10.1073/pnas.1521179113 (2016).

5. Jeschke JM and Strayer DL, Invasion success of vertebrates in Europe and North America. *Proc Natl Acad Sci USA* **102**:7198–202 (2005).
6. Clout MN and Russell JC, The invasion ecology of mammals: a global perspective. *Wildl Res* **35**:180-184 (2007).
7. Genovesi P, Are we turning the tide? Eradications in times of crisis: how the global community is responding to biological invasions, in *Island invasives: eradication and management*, ed. by Veitch CR, Clout MN and Towns DR, IUCN, Gland, pp. 5-8 (2011).
8. Bertolino S, Cordero di Montezemolo N, Preatoni DG, Wauters LA, Martinoli A, A grey future for Europe: *Sciurus carolinensis* is replacing native red squirrels in Italy. *Biol Invasions* **16**:53–62 (2013).
9. Gurnell J, The grey squirrel in Britain: problems for management and lessons for Europe. *Proceedings of the I European Congress of Mammalogy*, ed. by Mathias ML, Museu Bocage, Lisboa: 1996. pp. 67–81 (1996).
10. Mayle BA, Ferryman M and Pepper HW, *Controlling grey squirrel damage to woodlands*, Practice Note, Forestry Commission, FCPN4 (revised), pp. 1-6 (2007).
11. Mayle BA and Broome AC, Changes in the impact and control of an invasive alien: the grey squirrel (*Sciurus carolinensis*) in Great Britain, as determined from regional surveys. *Pest Manag Sci* **69**:323–33 (2013).
12. Wauters LA, Gurnell J, Currado I and Mazzoglio PJ, Grey squirrel *Sciurus carolinensis* management in Italy - squirrel distribution in a highly fragmented landscape. *Wildl Biol* **3**:117-124 (1997).
13. Wauters L, Tosi G and Gurnell J, A review of the competitive effects of alien grey squirrels on behaviour, activity and habitat use of red squirrels in mixed, deciduous woodland in Italy. *Hystrix It J Mamm (ns)* **16**:27-40 (2005).
14. Sheail J, The grey squirrel (*Sciurus carolinensis*) - a UK historical perspective on a vertebrate pest species. *J Environ Manage* **55**:145–56 (1999).

15. Sheail J, Government and the management of an alien pest species: A British perspective. *Landscape Res* **28**:101–111 (2003).
16. Bertolino S and Genovesi P, Spread and attempted eradication of the grey squirrel (*Sciurus carolinensis*) in Italy, and consequences for the red squirrel (*Sciurus vulgaris*) in Eurasia. *Biol Conserv* **109**:351–358 (2003).
17. Schuchert P, Shuttleworth CM, McInnes CJ, Everest DJ and Rushton SP, Landscape scale impacts of culling upon a European grey squirrel population: can trapping reduce population size and decrease the threat of squirrel pox virus infection for the native red squirrel? *Biol Invasions* **16**:2381–2391 (2014).
18. Lawton C and Rochford J, The recovery of grey squirrel (*Sciurus carolinensis*) populations after intensive control programmes. *Biology & Environment: Proceedings of the Royal Irish Academy* **107**:19–29 (2007).
19. Parrott D, Quy R, Van Driel K, Lurz P and Rushton S, *Review of red squirrel conservation activity in northern England*, Natural England Contract No. 08/09/N/004, Peterborough, pp. 111 (2009).
20. Shuttleworth CM, Schuchert P, Everest DJ, McInnes C, Rushton S and Kenward RE, Developing integrated and applied red squirrel conservation programmes: what lessons can Europe learn from a regional grey squirrel eradication programme in North Wales?, in *Red squirrels ecology, conservation and management in Europe*, ed. by Shuttleworth CM, Lurz PWW and Hayward M, Woodbridge, Suffold, pp 233–249 (2015).
21. Genovesi P and Bertolino S, Human dimension aspects in invasive alien species issues: the case of the failure of the grey squirrel eradication project in Italy, in *The Great Reshuffling*, ed. by McNeely JA, IUCN, Gland, pp. 113–119 (2001).
22. Bertolino S, Animal trade and non-indigenous species introduction: the world-wide spread of squirrels. *Divers Distrib* **15**:701–708 (2009).
23. Bertolino S, Martinoli A and Wauters LA, Risk Assessment for *Sciurus carolinensis* (grey squirrel), in *Invasive alien species - framework for the identification of invasive species of EU concern*, ed. by Roy H, Natural Environment Research Council pp. 298 (2014).
24. Bertolino S, Currado I, Mazzoglio P and Amori G, Native and alien squirrels in Italy. *Hystrix It J*

*Mamm* **11**:65-74 (2000).

25. Benson E, The urbanization of the Eastern gray squirrel in the United States. *J Am Hist* **100**:691–710 (2013).
26. McNeely JA, *The Great Reshuffling. Human Dimensions of Invasive Alien Species*, IUCN, Gland and Cambridge, pp. vi+242 (2001).
27. Russell JC, Jones HP, Armstrong DP, Courchamp F, Kappes PJ, Seddon PJ, Oppel S, Rauzon MJ, Cowan PE, Rocamora G, Genovesi P, Bonnaud E, Keitt BS, Holmes ND and Tershy BR, Importance of lethal control of invasive predators for island conservation. *Conserv Biol*, DOI: 10.1111/cobi.12666 (2016).
28. Estévez RA, Anderson CB, Pizarro JC and Burgman MA, Clarifying values, risk perceptions, and attitudes to resolve or avoid social conflicts in invasive species management, *Conserv Biol* **29**:19–30 (2015).
29. Howald G, Donlan CJ, Galván JP, Russell JC, Parkes J, Samaniegio A, Wang Y, Veitch D, Genovesi P, Pascal M, Saunders A and Terchy B, Invasive rodent eradication on islands, *Conserv Biol* **21**:1258–1268 (2007).
30. Signorile AL, Paoloni D and Reuman DC, Grey squirrels in central Italy: a new threat for endemic red squirrel subspecies. *Biol Invasions* **16**:2339–2350 (2014).
31. Genovesi P and Bertolino S, *Linee guida per il controllo dello Scoiattolo grigio (Sciurus carolinensis) in Italia*, Quad Cons Natura, Min Ambiente - Ist Naz Fauna Selvatica, Roma, pp. 52 (2001).
32. Marcot BG, Hohenlohe PA, Morey S, Holmes R, Molina R, Turley MC, Huff MH and Laurence JA, Characterizing species at risk II: Using Bayesian belief networks as decision support tools to determine species conservation categories under the Northwest Forest Plan, *Ecol Soc* **11**:12 (2006).
33. Pourret O, Naïm P and Marcot B, *Bayesian Networks: a practical guide to applications*, John Wiley & Sons, Chichester, pp. 446 (2008).
34. Barr JJF, Lurz PWW, Shirley MDF and Rushton SP, Evaluation of immunocontraception as a publicly acceptable form of vertebrate pest species control: the introduced grey squirrel in Britain as an example. *Environ Manage* **30**:342–351 (2014).

35. Bremner A and Park K, Public attitudes to the management of invasive non-native species in Scotland. *Biol Conserv* **139**:306–314 (2007).
36. Peacock DE, The grey squirrel *Sciurus carolinensis* in Adelaide, South Australia: its introduction and eradication, *Victorian Naturalist* **126**:150-156 (2009)
37. Shuttleworth CM, Lurz PWW and Halliwell EC, *Shared experience of red squirrel conservation practice*, European Squirrel Initiative (ESI), Woodbridge, Suffolk, pp. 210 (2015).
38. Gurnell J and Steele J, *Grey squirrel control for red squirrel conservation: a study in Thetford Forest.* English Nature Research Report 453, English Nature, Peterborough (2002).
39. Cain J, *Planning improvements in natural resources management. Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond*, Center for Ecology and Hydrology, Oxon, pp. 132 (2001).
40. Marcot BG, Steventon JD, Sutherland GD and McCann RK., Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation, *Can J For Res* **36**:3063–3074 (2006).
41. McCann RK, Marcot BG and Ellis R, Bayesian belief networks: applications in ecology and natural resource management, *Can J For Res* **36**:3053–62 (2006).
42. Buckland ST, Anderson DR, Burnham KP and Laake JL, *Introduction to distance sampling. Estimating abundance of biological populations*, Oxford University Press, Oxford, pp. 432 (2001).
43. Thomas L, Buckland ST, Burnham KP, Anderson DR, Laake JL, Borchers DL and Strindberg S, Distance sampling, in *Encyclopedia of Environmetrics*, ed. by El-Shaarawi AH and Piegorsch WW, John Wiley & Sons, Ltd, Chichester, **1**:544-552 (2002).
44. Wang H, *Building Bayesian Networks: elicitation, evaluation, and learning*, PhD Dissertation, University of Pittsburgh, pp. 125 (2004).
45. Stone M, The Opinion Pool. *Ann Math Statist* **32**:1339–1342 (1961).
46. R Core Team, *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna (2015). http://r-project.org/ [accessed 28 March 2016]
47. Højsgaard S, Graphical Independence Networks with the gRainPackage for R. *J Stat Software* **46**:1-16 (2012).

48. Rushton SP, Lurz PWW, Gurnell J, Nettleton P, Bruemmer C, Shirley MDF and Sainsbury AW, Disease threats posed by alien species: the role of a poxvirus in the decline of the native red squirrel in Britain. *Epidemiol Infect* **134**:521–533 (2006).

49. Wallach AD, Bekoff M, Nelson MP and Ramp D, Promoting predators and compassionate conservation. *Conserv Biol* **29**:1481–1484 (2015).

50. Cowan P and Warburton B, Animal welfare and ethical issues in island pest eradication, in *Island invasives: eradication and management*, ed. by Veitch CR, Clout MN and Towns DR, IUCN, Gland, pp. 418-421 (2011).

51. Nyberg JB, Marcot BG and Sulyma R, Using Bayesian belief networks in adaptive management. *Can J For Res* **36**:3104–3116 (2006).

52. Zhu X and Dale AP, Identifying opportunities for Decision Support Systems in support of regional resource use planning: an approach through soft systems methodology. *Environ Manage* **26**:371–384 (2000).

53. Maguire LA, Seal US and Brussard PF, Managing critically endangered species: the Sumatran rhino as a case study, in *Viable populations for conservation*, ed. by Soule ME Cambridge University Press, Cambridge, pages 141–58 (2009).

54. Tremblay J-P, Hester A, Mcleod J and Huot J, Choice and development of decision support tools for the sustainable management of deer–forest systems. *Forest Ecol Manag* **191**:1–16 (2004).

55. Regan HM, Ben-Haim Y, Langford B, Wilson WG, Lundberg P, Andelman SJ and Burgman MA, Robust decision-making under severe uncertainty for conservation management, *Ecol Appl* **15**:1471–1477 (2005).

56. Paterson B, Stuart-Hill G, Underhill LG, Dunne TT, Schinzel B, Brown C, Beytell B, Demas F, Lindeque P, Tagg J and Weaver C, A fuzzy decision support tool for wildlife translocations into communal conservancies in Namibia, *Environ Modell Softw* **23**:521–34 (2008).

57. Liu S, Proctor W and Cook D, Using an integrated fuzzy set and deliberative multi-criteria evaluation approach to facilitate decision-making in invasive species management, *Ecol Econ* **69**:2374–2382 (2010).

58. Cain J, Batchelor C and Waughray D, Belief Networks: A framework for the participatory

development of natural resource management strategies, *Environment, Development and Sustainability* **1**:123–33 (1999).

59. Thompson KM, Variability and uncertainty meet risk management and risk communication, *Risk Anal* **22**:647–54 (2002).
60. Kangas AS and Kangas J, Probability, possibility and evidence: approaches to consider risk and uncertainty in forestry decision analysis, *Forest Policy Econ* **6**:169–88 (2004).
61. Goldstein BD, Demak M, Northridge M and Wartenberg D, Risk to groundlings of death due to airplane accidents: A Risk Communication Tool, *Risk Anal* **12**:339–41 (1992).
62. Thompson KM, Rabouw RF and Cooke RM, The risk of groundling fatalities from unintentional airplane crashes, *Risk Anal* **21**:1025–1038 (2001).
63. Uusitalo L, Advantages and challenges of Bayesian networks in environmental modelling, *Ecol Model* **203**:312–318 (2007).
64. Spaccasassi C and Deleris L, A web-based tool for expert elicitation in distributed teams, *Proceedings of the 8th UAI Bayesian Modeling Applications Workshop* (UAI-AW 2011), ed. by Nicholson A, Barcelona, pp. 125-133 (2011).

Table 1. Specific attributes of the critical elements of the Influence Diagram (ID) for grey squirrel management in Umbria. Attributes denoted by "*" were evaluated from existing data, using GIS databases or data on squirrel presence and distribution gathered within the project (MU - Management Unit). The number of states differs among attributes, being generally three (e.g. small, intermediate, large) except for 'subzone' (five states) and for 'grey squirrel foraging' and 'agricultural damage' (two states).

| Critical elements (endogenous variables) | Specific attributes | States of the attributes | | | | |
|---|---|---|---|---|---|---|
| Spatial issues | Subzone* | Perugia | Monte Malbe | Southern Perugia | Northern Perugia | Outer areas |
| | Distance from the core area of grey squirrel locations* | Short (superimposed on or adjacent to the core area) | Intermediate (adjacent to MU[1] at small distance from the core area) | Large (all other MUs) | | |
| | Ecological connectivity* | Low (ecologically isolated MUs) | Intermediate (stepping stone area) | High (all other MUs) | | |
| | Extent* | Small | Medium | Large | | |
| Ecological background | Protection level* | Low (MUs located far away from Natura 2000 sites) | Intermediate (MUs adjacent to Natura 2000 sites) | High (MUs totally or partly overlapping Natura 2000 sites) | | |
| | Urban area (%)* | Small | Intermediate | High | | |
| | Distance from red squirrel areas* | Short (MUs totally or partly superimposed on red squirrel range) | Intermediate (MUs adjacent to red squirrel range) | Large (all other MUs) | | |
| | Woodland type* | Scattered trees | Fragmented woodlands | Continuous forests | | |
| Social environment | Attendance level | Low | Intermediate | High | | |
| | Grey squirrel foraging | Yes | No | | | |
| | Agricultural damage | Yes | No | | | |
| | Presence of public green areas, gardens, urban parks | Very limited (no or very limited urban parks) | Limited (urban parks of limited extent, but tightly embedded with urban areas) | Relevant (large and/or very popular urban parks) | | |
| Status of squirrel population | Squirrel presence* | Red squirrel only | Presence of both red and grey squirrels | Grey squirrel only | | |
| | Grey squirrel density* | Low (occasional reports) | Intermediate (less than 4 animals/ha) | High (more than 4 animals/ha) | | |
| | Grey squirrel distribution* | Scattered | Clustered | Homogeneous | | |

| | | | | |
|---|---|---|---|---|
| Sanitary risks | Sanitary risk* | Low (sporadic reports of pathogens related to not notifiable diseases) | Intermediate (dermatophytes with high prevalence) | High (report of legally notifiable diseases and/or Poxvirus and/or Adenovirus) |
| Success probability | Control method | Capture and surgical sterilization only | Capture and direct removal + capture and surgical sterilization | Capture and direct removal only |
| | Citizens' support | Low (access granted for less than 50% of private areas) | Intermediate (access granted for less than 50-75% of private areas) | High (access granted for at least 75% of private areas) [2] |
| | Ecological connectivity* | Low (ecologically isolated MUs) | Intermediate (stepping stone area) | High (all other MUs) |
| | Extent* | Small | Medium | Large |
| Working environment | Communication profile | Low | Medium | High |
| | Citizens' support | Low (access granted for less than 50% of private areas) | Intermediate (access granted for less than 50-75% of private areas) | High (access granted for at least 75% of private areas) [2] |

[1] MU = Management Unit

[2] 75% refers to the percentage of private, fenced areas only and it is intended as a lower limit. Adding up access to unfenced areas, the percentage of accessible woodlands should be higher than 75%, as a very broad consensus, ensuring the access to most woodlands, is required for successful local eradication.[20]

**Figure captions**

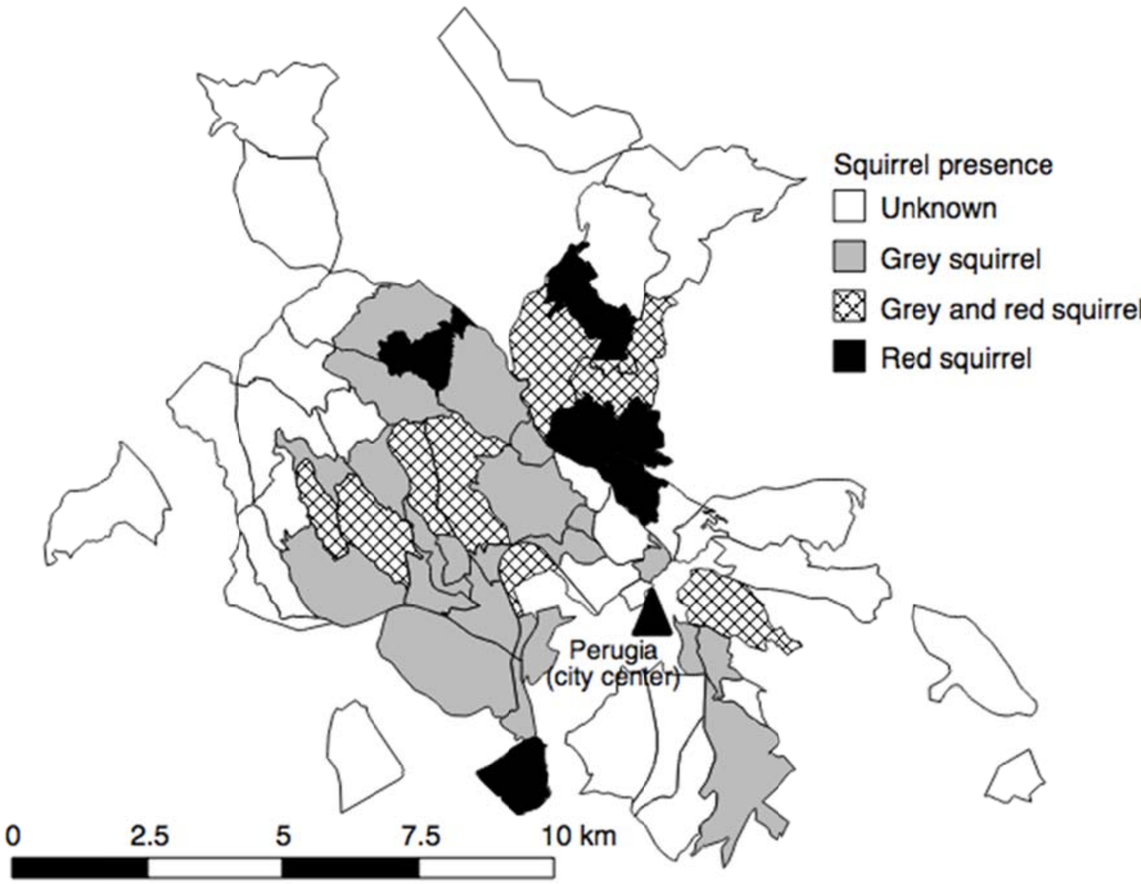


Figure 1. Borders of the squirrel Management Units and distribution of both red and grey squirrels (according to data collected during the LIFE U-SAVEREDS Project).

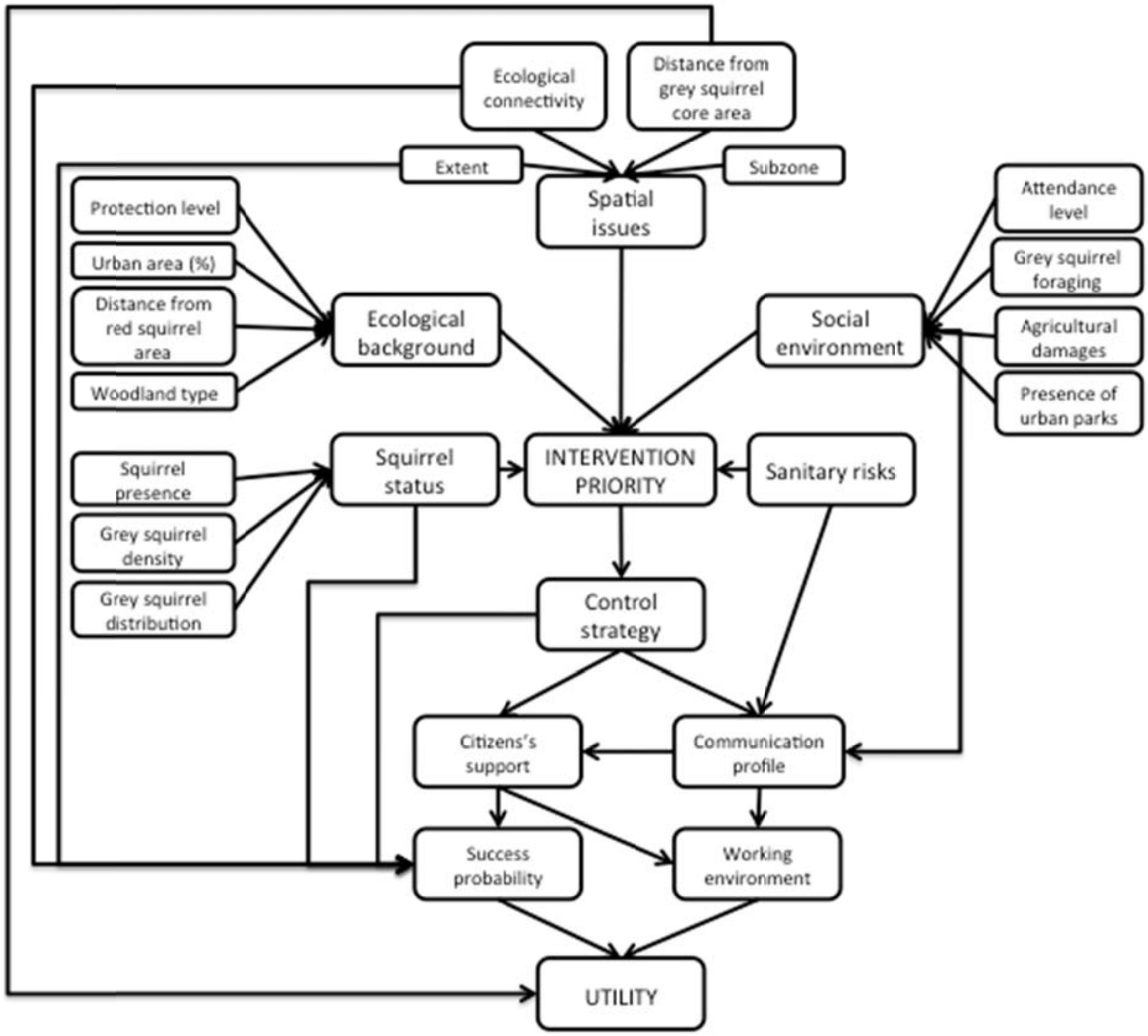


Figure 2. Influence Diagram showing key factors (critical elements and attributes) affecting the intervention priority and then the utility of intervention in each Management Unit for grey squirrel management in Umbria. The utility is dependent on success probability and working environment, which in turn depend on other parent (both endogenous and exogenous) nodes of the Directed Acyclic Graph, as described in Table 1. Note that the graph label "Squirrel precence" refers to the presence of red and/or grey squirrels.

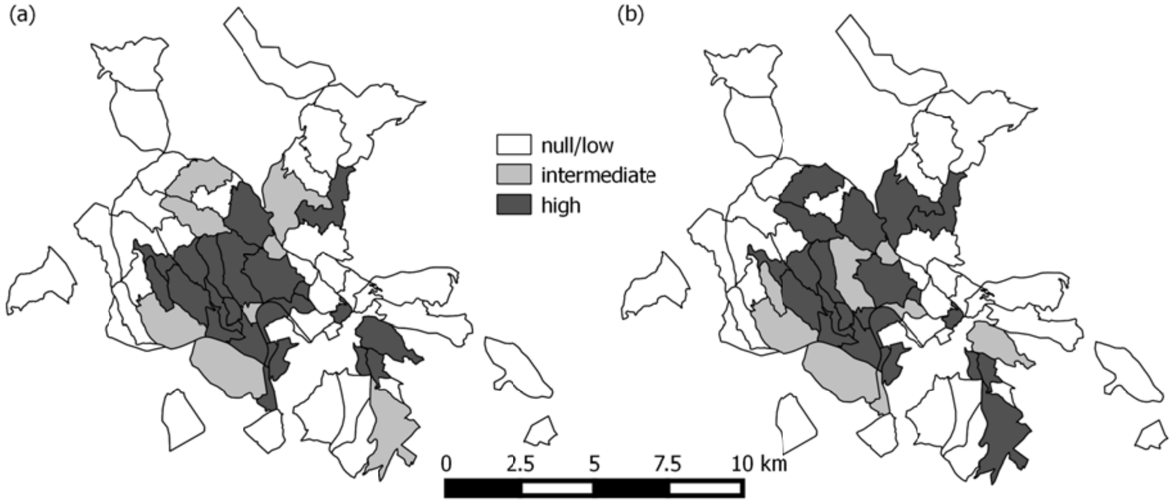


Figure 3. Map of the priority (a) and utility (b) of intervention in the grey squirrel management units in Umbria.

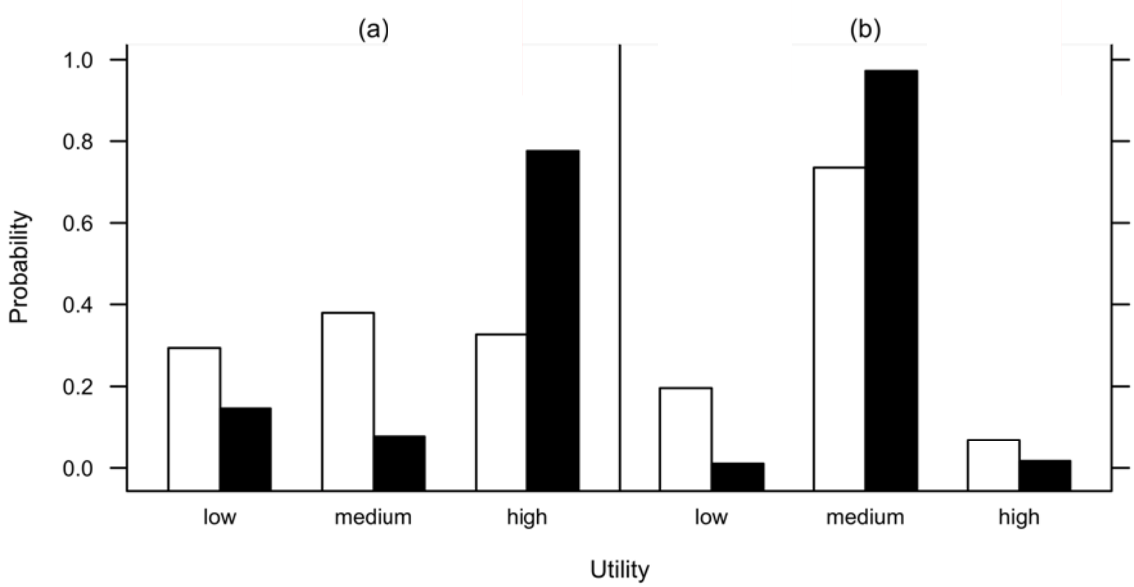


Figure 4. Change in probability of low, intermediate and high utility for two (a and b) Management Units. The white bars indicate the probability (belief) in each utility class, as obtained with the base model, while the black bars report the final outcome when the model was updated with information gathered through the communication campaign.