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Effects of stakeholder empowerment on crane population and agricultural production

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ABSTRACT

Conflicts between opposing objectives of wildlife conservation and agriculture are increasing globally due to rising human food production and competition with wildlife over land use. Conservation conflicts are often complex and driven by variability and uncertainty in wildlife distribution and stakeholder wealth and power. To manage conflicts, empowering local stakeholders by decentralizing decisions and actions has been suggested to promote democratization and awareness of stakeholders. There is, however, a current gap in the understanding of how stakeholder empowerment (*e.g.,* farmers' and managers' practical, time or monetary resources) affects policy effectiveness. In this study, we apply an individual-based model of management strategy evaluation to simulate the conservation conflict surrounding protected and thriving common cranes (*Grus grus*) causing damage to agricultural production in Sweden and along the European flyways. We model the effect of farmer empowerment (*i.e.,* increasing budgets to affect populations and agricultural production) in four management scenarios, in which we manipulate the availability and cost of two actions farmers may take in response to crane presence on their land: non-lethal (scaring) or lethal (culling) control. We find that lower budgets lead to increases in population size due to increased use of less costly scaring instead of shooting. Higher farmer budgets lead to increased population extinction risk. Intermediate budgets allow farmers to control the population size around the management target and limit impact on agricultural production to intermediate levels. Our study highlights that stakeholder empowerment and culling strategies based on the number of stakeholders, and particularly their power to implement effective actions, needs careful consideration and monitoring when setting management targets and strategies. Further, our results show that empowering individual farmers has the potential to contribute to conflict management and to balance agricultural with conservation objectives, but increased stakeholder involvement also requires careful planning and monitoring.

1. Introduction

Conflicts between the objectives of wildlife conservation (*i.e.,* species protection, habitat restoration) and sustainable agriculture are increasing globally due to a rising human demand for food production and consequent competition with wildlife over land use (Henle et al., 2008; Redpath et al., 2013). Such conflicts have been identified as one of the major causes of failed management strategies and can thus result in negative impacts on conservation outcomes and stakeholders' livelihoods and psychosocial wellbeing (Barua et al., 2013; Hodgson et al., 2019; Redpath et al., 2013). Due to their complex and dynamic nature, conflicts like these are often described as 'wicked problems', characterized and driven by the variation and uncertainty in, *e.g.,* wildlife distribution and inequity in stakeholder wealth and power (Bennett et al., 2017; Mason et al., 2018; Young et al., 2016). In the case of herbivore populations, conflicts often arise when wildlife forage on and cause damage to crops, and when management options to reduce this are limited due to protection of the species or social opposition towards mitigation interventions (Dickman, 2010). Particularly good examples of such 'wicked' conservation conflicts involve protected cranes (*Grus spp.*) and geese (*Branta, Anser spp.*), which currently have exponentially increasing populations causing negative impacts on agricultural land in Europe and North America, especially on land surrounding protected areas designated for those species and biodiversity in general (Cusack et al., 2019; Fox and Madsen, 2017; Nilsson et al., 2019). Negative impacts caused by wildlife are often managed by culling to reduce

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populations under the assumption that agricultural loss will decrease accordingly (Montràs-Janer et al., 2019). However, due to protection or practical limitations, non-lethal mitigation methods (*e.g.,* scaring, diversionary feeding, monetary compensation) are often required instead of culling (Cusack et al., 2019; EC, 2009; Owen, 1990). Yet, the management of many species, including cranes and geese, remains problematic in part due to time lags in centralized managers' actions as a response to negative impact on agricultural production (Cusack et al., 2019). This may aggravate conflicts by weakening stakeholder trust and willingness to act in line with policy (Bennett et al., 2017; Cusack et al., 2019; Young et al., 2016). To manage conflicts like these, empowering local stakeholders and their expertise by decentralizing decisions and actions has been proposed to integrate complexity and democratization into the management process (Mason et al., 2018; Raik et al., 2008; Redpath et al., 2017). However, there is currently a gap in the understanding of how stakeholder empowerment (*i.e.,* practical, time or monetary resources) affects sustainability and extinction risk of the population as well as agricultural production. In the extreme, decentralizing decisions to farming stakeholders without providing budgets to enact actions may fuel frustration and conflict with policy makers and managers and lead to ineffective management; whereas unlimited farming stakeholder budgets may cause conflicts when conservation stakeholder objectives supersede management objectives (Mason et al., 2018; Redpath et al., 2013).

Decision making in natural resource management is traditionally assumed to be based on stakeholder objectives to maximize their returns in terms of livelihood given a limited set of actions, ability and budget to perform them (D. Hodgson et al., 2020; Milner-Gulland, 2011). For example, farmers aim to maximize their agricultural production given the land and labor they have, whereas managers might instead aim to keep wildlife populations within a range where long term viability is ensured given their ability to monitor the population and enforce their policies. In pursuing these aims, practical limitations (*e.g.,* available time and resources) will constrain the power of both farmers and managers to act, leading to trade-offs in decision-making. Game theory formally describes situations with such strategic actions, in which the consequences of an individual's decisions are influenced by the decisions taken by others (Hauert et al., 2006). For example, the success of a manager's decisions toward fulfilling conservation objectives through policy or economic incentives might be affected by the decisions of stakeholders to comply or not (Colyvan et al., 2011; Milner-Gulland, 2011; Redpath et al., 2018). Hence, while many existing models assume that policy will be enacted faithfully, this assumption might not always be realistic, such as under used culling quotas due to deficient number of hunters (Butterworth, 1999; Milne, 2018; Milner-Gulland, 2012).

Small perturbations in stakeholder behavior or policy in uncertain and dynamic systems might result in severe and unforeseen implications for the dynamics of the entire system, including both human behavior (*i.e.,* social tipping points) and increased extinction risk in the focal wildlife population (*i.e.,* ecological tipping points) (Heal and Kunreuther, 2012; Scheffer et al., 2012). Complexity and uncertainty make empirical evaluation of management outcomes (*i.e.,* agent responses) challenging. To account for uncertainty at multiple points in the management process, the management strategy evaluation (*i.e.,* MSE) framework has been developed (Smith, 1999). However, until now, MSE models have incorporated constant decision-making rules for single managers or farmers over time (Bunnefeld et al., 2013; Melbourne-Thomas et al., 2017; Milner-Gulland, 2011). A newly developed framework for generalized management strategy evaluation (*i.e.,* GMSE) includes scenarios that can include multiple independent stakeholders making individual decisions, as influenced by changes in resources, policy, and individual circumstance (Duthie et al., 2018).

In this study, we apply the management strategy evaluation framework using the GMSE R package to simulate the conservation conflict case of protected common cranes congregating in large numbers (*i.e.,* up to 26,000 ind.) at agricultural staging sites in Sweden, causing significant damage to agricultural production (inspected and compensated damage totals up to 200.000 Euros/year) (Montràs-Janer et al., 2019; Nilsson et al., 2019). Cranes are protected in Annex I in the European Birds Directive and thus from culling to regulate the population. The directive states that the listed species' survival and reproduction must be ensured in their distribution range, but allows for licensed lethal culling to mitigate negative impact on human livelihoods and when non-lethal damage preventive measures (*e.g.,* scaring, diversionary feeding) have been found unsuccessful (EC, 2009). Due to the protective legislation, no management targets are defined for the maximum populations size on either staging site or flyway level, but as these populations will likely continue to grow, so will the stakeholder demand for lethal or non-lethal crop damage preventive strategies and the severity of the conservation conflict (Fox and Madsen, 2017; Montràs-Janer et al., 2019). By applying the MSE framework in this study, we aim to identify the effect of increasing stakeholder power (*i.e.,* decentralizing decisions to enact policy), on all aspects of the system, including the objectives to keep a viable wildlife population and sustainable agricultural production over time, and the implications for managing conflict. More specifically, we investigate how increasing the ability of individual stakeholders to enact decisions at the farm scale affects broader scale changes in expected crane population sizes and agricultural production in four possible management scenarios: *a.*) no management and no stakeholder power to affect cranes, *b.*) scaring and culling of cranes, with a management objective to allow the population to increase to an effectively high management target (*i.e.,* 100,000 ind.), *c.*) only culling allowed, but with an effectively high management target and *d.*) scaring and culling with a management objective to keep the population at a lower target (*i.e.,* 15,000 ind.) to lower the negative impact on agricultural production.

2. Model

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al., 2006), as updated by Grimm et al. (2020). The full ODD description, including the Details section and R code to replicate all simulations can be found in Supplementary Material 1.

2.1. *Purpose and patterns*

The purpose of the model is to predict how increasing the ability of individual stakeholders to enact decisions at the farm scale affects broader scale changes in expected crane population sizes and agricultural production in four possible management scenarios over 30 years. To do this, we used the package GMSE v0.6.0.4 in R (Duthie et al., 2018). GMSE simulates the management strategy evaluation process in a way that models goal-oriented behavior and spatial distribution of individual stakeholders, managers and wildlife using an individual-based (*i.e.,* agent-based) framework (Bunnefeld et al., 2011; Duthie et al., 2018). The four management scenarios simulated were: *a.*) no management and no stakeholder power to affect cranes, *b.*) scaring and culling of cranes, with a management objective to allow the population to increase to an effectively high management target (*i.e.,* 100,000 ind.), *c.*) only culling allowed, but with an effectively high management target and *d.*) scaring and culling with a management objective to keep the population at a lower target (*i.e.,* 15,000 ind.) to lower the negative impact on agricultural production.

2.1.1. *Management scenario a*

Scenario *a* is a null model for population size and mean agricultural production when no scaring or culling is conducted and the crane population can grow exponentially. Currently, there is a lack of management targets both nationally and for the whole population along the flyways, so this reflects the current lack of population regulation.

2.1.2. Management scenario b

Scenario *b* models current management in Sweden, which allows for intensive scaring methods to reduce loss in agricultural production (specifically using scaring by the use of gas cannons, scare crows, flags). Very limited culling (*i.e.,* up to 15 individuals licensed to a minority of the farmers) is occasionally permitted by the managing authorities (EEA, n.d.). In our model, the strict licensing procedure for culling is represented by a high cost for culling for the farmer, unlike scaring, and was regulated in the simulations by setting a very high management target, *i.e.,* ensuring a condition where the manager would always set a high cost for culling. Non-lethal scaring may divert cranes from single cells at the landscape, but will not affect population size and a scenario only permitting scaring was therefore not considered.

2.1.3. Management scenario c

Scenario *c* models a hypothetical scenario where although culling is expected to be costly, thus the manager is expected to keep costs of culling very high) there either is no alternative action possible, or alternative actions like scaring are prohibited or widely perceived to be ineffective and therefore never taken.

2.1.4. Management scenario d

Scenario *d* models a situation where managers permit both scaring and culling, but managers attempt to keep the crane population at a size well below presumed carrying capacity. This allows for a more dynamic allocation of budget for both farmers and managers, which consequently mimics a trade-off between the objectives to sustain agricultural production while ensuring viability of the crane population.

We evaluate our model by its ability to reproduce the pattern of population growth in the previous 30 years leading up to the current population year 2020. By parameterizing the model with the parameter values (*i.e.,* initial population size and reproductive output, for details see *Initialization* in Supplementary Material 1) derived from the model simulations and based on previous empirical data on crane numbers, we can test if the model reproduces the pattern of population growth given realistic initial conditions. Recovering this pattern demonstrates that the model was fit for purpose in that we could then use it to test new scenarios against (*i.e.,* management scenario *a-d*).

2.2. Entities, state variables and scales

Farmers, managers and cranes operate on an agricultural landscape (L), modelled as a torus of discrete cells owned by individual farmers and producing a potentially variable yield of agricultural crop (*i.e.,* agricultural production). Each landscape cell thus has unique traits including farmer ownership, *x-y* location (L_{xy}), agricultural production and density of cranes in each time step. Only one farmer can own a single L_{xy} cell, but any number of cranes can occupy a single cell. In this study, L was constructed as a grid of 100 × 100 cells, representing a total staging area of about 200 km^2 (Nilsson et al., 2018), utilized by a total of 50 farmers earning the majority of their livelihood from agriculture ($\geq$ 1 km^2 per farmer; Holmer, 2016; The Swedish Board of Agriculture, 2017).

GMSE models discrete individuals, which here include farmers, managers, and cranes. Each individual has potentially unique traits, which potentially affect their behavior. Each farmer owns a fixed number of contiguous landscape cells (L, see above) on which they can perform one or more types of actions. Each farmer has a budget B_f for performing actions, which can be broadly interpreted to encompass one or more factors limiting the total number of actions possible for the farmer during a single time step such as time, money, or available equipment. Thus, individual farmers' traits include their budget and farm location. Managers do not own landscape cells, but instead set policy that affects the costs of performing actions for farmers (C_{action}). Managers have traits in terms of a budget B_m for setting policy, which can be broadly interpreted to encompass the factors that limit the power of managers to make and enforce policy decisions. Managers either do not attempt to regulate crane population density, or attempt to maintain cranes at some target population density ($N^{\dagger}$) at every time step by setting policy (*i.e.,* costs for farmer actions). The traits for individual cranes are location, age and reproductive output. In this study, a single time step is modelled as one year. For a definitions of state variable entities, landscape and model parameters, see Table S1 in Supplementary Material 1.

2.3. Process overview and scheduling

The model includes four sub models operating in sequence over a single time step (Fig. 1). For detailed information on definition and use of parameters and modeling procedure, see Supplementary Material 1.

2.4. The crane population sub model

The first sub model simulates the population dynamics of N_t cranes in time step t. Cranes arrive at a randomly selected cell within R_m cells of the one that they left in $t\text{-}1$ with equal probability (crane cell location is randomly selected in $t = 1$), then feed R_{fe} times. Between each feeding, cranes move to a cell within R_m cells in any direction from the currently occupied cell on the landscape randomly selected with equal probability. Cranes then give birth to young, then potentially die of old age.

Initial population size for each simulation was independently sampled from the distribution of simulated terminal abundances from the 100 n_{rep} replicate simulations in years 1989–2019 (see '*Initialization*' in Supplementary Material 1. & Fig. S1 in Supplementary Material 2.).

2.5. The observation sub model

The observation model uses a monitoring method in which cranes are counted with complete accuracy on a subset of the landscape (*i.e.,* 10 × 10 cells) and density is then extrapolated to estimate the crane population size assuming the same density over the entire landscape. Hence, estimated population size $\hat{N}$ might deviate from the true N.

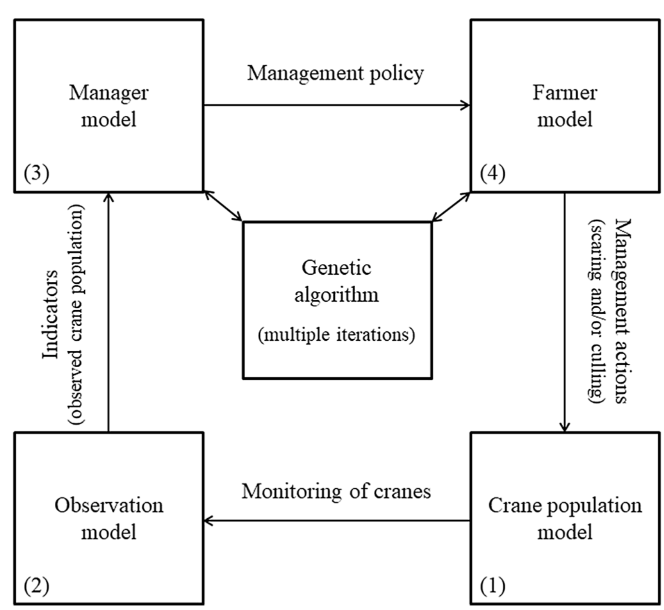

Fig. 1. The concept of the generalized management strategy evaluation modeling (GMSE) framework. The model consists of four sub model (see number 1–4) operating in sequence for each time step.

2.6. The manager sub model

The manager sub model assesses N̂ in relation to a management target, and sets policy by defining action costs (C_{action}; these may be conceptualized as, *e.g.,* time, practical or monetary costs for different actions farmers may take to affect agricultural production, including culling or scaring cranes). Managers use an evolutionary algorithm to set costs for each action; this algorithm models the heuristic process of the manager considering different potential policies and choosing one that will result in a crane population density nearer to the manager's target (see Supplementary Material 1). Once the algorithm is completed, managers enact the cost of each available farmer action. The total budget for the manager was kept constant in the model (*i.e.,* $B_m = 1000$). See Supplemental Material 1 for details on parameterization of the evolutionary algorithm.

2.7. The farmer sub model

In the farmer sub model, farmers implement actions with the objective to maximize their own agricultural production, constrained by the costs of individual actions as set by the manager's policy and the farmers' annual budgets (B_f). As with manager policy decisions, farmer decisions are chosen by running a single independent evolutionary algorithm for each farmer in each time step. Farmers recognize that the presence of cranes on a landscape cell has a negative effect on agricultural production, and will therefore adaptively use actions to try to effectively decrease the presence of cranes. Individual stakeholder decisions consequently affect cranes and agricultural production over multiple time steps. All actions of all farmers are performed in a random order so that, for example, one farmer does not do all of their scaring or culling before another farmer and thereby cause differences in farmer's agricultural production due to the order of farmer actions. Farmers can only take actions on land that they own.

2.8. Design concepts

2.8.1. Basic principles

To account for uncertainty at multiple points in a natural resource management process, the management strategy evaluation (*i.e.,* MSE) framework has been developed (Smith, 1999). MSE models have incorporated constant decision-making rules for single managers or farmers over time (Bunnefeld et al., 2013; Melbourne-Thomas et al., 2017; Milner-Gulland, 2011). However, the generalized management strategy evaluation framework (*i.e.,* GMSE) used in this study includes multiple independent stakeholders making individual decisions, as influenced by changes in resources, policy, and individual circumstance (Duthie et al., 2018). GMSE simulates the management strategy evaluation process in a way that models goal-oriented behavior and spatial distribution of individual stakeholders, managers and wildlife using an individual-based (*i.e.,* agent-based) framework (Bunnefeld et al., 2011; Duthie et al., 2018).

The observation model uses a "virtual ecologist" approach (Zurell et al., 2010) to model manager observation of the crane population.

2.8.2. Emergence

Crane population dynamics and agricultural production emerge over time, based on the individual decisions of the manager (*i.e.*, setting policy) and farmers (*i.e.*, taking action).

2.8.3. Adaptation

Evolutionary algorithms are useful heuristic tools that mimic the process of biological evolution to find solutions to highly complex problems (Hamblin, 2013). In our simulations, these complex problems refer to modeling the goal-oriented decision making of managers and farmers. Managers must attempt to use their available budget to set costs that keep crane populations near a pre-specified target, while farmers must attempt to use their available budget and any actions available to maximize agricultural production. The possible actions that farmers can take to reduce impact on agricultural production include non-lethal scaring, one action of which causes one crane to randomly relocate to a new cell before damaging crops (note, this could potentially result in the crane resettling on another cell owned by the acting farmer), or culling, one action of which causes one crane to be completely removed from the landscape before damaging crops (see scenario a-b). Decisions within the model are made under uncertainty, as is realistic for stakeholders in empirical social-ecological systems, and behavior is consequently heuristic often suboptimal. The Section "The evolutionary algorithm used in the manager and farmers sub models" in Supplementary material 1 explains how the evolutionary algorithm is used to model manager and farmer decision making, with further detail of this general approach available in Supporting Information 1 of Duthie et al. (2018).

2.8.4. Objectives

The objective of the farmers is to maximize total agricultural production Y_f across all of the landscape cells that they own. Whereas the managers' objective is to set a policy (in terms of action costs) that minimizes the distance between the crane population target and the current population level (Duthie et al., 2018).

2.8.5. Learning

We included a learning process in each run of the evolutionary algorithm by seeding it with 20 copies of the strategy from the previous time step, allowing it to potentially learn from the previous time step and more efficiently find a successful strategy given similar conditions.

2.8.6. Prediction

Managers predict farmers' actions in the evolutionary algorithm fitness function by assuming that the total number of actions in a time step will be proportional to those in the previous time step weighted by its cost, *e.g.*, if the cost doubles, then half the number of actions are predicted.

2.8.7. Sensing

Sensing is incorporated in the modeling in that farmers know that cranes decrease agricultural production Farmers also know which landscape cells and what proportion of the landscape that they own, the costs of actions, and the probability of cranes landing back in their owned cells after being scared. Managers estimate how many cranes are on the landscape. They also know the total number of actions taken by farmers in the previous time step, that culling decreases the number of cranes by one plus the number of offspring that it is expected to produce, and that scaring does not decrease the crane number.

2.8.8. Interaction

Cranes interact with the landscape by decreasing the agricultural production on the cell that they occupy and feed. Individual farmers, manager and cranes also interact with each other by adaptively making decisions based on current conditions. Managers make decisions based on estimated crane abundance and previous farmer actions, whereas farmers make decisions based on crane distribution on their land, management policy (*i.e.*, available actions) and budget. For details about interactions, see descriptions of sub models and sensing.

2.8.9. Stochasticity

In dynamic socio-ecological systems like the one studied here, it may be likely that empowerment of farmers (*i.e.*, budgets B_f) to perform actions varies among individuals at a given time step. To assess the effect of such potential variability in farmer's budgets, we repeated simulations for each of the scenarios with budgets varying among individuals by $B_f \pm 50$ in each time step. Stochasticity was also included in the crane population sub model by allowing movement of cranes to random cells

Table 1
The management scenarios simulated over 30 time steps, in the GMSE v0.6.0.4 R package (Duthie et al., 2018). The management target is set by the manager and is given in number of cranes on the simulated landscape (*i.e.,* staging site).

Scenario	Target	Culling	Scaring	Addressed management
A	NA	No	No	No management w. objective to sustain an increasing crane pop
B	NA	Yes	Yes	Scaring, culling, w. objective to sustain an increasing crane pop
C	NA	Yes	No	Culling, w. objective to sustain an increasing high crane pop
D	15,000	Yes	Yes	Scaring, w. objective to sustain crane pop and agri.prod

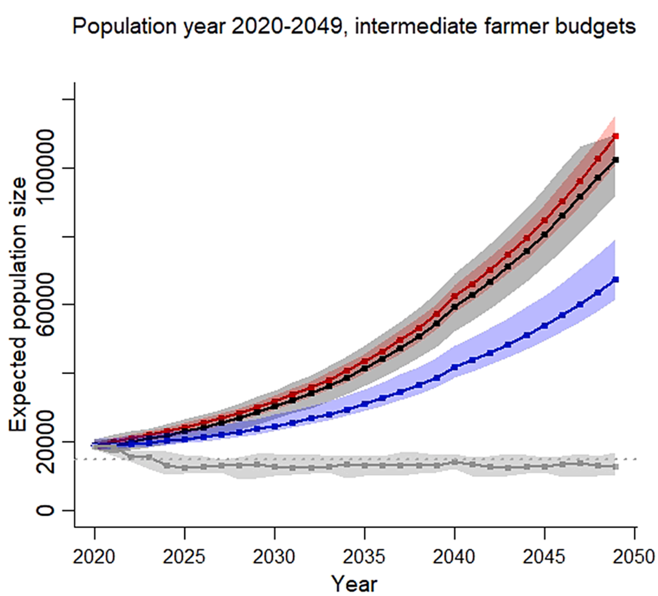

Fig. 2. Population size of common cranes over 30 years, given four different management scenarios and given intermediate farmer budgets (Bf: 1000) for 50 stakeholders. The management scenarios are: a.) no management (red lines), b.) scaring and culling, without a realized management target (black lines), c.) only culling, without a realized management target (blue lines), d.) scaring and culling (gray lines), with a management target of 15,000 cranes (dotted gray line). The mean (points joined by lines), minimum and maximum (shaded areas) expected population sizes are based on data from 40 model simulations.

within a given spatial range and by sampling the crane offspring number from a Poisson distribution with a rate parameter of $R_b = 0.118$.

2.8.10. Collectives

No collectives are implemented in the model.

2.8.11. Observation

We simulated increasingly empowered farmers, running simulation for a range of available budgets $B_f = \{50, 100, \ldots, 3950, 4000\}$, with 40 simulation replicates for each budget value across four management scenarios (a-d) over 30 years. We extracted selected performance metrics for each time step t (year 2020–2049); crane population size N, percentage of maximum agricultural production (*i.e.*, observed agricultural production (Y_f)/maximum agricultural production) over the individual farmers' cells (scenario a-b), number of culled individuals per farmer (scenario b-d) and number of scaring actions performed per farmer (scenario b & d; Table 1).

3. Results

We found that empowering farmers to enact actions affects management outcomes in terms of crane population size at staging sites and agricultural production at farm level (Figs. 2–4, & S2 in Supplementary Material 2). Very low levels of farmer budget led to increases in the population because farmers chose scaring as a less budget demanding action, which helped individual farmers in the short term by scaring birds off their land, but led to high population size across all farms on the landscape in the longer term (Figs. 2–4c,d & S2 in Supplementary Material 2). On the contrary, very high farmer budgets led to high extinction risk (up to 22.5%) of the population (Fig. 3d & S3 in Supplementary Material 2), whereas simulations of intermediate budgets allowed farmers to control the population size around the management target and kept the impact on agricultural production to intermediary levels (Figs. 2–4d).

3.1. Management scenario a

Scenario a illustrates a long-term and exponential increase of the crane population from year 2020 (mean $N = 19{,}123$) to 2049 (mean $N = 109{,}298$; Fig. 2a). Changing farmer budget did not affect expected population size or agricultural production at $t + 5$ (year 2024) (Figs. 3a & 4a) due to lack of management and inability to scare or cull (*i.e.,* scaring and/or culling and targeted population ($N^{\dagger} > N$)).

3.2. Management scenario b

Results from *scenario b* demonstrate a long-term and exponential population increase over years in the same way as in *scenario a* (year 2021 mean *N*: 19,018 ind. and for 2050 mean *N*: 102,275; Fig. 2a, b). As the management target was always higher than the realized population (*i.e.,* $N^{\dagger} > N$ at year 2024), the manager set the costs for culling high relative to scaring (mean $C_{culling} = 7.1 \times C_{scaring}$) to sustain the

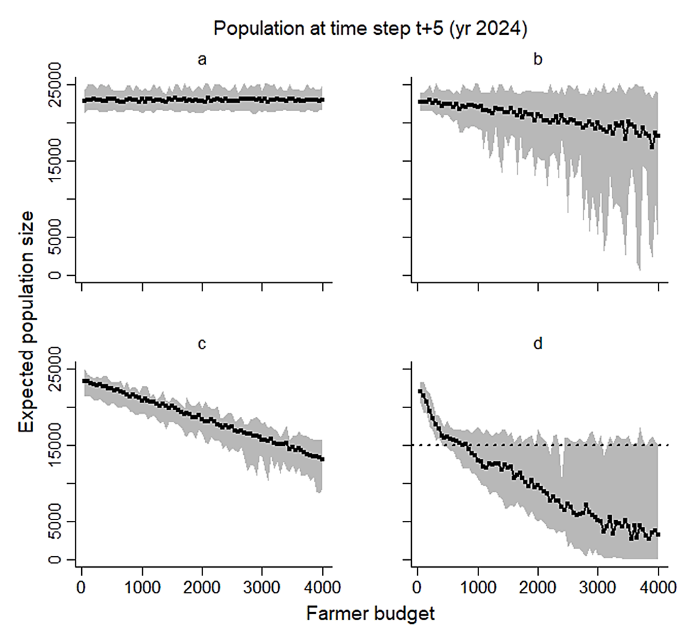

Fig. 3. Effect of farmer budgets on expected population size of common cranes at year 2024 year in four different management scenarios; a.) no management, b.) scaring and culling, without a realized management target, c.) only culling, without a realized management target, d.) scaring and culling, with a management target of 15,000 cranes (dotted black line). The mean (black line), minimum and maximum (gray shaded areas) expected population sizes are based on the simulation output data at year 2024, given 50 stakeholders and are produced from 40 model simulation replicates.

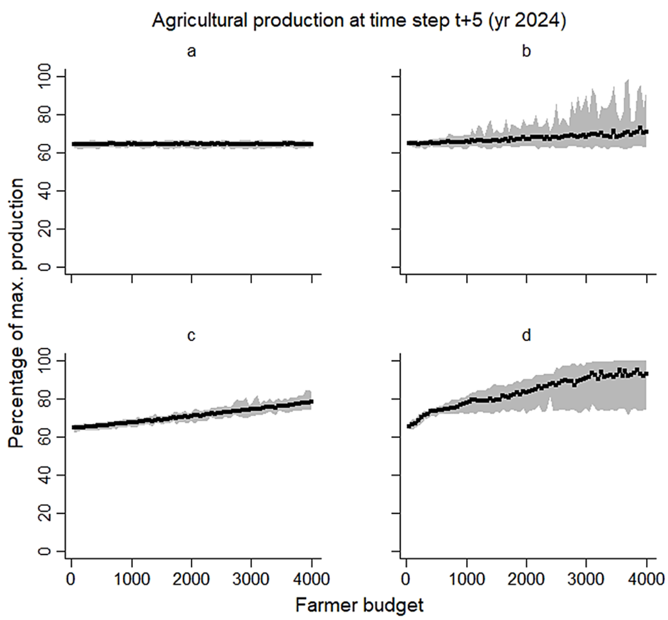

Fig. 4. Effect of farmer budget on mean agricultural production per farmers' land at staging sites of common cranes in four different management scenarios, a) no management, b) scaring and culling, without a realized management target, c) only culling, without a realized management target d) scaring and culling, with a management target of 15,000 cranes. The mean (black line), minimum and maximum (gray shaded areas) mean agricultural production per farmers' land are based on the simulation output data at year 2024, given 50 stakeholders and produced from 40 model simulation replicates.

population, which incentivized the farmers to allocate their budget to scaring instead of culling in year 2024 (Fig. S4 in Supplementary Material 2). Nevertheless, occasional and limited culling (mean culled cranes per farmer: 0.004) occurred as farmer budget increased. Consequently, the population size in year 2024 decreased slightly relative to *scenario a* (mean N from 22,691 to 18,201 ind; Fig. 3b.) and mean agricultural production increased from 64.9% to 71.0% of total expected production (Fig. 4b), within the range of increasing farmer budget (B_f: 50–4000).

3.3. Management scenario c

In *scenario c,* the population increased exponentially over years, given intermediate farmer budgets (B_f:1000, for 2021 mean $N = 18{,}931$, and for 2050 mean $N = 67{,}496$, Fig. 2c.). However, the population growth was slower compared to scenario *a* and *b* (Fig. 2a, b, c). Further, for a given time step ($t > 5$) increasing farmer budgets caused the population size in 2024 to decline (*e.g.,* mean $N = 23{,}392$ for B_f: 50 and $N = 13{,}120$ for B_f: 4000; Fig. 3c) as a consequence of increased number of culled cranes per farmer (*i.e.*, 0–36 cranes for B_f: 50–4000; Fig. S5c in Supplementary Material 2). As a result of population limiting effects, the agricultural production increased from 64.7% to 78.4% along the same range of farmers budgets (Fig. 4c). Since culling is the only available but yet costly action, stakeholders will have no alternative to culling when budget allows. This causes stakeholders to take action uniformly when budgets exceed the cost of culling ($B_f > C_{action}$; Fig. S5c in Supplementary Material 2). However, when adding variability to the farmer budget, the small threshold effects in population size and agricultural production smooths out, as the farmer budgets exceeds their costs and incentivize actions at varying times (Fig. S6 in Supplementary Material 2).

3.4. Management scenario d

In *scenario d*, the population approached the management target of 15,000 cranes with increasing farmer budgets and aligned with the targeted population size for a limited intermediate budget range (B_f: 550–850). However, the population declined to below the targeted population size when farmer budgets further increased ($B_f > 850$) as result of stakeholder power overriding manager ability to set costs to minimize culling (Figs. 3d & 4d). The lowered manager target, compared to *scenario a-c*, caused the manager to dynamically adjust the relative costs of scaring and culling depending on the size of the current population relative to the target. When current population size was greater than the defined target, the managers incentivized culling by lowering the culling costs relative to scaring, whereas the opposite occurred if the population is lower than the defined target. This is also illustrated by a continuously increasing number of culled cranes per farmer (*i.e.,* up to 35 cranes per farmer; Fig. S5d in Supplementary Material 2) until the population aligns with the management target (B_f: 550–850; Fig. 2d & Fig. 3d), and occasionally with even greater number of culled cranes per farmer (maximum 57 ind; Fig. S5d in Supplementary Material 2) as farmer budget outstripped the power of managers to set culling cost. Mean agricultural production varies between 73.9–75.9% when the population aligned with the targeted population size, but increased further up to 95.3% as the population declines along the range of further increasing farmer budgets (B_f: 900–4000) and below the targeted population size with an extinction risk of 22.5% (Fig. 4d & Fig. S3d in Supplementary Material 2.)

4. Discussion

4.1. Stakeholder empowerment in multi-objective management

In order to manage conservation conflicts, collaboration between stakeholders and managing authorities to decide on trade-offs between multiple objectives (*e.g.,* sustaining crane population and agricultural production) and providing local stakeholders with power to enact management have been addressed as critical and potentially more important than merely reducing negative impact from wildlife (Mason et al., 2018; Redpath et al., 2017, 2013). However, predicting the effects of providing stakeholders with power on the likelihood of adverse negative consequences (*e.g.,* high extinction risk or the crane population being far from the management target and low agricultural production) have generally been over-looked when predicting management outcomes and risk of conflict from models (but see Bunnefeld et al., 2017; Milner-Gulland, 2011). Our findings demonstrate that empowering a large number of stakeholders comes with the challenge of finding a delicate balance of the degree of empowerment. Very high farmer stakeholder power means the wildlife population is at an increased risk of extinction (*e.g.,* up to 22.5%, year 2024 in scenario *d*) when lethal control is an option whereas very low stakeholder power means high wildlife populations and extensive negative impact on agricultural production. Our study shows that knowledge and management of stakeholder power and actions is needed to manage a sensitive trade-off between wildlife conservation and agriculture. Furthermore, our study shows that by modeling the interaction between two groups of stakeholders (manager and farmers) with potentially opposing views, we contribute to our understanding of the complexity as well as challenges and risks of stakeholder empowerment and decentralization of decision making.

As the protected crane population along the European flyways likely will continue to increase, so will the negative impact on agricultural production, and trade-offs in management objectives between agricultural production and a sustainable crane population, affecting associated conservation conflict. A multiple-objective management will require interventions to regulate the population size with sustainable culling strategies, careful monitoring and modeling efforts to predict the likely impacts of alternative strategies (Cusack et al., 2019; Johnson et al., 2014). Our modeling demonstrates that a large community of farmers managing the crane population in a coordinated fashion may effectively regulate the population, and thus maintain (or even increase) agricultural production (scenario c-d). The specifics of the quota system set by the manager will have an effect on population size. For example, culling quotas of a limited number of cranes to all individual farmers (as opposed to, *e.g.,* higher quotas to a very small number of individuals, as currently is the case) may be an approach to increase equitable distribution of individual power (Redpath et al., 2017). However, our simulations also highlight that the total number of licenses to cull cranes needs to be carefully considered to maintain population sustainability (Fig. 2c,d & S5 in Supplementary Material 2). This is true especially if no other management actions (*e.g.,* scaring, diversionary fields) are possible, as even small increases of a few cranes to cull per stakeholder may cause the population growth rate to decline (scenario c & d). Today's license system in Sweden is based on very limited quotas from the county administrative boards (up to 10 cranes) to a minority of the farmers (EEA, n.d.), which based on our results likely have insignificant effects on either population size or agricultural production. Yet, our findings show that the extent to which farmers' impact on the crane population and agricultural production can be significant and is dependent on the power given to the farmers. This could be an effective way to perform management in line with policy and to decrease practical or monetary costs for farmers. It could for example include compensation schemes for farmers to pay for labor connected to culling or scaring actions, provision of scaring devices, decoys or hides for culling, and coordination and help by employed personnel to scare and cull cranes (Hake et al., 2010; Nilsson et al., 2018). Our study exemplifies that if licensed culling would be permitted (*i.e.,* relocated from annex I to annex II in the EU Birds directive; EC, 2009), extensive stakeholder effort would be needed to reduce the population to a lower management target (*e.g.,* >25 culled individuals per farmer after 5 years in our model). Accordingly, our findings have implications for the evidence-informed flyway management plans implemented for several thriving goose species under the United Nations African Eurasian Waterbird Agreement (AEWA) (Madsen et al., 2017; Stroud et al., 2017). These management plans consist of agreed population targets, to be delivered via adaptive management, population monitoring, population estimation and country-specific culling quotas (Madsen et al., 2017). Our study highlights that stakeholder empowerment and culling strategies based on the number of stakeholders, and particularly their power to implement effective actions, needs careful consideration and monitoring when setting population targets and decentralized policy (Baynham-Herd et al., 2018; Mason et al., 2017; Williams and Madsen, 2013).

4.2. The management strategy evaluation framework to model social-ecological systems

Our findings demonstrate how individual-based modeling and the management strategy evaluation framework can be used to investigate the effects of manager's and stakeholders' interactive decisions in management of natural resources and 'wicked' conservation conflicts in complex and uncertain systems, such as for a protected and increasing crane population causing negative impact on agricultural production (Bunnefeld et al., 2011; Duthie et al., 2018; Smith, 1999). Until now, MSE models have used constant decision-making rules for single stakeholders over time (Bunnefeld et al., 2013; Melbourne-Thomas et al., 2017; Milner-Gulland, 2011), whereas we used GMSE to simulate scenarios including a large number of individual stakeholders taking decisions independently, as influenced by changes in the wildlife population, agricultural production and policy set by the manager. GMSE is freely available as a package in the R environment and includes a graphical user interface that can be accessed from the R console or a browser online (GUI; Duthie, 2020). All GMSE code is open-source, further allowing the development of increased use of the model and the empowerment of all stakeholders through investment in communication and co-development of the model (Duthie et al., 2018).

Socio-ecological and individual-based models like these simplify empirical systems to investigate key concepts and clarify theory, and inevitably make complex trade-offs between the extent of realism and integration of knowledge (Schlüter et al., 2019). Our model necessarily makes some restrictive assumptions about crane ecology and management due to limited access to empirical data for model parameterization. For example, we do not have data on individual cranes' impact on agricultural production, or on the exact economic consequences for farmers, which likely is influenced by, *e.g.*, market prices, weather, and timing of harvest (Montràs-Janer et al., 2019; Nilsson et al., 2016). Further, socio-ecological and individual-based models are based on the assumption that human decision-making is bounded rationale (Schlüter et al., 2019). In our model, farmers and managers are assumed to make decisions relating to a single objective (*i.e.,* farmers to maximize production, managers to minimize the difference between current and targeted crane population size). Instead, in real-world situations, individual managers and farmers with diverse norms are likely to adaptively make trade-offs between multiple objectives over time and in relation to decisions taken by other stakeholders (Schill et al., 2019). In the context of cranes and farming, an example could be farmers potentially tolerating a certain number of cranes and thus negative impact on their agricultural production to sustain biodiversity, given certain management conditions. The mechanisms for such stakeholder multi-objective trade-offs are not very well understood to date, and require further empirical and theoretical study (Bunnefeld et al., 2017; Schill et al., 2019)

4.3. Conclusions

A large number of stakeholders, *e.g.*, farmers and managers, naturally causes complications to optimal trade-offs in decision making in natural resource management, and small changes in stakeholder behavior or policy are found to potentially have large scale implications for the dynamics of entire socio-ecological systems (Heal and Kunreuther, 2012; Scheffer et al., 2012). To advance previous modeling of the MSE framework, we used the GMSE model to simulate and predict the long-term effects of empowering multiple farmers to dynamically respond to policy, the crane population and impact on agricultural production under uncertainty. Our findings demonstrate that empowering a large number of farming stakeholders to pursue their management objectives comes with the challenge of finding a sensitive balance of the degree of empowerment. Not providing stakeholders with budgets to enact actions may lead to frustration, ineffective management and risk of conflict; whereas unlimited farming stakeholder budgets may cause conflicts when conservation stakeholder objectives override management objectives (Mason et al., 2018; Redpath et al., 2013). This suggests that collaboration between managing authorities and stakeholders may be critical to agree on and act in line with multi-objective management targets. Carefully considered levels of stakeholder empowerment may so enhance democratization and trust between parties with the aim to manage 'wicked' conservation conflicts (Mason et al., 2018; Redpath et al., 2017; Williams and Madsen, 2013).

CRediT authorship contribution statement

L. Nilsson: Conceptualization, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **N. Bunnefeld:** Conceptualization, Methodology, Software, Writing - review & editing, Funding acquisition. **J. Minderman:** Conceptualization, Methodology, Software, Writing - review & editing. **A. B Duthie:** Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Writing - original draft, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

None of the authors have any conflicts of interests to declare.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2020.109396.

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