Individual-based modelling as a tool for elephant poaching mitigation

ODD Protocol

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1. Purpose

The model predicts how interactions between elephants, poachers, and law enforcement affect poaching levels within a virtual protected area. We compare four scenarios, as shown in Fig 1. We first compared a scenario in which poachers have prescribed, non-adaptive decision-making and move randomly across the landscape (scenario A), to one in which poachers adaptively respond to their memories of elephant locations and where other poachers have been caught by law enforcement (scenario B). In both scenarios, law enforcement effort is distributed unevenly across the protected area. This comparison shows how IBMs can complement equation-based approaches by allowing for dynamic and adaptive poachers.

We then compare a situation in which ranger effort is distributed unevenly across the protected area (scenario B) to one in which rangers patrol by adaptively following elephant matriarchal herds (scenario C). Poachers are adaptive in both scenarios B and C. This experiment shows how IBMs can build upon game theoretical approaches by incorporating the behaviour and ecology of elephants, and by opening up the possibility of exploring new management techniques outside of planning optimal patrol routes. Finally, we consider a scenario in which poachers move randomly, but law enforcement adaptively follows matriarchal herds (scenario D).

The model is theoretical at this stage and is not meant to provide a realistic depiction of poaching, but instead to demonstrate how IBMs can complement and extend the existing modelling work done in this field, and to provide a framework for future research. The model could be further developed into a useful management support tool to predict the outcomes of various poaching mitigation strategies at real-world locations. The model was implemented in NetLogo version 6.1.0 (Wilensky, 1999). The code and the complete model description in the Overview, Design Concepts, and Details format (ODD; Grimm et al., 2010) are available and open-source in the Supplementary Material and on the CoMSES Net Computational Model Library (Neil et al., 2019).

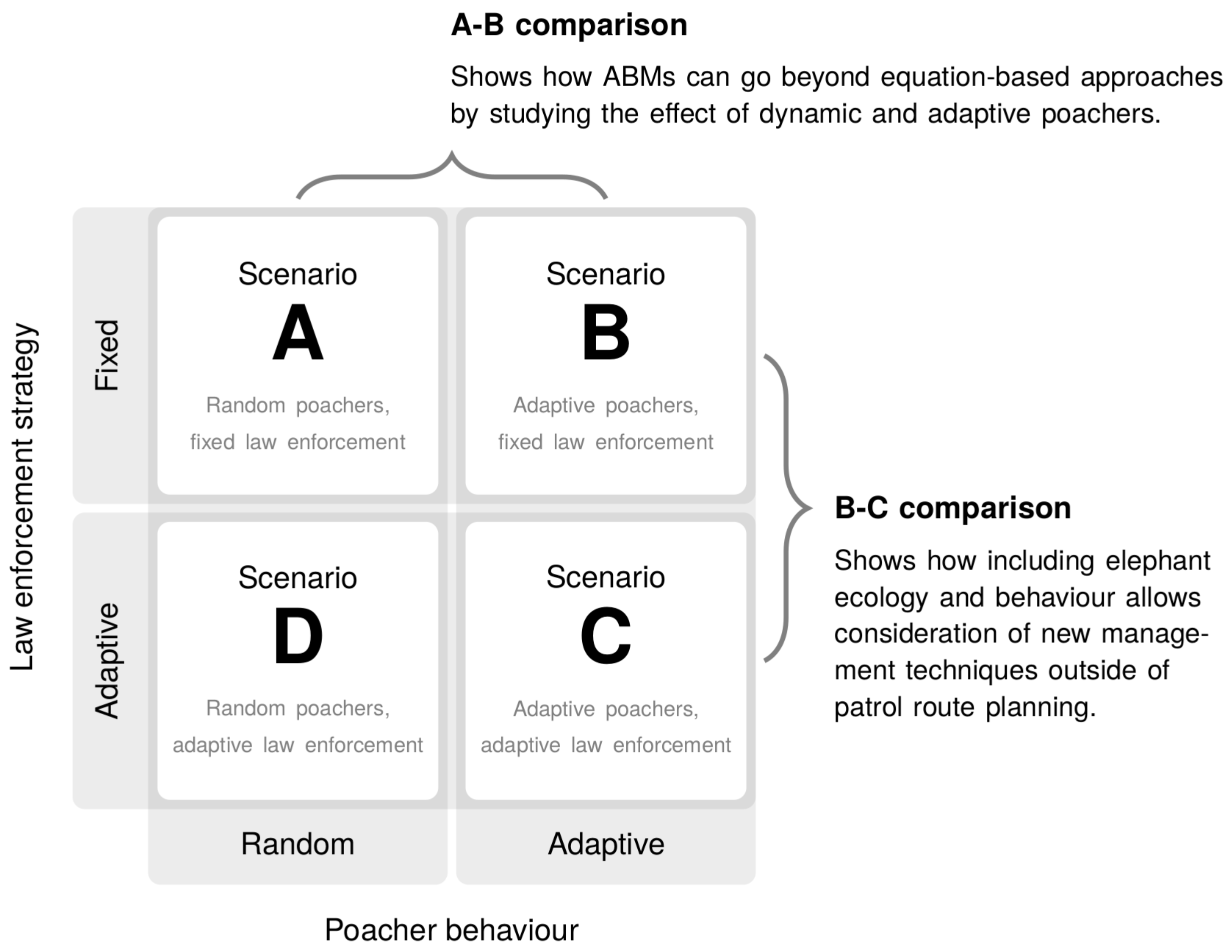

Figure 1: Descriptions of the three scenarios explored in the model. In scenario A, poachers have prescribed, non-adaptive decision-making and move randomly across the landscape. We compare this to scenario B, in which poachers adaptively respond to their memories of elephant locations and where other poachers have been caught by law enforcement. In both scenarios, law enforcement effort is distributed unevenly across the protected area. This comparison shows how IBMs can complement equation-based approaches by allowing for dynamic and adaptive poachers. In scenario B, ranger effort is distributed unevenly across the protected area. We compare this to scenario C, in which rangers patrol by adaptively following elephant matriarchal herds. Poachers are adaptive in both scenario B and C. This experiment shows how IBMs can build upon game theoretical approaches by incorporating the behaviour and ecology of elephants, and by opening up the possibility of exploring new management techniques outside of planning optimal patrol routes. We also consider a scenario in which poachers move randomly, but law enforcement adaptively follows elephant herds (scenario D).

2. State Variables and Scales

The model landscape is a simplified representation of a theoretical protected area (Fig 1). The protected area is split equally into four zones to which law enforcement can dedicate different amounts of effort, leading to different probabilities of catching poachers. Unequal ranger effort across different areas is often the case in reality (Leader-Williams & Albon, 1988; Plumptre et al., 2014). The 'checkerboard' colouring of the landscape is arbitrary, meant only to distinguish the four zones. The size of the landscape and the timing of events are arbitrary and do not coincide with a real-world situation.

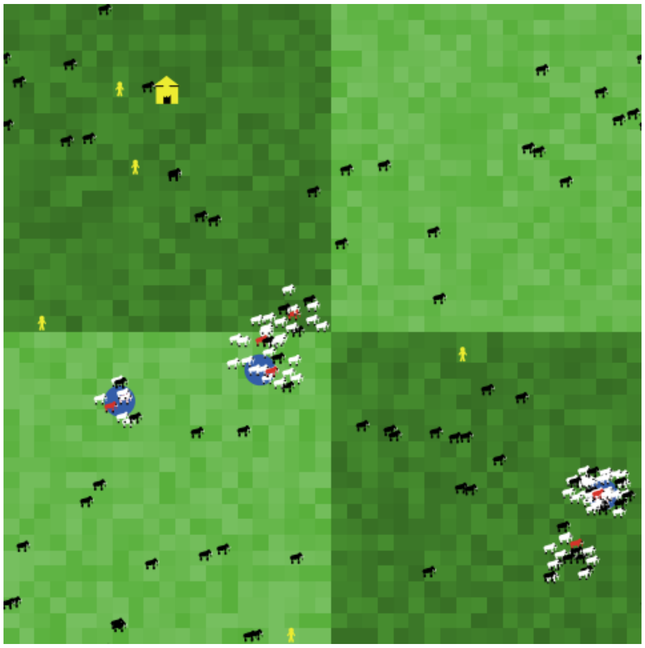

Figure 2: Image of the virtual park with elephants and poachers distributed across a landscape. The landscape is divided into four zones, as shown by 'checkerboard' green pattern. Each zone has a different probability of catching a poacher. White elephants are female, black are male, and red are matriarchs. Each herd is led by a single matriarch, who is the eldest female in the group. Elephants undergo seasonal migrations to the waterholes (blue circles). Male elephants disperse from the herd and move independently when they reach sexual maturity (>14 years old). Poachers (yellow people) leave the village (yellow house) to hunt in one of the four zones.

The landscape is populated by elephants and poachers. The initial number of elephants in this simulation is 150, split into 10 herds. In reality, elephants may form herds of 3 to 100 or more individuals, but 12-17 is the average for many populations (C. J. Moss, 2001; Pimm & Aarde, 2001). Individual elephants have attributes related to sex, age, and status within the herd; these are described in Table 1. The ratio of male to female elephants is 50-50, and ages range from 0 to 60 years old.

The initial number of poachers in the model is 15. In reality, there is little empirical data on how many poachers there are in a protected area, and the number likely varies greatly from site to site and over time. Poachers move from the village into one of the four zones to hunt for elephants. Poachers caught by law enforcement permanently leave the system.

Entity	**Parameters**	**Range and Unit**
Elephants	Initial number of elephants	150
	Number of herds	10
	Sex	M/F
	Age	0-60 years
	Status	Matriarch or follower

	Herd Number	A unique number that determines which matriarch the elephant will follow
	Water source	Herds are randomly assigned to one of the three water sources, and this determines which water source they will migrate to during the dry season.
Poachers	Number of poachers	15
	Exploration probability	10%
	Profit memory	A set of values associated with zones, based on where the poacher has previously seen elephants, and on where other poachers have been caught by law enforcement
	Hunting effectiveness	50%

Table 1 Attributes for the individuals in the model

3. Model Schedule

The model processes and schedule are shown in Figure 3. Each elephant is part of a specific herd and follows a specific matriarch. Each day, females and young (<14 years old) male elephants follow their assigned matriarch and move as a herd, according to a seasonal migratory pattern following resources (Boult et al., 2019) such as food (Bohrer et al., 2014; Loarie, Aarde, & Pimm, 2009), water (Chamaillé-Jammes, Valeix, & Fritz, 2007; Redfern et al., 2003), and social partners (Chiyo et al., 2014). Elephant herds aggregate near water sources for seven months of the year (the 'dry season') and then disperse and move randomly throughout the landscape for the remaining months (the 'rainy season'). Elephants in the model have complete knowledge of water locations in their range. Sexually mature male elephants (>14 years old) disperse from the matriarchal herds and move independently, dispersing randomly throughout the landscape during the year (Moss, 2000). Female elephants in the model have a 20% chance of reproducing each year if they are above the age of thirteen, resulting in new elephants being added to the model. Each year, all elephants increase in age by one year. Elephants die if they are over >60 years old, or if they are killed by poachers. The eldest female in a group is the matriarch, and if the matriarch dies, the next eldest female takes over the role (Moss, 2000).

All poachers begin the simulation in the village, and each is assigned a random number of days, between 1 and 10, to stay in the village before beginning a poaching trip. For the first five trips, poachers will choose a zone to poach in at random, in order to gain an understanding of where elephants are located and where poachers are more likely to be caught by law enforcement. Following this, the poachers' decision-making will differ depending on the scenario being tested by the modeller: they will either continue to choose a zone to poach in at random, or they will adaptively update their beliefs and choose where they are most likely to kill elephants and where they are least likely to be caught by law enforcement. If a poacher moves to a zone and an elephant is there, the poacher has a 50% probability of effectively catching and killing the elephant. This probability is meant to simulate differences between hunting effectiveness, as different types of weapons and technologies will change the success rates of poachers. The poacher stays in this zone for 3 days, then returns to the village for a random number of days between 5 and 10 before beginning another poaching trip. Poachers caught by law enforcement permanently leave the system. The village in this model is inside the protected area, but poachers are not caught by law enforcement if they are in the village between poaching trips.

Each of the four zones has a different probability of catching a poacher (0-0.05%), adding up to a total of 10% over the entire protected area. Depending on the scenario being tested, the exact probability of catching a poacher differs per zone and over time. In scenarios A and B, law enforcement effort is distributed unevenly across the entire protected area, and rangers 'patrol' at a rate of once per week. This means the probability of a poacher being caught by law enforcement is 0% for six days of the week, and between 0-0.05% depending on the zone for one day per week. In scenarios C and D, rangers patrol once per week by adaptively following elephant matriarchal herds, and the probability of catching a poacher is therefore highest where the highest density of matriarchal herds are located.

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For each time step (day)
  If there are not any elephants or poachers left, or if we have reached 10 years, stop

  For each elephant
      If the elephant is a matriarch
        If it's dry season, move to the herd's water source
        else move randomly
      else if the elephant is a male over 14 years old
        Move randomly
      otherwise
        Follow the matriarch
    If the elephant has reached maximum age, die
    If it's the end of the year, increment the elephant's age by one
    If the elephant is a female over 13 years old
      Have a 20% probability of creating an offspring

  For each poacher
    Decrement countdown by one
    If the countdown has reached zero
      If the poacher is in the village
        set countdown to three days
        If poacher strategy8/1/19 6:16:00 PM is random
          Visit a random zone
        else if poacher strategy is adaptive
          Visit the zone where the ratio of elephants seen to poachers caught is the highest
        catch-elephants
        die-poacher
      else if the poacher is not in the village
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go to the village
set the countdown to between 5 and 10 days

If law enforcement strategy is fixed
Set the probability of catching a poacher in each zone to a fixed value depending on the schedule
If law enforcement strategy is adaptive
Set the probability of catching poachers in each zone to be proportional to the number of matriarchs in the zone

Figure 3: Model schedule, showing the processes that occur at each time step and the order in which they occur

4. Design concepts

4.1 Adaptation

Depending on the scenario being tested by the modeller, poachers will either move randomly across the four zones, or they will dynamically adapt to elephant whereabouts and to avoid law enforcement. The adaptive decision-making is modelled using an epsilon-greedy bandit algorithm (R. Sutton & Barto, 2018), meaning poachers explore a zone at random according to probability epsilon ($\varepsilon \in [0, 1]$), or otherwise return to the zone that had the best outcome (the zone in which they saw the most elephants, and in which the fewest poachers were caught by law enforcement) (Kuleshov & Precup, 2014; R. Sutton & Barto, 2018). In other words, poachers face an exploitation-exploration trade-off: they must choose between hunting in the best zone or continuing to learn about the system (Bubeck, 2012; Kuleshov & Precup, 2014). Individual poachers thus learn which zone is most profitable to poach in as a consequence of theirs and other poachers' experiences: they remember how many elephants they have personally seen in each zone, and they remember in which zones poachers have been most frequently caught by law enforcement.

4.2 Interaction

Poachers directly interact with elephants to catch and kill them. Law enforcement is abstracted instead of being made discrete agents, and indirectly interacts with poachers by catching them and removing them from the system according to a probability that differs according to zone. Depending on the scenario being tested, law enforcement also has abstracted interactions with elephant herds, as they will follow matriarchal herds on their patrol.

4.3 Sensing

Poachers are assumed to immediately have access to all information regarding the location of other poachers who have been caught by law enforcement. They use this information to update their beliefs about which zone is the best to hunt in.

4.4 Stochasticity

When initialising the model, elephants are randomly assigned sex, age, and herd number, and herds are randomly assigned to one of the three water sources that they migrate to during each dry season. Poacher and law enforcement strategies also add stochasticity to the model: depending on the scenario being tested, poachers either choose a zone to poach in at random, or they will adaptively update their beliefs and choose where they are most likely to kill elephants and where they are least likely to be caught by law enforcement. Law enforcement strategies differ depending on the strategy being tested; ranger effort is either distributed unevenly across the entire protected area, or rangers adaptively follow elephant matriarchal herds.

5. Initialization

Elephants are initialised by creating 150 individuals split into 10 herds. Their location is set randomly within the protected area, clumped around their assigned matriarch, who is assigned to the eldest female in the group. Elephants are randomly assigned sex, an age between 0 and 60 years, and a herd number, and herds are assigned a water source that they migrate to during the dry season. Poachers are initialized by creating 15 individuals, with a hunting effectiveness of 50%, and an exploration probability of 10%. All poachers begin the simulation in the village, and each is assigned a random day, between 1 and 10, to stay in the village before beginning a poaching trip.

6. Submodels

6.1 Elephant Migration and Dispersal

Each day, females and young (<14 years old) elephants follow their assigned matriarch and move as a herd, following a seasonal migratory pattern following resources (Boult et al., 2019) such as food (Bohrer et al., 2014; Loarie, Aarde, & Pimm, 2009), water (Chamaillé-Jammes, Valeix, & Fritz, 2007; Redfern et al., 2003), and social partners (Chiyo et al., 2014). Water availability is a major driver of seasonal patterns in elephant migrations; elephants concentrate at permanent water during the dry season and then disperse after the rains (Western, 1975). In our model, elephant herds aggregate near water sources for seven months of the year (the ‘dry season’) and then disperse and move randomly throughout the landscape for the remaining months (the ‘rainy season’). The pattern of seasonality follows that of the Amboseli Ecosystem in Kenya, which has dry seasons from January-February and June-October, and rainy seasons from March-May and November-December (C. J. Moss, 2001). Elephants in the model have complete knowledge of water locations in their range. Sexually mature male elephants (>14 years old) disperse from the matriarchal herds and move independently, dispersing randomly throughout the landscape during the year (Moss, 2000). Migratory routes do not change from year to year in the model, and different elephant herds can overlap at the same water source.

6.2 Reproduction

Female elephants in the model have a 20% chance of reproducing each year if they are above the age of thirteen (Moss, 1988), resulting in new individual elephants being added to the model over time. All elephants reproduce at the same time, on the first day of each year.

6.3 Death

Elephants die if they are over >60 years old, or if they are killed by poachers. The eldest female in a group is the matriarch, and if the matriarch dies, the next eldest female takes over the role (Moss, 2000). Poachers "die" – permanently leave the system - if caught by law enforcement.

6.4 Poacher Movement and Decision-Making

All poachers begin the simulation in the village, and each is assigned a random day, between 1 and 10 days, to stay in the village before beginning a poaching trip. For the first five trips, the poachers will choose a zone to poach in at random, in order to gain an understanding of where elephants are located and where poachers are more likely to be caught by law enforcement. Following this, the poachers' decision-making will differ depending on the scenario being tested by the modeller: they will either choose a zone to poach in at random, or they will adaptively update their beliefs and choose where they are most likely to kill elephants and where they are least likely to be caught by law enforcement, according to an epsilon-greedy bandit algorithm (R. Sutton & Barto, 2018).

6.5 Killing Elephants

If a poacher moves to a zone and an elephant is on that particular patch, the poacher has a 50% probability of effectively catching and killing the elephant. This probability is meant to simulate differences between hunting effectiveness, as different types of weapons and technologies will change the success rates of poachers. Poachers caught by law enforcement permanently leave the system.

6.6 Law Enforcement Techniques

Each of the four zones has a different probability of catching a poacher (ranging from 0-0.05%, adding up to a total of 10% over the entire protected area); this is meant to be an abstracted representation of heterogeneous law enforcement effort across the protected area. Law enforcement is often unevenly distributed in reality, as some regions of a protected area are better covered by law enforcement than others. There is very little empirical data available on the probability of catching poachers and the number is likely to differ depending on the site; one study estimated poachers in Western Serengeti, Tanzania, faced just a 0.07% chance of being arrested per day spent poaching (Knapp, 2012).

The model tests four different scenarios comprised of two forms of poacher decision-making and two different law enforcement techniques. In scenarios A and B, law enforcement effort is distributed unevenly across the entire protected area, and rangers 'patrol' at a rate of once per week. This means the probability of a poacher being caught by law enforcement is 0% for six days of the week, and between 0-10% depending on the zone for one day per week. This is to simulate law enforcement scheduling, as they may patrol every day of the week and may be distributed heterogeneously across the protected area. In scenario C, rangers patrol once per week by adaptively following elephant matriarchal herds, and the probability of catching a poacher is therefore highest where the matriarchal herds are located.

7. Data Analysis

The model was run using BehaviorSpace, a Netlogo tool that can run many simulations of a model and vary the parameters of interest, and then records the results of each iteration (Wilensky, 1999). We ran each simulation 607 times, as determined by a power calculation, designed specifically for IBMs, for t-test of means[1] (Lipsey, 1990; Seri & Secchi, 2017), for ten years (3650 'ticks'). We simulated the scenarios described in Table 2 and counted the number of elephants and poachers remaining after ten years. The data was analysed using R (version 1.0.136).

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[1] power = 0.8; effect size (d) = 0.2; significance level = 0.05

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