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RESEARCH

Trophy Hunting or Ecotourism? Management Strategies for White Rhino on Private Land in South Africa

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Abstract

White rhino (*Ceratotherium simum*) populations on private land in South Africa have defied the trend in rhino numbers, both globally and in South Africa as a whole, showing an increase over time. Many have argued that this is due to legal trophy hunting of white rhino. But will this trend continue in the future? A bioeconomic model for rhino is developed using data on white rhino populations in South Africa. Under the baseline of trophy hunting with poaching, populations of white rhino on private land continue to increase until around 2040–2045, and then decline to almost zero by around 2050–2055. Even the elimination of poaching does not improve this situation. Profits are higher for ecotourism compared with the trophy hunting option and stocks more sustainable. The argument that trophy hunting is required to pay for high security costs therefore is not supported by the outputs of the present model. Furthermore, the assumption that ecotourism and trophy hunting are complementary is also not supported by the present model. The main driver for the decline in white rhino under the trophy hunting scenario is the high increase in trophy price. In these open access models, price drives species abundance. This is what is known as "trading on extinction". This has implications for other exploited species that command high prices on markets, and also other iconic species that are threatened. There appears to be sufficient incentive for game farms to switch to ecotourism. The only constraint to this actually occurring could be government's recent policy on land expropriation without compensation.

Keywords Bioeconomic · *Ceratotherium simum* · Ecotourism · South Africa · Trophy hunting · Vensim

1 Introduction

Terrestrial species are at a heightened risk of extinction, largely due to human induced effects [1]. Large bodied herbivores often have the highest proportions of threatened species [2]. The white rhino (*Ceratotherium simum*) population of South Africa is one of the few extant rhino populations remaining [3]. However, it has declined from 15,625 individuals at the end of 2017 to 12,968 at the end of 2021 [4]. This decline has mainly been attributed to poaching [5, 6]. Poaching is an important driver for abundance in many other species, including Indian tigers [7], and game hunting probably caused the demise of the passenger pigeon [8].

However, there is a difference in public versus private game reserves in terms of white rhino population trends. White rhino populations for Kruger National Park have declined by 75% between 2010 and 2020, whereas private game reserves have managed to achieve a growth in white rhino populations of 14.4% per annum between 1984 and 2021 [9]. It is important to understand why private game reserves have been able to achieve growth in white rhino abundance, while public game reserves such as Kruger National Park have experienced declines.

In a study of white rhino farming on private land in South Africa, it was found that the majority (62%) of white rhino owners are pursuing ecotourism [10]. The IUCN has defined ecotourism as the visitation to natural areas to enjoy nature [11],. Apart from the viewing of nature, ecotourism also has various other socio-economic benefits that are helpful for developing countries such as South Africa [12]. As a result it has long since been put forward as the solution for both developing the economy as well as promoting biodiversity conservation.

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Trophy hunting has proved to be a strong contender to solve Africa's wildlife problems. There is more than five decades of empirical evidence that suggests that trophy hunting has been biologically sustainable [13, 14 for example]. For white rhino, legal offtake does occur. Trophy hunting activities persist. In fact, the new environment minister has recently "doubled down" on the trade in rhino trophies [15]. Some conservationists, however, object to the killing of wildlife for sport [16]. But the trophy hunting industry in South Africa is a multibillion rand industry and creates 16,000 jobs [17].

In addition to the profits associated with trophy hunting, white rhino populations on private land have increased since the inception of the trophy hunting. For example, Selier and Di Minin [18] argue that "allowing sustainable trophy hunting has paid off and conservation efforts by the private sector are currently instrumental in preventing further declines in the white rhino population". The evidence appears very strong that trophy hunting is both profitable and beneficial to wildlife populations. There have been studies comparing ecotourism and trophy hunting for South African lion [19] and hunting versus protection of tigers [20]. No commensurate empirical study comparing ecotourism and trophy hunting for white rhino was found in the literature. This paper attempts to address this deficiency.

The practice of legal white rhino hunting on private land in South Africa has been carefully established and managed over several decades and is widely acknowledged to have played a crucial role in the remarkable recovery of the southern white rhino sub-species [21]. At the same time, the issue of legal recreational hunting of iconic and threatened species is currently an issue under intense scrutiny and subject to conflicting ideological positions [22]. Policy-makers can benefit from evidence-based guidance on such controversial issues, especially the question of whether hunting is beneficial or detrimental to conservation [23].

Here, a bioeconomic model is developed to investigate the economic benefits vis-à-vis the impacts on densities for different rhino strategies. The model is based on the open access fisheries economics literature applied to a terrestrial species. For seminal articles on using these types of models for terrestrial wildlife species, including rhino, see Milner-Gulland and Leader-Williams [24] and more recently Bulte [25]. Two strategies are considered, a trophy hunting strategy and ecotourism. The model estimates the net present value of the different strategies, and also determines the density of the rhino herd at the end of the time period. The model is developed using data from South Africa and also considers rhino poaching, security and maintenance costs. The model focusses on the management strategies of private sector operators.

The aim of this study, therefore, is to conduct a comparison between an ecotourism option for the management of white rhino on private land and a trophy hunting scenario. Key research questions are the following:

- Is the current trajectory of trophy hunting with poaching sustainable in the future?
- Is trophy hunting and ecotourism mutually exclusive or complementary?
- If mutually exclusive, which option is most beneficial for white rhino management on private lands going forward?

2 Study Area

The area of the study is the entire region of South Africa. As of 2024 there is an estimated 300 private game farms that stock white rhino in South Africa, down from 423 in 2010 [9]. The reason for these declines is complex, but could include some consolidation of farms to take into consideration economies of scale. For example, Clements [10] in their 2019 study found that 28% of rhino owners were disinvesting, and another 15% were investing in more rhinos. At the same time, according to Caalsen [9], the number of game farms was 300 in 2019, and again five years later in 2024, so it is unclear (but possible) that a turning point has been reached in the data. Owing to security reasons it is not possible to show the location of these farms on a map. In 2014 the number of private game farms in South Africa totalled 11,600, covering around 21 million hectares, with a total value of US$1 billion, based on sustainable use [26]. This had also decreased to 9,000 private game farms by 2019, covering an approximate area of 16 million hectares of land [27]. Despite the proportionately few (circa 300/9000 ~ 3.3%) private farms that stock white rhino, their impact is nonetheless disproportionately large, with around 25% of South Africa's rhinoceroses currently under the custodianship of private owners [28]. However, according to Clements et al. [29], this proportion has been steadily increasing from 25% in 2010 to 53% in 2021. Private landowners therefore currently own the majority of white rhinos in the country and are becoming major conservation custodians of the species.

3 Methods

3.1 Basic Model

The model is based on a standard Lotka-Volterra predator-prey formulation (see Wilen's seminal article applying open access dynamics to the North Pacific Fur Seal Fishery [30], and more recently, Bjorndal and Conrad [31] and Opsomer and Conrad [32] applying this model in the fisheries economics literature). However, these models are not only used for fisheries. Other natural resources are also modelled using this approach (e.g. Mugabi and Duffy [33]). Under this formulation, the predator increases as the prey increases, and decreases as the prey decreases. The prey decreases when the predator increases. A detailed synopsis of these types of models is given in Crookes [34]. At the same time, Crookes and Blignaut [35] demonstrate that the techniques used here (namely open access modelling linked with the system dynamics modelling framework) is suitable for assessing extinction risk in populations, including terrestrial populations, where data availability is limited.

In the current formulation, the white rhino stock in private game reserves in time t (Xt, measured in number of animals per km^2) is the prey. It evolves according to the following growth curve [36]:

$$X_{t+1} = X_t + rX_t \left(1 - (X_t/K)^Z\right) - H_t - O_t, \tag{1}$$

where z is the Fowler density dependence term [37], r is the intrinsic growth rate, K is the carrying capacity, and H_t is trophy hunting harvests per km^2 in time t and O_t is the poaching losses per km^2 in time t. Trophy hunting harvests per km^2 in time t (H_t) is given as:

$$H_t = T_E q E_t X_{t,} \tag{2}$$

where T_E is a binary variable the allocates revenues to trophy hunting and ecotourism respectively (if TE = 1 then only trophy hunting revenues are used in the model), q is the catchability coefficient of white rhinos as trophies, and E_t is the number of private game farms stocking rhino in time t.

The poaching losses per km^2 in time t (O_t) is assumed a constant proportion of the while rhino population in time t (X_tR_p).

The number of farms stocking rhino in time t (E_t) is the predator. Although the prey specification is fairly typical of these bioeconomic systems, the predator specification is somewhat unusual in that a farm is the predator. As profitability increases the number of farms increases and when profitability decreases the number of farms decreases. A recent example that models farm dynamics in a similar way (except large farms are the predator and small farms are the prey), is Appel and Balmann [38]. Number of farms evolve according to the following:

$$E_{t+1} = E_t + n(P_tH_tA + (1 - T_E)B_tX_tA - (C_s + C_m)E_t - dM_tA), \tag{3}$$

where n is an adjustment coefficient relating changes in profits to changes in the number of farms stocking white rhino, hP_t is the trophy value for a white rhino (in $/animal), A is the area of private game farms which stock white rhino in km^2 and B_t is the ecotourism value for white rhinos (in $/animal). Security ($C_s$) and maintenance ($C_m$) costs respectively are the costs per farm for anti-poaching measures and maintenance of white rhinos (employment costs and so on), measured in $/farm. The final term dM_tA estimates the cost of replacing a lost rhino that has either been poached or hunted for a trophy (d is the auction value of a young rhino bull, in $/animal), and M_t (mortality) is the sum of deaths through poaching and other losses (measured in animals/km^2).

Equations (1) and (3) represent a system of first order non-linear difference equations analogous to the open access models alluded to earlier. Although all prices in the study are real values (in other words inflation adjusted), in some cases it appears that prices have increased in excess of inflation. These include the trophy hunting price P_t, the ecotourism price B_t and security costs $C_{s,\,t}$. Three further dynamic components are therefore added to the system, namely the evolution of P_t, B_t, and $C_{s,\,t}$. Both are said to evolve according to the logistic growth curve, which implies that there is are "limits to growth" as far as the trophy hunting and ecotourism price, and security cost is concerned [39]:

$$P_{t+1} = P_t + P_r P_t \left(1 - (P_t/P_{max})\right), \tag{4}$$

$$B_{t+1} = B_t + B_r B_t \left(1 - (B_t/B_{max})\right), \tag{5}$$

and

$$C_{s,t+1} = C_t + C_r C_{s,t} \left(1 - (C_{s,t}/C_{max})\right), \tag{6}$$

where P_r, B_r and C_r are the intrinsic growth rate of trophy price P_t ecotourism price, B_t and security costs $C_{s,\,t}$ respectively, and P_{max}, B_{max} and C_{max} are the theoretical maximum value that trophy prices, ecotourism prices and security costs, respectively, could conceivably reach. A similar function was used to model limits to growth in several other simulation papers [40, 41].

Profitability is estimated as the present value of net benefits (NPV) over the time horizon of the model (2025–2065) and can be presented as follows:

$$NPV = \sum {}_{t=0}^{40} \rho^{\,t} \pi \ (X_t, E_t,\ P_t), \tag{7}$$

and $\rho = 1/(1+i)$ is called the discount factor, and $1 > i > 0$ is the per-period discount rate.

Profits are given as follows:

$$\pi(X_t, E_t, P_t) = P_t H_t A - C_s Et - dH_t A + \beta X_t A - C_m Et - dO_t A, \quad (8)$$

where some users get a benefit from hunting the stock ($P_t$no of trophy hunting kills=P_tH_tA) (consumptive use) and others get a benefit from viewing the stock ($\beta X_t A$) (non-consumptive use). The parameter $\beta \geq 0$ is the viewing (ecotourism) value of a rhino, measured as $/animal. Conrad [42] and a number of other authors [43, 44] assume a logarithmic function for the existence value parameter (i.e. $\beta \ln Xt$). This has the advantage of having the characteristic of the value increasing as $Xt \rightarrow 0$. However, in the current context a more simple function is assumed, in order that profits may be benchmarked against literature estimates to ensure model accuracy and validity. Some studies have found that the security costs for white rhino ecotourism are zero, and that poaching is also zero. Clements et al. [10] in their survey of 171 private rhino owners in South Africa found that "Ecotourism properties may … be less sensitive to poaching and less inclined to invest heavily in security. Furthermore, the widespread distribution of business-as-usual (largely ecotourism) properties suggests that many fall outside of current poaching hotspots" (p. 6, my parenthesis). However, it would be irresponsible to model ecotourism without including a poaching parameter and security costs. Therefore two scenarios are presented for both trophy hunting and ecotourism (a poaching and a non-poaching scenario). Four scenarios are presented in total and security costs are included for all four scenarios. The model was constructed in Vensim DSS for Windows version 6.4b [45]. The stock flow diagram for the model is given in Fig. 1 and encompasses

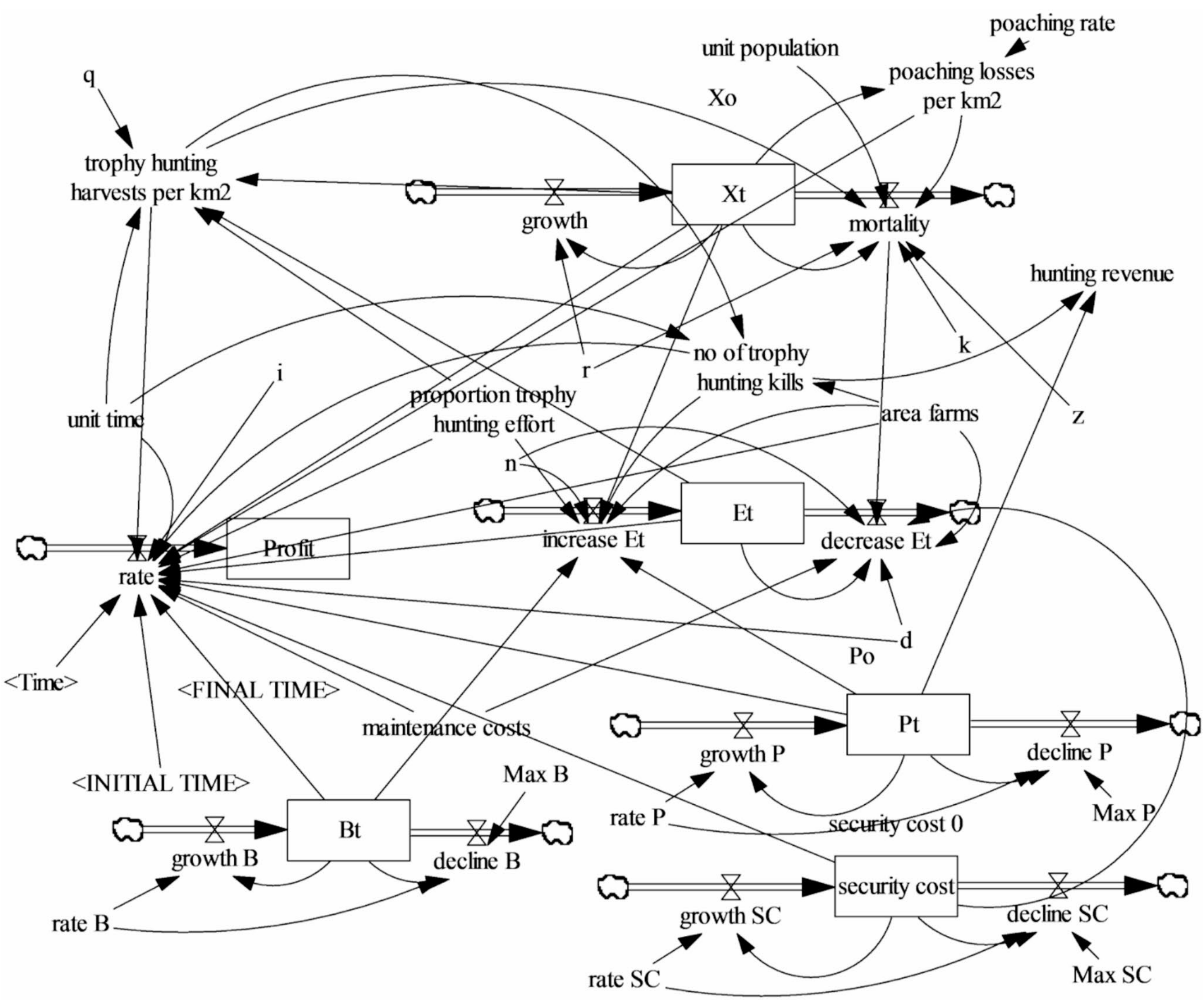

Fig. 1 Stock flow diagram for the rhino model. The model is a standard Lotka-Volterra model, with white rhino stock (X_t) the prey and the number of game farms (E_t) the predator (effort in the traditional bioeconomic model). Prey is reduced by poaching, and trophy hunting offtake. Effort is influenced by game farm profitability. The trophy hunting price (P_t) is exogenous, but influences various other parameters in the model, including hunting revenue, profit and effort

the relationships discussed above. The source code for the model is given in the supplementary material.

The model was calibrated with historical data from 2010 to 2024 (15 years), and then projected forward to the year 2065.

The parameter values used in the model are given in Table 1. The model estimates are all derived from the literature, or estimated as part of the model development process.

3.2 Data

Apart from the data sources reported in Table 1, time series data on the trophy price for white rhino from 1972 to 2018 was obtained from 't Sas-Rolfes et al. [13]. The real (inflation adjusted) data from this source were used, and are expressed in 2021 constant prices. Polynomial fitting of the curve with the data points produced a fit that captured the overall long-term trend in the data (R2 = 0.66, Fig. 2). To estimate future datapoints the polynomial curve was projected forward.

Table 1 Parameters in the rhino model, their values and the source of the data

Parameter	Value	Unit	Description	Source/comment
A	22,274	km^2	Area covered by private game farms (2010)	[66]
Po	67,039	$/animal	Trophy price white rhino (2010)	Model estimate [derived from the polynomial]
D	19,769	$*Year/animal	Auction value (young rhino bull) (2012)	[40]. Real prices did fall from 2008 to the early 2010s. seem to have levelled off since then. A constant real price is assumed.
Eo	423	farms	Initial number of private game farms (2010)	[9]
N	1.4e-007	farm/$/Year	Adjustment coefficient	Estimated through calibration with historical data
P_{max}	1e+006	$/animal	Maximum real trophy hunting price	Hypothetical maximum (no data)
B_{max}	1e+006	$/animal	Maximum real ecotourism price	Hypothetical maximum (assumed the same as P_{max})
C_{max}	1e+006	$/farm	Maximum real security cost	Hypothetical maximum (not binding over the time-frame of the model)
R_p	0.005	1/Year	Proportion of rhinos poached on private game farms	[10] Scenarios Sc2 and Sc4 assume that this is zero.
C_m	123,000	$/farm	Real Costs of taking care of rhinos. Includes feed, veterinary, water, tracking and monitoring (2010)	Own calculation based on limpoporhinoconservation.co.za (22 Jan. 2026). See annotated source code (Suppl. mat.) for more details. It is assumed that real (inflation adjusted) costs have remained constant over time.
P_r	0.075	1/Year	Growth rate of real trophy hunting price	Estimated using calibration with historical data
B_r	0.067	1/Year	Growth rate of real ecotourism price	Anecdotal evidence suggests that the real ecotourism price increased seven fold between 1991 and 2021.
C_s	90,715	$/farm	Cost (real) of providing security for rhino on private game farms (2010)	Own calculation based on Clements et al. [29]. See under annotated source code in the supplementary material for more details of how this was calculated.
C_r	0.03	1/Year	Real growth rate of security costs	Own calculation based on Clements et al. [29]. See under 'annotated source code' in the supplementary material for more details of how this was calculated.
T_E	0	Dmnl	0 = no trophy hunting effort; 1 = trophy hunting effort	No reference
Z	7	Dmnl	Fowler Curvilinear factor	[37]
B_0	12,143	$/animals	Ecotourism value for rhino (2010)	Own calculations based on DFFE [67]
Xo	0.2	$animals/km^2$	White rhino population private game farms (2010)	stoprhinopoaching.com
K	3.38	$animals/km^2$	Carrying capacity white rhinos	[47]
i	0.06	Dmnl	Discount rate for South Africa	[68]
q	0.0001	1/farms	White rhino catchability coefficient (white rhinos)	Estimated by calibration with historical data
r	1	1/Year	Intrinsic growth rate of white rhinos	[69]
FINAL TIME	2065	Year	The final time for the simulation	
INITIAL TIME	2025	Year	The initial time for the simulation	

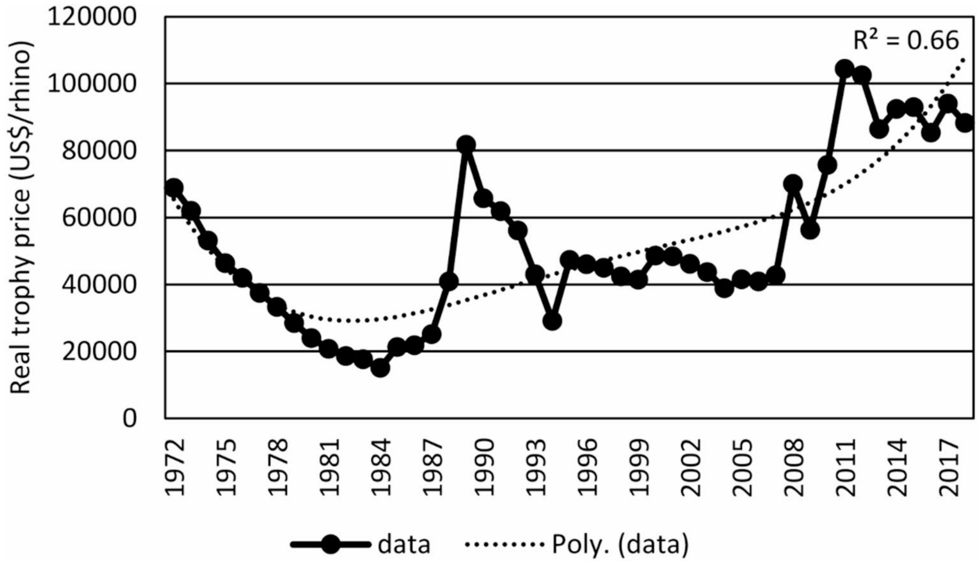

Fig. 2 Polynomial fit of the historical white rhino trophy price (T_P) with the curve. The data (1972–2018) were obtained from 't Sas-Rolfes et al. [13] and are in 2021 constant prices (i.e. the effect of inflation has been removed). Although over the short term there have been fluctuations, over the long term (since 1984) the trend in T_P has been that of growth in real terms. The study uses the polynomial data in order to calibrate the model

3.3 Sensitivity Analysis

A sensitivity analysis was conducted on the real trophy price in order to determine the impact on the white rhino population, as well as on trophy hunting kills. In other words, the trophy price was gradually increased, and the impact thereof was measured on white rhino stocks and trophy hunting kills.

Private game farms in South Africa lost only 0.5% of their rhinos to poaching in 2020 [29]. The reasons mentioned for this include the fact that smaller private properties are easier to secure, and because private game farms spend more on security ($2,200 per rhino in 2017, compared with $520 per rhino spent by South African National Parks). Given that this estimate was during COVID, it is appropriate to test the sensitivity of the model to higher poaching rates. A further sensitivity analysis was therefore undertaken by making the constant poaching losses (O_t) stochastic, at a higher poaching rate (ranging between 1 and 2% of rhinos lost per annum). Monte Carlo simulations were conducted, such that $O_t \sim$ UNIFORM (0.01;0.02). Poaching losses were drawn from an ensemble of 200 realisations. The impact was assessed on rhino populations.

A final sensitivity analysis was conducted on the initial ecotourism value (B_0). Again, a Monte Carlo simulation was conducted, with B0 ~ (UNIFORM (1000; •), where • is the original value used in the simulation. Poaching losses were drawn from an ensemble of 200 realisations. The impact was assessed on profits.

3.4 Scenarios

There are four scenarios in the model:

- **Sc1** (Scenario 1): Only trophy hunting and poaching continues at existing levels.
- **Sc2** (Scenario 2): As for Sc1 except that there is no poaching.
- **Sc3** (Scenario 3): Only ecotourism is allowed and poaching included.
- **Sc4** (Scenario 4): As for Sc3, except that there is no poaching.

3.5 Ecotourism and hunting: complementary or competing?

Some authors (e.g. 't Sas-Rolfes et al. [13]) have argued that ecotourism and hunting are not mutually exclusive but are in fact complementary. In most resource economics frameworks, these uses reflect competing claims over the same resource, particularly when existence value is considered (e.g. Lopes and Atallah [44]). In this simulation the model tests this assumption. Although in the preceding scenarios trophy hunting effort parameter (T_E) was used as a binary value (either 0 or 1, in other words if trophy hunting is 1 then ecotourism is 0), it can also be used as a proportion parameter, with revenues and costs for trophy hunting and ecotourism assigned different shares (in other words, if the parameter is 0.5 it means half the values come from trophy hunting, and half from ecotourism). Optimisation was then run on the model, to determine what share of ecotourism or trophy hunting maximises profits, and what share maximises rhino numbers. To ensure comparability between ecotourism and trophy hunting, this scenario assumes poaching and all security costs for both ecotourism and trophy hunting, and trophy prices and ecotourism values are allowed to rise based on their long-term historical trajectories.

3.6 Model validation

Model building is an iterative process where confidence in the model is gradually increased with each iteration. The model was validated through peer review, as well as by performing a number of validation tests on the model. These tests included sensitivity analysis (as outlined in a previous section, but also through 'on the fly' checks) and reality checks, the model passes the dimensional consistency (units) check as well as the behaviour verification checks.

The logistic formulation used in this model has also been extensively used for rhino (e.g. Milner-Gulland and Leader-Williams [24]; Crookes [46]; Ferreira and Dziba [47]) and the predator-prey formulation for other large bodied terrestrial mammals (e.g. Holden and Lokyer [48]). The model is widely used in terrestrial ecology.

A possible criticism is that trophy hunting of rhino specifically targets older bulls which, it has been argued, increases sustainability [13]. The reasons put forward is that older bulls that are not sexually productive, could be sold as trophies, and the money used for conservation (see also [48]. This component is not modelled as the model does not distinguish on the bases of sex, but future work should include this component. Also, further work needs to be conducted on the effect of killing dominant males on herd dynamics and relationships between less dominant animals in the herd. For example, Slotow and van Dyk [49] found that younger "orphan" male elephants were killing white rhino at Pilanesburg National Park. This was caused by a lack of older elephant males in the herd that had been removed due to translocation. Fatal animal attacks ceased after six older male elephants were introduced to the herd [50].

Although there is an element of uncertainty associated with any forecasting (by its very nature), these predator-prey models have proved remarkably accurate at forecasting phenomena. For example, Crookes [34, 46] reviewed the forecasting capability of a predator-prey model for rhino and found that the model accurately predicted the turning point of rhino abundance. Crookes also found that these types of models are remarkably accurate at forecasting over the longer term (around 10 years and even longer). These models are strongly empirical, parameter driven and not based on normative considerations.

A limitation of the model, is that security and maintenance costs are reported per farm rather than per km^2 or per rhino. The reality is that security and maintenance costs are likely to vary based on the number of rhinos held, or the farm size. While reporting security cost and maintenance cost per rhino or per km^2 would be preferable, due to number of farms being the predator in the model, it is necessary to express the other parameters in the model in terms of this parameter.

Another possible limitation of the model is that in South Africa, there are some properties that specialise in hunting only, others in ecotourism only, and yet others that practice both through carefully designed systems to avoid conflict. Whereas these details may not appear explicitly in the peer-reviewed academic literature, it is reasonably well-known in conservation circles. Although there may be some farms that practice both conservation and trophy hunting, it is important to emphasise that the model does not assume either one or the other. The outcome that maximises profits or biodiversity is modelled, and then the resultant composition is derived. The model therefore predicts this binary outcome. In reality, it is worth bearing in mind that the model is applicable for the whole of South Africa. There may be some farms that defy the model predictions, but on the aggregate it is believed that the model holds.

A further criticism is the assumption that private rhino owners view rhino management through a singular lens of profit maximisation. In almost all cases, rhinos are only one of several income-generating species on private lands, and private landowners typically have mixed motives (including some philanthropic) and other sources of supplementary income. Again, the response is that the model assesses two outcomes, a profit outcome and an ecosystem outcome, so philanthropic perspectives are also included. Although the model does not consider income earning beyond rhino, this is because it is intended to isolate the effect of rhinos on the system. A broader model would take more elements into consideration (for example, Kibira et al. [51], whose model of the Serengeti took into consideration livestock, Maasai, wildlife predators and wildlife grazers) but models are necessarily abstractions of reality and making them too large renders them unmanageable.

It is important to note that the model is not set up the same as a standard open access fisheries model. In those models, vessels/fishers/poachers enter or exit based on profitability. The present model has as predator a rhino farm, which attracts further rhino farms when the industry is profitable, and fewer when the industry is unsuccessful. Is this a valid assumption? Rhino on private land in South Africa are far closer to private goods in nature [14]. Furthermore, it has been argued that trophy hunting does not conform to assumptions of open access [52]. These arguments are probably accurate. However, it is based on restrictions on control of access and harvest. In the present model the open access nature of the model is based on the effort parameter, which in this case is the dynamics of the game farms themselves. The model assumes that the market for farms is open access, in other words that there are no barriers to entry, but allows for the management of rhinos themselves to be a private resource. In a sense price is a barrier to entry, but in fact in the open access model this is what drives the dynamics of the model. The South African government pursues market-based principles as far as land ownership is concerned [53, 54], in other words, anyone with money can buy or sell property. The president has recently recommitted the government to promoting a vibrant private sector [55]. In that sense, trade in property is open access. While the president has also recently signed the land expropriation without compensation bill, with uncertain effects on property rights [56], it seems apparent that land that is being used will not fall within the scope of this bill [57].

Another possible limitation of the model is that the model does not explicitly include the cost of farms in the profit functions. The reason that the cost of farms is omitted from the analysis is three-fold. The first is that on aggregate the purchase of farms cancels out the sale of farms (provided the price remains constant, which may be true if prices are expressed in dollar terms). Secondly, the value of a farm is a capital item, whereas profits are annual values that are treated differently. A third reason, also argued by Rubino and Pienaar [58] as a reason why they did not include the value of a game farm in their financial cost benefit analysis, is that it is assumed that landowners have already invested in land and an initial stock of rhino. It is therefore a sunk cost.

The concept of assigning a carrying capacity limit on the growth of prices and costs (P_{max}, B_{max}, and C_{max}) is justified in the sense that these are real values and not nominal values. Many resource economics papers assume constant real values for these parameters e.g. Opsomer & Conrad [32]. The data suggests that P, B and C have increased in real terms, but for how long will this continue in the future? Although the limits to growth hypothesis is well-established in the literature, it is acknowledged that the point at which the carrying capacity limit is reached in this study is somewhat arbitrary, owing to a lack of actual data. Although this assumption is unlikely to affect the model outcome, alternative specifications such as random walk could be considered in future work.

4 Results

4.1 Baseline Model

The model produces a "highly accurate" replication of the historical data from 2010 to 2024, for rhino density (Fig. 3(a)), trophy hunting price (Fig. 3(b)) and number of farms stocking white rhino (Fig. 3(c)). It is evident from this data that white rhino numbers on private land increased between 2010 and 2021, and the number of farms stocking white rhino has declined.

Under the Scenario 1 (Sc1) scenario of trophy hunting along with poaching, white rhino populations on private land continue to increase until between the year 2045 and 2050, and then decline to zero by the year 2060 (Sc1, Fig. 4(a)), profits increase initially and thereafter level off (Fig. 4(b)) and the number of farms stocking white rhino increases marginally (Fig. 4(c)).

For Sc2 (trophy hunting with no poaching) the results are very similar to the Sc1 scenario: stocks increase further but then still also decline to zero (Fig. 4(a)), and profits are slightly higher but still level off (Fig. 4(b)), and number of game farms increase by slightly more than Sc1 (Fig. 4(c)).

For Sc3 (Ecotourism with poaching), stocks recover to around 3.38 animals/km^2 (Fig. 4(a)), profits increase (Fig. 4(b)), and number of farms increases quite dramatically (Fig. 4(c)).

For Sc4 (Ecotourism, no poaching) stocks also recover to the same levels as Sc3 (Fig. 4(a), but profits are slightly higher than the Sc3 scenario (Fig. 4(b). Number of farms (E_t) increases by slightly more than the Sc3 scenario (Fig. 4(c), since profits are slightly higher.

4.2 Sensitivity Analysis

The first sensitivity analysis indicates that white rhino stocks reach a maximum at around 45% of carrying capacity before they decline to zero (Fig. 5(a)). The maximum is achieved at a real trophy price of around $522,491 per rhino.

The second sensitivity analysis assesses the impact of increasing the real trophy price on white rhino kills. Maximum kills are achieved at a real trophy price of $614,650 per rhino (Fig. 5(b)). For further increases in the trophy price, the number of kills declines until there are no white rhino left.

The stochastic poaching losses sensitivity analysis indicates that a higher poaching rate of 1–2% of white rhinos lost per annum does not have a major impact on the results of the study (Supplementary material, Figure S1). The stochastic model shows a very small impact of the stochastic poaching losses on both the trophy hunting allowed scenario (Sc1, top figure), and ecotourism only scenario (Sc3, bottom figure).

The stochastic initial ecotourism value (B_0) sensitivity analysis indicates that profitability is sensitivity to changes in B_0 (Supplementary material, Figure S2). Profits under the ecotourism scenario decline dramatically with a reduction in B_0. The tipping point for B_0 is around $1,000 per animal. Above that, profits that are higher for ecotourism compared with the trophy hunting scenario. Even at the lower ecotourism value, stocks of white rhino still recover to carrying capacity.

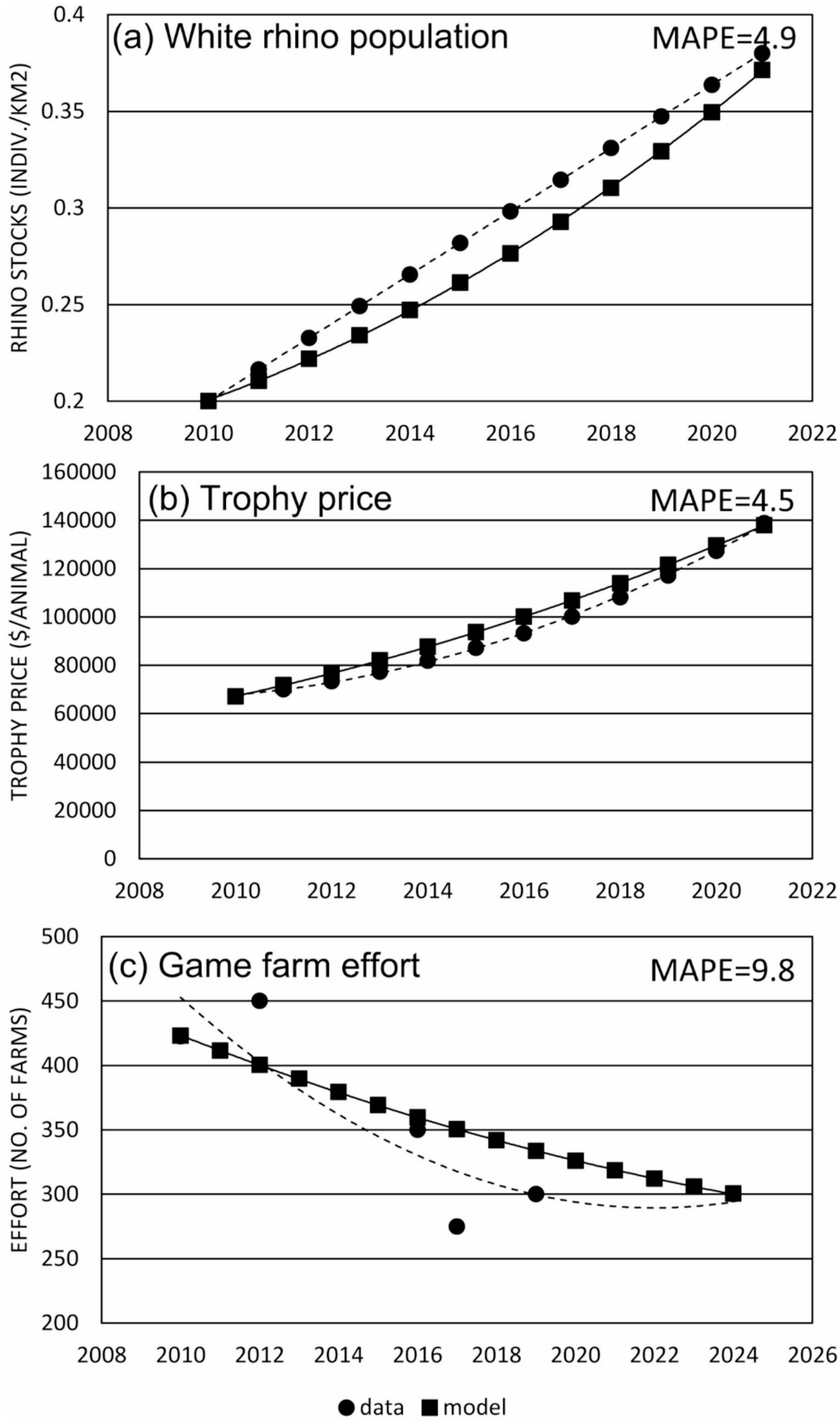

Fig. 3 Comparison between historical data and model simulation for (**a**) white rhino density on private lands (Xt) (**b**) trophy hunting price of white rhino (Pt) and (**c**) number of private game farms stocking white rhino (Et). Note: Mean absolute percentage error (MAPE) measures the calibration accuracy of the model compared with the historical data. Key: 0–10% = highly accurate; 10–20% = good; 20–50% = reasonable; 50–100% = poor

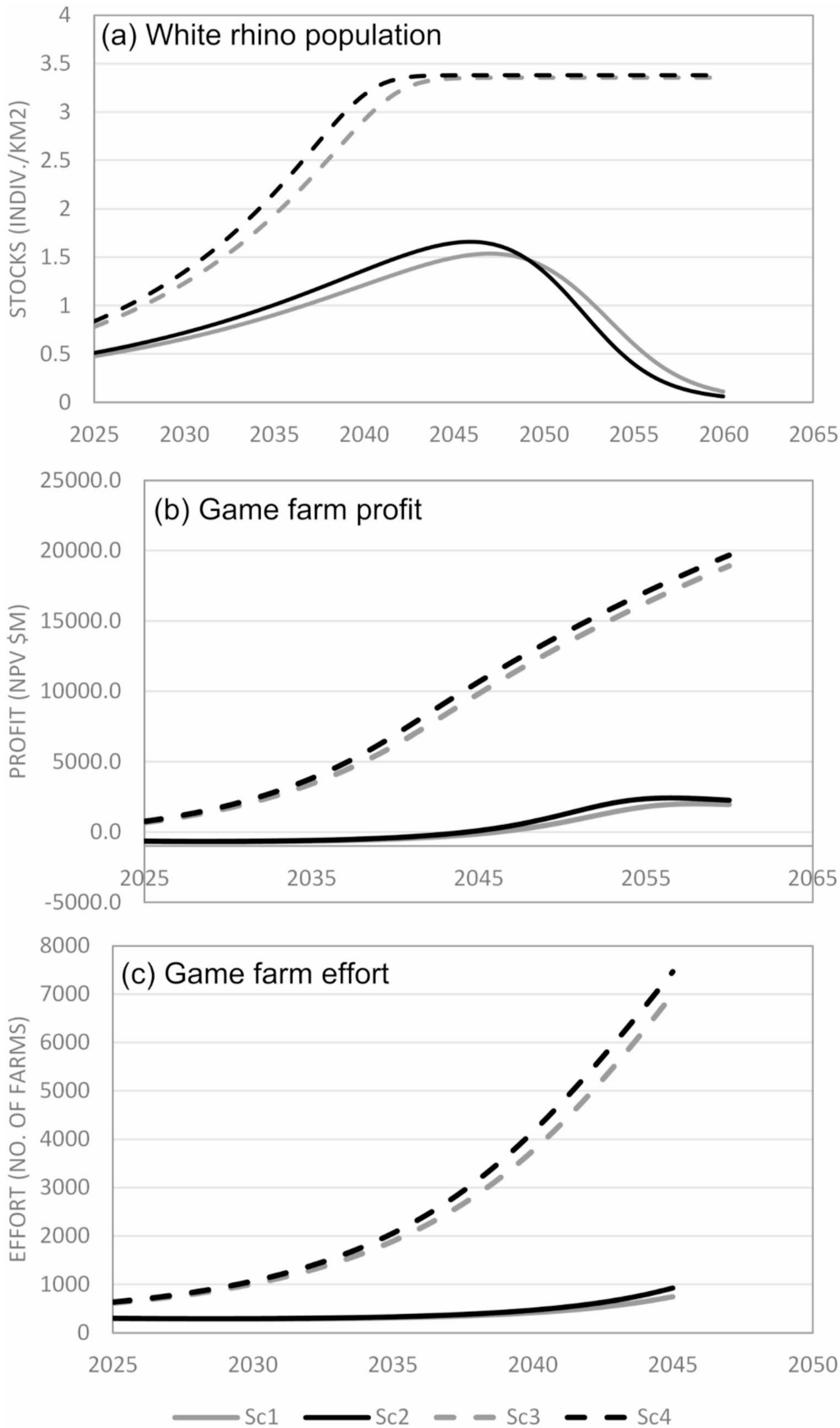

Fig. 4 Model generated results for the different scenarios, for (**a**) white rhino densities, (**b**) profits (NPV) and (**c**) white rhino farming effort. The baseline (BAU) scenario represents trophy hunting with poaching; Sc1 is trophy hunting without poaching; and Sc2 is the ecotourism scenarios

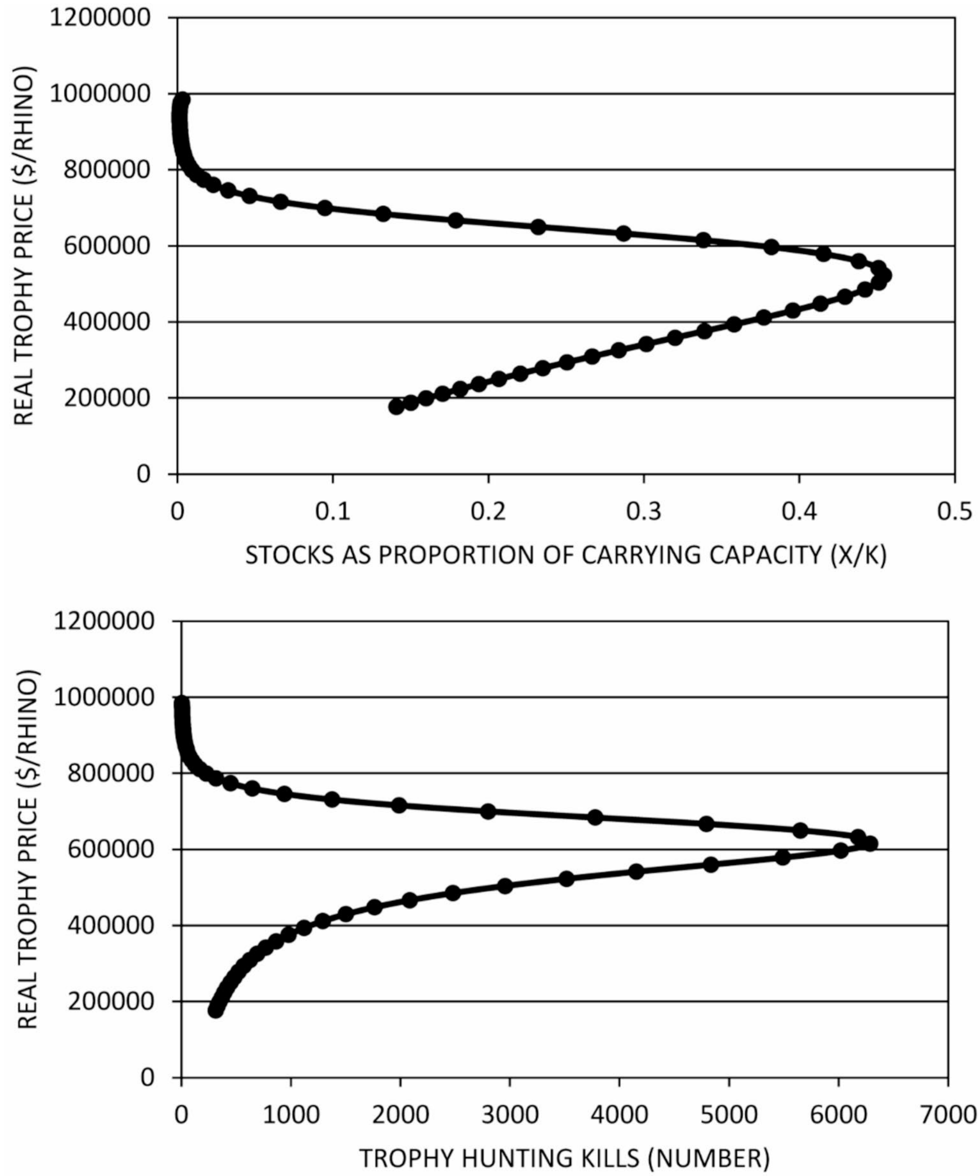

Fig. 5 The top figure shows the real trophy price T_P at which maximum sustainable yield (MSY) is achieved, and the point at which rhino stocks are extirpated. The bottom figure show the real trophy price plotted against trophy kills per annum. At the higher trophy price, trophy kills are zero because there is no more stock left. Both simulations are based on the Sc1 scenario

4.3 Ecotourism: Complementary or Competing?

The simulation that maximised profits was the one where game farms only pursue ecotourism (in other words, the Sc3 scenario, T_E=0), and no trophy hunting activities would persist. At the same time, if rhino abundance is maximised, the optimal solution is for there to be no trophy hunting (T_E=0) and only ecotourism activities would persist (again, this predicts the Sc3 scenario is optimal).

5 Discussion

The debate around whether to allow trophy hunting or ecotourism is likely to affect whether or not white rhinos decrease in the future or not. Here a model is developed that takes into consideration poaching, security and maintenance costs (feed, veterinarian costs, water and tracking and monitoring) as well as the trophy hunting price and ecotourism value for an iconic but also threatened species. Under the basic model, trophy hunting appears initially to result in an increase in rhino populations, and economic returns to the game manager. However, at higher trophy hunting prices, the adverse environmental impacts are far more pronounced. Under trophy hunting rhinos will go extinct in the longer term.

In these open access models of exploitation it is price that drives species abundance: the higher the price the more likely it is that the species will be extirpated. How this works in practice is that, as price increases, more entrants are attracted (in this case, the number of game farms stocking rhinos increases). Trophy hunting, as measured by the number of kills, therefore also increases. This is what ultimately results in the declines in white rhino populations under trophy hunting. Conversely, no such mortality occurs under the ecotourism scenario. Additional game farm entrants under the ecotourism option do not result in an increase in rhino mortality. Therefore, if the central premise of the real trophy hunting price increasing does not hold, then the trophy hunting option would not predict a decline in white rhino population. However, even if the trophy price does not rise as predicted by the model, the ecotourism outcome would still remain a preferable option, at least from a financial perspective.

Secondly, the prediction that the number of game farms will increase based on game farm profitability is predicated on the expectation that open access trade in game farms will continue. There is a risk that the government's recent policy of land expropriation without compensation may threaten that expectation. It is recommended that government recommit itself to free market principles, to reassure the private sector. This would likely further result in game farm numbers increasing again, further assisting in the recovery of white rhino populations.

Nhleko et al. [6] found that poaching was driving white rhino declines in South Africa. While this is probably true for Kruger National Park, where they did their study, in the present study it was found that on private game farms white rhino abundance is driven by the trophy hunting price. There is an inverse relationship between the trophy hunting price and rhino abundance. This result is consistent with the Anthropogenic Allee Effect (AAE) literature (e.g. Palazy et al. [59]), not in so far as rarity drives an increase in price (that remains to be tested but is not the topic of this paper), but rather that an increase in price drives an increase in rarity [60]. High prices increase the demand for trophy hunting, which increases the likelihood of extirpation of the species [59]. However, it is important to note that increases in prices causing an increase in rarity alone is insufficient to indicate an AAE [52].

The model finds that there is no trade-off between profits and conservation. The option that maximises profits and rhino stocks is the ecotourism scenario. It is acknowledged that future price and cost trends in the current paper are highly speculative, At the same time, the results of this model hold even holds if there is poaching assumed and the initial ecotourism price were to decrease to around $1,000 per animal. The argument that trophy hunting is required in order to generate sufficient profits so that security measures can be put in place to combat poaching, therefore, is not supported by the present paper.

At the same time, the trophy hunting result of high trophy prices being contrary to a conservation perspective was also predicted by other authors. Crookes [46] found that under certain conditions, namely where species are traded for high prices and there is exploitation of those species, profit maximisation may actually be sub-optimal from a sustainability perspective. This effect that was termed "trading on extinction". Nlom [61] also found that there is a trade-off between profits and sustainability. Allowing trade at Campo-Ma'an National Park, Cameroon, would result in reduced poaching costs but also in a lower biomass compared with a no-trade option. Conrad and Lopes [62] found that for small species, increases in black market prices resulted in a decline in species abundance. However, for mega faunal species such as rhino, increases in the black market price initially increased species abundance, but at higher prices species decline. In the present model, trophy hunting under poaching (the baseline case) also initially resulted in the increase in rhino stocks, but thereafter a decline in rhino abundance, as well as a decline in the number of farms stocking white rhino.

The paper found that it is only the ecotourism option that provides a win-win outcome of rhino populations recovering and game farm profitability. This study debunks the myth that trophy hunting and ecotourism are complementary. Ecotourism is preferable from both a financial as well as a biological perspective. Game farm profitability is based only on rhino viewing values. In the context of ecotourism, other species are also likely to be important [63]. Overall profits for farms stocking multiple species are also likely to be substantially higher. The present study only considers the ecotourism value associated with viewing rhino.

The study shows that ecotourism could generate profits that are much higher than trophy hunting values, as well as resulting in greater sustainability. This seems logical, since trophy hunting is a once off value, whereas ecotourism generates recurring revenue over time, surpassing the hunting value over time. At the same time, a study at private reserves in the Eastern Cape Province of South Africa indicated that tourists prefer seeing rhinos, and are increasingly opposed to trophy hunting or rhino darting experiences [64].

The study finds that trophy hunting does not meet the requirements for "sustainable use" posited by Milner-Gulland and Rowcliffe [65], by failing the "biological sustainability" component of the definition. Only the ecotourism outcome meets the biological, social and financial criteria of the definition. This paper furthermore finds that there is evidence for the so called "trading on extinction" outcome in the trophy hunting scenario, with high trophy hunting prices resulting in profitability, but driving white rhino ultimately to extinction. The present study however finds that there is a strong financial incentive for game farms to pursue ecotourism rather than trophy hunting. It is what many tourists prefer, it is more sensible biologically. It seems to provide the best solution to ensure private game farms continue to play an important role as custodians of this important and threatened species. The only constraint to this occurring appears to be the threat to free market trade in private land. A recommendation of the study therefore is that government reasserts its promotion of a free-market system in the buying and selling of property in South Africa.

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Data Availability All data generated or analysed during this study are included in this published article [and its supplementary information files].

Declarations

Ethics Approval and Consent to Participate Not applicable. The study is a desktop study and uses secondary data.

Consent for Publication Not applicable.

Competing interests The authors declare no competing interests.

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