Appendix S1 Supplementary methods

S.1 Model validation

Model validation is a process whereby confidence in the system dynamics model is achieved, with iterations through a number of tests. When these test are passed to a satisfactory degree, the model is sufficiently robust for use. Although there is no agreement on which tests are sufficient in order to ensure that the model is suitable for use, a review of five reputable modelling sources on validation by Crookes (2012) indicated that the following tests were most commonly reported: structure assessment tests, parameter verification tests, dimensional consistency test, boundary adequacy test, extreme conditions test, surprise behaviour test, sensitivity analysis and behaviour reproduction. Each of these tests is briefly described, and how it is conducted in the article is discussed. A full description of each test is given in Sterman (2000).

The structure assessment test compares the model structure with structures prevalent in real world situations, or patterns of relationships found in the literature, from established models, or through expert opinion. Our model uses the well-known predator-prey model, with modifications from the peer reviewed literature. The structure is therefore regarded as adequate.

In the same way that model structure may be compared with real world situations, model parameters (constants) may also be validated by comparing with actuality through the parameter verification test. Parameter validation is closely related to structure validation as different parameter values influence the outcome of model structure. In our model, parameters are all derived from the published literature, determined through arithmetic means (see supplementary material) or estimated by the model. The parameters are therefore robust.

The dimensional consistency test analyses a model's equations in order to test whether or not the model's dimensions (units) are consistent. Coyle and Exelby (2000) regard this test as being a "sine qua non". Most good system dynamics modelling software packages provide a means of testing the dimensional consistency of the model while building the model. Our final model satisfies the requirements for dimensional consistency.

The boundary adequacy test comprises three separate tests, namely the structure boundary adequacy test, the behaviour boundary adequacy test and the policy boundary adequacy test, but contain essentially the same logic. The structure boundary adequacy test considers whether or not all the important elements of structure are contained in the model, and what level of aggregation is appropriate. The behaviour boundary adequacy test asks whether or not model behaviour would change significantly if boundary assumptions were changed. The policy boundary adequacy test investigates whether or not policy recommendations would change as a result of a change in the model boundary. Using models from the literature ensured that appropriate boundary structures were followed. Behaviour and policy were consistent with real world considerations. This was assessed by comparing model outcomes with other literature that predicted similar behaviour in the system.

Extreme conditions test assigns extreme but realistic values to parameters to investigate whether or not the model responds in the expected manner. Various extreme conditions are applied to parameters in order to ascertain how the system responds. One way of testing extreme conditions is by assigning maximum and minimum values to policy variables. This is undertaken using the Bayesian Belief Network model. The results are discussed in Section 3.

A surprise behaviour is a model behaviour that is not anticipated by the model analysts. Sometimes this is due to a formulation flaw in the model, and other times this may lead to an identification of behaviour previously unrecognised in the real world system. In the latter case, confidence in the model's usefulness is strongly enhanced. If a test for surprise behaviour leads to unexpected results, the modeller must understand the causes of the unexpected behaviour in the model. A number of surprising results were observed, and these are discussed in Section 3.1.3.

Sensitivity analysis tests the robustness of the model to underlying assumptions. Following Sterman (2000), three types of sensitivity are distinguished: numerical, behavioural and policy. Numerical sensitivity is a feature of the model, while behavioural sensitivity and especially policy sensitivity is important and requires testing. Sensitivity analysis involves testing the sensitivity of model results to changes in parameter values. Sensitivity analysis on all the major policy variables was conducted using Monte Carlo simulation and the results are presented in Section 3.1.4.

The behaviour reproduction test is not reported by all modellers, but uses qualitative and quantitative measures for comparing how best the model is able to replicate the actual behaviour of the system. Quantitative methods include statistical measures such as using the coefficient of determination (R^2), MAE (mean absolute error), MSE (mean square error) and Theil's Inequality Statistic to investigate how much the simulation model deviates from actual values. This test was conducted and the results are presented in Section 3.1.2.

System dynamics modelling is an iterative process of model building, testing and use, in which confidence is gradually developed in the suitability of the model (Sterman 2000). A final discussion of the validity of the model will be done in Section 4. Section 3 presents the results from the model, where the model is used to address the research question, as well as estimate the value of unknown parameters (step 3 in the modelling process).

S.2 Supplementary calculations

The following methods were used to calculate the values for the different parameters (for a summary see Table 2 in the main article).

S2.1 Price of a rhino horn

Poachers receive up to 5000 $/kg for the sale of rhino horn (Crookes and Blignaut 2016).

The average weight of a rhino horn is 3 kg (Milner-Gulland et al. 1992).

This gives a conservative estimate of the price received by poachers of $15 000 per horn set. A horn set could weigh up to 4kgs (Eustace 2012), thereby making the price received by poachers up to $20 000 per horn set.

S2.2 Cost of poaching

Most poachers come through from Mozambique, where the border with KNP is porous (Macleod 2014). Poaching occurs in groups of three and each group spends 4 days in the park on each trip (Macleod 2014).

Method 1: Using Gross National Income (GNI)

Mozambique GNI per capita: US$590 (2013, source: data.worldbank.org)

Wage rate per day $1.62/poacher

Estimated cost per trip (daily wage rate x 3 poachers x 4 days): $19.40

Method 2:

Poachers obtain R160 000 per horn set of 4 kgs (Eustace 2012). This is an average of 6 years wages for each of two poachers at Mozambique rates (Eustace 2012).

Daily wage rate per poacher: (R160 000/2/6/365): R 36.53

2012 Rand/Dollar Exchange rate (2012): 8.2206

Daily wage rate per poacher (in US dollars): 4.4437

Estimated cost per trip (daily wage rate x 3 poachers x 4 days): $53.32

Cost of poaching

Average cost per trip (method 1 and method 2): (19.40 + 53.32 / 2) = $36.36

S2.3 Catchability coefficient

The Schaefer harvesting equation states that h=qEx, where h is the harvests, q is the catchability coefficient, E is the effort and x is the population size. According to data from Macleod (2014), 1 rhino is killed each trip, which implies that h=E. Therefore, q is equal to 1/x.

S2.4 Mortality coefficient

Another parameter that is frequently unknown in bioeconomic analyses is the mortality coefficient m. Usually, a reasonable assumption is that the mortality coefficient is 1, namely that every individual killed is also harvested, although sometimes a mortality coefficient of greater than 1 is also observed (e.g. Wilen 1976). This model, however, was relatively invariant with respect to m. Optimisation is used to test the sensitivity of m for different values of n' and r. For r=0.06 and n'=0.275 the optimal value of m is 0.597. However, if m is increased to 10, the optimal value for r and n' changes by considerably less, to 0.084 and 0.204 respectively. The dynamics of the model remains the same for both sets of parameter values. An assumption of m=1 therefore seems reasonable in the current context.

S2.5 Estimating the probability of arrest and conviction

The probability of conviction following arrest = 0.05 (Eustace 2012)

We can estimate the total number of poachers since there are 3 poachers per kill (see section S1.2)

	Kills (a)	Poachers (b=a x 3)	Arrests (c)	Probability of detection (d=c/b)	Probability of conviction (e)	Probability of detection & conviction (d x e)
2010	333	999	165	0.17	0.05	0.008
2011	448	1344	232	0.17	0.05	0.009
2012	668	2004	267	0.13	0.05	0.007
2013	1004	3012	343	0.11	0.05	0.006
					Average	0.007

It is important to distinguish between the probability of detection prior to a poaching event, as opposed to the probability of detection after a poaching event (Crookes 2016). It is unclear from the data whether these arrests are prior to poaching, or after poaching. Probably a combination of both, since poachers may be arrested for simply being in a protected area. The model requires estimates of the probability of detection prior to a poaching event for policies to be effective in improving the sustainability of wildlife populations, since improving the probability of detection after a poaching event does not improve the sustainability of wildlife populations since the animal is already dead at the time those arrests are made (Crookes 2016). Therefore, using the values in the above table as a proxy for the unknown probability of detection prior to a poaching event probably overstates the true baseline value of the parameter b in the model.

S2.6 Estimating the fine coefficient

The penalty F is a flat rate

F = f + p

In actuality, poachers receive prison sentences rather than fines. A poacher receives 16 years in prison for killing a rhino and taking its horn (Associated Press 2014). We therefore need to convert the penalty into a monetary value.

Estimating the annual wage rate of a poacher

Method 1: GNI per capita = $590 (see section S1.2)

Method 2: Daily wage rate of poacher x 365= 4.4437 x 365 = $1621.94 (see section S1.2)

Annual wage rate = average (Method 1 + Method 2)= $1105.97

Therefore the penalty = $1105.97 x 16 years= $17695.5

References

Associated Press. 2014. Rhino poacher gets 77 years in jail. *News 24*, 23 July. Available at: http://www.news24.com/Green/News/Rhino-poacher-gets-77-years-in-jail-20140723.

Crookes, D.J. & Blignaut, J.N. 2016. A categorisation and evaluation of rhino management policies. *Development Southern Africa*. In press.

Crookes, D.J. 2016. Trading on extinction: an open access deterrence model for the South African abalone fishery. *South African Journal of Science*. In press.

Eustace, M. 2012. Rhino poaching: what is the solution? *Business day live*, 8 August. Available at: http://www.bdlive.co.za/articles/2012/01/20/rhino-poaching-what-is-the-solution.

Macleod, F. 2014. Kruger Park's sugar road to rhino hell. *Mail and Guardian*, 7 November. Available at: http://mg.co.za/article/2014-11-06-kruger-parks-sugar-road-to-rhino-hell.

Milner-Gulland, E.J., Beddington, J.R. & Leader-Williams, N. Dehorning African Rhinos: A Model of Optimal Frequency and Profitability. *Proceedings: Biological Sciences*, 249(1324):83-87.

Sterman, J.D. 2000. Business dynamics: systems thinking and modeling for a complex world. Boston: Irwin/McGraw-Hill.

Wilen, J.E. 1976. Common property resources and the dynamics of overexploitation: the case of the North Pacific fur seal. University of British Columbia Resources Paper No. 3, September.