The Economics of Rhino Poaching

DPhil Economics

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Acknowledgements

I owe my gratitude to a large number of brilliant people who have been instrumental in supporting and guiding me throughout my studies. Thank you to my examiners for their time and thoughtful comments: Erwin Bulte, and Stefan Dercon who has also provided support and feedback throughout the DPhil. Thank you to my supervisors Rick Van der Ploeg and Christopher Adam for all their countless hours of enthusiastic guidance. I could not have wished for better support and it has been a pleasure developing this research with them. A final special thanks to Pramila Krishnan, who has been a mentor to me throughout my undergraduate and graduate studies, and for encouraging me to research what I care about the most.

I would also like to thank all those who supported me through my research and studies; in particular, my family for supporting me throughout my university career, Madeline for her never-failing optimism and encouragement, and Michael 't Sas-Rolfes for his support, enthusiasm, and insight into the field.

Finally, I'd like to thank all those contributing to the conservation and protection of all animals, and especially to those who have given the ultimate sacrifice defending those animals across the world.

This thesis has been funded by the Economic and Social Research Council to whom I am also incredibly grateful.

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DPhil Economics, Trinity Term 2018

Abstract

This thesis analyses the economics of rhino and elephant conservation in light of the recent upsurge in poaching in Africa. Each chapter focuses on a particular component of the new poaching crisis.

Chapter One examines the development of market power by poachers and the implications for how owners should use patrols to defend their rhino. A dynamic model is developed and simulated. The owner is the Stackelberg leader, investing in anti-poaching patrols to protect rhino from poaching cartels who strategically compete in a closed-loop Nash Equilibrium 'game'. Understanding the industrial organisation of cartels is shown to be of paramount importance in designing optimal anti-poaching policy because, perversely, patrol spending works to increase strategic behaviour between cartels.

Chapter Two considers whether establishing a legalised trade in rhino horn could benefit conservation. A dynamic model is formulated and simulated. It is found that, even if the institutional arrangements are robust enough to support legalised trade, the economics suggest trade is not guaranteed to improve the conservation prospects of the species. In the absence of private sector speculation, a legalised trade could be used to sustainably conserve a rhino population when extinction would otherwise occur. However, with the introduction of speculation, speculative attack on the remaining stockpile is highly profitable, leading to extinction of the species.

Chapter Three determines the consequences of increasingly fragmented conservation policy. A new panel of elephant census data for 1,262 reserves across 37 countries in Africa is used to examine the effect of varying anti-poaching policy across borders. An international border is found to result in an elephant population up to 2.5 times smaller than a reserve without a border. In addition, evidence that poachers arbitrage across reserves is found. The policy consequence is clear: as populations become increasingly fragmented, transfrontier conservation policy becomes more important.

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Introduction

The world's wildlife are under threat. Over half of all vertebrates have been lost since 1970 (WWF, 2016). The most iconic example of this epidemic is the decimation of rhino and elephant populations in Africa. Now, both of these magnificent creatures are faced with possibility of extinction.

This thesis analyses the economics of rhino and elephant conservation in light of the recent upsurge in poaching in Africa. Each chapter focuses on a particular component of the new poaching crisis. These are: the evolving industrial organisation and sophistication of poacher behaviour, the renewed questions and economics surrounding a legalised trade, and the increasing importance of policy coordination across reserves and borders, as elephant and rhino populations become increasingly fragmented.

The analysis will be made in the context of rhino and elephant conservation in Africa. The conclusions and analysis apply directly to rhino and elephant in Asia, as well numerous other endangered species. This example is chosen for clarity and because of the dramatic increase in poaching of these two species since 2008.

This introduction provides a background to the ongoing fight to save the rhino and elephant. First, a brief guide to the two animals, their distribution, and historic population trends is given. Next, an examination of the rise in poaching is made to generate stylised facts relevant to the recent upsurge in poaching. Then conservation policy is discussed. Both current policy and potential policies are outlined to provide context to the decision facing

the modern policy maker. Lastly, the thesis is outlined, both in aim and methodology, assessing these policies in line with the stylised facts.

Rhino

Rhinoceros, from the Greek for 'nose-horned', are the second largest land animal in the world. Five species in the family *Rhinocerotidae* are extant, two of which are native to Africa: the black rhino (*Diceros bicornis*) and the white rhino (*Ceratotherium simum*). White rhino are grazers, distinguished by their greater size and adapted wide, broad mouths. Females are herd animals whilst males are territorial. Black rhino are characterised by a triangular lip suited to browsing and are largely solitary. Both are megaherbivores, defined as an ecological keystone species capable of a disproportionately large impact on the ecosystem relative to their abundance (Owen-Smith, 1988). Rhino are often thought of as cumbersome, historic creatures. In fact, they are quick and nimble, reaching speeds of 55km/hr (Alden, 2016). One need only be fortunate enough to see a rhino calf chasing birds around a waterhole (to the embarrassment of their mother) to understand the importance in protecting these animals.

Rhino horns, like human fingernails, are made entirely of keratin. White and black rhino (unlike their Asian counterparts) have two horns, the larger of which weighs 2-3kg on average. The horns are largely for defence, but are used aggressively in territorial battles between males. A rhino can be dehorned (90% of the horn can be removed) and, like fingernails, a new horn will grow back within approximately three years (Lindsey and Taylor, 2011). The cropped horn is storable, however it is prone to natural degradation e.g. weevil infestation.

Rhino used to be abundant throughout Africa. An ability to eat coarse plant material, seconded only by the elephant, allowed for their historic range to stretch to all but the driest and wettest of areas (Kingdon, 2015). This diverse diet meant food scarcity was rarely an issue for rhino and instead, populations were historically controlled by the availability of

water. Thus rhino had long life expectancies, up to 50 years, but relatively slow breeding rates, with gestation periods of up to 16 months. In 1900 there were 600,000 black rhino across Africa. Now, there are only 4,880 in 38 protected areas (in 2010, ibid.).

White rhino were once a conservation success story. The southern white rhino sub-species numbered 20-50 animals in a single population in the Hluhluwe-iMfolozi Reserve, South Africa, in the early 20^{th} century. Now the population numbers around 20,000 in Botswana (re-introduced), Kenya (introduced), Namibia (re-introduced), South Africa, Swaziland (re-introduced), Zambia (introduced), Zimbabwe (re-introduced). Unfortunately, only a miracle can save the northern white rhino from extinction. Abundant in the early 20^{th} century, the population fell to 2000 animals in 1960. Now extinct in the wild, only 3 females remain in captivity. The last male died during the writing of this thesis.

Elephant

Elephant, from the family *Elephantidae*, are the largest animal in the world, weighing up to 6,000kg (Alden et al., 2016). Two species are native to Africa: the forest elephant (*Loxodonta cyclotis*) and the larger bush elephant (*Loxodonta africana*). A varied diet and ability to travel long distances to find water resulted in a historic range that extended throughout all but the driest parts of the Sahara (Kingdon, 2015). Elephant live in matriarchal herds averaging 11 animals, but these can grow up to 100 animals depending on habitat and season. Males break off from nursery herds once of breeding age, and are solitary or form small bachelor herds. The main natural restrictions on populations are drought periods and tooth regeneration. With no natural predators of adult elephant (except humans), historic populations were abundant. However with poaching, populations have fallen from 5-10 million in 1940 to 600,000 today.

Elephant shape the landscape and have great ecological importance. An elephant will eat up to 300kg (5% of their body weight) every day. In an attempt to gain access to nutrient rich roots during the dry season, elephant knock over trees. Tree losses in savannah with

elephant are up to six times higher than without (Asner, 2015). The felled trees provide micro-habitats where nocturnal animals can shelter, e.g. the civet cat, or smaller antelope can hide their fawns, e.g. the duiker, or for a concentration of insects where rodents, e.g. the elephant shrew, may feast. Furthermore, removal of trees reduces competition and allows new plants to flourish.

Elephant tusks are made from ivory and, unlike rhino horns, do not grow back once removed. Ivory is storable and more resilient than rhino horn. It is often buried by poachers for smuggling. Unlike Asian elephant, African female elephant also have tusks. Elephant use their tusks in conjunction with their trunks to feed, breaking roots, branches, and grass across them. Just like humans, an elephant can be right or left handed, and this can be observed through the relative wearing down of one tusk over the other. Male elephant also use tusks in territorial battles. Tusk length is genetic, and has been observed to fall over time as larger tusked elephant have been targeted for poaching or trophies. In fact, 2-6% of females are naturally born without tusks. However, the geographic variation is substantial and depends on the extent of poaching. It can be as high as 98% in heavily targeted populations (Berman, 2017). Now, tusks can weigh 45kg each, but have historically been recorded up to 60kg.

Poaching

Elephant and rhino poaching increased substantially in the 1970s and 1980s. Growing demand in South East Asia decimated the rhino population. The black rhino population was reduced by 96% in 25 years (from 70,000 animals in 1970 to 2,410 in 1995)(Save the Rhino, 2018). Meanwhile rising demand for ivory in Japan, Europe, and the USA led to a large reduction in West and Central African elephant populations. Growing concern from the international community led to international bans on the trade in rhino horn in 1976 and on ivory in 1989.

From here, the two animals have followed different paths. The few remaining black rhino

populations exist in protected, managed reserves. Here, their numbers recovered thanks to anti-poaching enforcement and conservation programmes.[1] Meanwhile white rhino numbers continued to rise after the losses sustained in the 19^{th} century. Now, the African rhino population totals around 25,000 animals, of which 85% are conserved in South Africa and 25% of which are privately owned (Milliken and Shaw, 2012). Meanwhile elephant population trends are more varied throughout the continent. Only 70% of elephant are in managed reserves and therefore protection (and poaching) varies significantly across populations (African Wildlife Foundation, 2018). Some populations, in East and Southern Africa, recovered from the poaching leading up to the ivory ban. In some reserves e.g. The Kruger National Park (KNP), South Africa, elephant populations became too large and required regular culling (Fulton, 2012).[2] However, other elephant under no formal protection continued to be decimated by poaching. This is particularly true of forest elephant in Central and West Africa.

In the last decade, rhino poaching has risen at an unprecedented rate. On average, 14 rhino were poached each year in South Africa from 1990-2007. However, poaching has increased 7800% since 2007, see Figure 1 (South African Department for Environmental Affairs, 2018). The upsurge in poaching has been fuelled by rising Chinese and Vietnamese demand for rhino horn. In Vietnam and China, rhino horn is falsely believed to be an anti-inflammatory in traditional 'medicine', and is a status symbol for the elite.

Elephant poaching has been sustained at a high rate, albeit with geographical differences across Africa. Since 2008, the price of ivory has risen substantially, resulting in a further rise in poaching. This is thought to be largely fuelled by Chinese demand where ivory is used for ornamental pieces and occasionally in traditional 'medicine'. Few remaining populations are growing.

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[1] The black rhino population now stands at around 5,400 animals.

[2] This is largely due to the implementation of man-made water for tourism and high degree of anti-poaching enforcement. This reduces natural regulation of populations due to drought. Too many elephant are a problem as they destroy trees at an unsustainable rate.

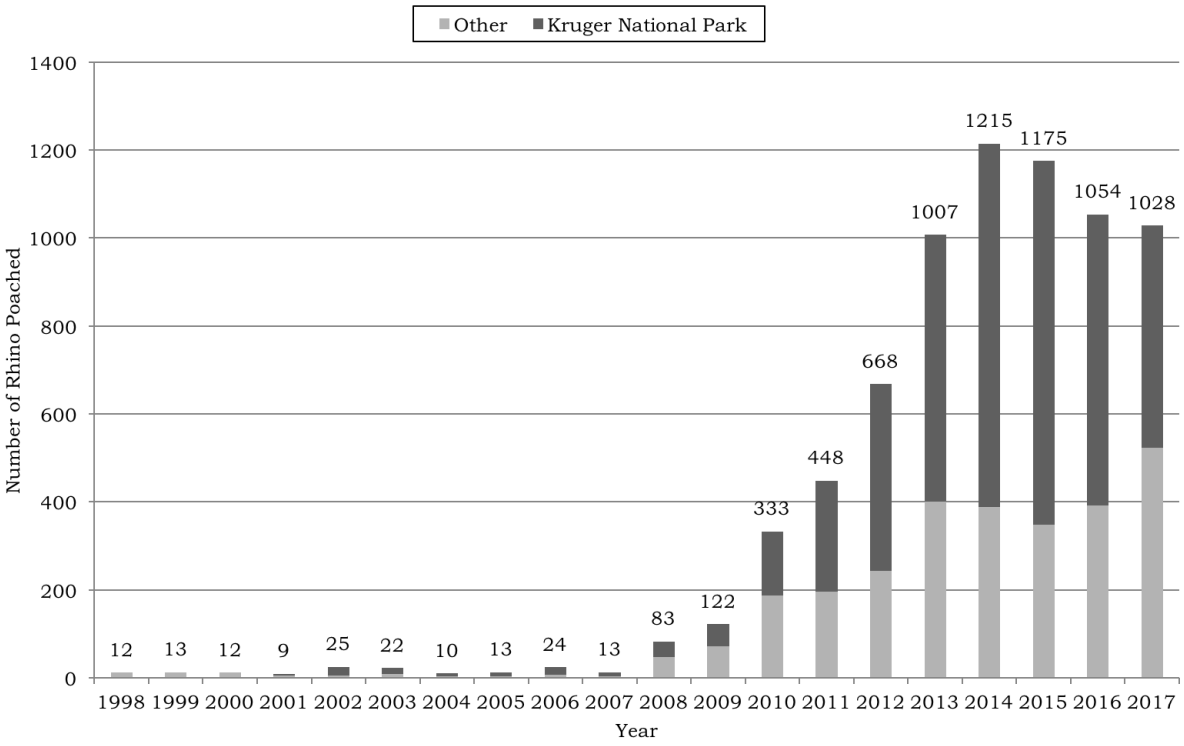


Figure 1: Rhino poaching in South Africa, 1998-2017 (Department of Environmental Affairs, 2018).

Poacher organisation has also evolved over time. With fewer restrictions on international trade and less formal protection, poaching in the 1970s and 1980s required relatively little technology or organisation. Now, poaching and transportation of rhino horn and ivory from Africa to markets in China and South East Asia are a highly organised, illicit operation. This evolution in organisation for poachers characterises the recent increase in rhino poaching. Figure 2 provides a basic overview of the operation. Poaching groups, of up to 16 poachers in local communities, work to poach rhino from the reserves, e.g. the KNP. Whilst poaching attempts used to be opportunistic, they are now highly organised with sophisticated equipment and efficiently divided labour to escape patrols. Bribed park or government officials are known to have orchestrated or advised these operations. These groups poach horns and sell to international couriers who smuggle the horn from South Africa to S.E. Asia using air and sea freight. Commonly this involves movement through Mozambique.

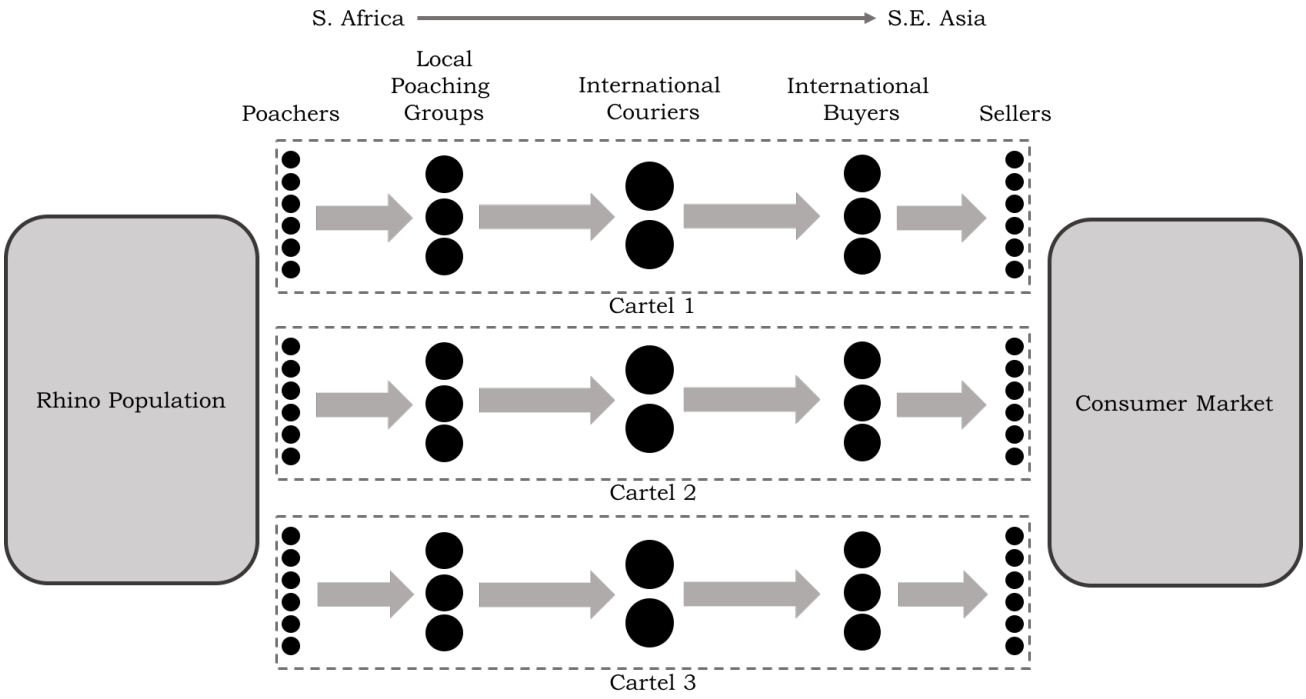


Figure 2: Illustration of the poaching operation from Southern African rhino populations to South East Asian consumer markets (Milliken and Shaw, 2012; and Maggs, 2011).

It is thought that a small number of African-based Asian cartels orchestrate the entire operation (Milliken and Shaw, 2012). They act as employers and managers of a network of couriers and organise distribution in consumer markets. The bribery of agents, including Asian government officials, is common. Seizure data suggests route to markets in China and Vietnam is often indirect and horns pass through Laos or Thailand. These cartels are thought to control the entire operation and indirectly determine the wages paid to local poaching groups as well as the price of rhino horn in retail markets.

Modelling poacher behaviour is key to understand the appropriate response of conservation policy. At its simplest, this reduces to an optimal model of extraction from a renewable resource. The basis of this model is a Gordon-Schaefer fishery model, where a number of agents 'harvest' from a single, open access, renewable resource to profit maximise (Gordon, 1954; Schaefer, 1957). In these models, the cost of harvesting is increasing in the rarity of the population. A steady state is reached where harvesting each period equalises with the natural growth rate of the population. Clark (1973) adapts this model to examine extinction of animal species. Extinction occurs primarily because of low growth rates, high price-cost

ratios, and low discount rates. Bulte (2003) defines a non-concave harvest function to allow for multiple steady states, arguing that a small parameter change that can switch equilibrium may explain the sudden loss of black rhino populations.

The competition structure of the extracting agents is important in these models. Stiglitz (1976) examines the case of monopoly, showing that they are beneficial to conservation as they restrict harvesting to extract consumer surplus. Khalatbari (1977) extends the analysis to an oligopolistic case with property rights, finding a more conservative optimal extraction schedule compared to the open access result. Further studies examine the implications of varying oligopolistic competition on the extraction schedule. Van der Ploeg (1986, 1987) shows that assuming a closed-loop rather than open-loop Nash Equilibrium results in a faster harvesting rate.

Habitat Loss

The second largest threat to rhino and elephant populations, behind poaching, is habitat loss. Milner-Gulland and Beddington (1993) attribute the decline in elephant populations in the 19^{th} and first half of the 20^{th} century to loss of habitat. However, modelling and empirically examining habitat loss is not the main concern of this thesis because the recent decline in populations is largely due to poaching. Nevertheless, these two issues often go hand-in-hand. As poaching pressure rises, the cost of guarding rhino and elephant increases. For private owners, this reduces profitability of reserves and the incentives to provide habitat for the animals. Meanwhile, unlike rhino, elephant ranges extend beyond protected reserves. Rising demand for agricultural land has often been met through the use of displaced elephant habitat. This not only reduces the range of elephant populations but forces remaining populations into closer contact with humans. This can lead to increased poaching and sometimes revenge-killings for damage to crops (Hariohay et al., 2015). It is also known that logging-companies, and their infrastructure, are often involved in the poaching and smuggling of ivory.

Conservation Policy

International restrictions on wildlife trade, including ivory and rhino horn, are governed by CITES (Convention on International Trade in Endangered Species). However, domestic trade and policy are not governed by this agreement. CITES classifies populations into Appendices. The majority of rhino and elephant populations appear in Appendix I which contains the most endangered species. International trade for commercial purposes in animals or animal products is banned under Appendix I. Elephant populations in Botswana, Zimbabwe, South Africa, and Namibia; and rhino populations in South Africa and Swaziland, appear in Appendix II. These Appendix II populations are considered not immediately threatened with extinction, but they may become threatened if trade is not controlled. This classification allows for regulated trade through export permits. It also allows for trophy hunting of elephant in these populations.

Regulation of international trade in ivory is more complicated than that of rhino horn due to the use of ivory in durable products. There are three 'brackets' of ivory products. Trade in pre-1947 worked ivory with a form of proof of derogation is permitted. Trade in worked pre-1990 African elephant ivory and worked pre-1975 Asian elephant ivory is permitted with an Article 10 certificate. Trade in worked ivory after these dates or un-worked ivory is prohibited. Whilst international trade in new ivory is illegal, two 'one-off' sales have been permitted since the start of the ban. In 1997, Japan bought 49,574kg of government stockpiled ivory at $\sim$ \$100/kg from Zimbabwe, Botswana, and Namibia. In 2008, China bought 107,740kg of government stockpiled ivory at $\sim$ \$140/kg from the same countries and South Africa (Poaching Facts, 2018).

Despite strict international restrictions on the trade in wildlife products, the recent increase in poaching has placed more populations at risk of extinction. Therefore, the debate in conservation policy over how best to protect these species continues. The main issues in this debate, and existing previous research, are discussed below.

Anti-Poaching Patrols

Anti-poaching patrols are the most commonly used conservation strategy. As the sophistication of poacher strategies and equipment has increased in the new wave of poaching, so patrols have become more expensive and dangerous for rangers on the ground. 189 rangers were killed in Africa from 2009-2016 (International Ranger Foundation, 2016). Throughout this thesis, the effectiveness and cost of patrols are evaluated without reference to this potential loss of life. This is done for simplicity. It is recognised that omitting the risk of loss of life does not address a key decision when deciding the number of anti-poaching patrols. It is important to remember this risk.

The recent uptake in poaching is characterised by poaching cartels with market power. However, the majority of elephant or rhino poaching models were written with respect to the increase in poaching in the 1980s and 1990s, characterised by open access, perfectly competitive assumptions.

Determining the effectiveness of patrols is difficult, not only because of the lack of a counterfactual study, but because data is guarded, often with good reason, by owners. Milner-Gulland and Leader-Williams (1992) found intuitive results: rhino poaching is reduced with patrols, sentencing that increases in severity with the number of animals poached is more effective than a fixed penalty, and the probability of capture is a highly significant factor in the decision to poach. Bulte and van Kooten (1999) examine the ivory trade ban, modelling an owner who can invest in anti-poaching enforcement. This raises the cost of poaching for poachers who try to avoid patrols. It is argued that for reasonable parameter estimates, the ban on legal trade on ivory has led to higher elephant populations.

Lopes (2014) models the labour allocated to poaching when there is an exogenous probability of capture. In simulation, small policy changes were found to have large and unpredictable effects on the animal population. In addition, when examining a profit maximising poacher's decision to poach, the probability of capture was found to be a more important factor for the marginal poaching attempt than a change in the price of horn. A strategic mixed Nash

Equilibrium between patrols and poachers acting in space was also considered.

On the other hand, Barichievy et al. (2017) examine patrol effectiveness around 40 poaching incidents, finding patrols did little to deter poachers. Beale et al. (2018) use aerial surveys and spatial econometrics to determine the drivers of poaching, finding little evidence that patrol intensity was a key variable.

It is worth considering the factors that determine the incentive to provide patrols. Swanson (1994) models populations of animal species as economic assets. Their extinction is a result of higher return elsewhere. Three mechanisms through which extinction might occur are identified. Firstly, stock disinvestments which are direct sales of the animals or stocks and allocation of the remaining funds to more competitive assets. Secondly, re-allocation of base resources i.e. inputs and land to more competitive assets. In this sense, the allocation of land is endogenous to the profitability of the species. Thirdly, the reduction in management services which results in movement towards an open access resource. Swanson highlights the fact that open access is an effect and not a cause of the forces driving extinction.

Stockpiling and Farming

The most contentious debate in conservation policy is whether a legal trade in rhino horn or ivory should be permitted by CITES. At the latest CITES meeting, Swaziland put forward a motion to allow legal sales of rhino horn to consumer markets. The motion was rejected.

Ivory and rhino horn are storable products. Owners of rhino and elephant have accumulated large stockpiles in these commodities which could be sold to consumer markets. Proponents of the trade argue that selling stockpiled horn could reduce prices and poaching incentives. Meanwhile, revenue from sales could be channelled back into species protection. Opponents argue that a trade will reduce poaching costs by providing a channel to launder goods to market, undermine demand-reduction programmes in consuming nations, and increase total demand by allowing law-abiding consumers to purchase the products. Instead, burning the stockpiles will send clear a signal to consumers that these products should not be consumed.

The economics of stockpile management and speculation has been extensively developed in multiple settings. Perhaps the most applicable setting to this problem is the management of fixed exchange rates (Krugman, 1979; Henderson and Salant, 1978; Flood and Garber, 1984; Corsetti et al.; 1999, 2006; and Burnside et al.; 2001a, 2001b). Similarities to commodity price speculation (Deaton and Laroque; 1992, 1996; Hall and Rust, 2007; and Frankel, 2014), and the management of buffer stocks (Gustafson, 1958; and Newberry and Stiglitz; 1981, 1982) also exist.

However, there are a number of complications to the story of a legalised trade in rhino horn or ivory. Firstly, there are unusual interactions between the state (the population of animals) and the stockpiling rule. Most importantly, the number of animals is the objective of the owner, not profit as in the majority of stockpiling models. Furthermore, the stockpiling decision of the owner today affects the accumulation rate to the stockpile in the future. Secondly, speculation may occur on the owner's stockpile but there is not a direct commitment from the owner to maintain a particular price, unlike a fixed exchange rate model. Thirdly, there is the possibility of a double dividend from selling stockpiled horn or ivory because revenue can be channelled back into other forms of species protection, for example anti-poaching patrols. Fourthly, in the case of rhino, intensive farming through de-horning may be possible. These rhino would generate horn for sale at a greater rate than the wild population but are not the objective for the owner wishing to conserve wild rhino. Lastly, because of the movement from an illicit to legalised market, there are interactions with demand and demand-reduction programmes in consuming nations which require attention when evaluating the effectiveness of the policy.

Some existing work examines wildlife stockpiles directly. Kremer and Morcom (2000) allow for storage in an open access harvesting model. They find that anticipated future scarcity of the resource leads to faster poaching rates and higher prices. Hence, there is a dynamic between poaching incentives and expectations leading to multiple rational expectations paths of prices and animal populations. Stockpile management is not explicitly considered as a

policy tool for conservation.

Mason et al. (2012) recognise that stockpiles are already held by profit maximising private speculators who compete with poachers. The speculators find it optimal to either depress prices and deter poaching or bid up prices to encourage poaching, acting as a monopolist seller after extinction: the 'banking on extinction' strategy. Which strategy is followed depends on the initial animal population and stockpile of resource. 'Banking on extinction' is an important consideration, especially given the institutional background to the proposed legalised trade. However, it is perhaps better to think of an objective of conservation at the core to stockpile management rather than profit maximisation.

Other models include the possibility of farming rhino. Brown and Layton (2001) examine the potential benefits of de-horning rhino and supplying the market with a stream of horn to depress poaching. The owners acts as Stackelberg leader and can predict the poachers' reaction to the legal supply of horn in the market. The calibration suggests legalisation of trade would deter poaching and demand could be satisfied through de-horning. 't Sas-Rolfes and Fitzgerald (2013) build a similar model. The crucial extension is the distinction between intensive and extensive rhino owners. Intensive owners generate income from tourism, de-horning, sale of live animals etc. Extensive owners leave the rhino in a more natural state. Poachers can arbitrage between stocks. Again, legalisation of trade in rhino horn is argued to increase the extensive rhino population whilst lowering horn prices.

Collins et al. (2016) argue that for farming to be profitable, a high horn price would have to be maintained. This is so security costs can be covered across the breeding cycle. Therefore, poaching may actually be encouraged given a farmed trade. Damania and Bulte (2007) examine strategic effects between farmers, arguing that this may lead to further loss of wildlife. Harvey et al. (2017) argue a trade ban should be maintained indefinitely to prevent speculation bidding up prices.

One of the largest concerns with a legalised trade, is any possible interaction with the illicit

market. Fisher (2004) identifies four main threats. The first is that law abiding consumers might simply operate in a separate market. This may be true if farmed or stockpile horn is seen as an inferior good to 'wild' horn. Heltberg (2001) argues that legalising trade may increase demand and therefore trade should be banned. The second is that a legal trade reduces the stigma of consumption, undermining demand reduction programmes which are seen as the long term solution to the problem. Abbott and Van Kooten (2011) argue that, despite this stigma, trade in tiger bone could save the tiger from extinction when patrols would otherwise be insufficient. Third, it may be that a legal sale allows a channel for illegal horn to be laundered to market. Lastly, the supply costs of illegal supply may be reduced by a parallel legalised trade. Hsiang and Sekar (2016) find the 2008 one-off sale in ivory was associated with a 66% increase in illegal ivory production and 71% increase in smuggling out of Africa.

De-horning and Dyeing Rhino Horn

De-horning a rhino may reduce incentives for poaching. Zimbabwe announced in 2016 that they would de-horn their remaining rhino. Smaller reserves in Mozambique, Namibia, South Africa, and Swaziland have adopted de-horning with success. Lindsey and Taylor (2011) have an extensive study on the impact of de-horning rhino. A more recent study in Zimbabwe found that de-horning rhino resulted in a 29.1% increased chance of survival (du Toit, 2011). However, de-horning is not a substitute for law enforcement and patrols are more important for successful conservation. In the Hwange National Park, Zimbabwe, de-horning in the early 1990s saw the majority of animals killed within 12-18 months of de-horning due to a lack of law enforcement (ibid.). Furthermore, de-horning is costly, may adversely affect tourism income, and is infeasible in parks with larger rhino populations. Rhino must be de-horned once every year in order to significantly deter poachers (Milner-Gulland, Beddington and Leader-Williams, 1992). Dyeing rhino horn is an alternative, but with similar implications. Furthermore, dye cannot penetrate throughout the horn, and it is possible that poachers can cut around the dyed areas and sell the remaining parts of the horn.

Synthetic Rhino Horn

The development of synthetic rhino horn may provide a potential solution. Horns, indistinguishable from wild rhino horn, that are manufactured through 3D printing or alternative methods could be used to flood the market and reduce prices (Chen, 2017). However, in practice, this will work only if synthetic horn remain indistinguishable from real rhino horn. Otherwise, a segmented market will occur with a premium for wild horn. To ensure this, sellers who could conceivably sell real rhino horn must be identified. But, if these illicit sellers could be identified in the first place, then they would be shut down.

Trophy Hunting

Trophy hunting is one of the most controversial topics in elephant and rhino conservation. It is also a significant reason why Zimbabwe, South Africa, Botswana, and Namibia have historically fought for their elephant to be classified in Appendix II and not Appendix I of CITES. The mere thought of killing an endangered animal to benefit conservation seems perverse. It is also abhorrent that anyone would want to kill such animal. However some argue that trophy hunting may raise the value of owning animals and helps negate the security costs of protecting them. They argue that raising the profitability of keeping animals for trophy hunting may increase the habitat and area of land available for the species (Abensperg-Traun, 2009) and, therefore, population numbers may increase (Di Minin et al., 2016). Trophy hunting may be used to raise revenue for other conservation efforts. In Namibia, old rhino bulls who can no longer breed are singled out for trophy hunts. These hunts generate millions of dollars which are funnelled back into rhino conservation.

Regardless of whether trophy hunting is beneficial for conservation, it is important that a 'canned hunt' scenario is avoided whereby animals are farmed and released only when they are to be hunted. As can be seen, it is hard to maintain a distinction between an extensively managed wild animal, valuable to conservation, and an intensively managed farmed animal. Given the industry is still relatively young, self-governance on practice standards is still underdeveloped and will require significant progress in order to achieve an outcome centred around conservation

Community Engagement

Despite the fact that poaching operations are run by international criminal syndicates, it is local people that are employed to poach. Raising the value of these animals to local communities reduces the incentives to turn to poaching. Projects, such as CAMPFIRE in Zimbabwe, that direct revenues from tourism to local communities in return for wildlife protection, have proven to be a success (Fischer et al., 2011). Similar projects exist in Kenya with the Maasai (Zoological Society of London, 2016), India (Indian Rhino Vision - Save the Rhino, 2016), and Indonesia (RPU - Save the Rhino, 2016). However, community projects are often idiosyncratic and hence analysis of their success is difficult. In certain cases, community engagement has proven to be highly effective. However, these projects are harder to establish in larger parks and when poaching occurs across international borders, for example, Mozambicans poaching in the Kruger National Park. Furthermore, as the price of horn and ivory rises, it is unclear as to whether these projects will remain financially sustainable in the face of rising poaching incentives.

Demand Reduction

Historically, demand reduction strategies have worked for rhino horn. South Korea, Yemen, and Japan were all large consumers of rhino horn at different points in the late 20th century but are no longer significantly involved. Unfortunately, the current consumer market in Vietnam and China is poorly understood. This is because the trade is illicit and the data that exist, especially price data, are guarded closely for fear of incentivising further poaching. Published research is largely limited to interview evidence and reports from seizures. The most comprehensive study on the rise in contemporary demand is by Milliken and Shaw (2012). Researchers have used pre-ban data but it is unclear how relevant these conclusions are for the current situation (Milner-Gulland, 1993). For ivory, demand reduction strategies are more complex given the legal trade in antique ivory. However, given consumption of ivory is often for decorative pieces and not medicinal belief, the prospect of finding a substitute for ivory is promising. For example, it has been suggested that mammoth ivory could be used as a substitute for elephant ivory and can therefore alleviate poaching (Boyce and Farah, 2015).

This Thesis

This thesis analyses the economics of rhino and elephant conservation in light of the main characteristics of the recent upsurge in poaching in Africa. Each of the three chapters focus on a particular component of the new poaching crisis. These are: the evolving industrial organisation and sophistication of poacher behaviour, the renewed questions and economics surrounding a legalised trade, and the increasing importance of policy coordination across reserves and borders as elephant and rhino populations become increasingly fragmented.

The institutional issues surrounding the design of conservation policy are largely ignored in analysis. The policy landscape is too complex to focus on both the economics and institutional aspects simultaneously. Nevertheless, the conclusions from the economic analysis will be discussed in the context of the institutional challenges facing the policy maker.

In Chapter One the consequences of increasing poacher sophistication for optimal anti-poaching patrol policy are examined. A key characteristic of the rapid increase in poaching since 2008 has been the development of market power by criminal cartels, orchestrating the entire poaching and smuggling operation. This has important implications for the rate of poaching and the optimal response of anti-poaching patrols. In the model, the cartels strategically compete, understanding that poaching a marginal rhino increases the marginal cost of poaching for all the other cartels by making rhino harder to find. This model of strategic competition is developed from Van der Ploeg (1987).

It is found that this strategic effect, derived from poacher market power, is important for owner policy. The effect means anticipated future scarcity of the rhino or elephant population works to increase the poaching rate. This has surprising consequences for optimal owner behaviour, as it is found that anti-poaching patrol spending increases the strategic effect between cartels.

In Chapter Two the economics behind the proposed legalised trade are examined. An optimal stockpiling rule for an owner attempting to use horn sales to conserve a rhino population

is derived. Unlike previous research, the owner's objective is animal conservation and not profit maximisation. It is shown that this has important consequences for the stockpiling strategy. Milliken and Shaw (2012) provide evidence that private speculators are also stockpiling rhino horn. Despite this, proposals for the trade have often failed to recognise that the presence of these private speculators could constrain the owner's optimal stockpiling strategy. Hence, owner behaviour is examined under the constraint of private speculation.

It is found that, even with the assumption that institutional arrangements could be robust enough to support a legalised trade, the economics suggest a trade is not guaranteed to improve the long term conservation prospects of the species. In the absence of private sector speculation, a legalised trade could be used to sustainably conserve a rhino population when extinction would otherwise occur. However, with the introduction of speculation, there comes a point where speculative attack on the remaining stockpile is highly profitable, leading to extinction of the species. The timing of this attack is inversely related to the size of the initial population.

Finally, Chapter Three examines the consequences of rhino and elephant populations becoming increasingly fragmented due to poaching. Whilst most rhino populations have existed in managed reserves since the 1980s, elephant populations have continued to exist outside such reserves. However, this is becoming increasingly uncommon as these marginal populations have been targeted (due to lack of formal protection) in the recent uptake of poaching. Therefore the population distribution of the remaining elephant in Africa is fragmented, characterised by many individual populations with varying degrees of intensive management and anti-poaching enforcement.

Fragmented elephant populations and varying degrees of anti-poaching enforcement provide arbitrage opportunities for sophisticated cartels. Given CITES only dictates international conservation policy, large differences in domestic conservation policy and the severity of punishments for poachers have occurred. Furthermore, it is hypothesised that anti-poaching enforcement is more difficult across international borders. In the chapter, the effects of bor-

ders and consequences for elephant populations are empirically examined using a new panel of data for 1,262 reserves across 37 countries in Africa. To the author's knowledge, this is the first reserve-level panel of elephant population data empirically examined in the field since the ivory trade ban.

Significant border effects are found. An international border results in an elephant population up to 2.5 times smaller than a reserve without a border. In addition, evidence that poachers arbitrage across reserves within the same country is found. The effect of conflict is also analysed. It is found conflict significantly reduces elephant populations, particularly across international borders. The policy consequence is clear: even if the neighbouring country has no elephant of its own, their domestic policy towards poaching still matters for elephant conservation.

Finally, the main debates in conservation policy are briefly revisited in light of the conclusions derived in the chapters. A verdict, detailing the potential policy success and future developments required, is given in each case.

Chapter One

The Economics of Rhino Poaching

Abstract

A key characteristic of the rapid increase in poaching since 2008 has been the development of market power by criminal cartels orchestrating the operation. This chapter examines the implications for how owners should use patrols to defend their rhino. Optimal spending on patrols is found to rise and then fall with the rhino population, as the rhino owner equalises the marginal value of a rhino with the marginal cost of providing patrols. The steady state population of rhino rises with increased patrol spending but falls with increasing poacher competition. Understanding the industrial organisation of cartels is shown to be of paramount importance in designing optimal anti-poaching policy because, perversely, patrol spending works to increase strategic behaviour between cartels.

1.1 Introduction

Management of endangered species has never been a more important issue. Over half of all vertebrates have been lost since 1970.[1] The most iconic example of this epidemic is the upsurge in rhino poaching in Africa. Owners of rhino are now primarily concerned with protecting these animals in the face of rising poaching incentives. This chapter develops a model in order to analyse proposed solutions to the poaching problem.

Unlike the majority of previous research modelling rhino poaching, this chapter recognises that the recent poaching crisis is characterised by the development of market power by poaching cartels. This has two important consequences for owners defending their rhino with patrols. Firstly, if cartels recognise that they can affect each other's costs, then poaching will increase relative to 'standard' models of oligopolistic competition. This introduces the dynamic whereby anticipated scarcity of the resource increases the poaching rate. Secondly, it suggests that shutting down the marginal cartel will result in less competition and a more than proportionate reduction in poaching.

It is found that optimal spending on patrols should rise and then fall with the rhino population, as the rhino owner equalises the marginal value of a rhino with the marginal cost of providing patrols. Patrols are shown to increase the rhino population at the steady state. The strategic effect from cartel market power is found to be large. Anticipated future scarcity of rhino works to increase the current number of poaching attempts. This results in a much lower steady state population of rhino relative to the case with no strategic effect. Understanding the industrial organisation of cartels is shown to be of paramount importance in designing optimal anti-poaching policy because, perversely, patrol spending works to increase strategic behaviour between cartels.

[1] 58% of all vertebrates were lost between 1970 and 2012 (WWF, 2016).

1.1.1 The Kruger National Park and Poaching

Rhino are megaherbivores, an ecological keystone species capable of a disproportionately large impact on the ecosystem relative to their abundance (Owen-Smith, 1988). Nearly three quarters of the world's rhino reside in South Africa (Save the Rhino International, 2017). Poaching in South Africa has risen by 7800% since 2007, see Figure 1 (in the Introduction)(Department for Environmental Affairs, 2018). Rhino are poached for their horn, which can trade for up to $180,000 on the black market (Carrington, 2014).[2] The upsurge in poaching has been fuelled by rising Chinese and Vietnamese demand for rhino horn. In Vietnam and China, rhino horn is falsely believed to be an anti-inflammatory in traditional 'medicine', and is a status symbol for the elite. In fact, it is comprised of keratin, the same protein comprising human fingernails. International trade in rhino horn is illegal, however demand is so great that the illicit trade has flourished. The recent rise in poaching has already decimated the Javan and Sumatran rhino populations and now seriously threatens African white and black rhino with extinction.

The Kruger National Park (KNP) in South Africa is the focal case for this chapter. The KNP is a government owned reserve, the size of Israel, and is the habitat of nearly a third of the world's rhino.[3] It is also where the majority of rhino poaching has occurred since 2007. The reserve generates a large amount of tourism income to the government who do not harvest rhino horn from the population. In response to the rapid rise in poaching, the South African military have been assigned to mount anti-poaching patrol operations in the park. This is the context upon which this chapter is based. The strategic 'games': between the cartels, and between the cartels and government (owner) patrols, are modelled with an aim to derive a prescription for optimal behaviour by the owner to protect the rhino population.

[2]The remainder of the rhino has little value and is often discarded.

[3]Whilst the rhino in the KNP are publicly owned, there is little difference between public and private ownership.

1.1.2 The Poaching Operation

The poaching and transportation of rhino horn from South Africa to markets in China and South East Asia are a highly organised illicit operation. This evolution in poacher organisation characterises the recent increase in rhino poaching. Figure 2 (in the Introduction) provides a basic overview of the operation. Poaching groups, of up to 16 poachers, in local communities work to poach rhino from the KNP. Whilst attempts used to be opportunistic, they are now highly organised with sophisticated equipment and efficiently divided labour to escape patrols. Bribed park or government officials are known to have orchestrated or advised these operations. These groups poach horns and sell to international couriers who smuggle the horn to S.E. Asia using air and sea freight. Commonly this involves movement through Mozambique. Seizure data suggests the route to markets in China and Vietnam is often indirect and horns pass through Laos or Thailand.

It is thought that a small number of African-based Asian cartels orchestrate the entire operation (Milliken and Shaw, 2012). They act as managers of a network of couriers and organise distribution in consumer markets. These cartels indirectly determine the wages paid to local poaching groups and the price of rhino horn in retail markets.

This level of organisation suggests an element of market power for poaching cartels. The vast majority of previous studies assume an open access, free entry condition for poachers. This results in the maximum number of horns which can be profitably poached each period. Whilst it could be argued that the initial poaching and final selling of the horn is close to this open access behaviour, the wages paid and price in consumer markets are directly determined by the international cartels. Therefore, when modelling the operation it is important that poacher market power is included.

1.1.3 This Chapter

The number of cartels suggest a model of oligopolistic competition. Given the cartels dictate the supply of rhino horn, it makes sense to think about competition on quantity. Here, unlike previous studies which model oligopolistic competition in this setting, this chapter

uses a closed-loop Nash Equilibrium 'game'. This recognises that cartels make decisions with the knowledge that they can affect the behaviour of other competing cartels. In other words, they recognise that the resource is becoming rarer as poaching increases. This has important consequences for their behaviour, and by extension, for the behaviour of owners protecting the rhino.

In addition to recognising cartel market power, the model in this chapter allows for an endogenous, strategic interaction to take place between the owner and poaching cartels. It avoids assuming an exogenous probability of capture for poachers. This means that the incentive to provide managerial services, in this case anti-poaching patrols, can be directly examined. Unlike the majority of studies examining conflict between owners of animals and poachers, it is assumed that the rhino population is a restricted access resource. Whilst only 20% of elephant are under formal protection, the majority of rhino are in fenced, managed habitats. As Swanson (1994) notes, modelling these resources as open access, and then examining how the owner and poachers conflict, already assumes a failing in the initial managerial services required.

1.2 The Model

The model considers a single population of rhino that grows, in the absence of poaching, towards the carrying capacity of the habitat. A small, fixed number of cartels poach rhino from the population and sell the horn in a single consumer market. The cartels strategically compete, understanding that poaching a marginal rhino increases the marginal cost of poaching for all the other cartels by making rhino harder to find.[4] The owner of the rhino 'plays' a feedback Stackelberg game with the cartels, investing in anti-poaching patrols to reduce poaching. This is because patrols increase the probability of capture for cartels attempting to poach a rhino. The owner maximises a non-consumptive flow of utility which is increasing in the number of rhino in the population.

[4]This model of strategic competition is developed from Van der Ploeg (1987).

1.2.1 The Rhino Population

The population of rhino, x_τ, evolves over time, τ, according to,

$$dx_\tau = \{g(x_\tau) - T_\tau\}d\tau + \sigma(x_\tau)dw \tag{1.1}$$

where $g(x_\tau)$ is the net growth of the rhino population, T_t is the total number of rhino poached, $w(\tau)$ is standard Brownian motion, and $\sigma(x_\tau)$ is a diffusion process for uncertainty.[5] The size of the shock is proportional to the population size.[6] Without poaching, the population will grow to a maximum population dictated by the carrying capacity of the habitat K.[7] With poaching, the steady state population of rhino x^{ss} is dictated by the condition $g(x^{ss}) = T^{ss}$, assuming extinction does not occur. Here, net growth is exactly offset by poaching.[8]

1.2.2 The Poaching Cartel Problem

Poaching is undertaken by a fixed number of identical poaching cartels who otherwise receive no benefit from the population of rhino. Each cartel i is endowed with a fixed amount of labour in each time period which is normalised to a single unit, $\bar{l}_{i\tau} = 1$. For simplicity, a constant harvest function is assumed, so each unit of labour can attempt to poach ϕ rhino at every moment in time.[9] Additionally, labour can be assigned to an alternative activity where each unit earns a reservation wage $\bar{w}$. It is known that the poaching cartels operating in South Africa are international syndicates, involved in drugs, arms, and people trafficking in addition to rhino poaching (Milliken and Shaw, 2012). Furthermore, it has been shown

[5] Whilst an exact growth function is specified later, the model is derived under the assumption that $g(x_\tau)$ is continuously differentiable and concave. $g(0) = 0$, as an extinct population cannot breed.

[6] $\sigma(0) = 0$, $\sigma'(x_\tau) > 0$, $\forall x_\tau > 0$.

[7] $g(K) = 0$, $g'(K) < 0$.

[8] The stability of this steady state depends on $g'(x^{ss})$. In most cases, three steady states exist. Two of these are often ignored in analysis - the stable steady state at $x^{ss} = 0$ and an unstable steady state $x^{ss} > 0$, see Eisworth and Van Kooten (2009). The analysis instead focuses on the stable steady state where $x^{ss} > 0$.

[9] Bulte (2003) assumes a convex-concave harvesting function in species abundance resulting in the existence of multiple steady states. Switching between steady states may explain the dramatic changes observed in the black rhino population in the mid to late 20^{th} century.

that cartels may switch from poaching rhino to other species sharing the same habitat, e.g. elephant, depending on the relative prices of rhino horn to ivory. At each point in time, the cartel chooses the fraction of labour to commit to rhino poaching $l_{i\tau}$ which corresponds to $\phi l_{i\tau}$ poaching attempts. The remaining $(1 - l_{i\tau})$ units of labour are committed to the alternative activity.

Each successful poaching attempt yields one horn (of homogenous size and value) which is smuggled and sold in a single consumer market contemporaneously. The rhino dies as a result of a successful poaching attempt. The cartel faces a downward sloping isoelastic demand curve $p(T_\tau)$ where T_τ is the total number of rhino poached (i.e. the number of horns smuggled to the market) at each point in time.[10] In this model, rhino horn cannot be stored.[11]

The more abundant rhino are, the lower the marginal cost of poaching attempts $c(x_\tau)$ as it is easier for a cartel to find a rhino to poach.[12] With each poaching attempt the cartel may be caught by an anti-poaching patrol with probability λ_τ. If caught, they pay a penalty χ in addition to the marginal cost of a poaching attempt, and the rhino survives.[13] The cartel continues to trade, even if it is caught attempting to poach a rhino. Given that each cartel encompasses the entire poaching operation, capture is thought to entail a cost to change operations and pay fines, but does not lead to a complete shut down of operations. The total number of rhino poached is related to the aggregate labour dedicated to poaching attempts,

$$T_\tau = (1 - \lambda_\tau)\phi L_\tau \tag{1.2}$$

[10] $p'(T_\tau) < 0$, $\lim_{T_\tau \to 0} p(T_\tau) = \infty$.

[11] In reality, horn can be stored but is biodegradable so unlike ivory, it can only be stored under managed conditions. This would allow cartels to poach more when poaching costs are low and store the horn until costs and the price of rhino horn increased. Furthermore, consumers could speculate upon the price of rhino horn. These dynamics are beyond the scope of this chapter but are discussed in Chapter Two.

[12] $c'(x_\tau) < 0$, $c''(x_\tau) < 0$.

[13] It would not change the implications of the model significantly if it were assumed that the rhino does not survive the poaching attempt if the cartel is caught. This would simply act as a shift parameter on the effectiveness of anti-poaching patrol spending in the owner problem.

where $L_\tau = \sum_{i=1}^{N} l_{i\tau}$ is the aggregate amount of labour dedicated to poaching attempts, and N is the number of cartels.[14] Cartel, i, chooses their labour dedicated to rhino poaching, $l_{i\tau}$, to maximise the expected present value of profits, discounted at the cartel's discount rate, ρ, subject to the dynamics of the rhino population,

$$\max_{l_{i\tau}} J_\tau^i = E_\tau \int_{\tau=0}^{\infty} e^{-\rho\tau} \left\{ [(1-\lambda_\tau)p(T_\tau) - \lambda_\tau \chi - c(x_\tau)]\phi l_{i\tau} + \bar{w}(1-l_{i\tau}) \right\} d\tau \tag{1.3}$$

$$\text{s.t. } dx = \{g(x_\tau) - T_\tau\}d\tau + \sigma(x_\tau)\, dw \tag{1.1}$$

$$T_\tau = (1-\lambda_\tau)\phi L_\tau \tag{1.2}$$

$$L_\tau = \sum_{i=1}^{N} l_{i\tau} \tag{1.4}$$

$J_\tau^i(l_{1\tau}, l_{2\tau}, ..., l_{N\tau}, x_\tau)$ is convex in $l_{i\tau}$.[15] E_τ is the expectations operator for the cartel.[16] Whilst not explicitly modelled, the cartel is assumed to pay poachers from the local population at a premium to local wage, resulting in an abundant labour supply to the cartel. Hence, whilst a cartel is inconvenienced by the capture of a poacher, they are risk-neutral in their profit maximising decision.

The Probability of Capture

The probability of capture for poachers is endogenously determined by three variables. It is increasing in spending on anti-poaching patrols, s_τ.[17] It is decreasing in the size of the habitat, K. Rhino spread out over the habitat so a given number of patrols need to cover

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[14] An increase in the labour devoted to poaching does not necessarily translate into an increase in poaching of rhino, as the cartel faces the probability of capture. In aggregate, and from the owner's perspective, labour, L_τ and poaching, T_τ, are linked in expectation through (1.2).

[15] A transversality condition also applies,

$$lim_{\tau\to\infty} e^{-\rho\tau}\psi_\tau x_\tau = 0$$

where ψ_τ is the undiscounted shadow price of a rhino remaining in the population.

[16] The expectation is based on the cartel's information set at time τ. Given the stochastic process of the population is serially uncorrelated this amounts to knowledge over x_τ and x_0.

[17] $\frac{d\lambda_\tau(s_\tau, x_\tau, K)}{ds_\tau} > 0$ as $\lim_{s_\tau\to\infty} \lambda_\tau(s_\tau, x_\tau, K) = 1$, and as $\lim_{s_\tau\to 0} \lambda_\tau(s_\tau, x_\tau, K) = 0$.

a greater distance, reducing their effectiveness.[18] Finally, it is decreasing in the size of the rhino population, x_τ. As the number of rhino increase, patrols becomes less effective at guarding individual rhino.[19] For clarity, a suitable functional form for the determination of λ_τ might be,

$$\lambda_\tau(s_\tau, x_\tau, K) = \frac{s_\tau}{s_\tau + Kx_\tau} \tag{1.5}$$

In other words, the probability of capture is increasing in anti-poaching patrol spending, per rhino, per square acre. For the remainder of this chapter, $\lambda_\tau(s_\tau, x_\tau, K)$ is denoted λ_τ for brevity.

The Stackelberg Game

The owner and the poaching cartels engage in a strategic, sequential 'game'. The owner is the Stackelberg leader. They act first, determining anti-poaching patrol spending by anticipating the aggregate poaching reaction function to changes in spending. Spending is perfectly observed by the poaching cartels and enters their optimisation problem through the probability of capture, λ_τ.[20] The sequential nature of the game ensures that cartels do not believe that they can affect owner spending. However, the cartels do understand that poaching the marginal rhino today reduces the population of rhino tomorrow, increasing the probability of capture when attempting to poach tomorrow through $\frac{d\lambda_\tau}{dx_\tau}$.

The Strategic Game Between Cartels

The model of strategic interaction between poaching cartels is adapted from Van der Ploeg (1987). When optimising, each cartel understands that choosing to attempt to poach a marginal rhino increases the marginal poaching costs of all rival cartels. This is because

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[18] $\frac{d\lambda_\tau(s_\tau, x_\tau, K)}{dK} < 0$, as $\lim_{K\to\infty} \lambda_\tau(s_\tau, x_\tau, K) = 0$, and as $\lim_{K\to 0} \lambda_\tau(s_\tau, x_\tau, K) = 1$. In reality, increasing K can be achieved without increasing the acreage of the habitat e.g. by installing new waterholes. However, with a goal of intervening with ecological dynamics as little as possible, K is thought of as just the acreage here.

[19] $\frac{d\lambda_\tau(s_\tau, x_\tau, K)}{dx_\tau} < 0$, as $\lim_{x_\tau\to\infty} \lambda_\tau(s, x, K) = 0$, and as $\lim_{x_\tau\to 0} \lambda_\tau(s_\tau, x_\tau, K) = 1$.

[20] This same type of strategic interaction is used in Brown and Layton (2001). They model the market for rhino horn, examining the potential benefits of de-horning rhino and supplying the market with horn to depress poaching. The owners are the Stackelberg leader in the game and anticipate the poacher's reaction to the legal supply of horn in the market.

if the attempt is successful, the population of rhino falls, increasing the marginal cost of poaching. In other words, there is an incentive to poach at a faster rate because the species is becoming more endangered.

Solving the Cartel Problem

The Jacobi-Hamilton-Bellman equation of the cartel's problem with restricted entry, outlined in (1.3), is derived,

$$\rho V^i - \frac{dV^i}{d\tau} = \frac{1}{2}\sigma^2(x_\tau)V^i_{xx} + \max_{l_{i\tau}}\{[(1-\lambda_\tau)p(T_\tau) - \lambda_\tau\chi - c(x_\tau)]\phi l_{i\tau} + (1-l_{i\tau})\bar{w} + V^i_x[g(x_\tau) - T_\tau]\} \quad (1.6)$$

where $V^i(\tau, x_\tau)$ denotes the optimal stream of expected discounted profits accruing to cartel i from τ onwards. The reaction function describing the number of rhino optimally poached for each level of owner spending is found by taking the derivative of (1.6) with respect to the choice of labour allocated to poaching each period, $l_{i\tau}$. Cartels take spending on anti-poaching patrols as given.[21] Taking the derivative and rearranging, the reaction function of the cartel is derived,

$$\begin{aligned} T^*(x_\tau, s_\tau) &= (1-\lambda_\tau)\phi L^*(x_\tau, s_\tau) \\ &= E_\tau\left\{p^{-1}\left[\left(\frac{\eta}{\eta - \frac{1}{N}}\right)\left(\frac{c(x_\tau) + \chi\lambda_\tau + \frac{\bar{w}}{\phi}}{1-\lambda_\tau} + \frac{V_x}{N}\right)\right]\right\} \end{aligned} \quad (1.7)$$

There are two reaction functions here. $T^*(x_\tau, s_\tau)$ is the reaction function for the aggregate poaching rate relevant to the owner's problem. $L^*(x_\tau, s_\tau)$ is the reaction function describing the aggregate amount of labour devoted to poaching by cartels. The probability of capture, and owner patrol spending, $\lambda_\tau = \frac{s_\tau}{s_\tau + Kx_\tau}$, link these two functions. The following is deduced,

1. Poaching is increasing in the rhino population x_τ. Larger rhino populations reduce the marginal cost of poaching $c(x_\tau)$ because rhino are easier to find. In addition, larger populations reduce the effectiveness of patrols by lowering the probability of capture

[21] In addition, whilst each cartel understands that it can affect the poaching costs of other cartels contemporaneously when choosing the number of poaching attempts it undertakes, there is no contemporaneous feedback from poaching to the population when optimising.

for a given level of owner spending. Finally, more rhino means the marginal value of a rhino in the population to the cartel V_x is lower which further increases poaching.

2. Poaching is falling in patrol spending which increases the probability of capture and hence the expected poaching cost of the cartels.

3. Poaching is falling in the reservation wage per effective unit of cartel labour $\frac{\bar{w}}{\phi}$. As the reservation wage rises, the cartel finds it profitable to commit more labour to the reservation activity instead of poaching. As cartel poaching technology improves ϕ each unit of labour can make more poaching attempts and so poaching increases.

4. Poaching is increasing in the price elasticity of demand η and the number of cartels N.[22] Increasing these variables leads to more competition between cartels, lowering mark-ups, and therefore increasing the number of rhino poached. In other words, the ability of an individual cartel to restrict poaching and supply of horn, in order to extract consumer surplus, is diminished. The policy implication of this result is that authorities should work to shut down each cartel individually, instead of a policy of unilateral deterrence across all cartels. By eliminating one of the cartels, the remaining cartels will find it optimal to act in a more conservationist way.[23]

In addition, a modified Hotelling rule for the cartel is derived which the optimal rate of poaching satisfies over time (Hotelling, 1931).[24] Cartels equalise the expected marginal value of a rhino remaining in the population over time. Otherwise, the cartel could increase expected profit by poaching or saving a marginal rhino. The left hand side of the Hotelling rule details the benefit to the cartel of keeping a marginal rhino alive. Therefore, poaching is falling as the components on the left hand side increase. The right hand side details the incentive to poach a marginal rhino. Poaching is increasing as the right hand side increases

[22] It is assumed $\eta N > 1$ otherwise marginal revenue is negative.

[23] This result corroborates that of Damania and Bulte (2007) who examine the implications of Cournot competition between poachers and farmed wildlife products.

[24] This is found by aggregating (1.6) and taking the derivative with respect to the state variable, x_τ.

in magnitude.

$$\frac{E_\tau}{V_x}\frac{dV_x}{d\tau} + g'(x_\tau) + \varpi\frac{d\lambda}{dx_\tau} - \xi c'(x_\tau) = \rho + \delta^p + \underbrace{\vartheta\frac{dT^{j*}}{dx_\tau}(N-1)}_{\text{Strategic Effect}} \tag{1.8}$$

where,

$$\varpi \equiv \frac{\phi L_\tau}{V_x}[V_x - \chi - p(T_\tau)], \quad \xi \equiv \phi\frac{L_\tau}{V_x}, \quad \vartheta \equiv \frac{1}{V_x}\left[(1-\lambda_\tau)p(T_\tau) - \lambda_\tau\chi - c(x_\tau) - \frac{\bar{w}}{\phi}\right]$$

The rate of poaching increases if,

1. The cartel cares less about the future, ρ is higher. In other words, the cartel values profit today more than profit tomorrow.

2. The capital gain of a marginal value of a rhino in the population is lower, $\frac{E_\tau}{V_x}\frac{dV_x}{d\tau}$. This is the shadow value of a rhino in the population.

3. The marginal rhino increases the net growth of the population by a smaller amount, $g'(x_\tau)$. Otherwise, saving the marginal rhino would increase the population available for poaching by more in the future.

4. The marginal rhino increases the marginal cost of poaching by less, $c'(x_\tau)$ (note that $c'(x_\tau) < 0$ so this means $c'(x_\tau)$ becomes less negative). Otherwise, saving the marginal rhino would reduce the poaching costs by more in the future.

5. The marginal rhino increases the future probability of capture by less, $\frac{d\lambda_\tau}{dx_\tau}$. Therefore, the cost of poaching in the future will be lower if the rhino is left in the population.

The strategic effect between cartels leads to faster poaching rates. Each cartel knows that increasing their number of poaching attempts increases the expected cost of poaching for rival cartels as rhino become harder to find. Therefore, as rhino become rarer (x_τ falls) rival cartels should then find it optimal to reduce poaching (T^{j*} falls), so $\frac{dT^{j*}}{dx_\tau} > 0$. In turn, this increases the expected profitability of the original cartel's poaching as fewer horns in aggregate are sold in the market. However, given symmetry in beliefs across cartels, all cartels choose to poach at a faster rate. The strategic effect is increasing in the number of cartels N

indicating that conservation policy should target shutting down the marginal cartel. This will result in a more than proportionate reduction in poaching. The strategic effect is also increasing in the expected marginal profitability of poaching net of the opportunity cost of labour committed to poaching, ϑ.

Despite the risk neutrality of poaching cartels, the stochastic growth of the rhino population still affects the 'optimal' number of poaching attempts over time. Given that the value function for poaching cartels is concave, the derived cartel utility function is risk averse. This is captured by the risk premium $\delta^p \equiv -\sigma(x_\tau)\sigma'(x_\tau)\frac{V_{xx}}{V_x}$. Risk has an ambiguous effect on the optimal rate of poaching:

1. Risk encourages a faster rate of poaching because the variance of the shock is increasing in the size of the rhino population.

2. Risk encourages a faster rate of poaching because it increases the expected poaching costs over time (because $c(x_\tau)$ is convex).

3. Risk reduces the expected rate of growth of the rhino population (because $g'(x_\tau)$ is concave), increasing the rarity of rhino, the growth of rents, and hence reducing the rate of poaching.

The overall effect is ambiguous for a given rhino population. Pindyck (1984) shows that when the elasticity of demand is increased and $g(x_\tau)$ is skewed to the left, stochastic fluctuations increase the rent and the poaching rate.

1.2.3 The Owner Problem

The owner of rhino can invest in anti-poaching patrols s_τ but cannot change the penalty the cartel pays if caught: χ is exogenous.[25] There are two ways to justify this exogeneity.

[25] Previous studies have formulated the owner problem in a number of ways. Bulte and Van Kooten (1999) examine the incentive effects of an ivory trade ban. They model an owner who can invest in anti-poaching enforcement. This raises the cost of poaching for poachers who try to avoid patrols. The probability of capture for poachers is exogenous. Milner-Gulland and Leader-Williams (1992) model the relationship between incentives, detection, and penalties for poaching from an open access population of animals. They

Firstly, the penalty could be a cost to the cartel of having to change operations (if the capture of the poacher leads to the authorities monitoring an area of the cartel's network more closely). Hence, whilst the punishment of the poacher caught by the patrol may be within the control of the owner, the penalty to the cartel is plausibly outside of the owner's remit. Alternatively, given the model examines a population of rhino with single owner, it is unlikely that the owner has influence on criminal law. Furthermore, the fine is unlikely to be returned to the budget of the owner.

The cost of investing in anti-poaching patrols is increasing with the scale of operations and is described by a cost function, $\gamma(s_\tau)$.[26] The owner wants to protect the rhino because they receive a non-consumptive flow of utility, $W(x_\tau)$. This flow of utility is increasing in the size of the rhino population but at a diminishing rate.[27] This benefit is thought to contain the conservation value from maintaining a larger rhino population as well as tourism income that accrues from the population.

The owner chooses anti-poaching patrol spending to maximise the expected present value of this flow of utility discounted at the owner's discount rate β subject to the dynamics of the rhino population. As the Stackelberg leader, the owner anticipates the poacher's reaction function and the 'optimal' choice of labour devoted to poaching from the cartel's problem $L^*(s_\tau, x_\tau)$ enters into the owner problem as 1.7.

$$\max_{s_\tau} J^G(s_\tau, x_\tau) = E_\tau^G \int_{\tau=0}^{\infty} e^{-\beta\tau}[W(x_\tau) - \gamma(s_\tau)]\, d\tau \tag{1.9}$$

$$\text{s.t. } dx = \{g(x_\tau) - T^*(x_\tau, s_\tau)\}d\tau + \sigma(x_\tau)\, dw \tag{1.1}$$

$$T^*(s_\tau, x_\tau) = (1 - \lambda_\tau)\phi L^*(s_\tau, x_\tau) \tag{1.7}$$

find intuitive results: rhino poaching is reduced with patrols, sentencing that increases in severity with the number of animals poached is more effective than a fixed penalty, and the probability of capture is a highly significant factor in the decision to poach.

[26] $\gamma'(s) > 0$, $\gamma''(s) > 0$.

[27] $W'(x) > 0$, $W''(x) < 0$.

where E_τ^G is the expectations operator for the owner.[28] $J^G(s_\tau, x_\tau)$ is convex in s_τ.[29]

Solving the Owner Problem

The Jacobi-Hamilton-Bellman equation for the owner is,

$$\beta V^G - \frac{dV^G}{d\tau} = \frac{1}{2}\sigma^2(x_\tau)V_{xx}^G + \max_{s_\tau}\{[W(x_\tau) - \gamma(s_t)] + V_x^G[g(x_\tau) - T^*(x_\tau, s_\tau)]\} \quad (1.10)$$

where $V^G(\tau, x_\tau)$ denotes the optimal stream of expected discounted utility accruing to the owner from τ onwards. Taking the derivative with respect to anti-poaching patrol spending, s_τ, the optimality condition for spending is found,

$$\gamma'(s_\tau^*) = E_\tau^G\left\{-V_x^G\frac{dT^*(x_\tau, s_\tau^*)}{ds_\tau^*}\right\} \quad (1.11)$$

where the optimal level of spending is denoted s_τ^*. It is chosen so the marginal cost of spending equals the expected marginal benefit. The expected marginal benefit is calculated as the number of rhino saved by increasing spending by a marginal amount, $-\frac{dT^*(x_\tau, s_\tau)}{ds_\tau} > 0$, multiplied by the shadow value of a marginal rhino in the population to the owner, V_x^G. The number of rhino saved by increasing spending by a marginal amount depends on how responsive aggregate poaching T^* is to patrol spending s_τ. Optimal spending is increasing in this responsiveness and the shadow value of a rhino to the owner.

In addition, a modified Hotelling rule for the owner is derived which optimal spending satisfies over time.[30] The owner invests in anti-poaching patrols to equalise the expected marginal value of a rhino remaining in the population over time. As before, the left hand side of the Hotelling rule describes the incentives facing the owner to save the marginal

[28] The expectation is based on the owner's information set at time τ. Given the stochastic process of the population is serially uncorrelated this amounts to knowledge over x_τ and x_0.

[29] A transversality condition also applies,

$$lim_{\tau\to\infty}e^{-\beta\tau}\psi(\tau) = 0$$

where $\psi(\tau)$ is the undiscounted shadow price of a rhino remaining in the population.

[30] This is found by differentiating (1.10) with respect to the rhino population, x_t and rearranging.

rhino. Spending is increasing in the magnitude of these variables. The right hand side details the incentive to not save the marginal rhino. Spending is falling in the magnitude of these variables.

$$\frac{E_\tau^G}{V_x^G}\frac{dV_x^G}{d\tau} + g'(x_\tau) + \frac{W'(x_\tau)}{V_x^G} = \beta + \delta^G + \frac{dT^*(x_\tau, s_\tau)}{dx_\tau} \tag{1.12}$$

The owner is incentivised to spend more on anti-poaching patrols today if,

1. The increase in aggregate poaching from saving a marginal rhino is smaller, $\frac{dT^*}{dx_\tau}$. In other words, because saving a marginal rhino reduces future poaching costs, future poaching will increase. If this increase is relatively small, the owner is more likely to save the rhino.

2. The increase in the population growth rate from saving a marginal rhino is larger, $g'(x_\tau)$. Therefore, each rhino saved grows into more rhino in the future.

3. The expected capital gain of holding a rhino in the population is larger, $\frac{E_\tau^G}{V_x^G}\frac{dV_x^G}{d\tau}$. In other words, the shadow value of a rhino is high to the owner.

4. The marginal utility of a rhino to the owner is higher, $W'(x_\tau)$. Therefore, the marginal saved rhino is worth more to the owner.

5. The owner discounts the future less, so β is lower. In other words, as the owner becomes more patient, they work to save more rhino as the discounted future utility of those rhino is higher.

Risk enters the owner problem, despite the owner being a risk-neutral agent, through a risk premium factor $\delta^G \equiv -\sigma(x_\tau)\sigma'(x_\tau)\frac{V_{xx}^G}{V_x^G}$. Analogously to before, this is because the derived value function of the owner is concave. The effect of risk is ambiguous,

1. Population shocks increase with the rhino population size, incentivising the owner to maintain a smaller population of rhino.

2. However, the concavity of $g'(x_\tau)$ and $W'(x_\tau)$ means, through Jensen's inequality, that risk reduces the expected net growth rate of the population and the marginal utility from holding rhino, incentivising the owner to increase the population size.

1.2.4 Equilibrium

Equilibrium in the model is solved using numerical methods. Here, the poaching cartels are in a closed-loop Nash Equilibrium. This is defined such that the cartel's choice of poaching attempts is 'optimal' given their information set in the period. Crucially, this includes all past play of other cartels and it is through this belief that the strategic effect occurs.[31] In addition, the cartels are in stationary feedback Stackelberg Equilibrium with the owner. This means the number of poaching attempts made is optimal given the patrol spending choice by the owner, and vice versa. Equilibrium on the consumer side is ensured as the demand function can be thought to be derived from a utility maximisation problem. Given cartels are price takers and there is no storage, the market clears.

Equations for 'optimal' poaching (1.7), the cartel's Hotelling rule describing 'optimal' poaching attempts over time (1.8), optimal patrol spending (1.11), and the owner's Hotelling rule describing optimal spending over time (1.12), the model can be solved for the four variables, $V(\tau, x_\tau)$, $V^G(\tau, x_\tau)$, s^*_τ, and $l^*_{i\tau}$. An initial population of rhino, $x_{\tau=0}$, can then be used to trace the dynamics of the population, x_τ. An analytical solution is not possible, hence numerical solution methods must be used. For simplicity, stochastic fluctuations in the population growth rate are dropped for the numerical simulation.[32]

An exact calibration to the rhino poaching situation in the Kruger National Park (KNP) is difficult because of the lack of available data. However, a rough calibration may be possible. The choice of parameters and functional forms are summarised in Table 1.1. Further details of the solution method, chosen functional forms, and calibrated parameters can be found in Appendix I.

[31] See Fudenberg and Levine (1988) for a more formal exposition.

[32] As discussed, the impact of risk on both the poacher's and owner's optimal strategy is ambiguous. By not including risk, the only difference will be a lack of curvature in each agent's value function which may increase or decrease the poaching and spending strategies.

Variable/Function	Parameter/Functional form	Value adopted
$g(x_\tau) = rx_\tau(1-(x_\tau/K)^z)$	Population growth	$r = 0.09$, $z = 7$
K	Carrying capacity of land	$K = 12,000$
χ	Penalty if the cartel is caught	$\chi = 120,000$
η	Elasticity of demand	$\eta = 1.2$
N	Number of cartels	Depends on competition type
ρ	Cartel discount factor (no longer discount rate)	$\rho = 0.5$
β	Owner discount factor (no longer discount rate)	$\beta = 0.8$
$W(x_\tau) = ax_\tau^b$	Owner benefit from rhino population	$a = 290,000$, $b = 0.9$
$\gamma(s_\tau) = s_\tau^c$	Owner cost of anti-poaching patrol spending	$c = 1.2$
$p(T_\tau) = qT_\tau^{-1/\eta}$	Demand curve	$q = 3,000,000$
$c(x_\tau) = d/x_\tau$	Cost of poaching for cartels	$d = 9,000,000$
$\lambda_\tau(x_\tau, s_\tau) = \frac{s_\tau}{s_\tau + Kx_\tau}$	Probability of capture	Endogenous
ϕ	Poaching technology	$\phi = 100$
$\bar{w}$	Reservation wage	$\bar{w} = 100,000$

Table 1.1: Calibration values adopted. Further details are provided in Appendix I

1.3 Results

To begin, the results from an open access equilibrium are examined to identify optimal owner policy and the effect of patrols. The open access equilibrium is used for simplicity. Then, the case of a monopoly cartel is examined to understand the consequences of market power. Lastly, the case of a duopoly, with and without the strategic effect, is presented.

1.3.1 Open Access Equilibrium

Begin by examining the open access case. This is a special case of the model in this chapter where poaching cartels enter the market until profits are zero. Hence, the 'optimal' number of rhino poached by the cartels in each period is given by,

$$\begin{aligned} T^{OA}(x_\tau, s_\tau) &= (1-\lambda_\tau)\phi L^{OA}(x_\tau, s_\tau) \\ &= E_\tau \left\{ p^{-1} \left[\frac{c(x_\tau) + \lambda_\tau \chi + \frac{\bar{w}}{\phi}}{1-\lambda_\tau} \right] \right\} \end{aligned} \tag{1.13}$$

In other words, this is the point where the expected profit of devoting a marginal unit of

effective labour to poaching equals the reservation wage, $\frac{\bar{w}}{\phi}$. Assuming each cartel devotes all of its labour to poaching, the number of cartels operating is found to be proportional to the 'optimal' number of poaching attempts. The number of cartels could be endogenised, particularly when market power is introduced. However, this is not the focus here.[33]

No Patrols

For comparison, a case where the owner is unable to invest in anti-poaching patrols to protect an open access population is analysed. This corresponds to when $\lambda_\tau = 0$. With no patrols, extinction occurs, $x_{ss}^{OA'} = 0$.[34] The number of rhino 'optimally' poached by cartels is roughly a linear function of the existing rhino population and is shown in Figure 1.1.

Patrols

Now, the owner is allowed to protect the rhino by investing in patrols. The population converges to a much higher steady state of $x_{ss}^{OA} = 8696$ rhino. 'Optimal' poaching remains a relatively linear function of the population level, as shown in Figure 1.1. On average, aggregate poaching is 11% of the rhino population.[35] Each cartel is indifferent between the open access equilibrium with patrols x_{ss}^{OA} and without patrols $x_{ss}^{OA'}$ as the open access condition forces the expected profit per unit labour to the reservation wage. However, the owner's net benefit decreases 100% when they cannot use patrols to defend their rhino. The 'optimal' number of poaching attempts falls at every population level relative to the case of no patrols.

Optimal spending rises then falls as the population falls, as shown in Figure 1.2. At high population levels, the marginal rhino is worth relatively little to the owner, and therefore

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[33] The number of cartels can be solved for,

$$N^{OA} = \frac{T^{OA}}{(1-\lambda_\tau)\phi}$$

[34] A steady state population of zero is impossible in this model because of the functional forms adopted which prohibit poaching as $x \to 0$. Hence, it is only possible to conclude that extinction approximately occurs. In reality, with any minimum viable population requirement, this would be true of these population sizes.

[35] In the KNP in 2015, 13% of the rhino population was poached.

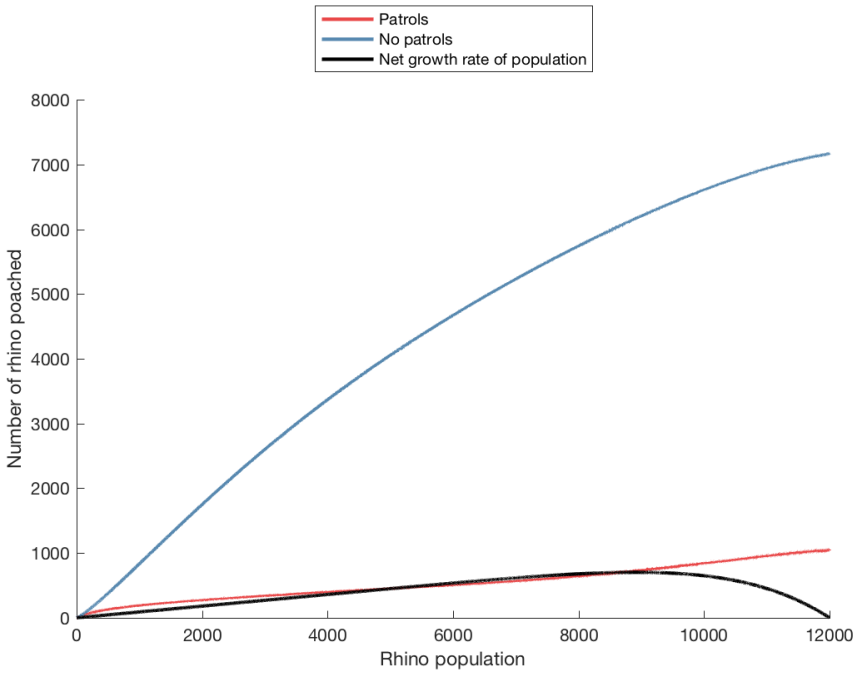


Figure 1.1: Simulated 'optimal' poaching with an open access population of rhino. Steady state occurs when the net growth rate of the population equals the number of rhino poached.

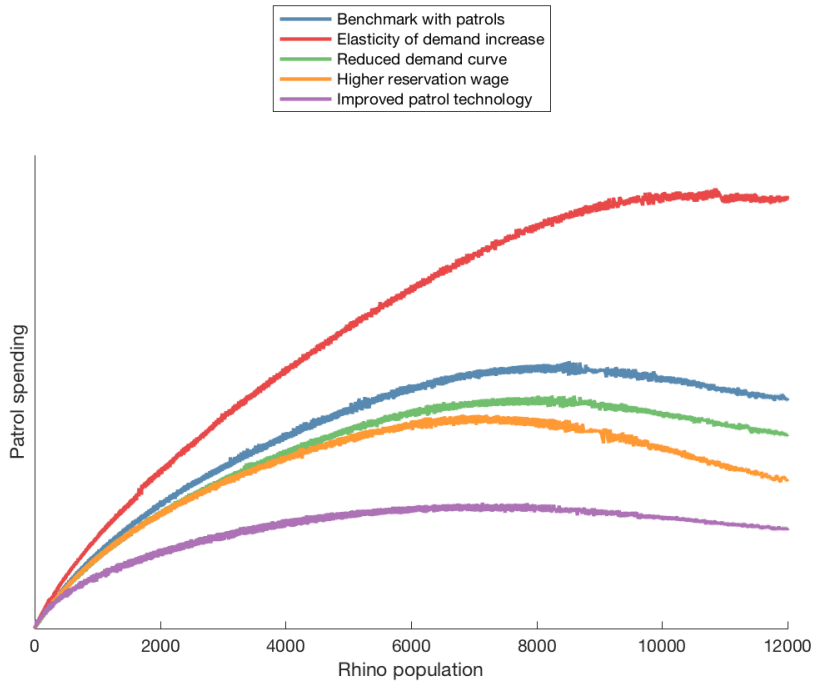


Figure 1.2: Simulated optimal spending on anti-poaching patrols by the owner across various rhino population sizes. Optimal spending rises then falls as the population falls. At high population levels, the marginal rhino is worth relatively little to the owner, and therefore spending is low. However, as the population falls, the marginal rhino becomes more valuable and so the owner fights harder to protect it. At low populations, the utility from the population is too low to justify high spending on patrols.

spending is low. However, as the population falls, the marginal rhino becomes more valuable and so the owner fights harder to protect it. Hence, spending rises. At low populations, the utility from the population, $W(x_\tau)$, is too low relative to the cost of patrols, $\gamma(s_\tau)$ to justify high spending.

Varying the Penalty if Caught

As χ increases, the net owner benefit and steady state rhino population increase. Increasing the penalty means that patrols are a more effective deterrent to poachers. Examining Figure 1.3, it is clear that the 'optimal' poaching attempt schedule is falling in χ as expected costs rise.

Figure 1.4 shows how the optimal owner spending schedule varies with χ. There are two things to observe.

1. Optimal spending still rises and then falls with the rhino population. However, as χ increases, the peak of this parabola occurs at a lower population level. This is because the marginal effect of increased spending on poaching is greater when the penalty is higher: patrols are more of a deterrent. Thus, the point at which the marginal benefit of increased spending on patrols is offset by the rising marginal cost of patrols occurs at a lower population level.

2. The amount of spending on patrols is falling in the penalty. This is because spending is costly and the same level of spending is more effective with higher χ.

1.3.2 Restricted Access Equilibrium

With barriers to entry, the poaching cartel becomes forward looking, discounting the future at a rate $\rho = 0.5$. It therefore has a value function which needs to be numerically solved in conjunction with the owner value function. The cartel now earns profits unlike the case of an open access resource. The degree of competition dictates cartel behaviour and the extent of these profits.

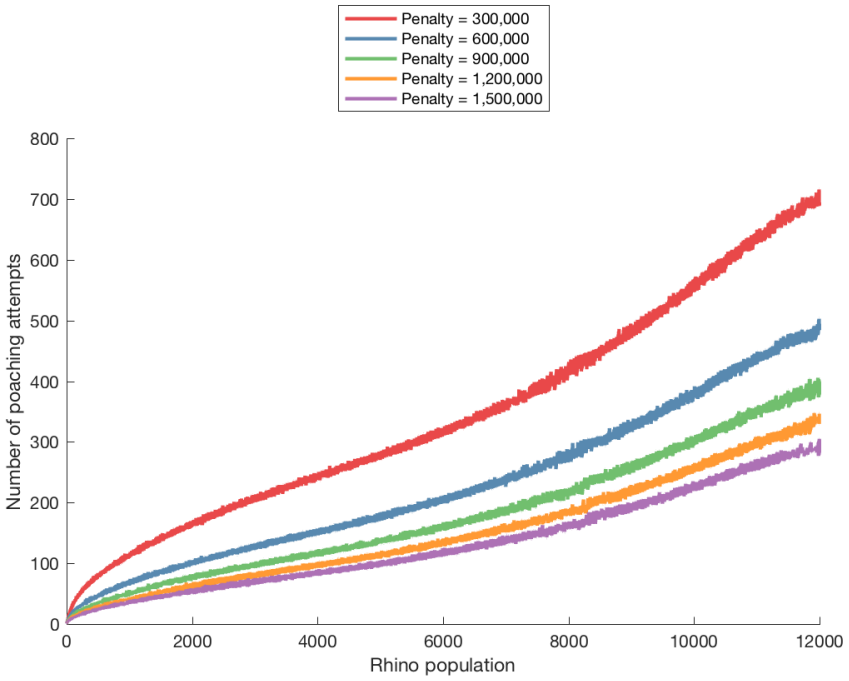


Figure 1.3: Simulated 'optimal' number of rhino poaching attempts across varying penalties, χ. The 'optimal' poaching attempt schedule is falling in χ as expected costs rise for poachers.

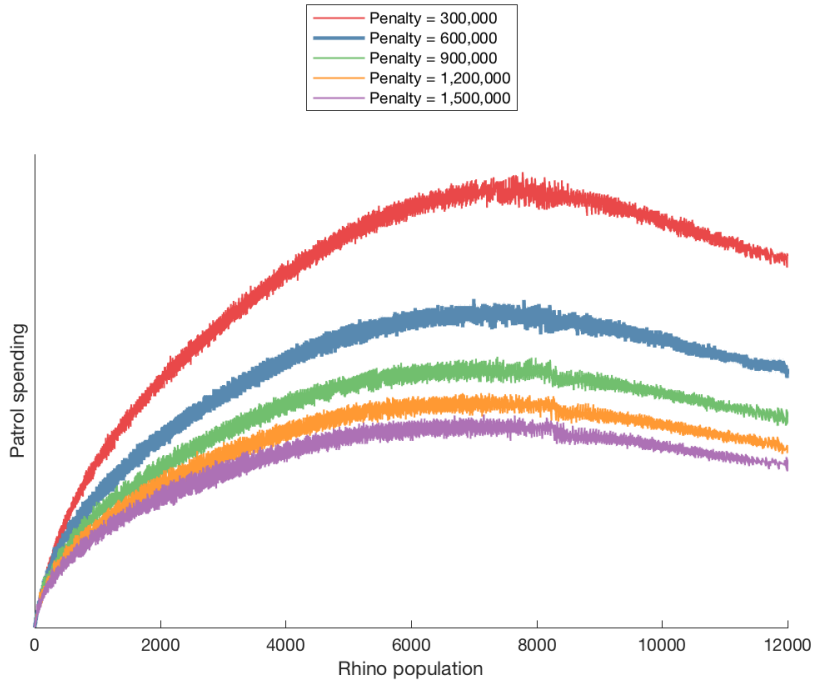


Figure 1.4: Simulated optimal anti-poaching patrol spending across varying penalties, χ. Increasing the penalty means that patrols are a more effective deterrent to poachers and thus spending is lower.

Monopoly

It is interesting to compare the case of an open access population of rhino to the case where only a single cartel has access to poach. The 'optimal' number of rhino poaching attempts by the cartel in each period is given by (1.7) but where $N = 1$.[36]

$$\begin{aligned} T^M(x_\tau, s_\tau) &= (1-\lambda_\tau)\phi L^M(x_\tau, s_\tau) \\ &= E_\tau \left\{ p^{-1} \left[\left(\frac{\eta}{\eta - 1} \right) \left(\frac{c(x_\tau) + \lambda_\tau \chi + \frac{\bar{w}}{\phi}}{1-\lambda_\tau} + V_x \right) \right] \right\} \end{aligned} \tag{1.14}$$

The model is simulated. The optimal spending schedule for the owner shifts downwards but remains unchanged in shape. Optimal spending still rises and then falls with the rhino population. Meanwhile, the 'optimal' number of poaching attempts made by the cartel falls drastically (but remains roughly linear in the rhino population). The result of Stiglitz (1976) is confirmed, even with owner intervention. The monopoly works to extract consumer surplus by restricting supply to the illicit market. Hence, a monopoly cartel is superior to open access competition for conservation.

The results of the population simulation are shown in Figure 1.5. The population converges to a much higher steady state x_{ss}^M. Reducing the poacher's discount factor to $\rho = 0.3$ does little to weaken this result. Only 3% of the rhino population are poached in each time period at the steady state. The owner net benefit is unsurprisingly higher at x_{ss}^M than x_{ss}^{OA} (by 59%). Now the cartel makes 19.1% more profit per unit of labour than the reservation wage.

Duopoly

The case of a duopoly is examined.[37] To begin, an open-loop Nash Equilibrium is considered. This is standard Cournot competition and there is no strategic effect between cartels.

[36] To add interest, the monopoly is assumed to have a sufficiently high labour endowment so that it is not constrained to only attempt to poach ϕ rhino in each time period.

[37] Similar to the case of the monopoly, each cartel is assumed to have a sufficiently high labour endowment so that it is not constrained to only attempt to poach ϕ rhino in each time period.

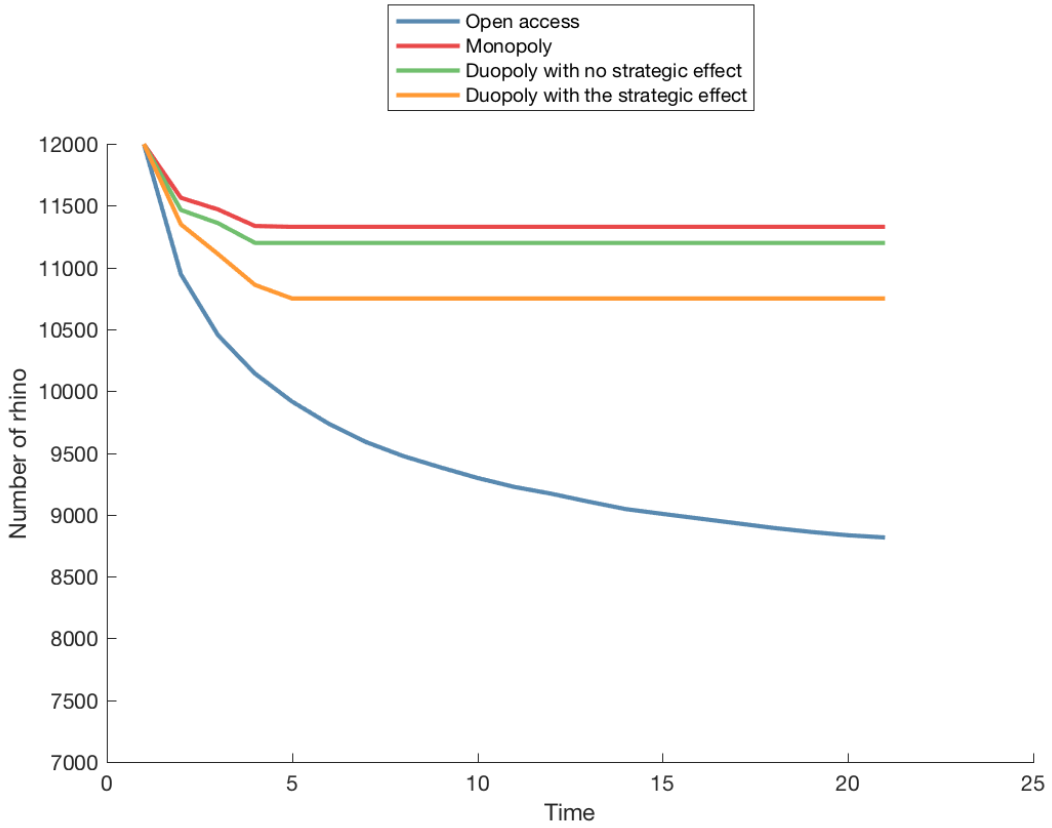


Figure 1.5: Rhino population simulation across varying forms of cartel competition ($x_0 = K$). The steady state population is falling in the degree of competition between cartels. The strategic effect's impact on the rhino population steady state is significant. The closed-loop Nash Equilibrium steady state population is 4% lower than its open-loop counterpart. Given the computational requirements, the policy and value functions for the owner and poaching cartels were solved on a sparser state matrix and then interpolated and smoothed to produce these results.

As is to be expected, poaching increases relative to the case of the monopoly but is much less than the open access case. Owner spending continues to rise and fall with the rhino population and lies between spending with a monopoly and with open access. The steady state population falls relative to the case of a monopoly by 1.1%.

Now consider a closed-loop Nash Equilibrium 'game' with a strategic effect between the two cartels, whose optimal behaviour is dictated by (1.7). This strategic effect works to increase the 'optimal' number of poaching attempts for both cartels.

The strategic effect's impact on the rhino population steady state is significant. The closed-loop Nash Equilibrium steady state population is 4% lower than its open-loop counterpart. Surprisingly, it is not the rise in poaching attempts made by cartels which is the primary driver of this result. Instead, optimal owner spending on patrols is significantly lower than the open-loop Nash Equilibrium case, and this results in more successful poaching attempts. Despite lower spending, owner benefit falls at the steady state relative to the open-loop and monopoly cases.

The owner optimally spends less because patrol spending increases the size of the strategic effect. The effect stems from the cartel understanding that increasing poaching will make rhino rarer and therefore make it more costly for other cartels to poach. Patrol effectiveness is also increased for a given level of spending when there are fewer rhino. Therefore the amount of patrol spending strengthens the strategic effect by raising the competing cartel's costs by more. Hence, perversely, spending works to increase the incentive to poach through the strategic effect.

Summary

A number of conclusions for conservation policy are drawn:

1. Increasing poaching cartel competition is bad for conservation. The steady state population of rhino falls with increasing competition. As such, conservation policy should attempt to shut down the marginal cartel rather than strive for unilateral deterrence

to poachers. This will result in a more than proportionate reduction in poaching.

2. The strategic effect is significant. Anticipated future scarcity of rhino works to increase the current number of poaching attempts. This results in a significantly lower steady state population of rhino relative to the case with no strategic effect. Whilst more complicated, future research should incorporate the strategic effect into poaching models with market power so as to capture this dynamic. Otherwise model conclusions for the outlook of the species will be too optimistic.

3. The strategic effect has surprising consequences for optimal owner behaviour. Counter-intuitively, owner spending on patrols should fall because patrol spending works to increase the strategic effect between cartels.

Unfortunately, as N becomes larger, the curse of dimensionality becomes an issue when simulating the model and therefore only the duopoly case is considered here. However, the results directly extend to $N > 2$ cartels.

1.4 Conservation Policy

The model is now used to evaluate possible conservation policies. This analysis will serve as a robustness check to the choice of model parameter values in the calibration. For simplicity, this is completed with the open access model but the results directly apply to the other forms of competition between poachers. The only thing not examinable using the open access case is the impact on poaching profits, as these are tied to the reservation wage. For each of the policies, changes in the optimal spending strategy are displayed in Figure 1.2. Changes in the 'optimal' poaching strategy for cartels are shown in Figure 1.7. Population simulations and steady states are displayed in Figure 1.6. A summary of results across specifications is found in Appendix II.

1.4.1 Community Projects

Involving local communities in conservation is an important policy tool, particularly for smaller reserves. Projects, such as CAMPFIRE in Zimbabwe, that direct revenues from

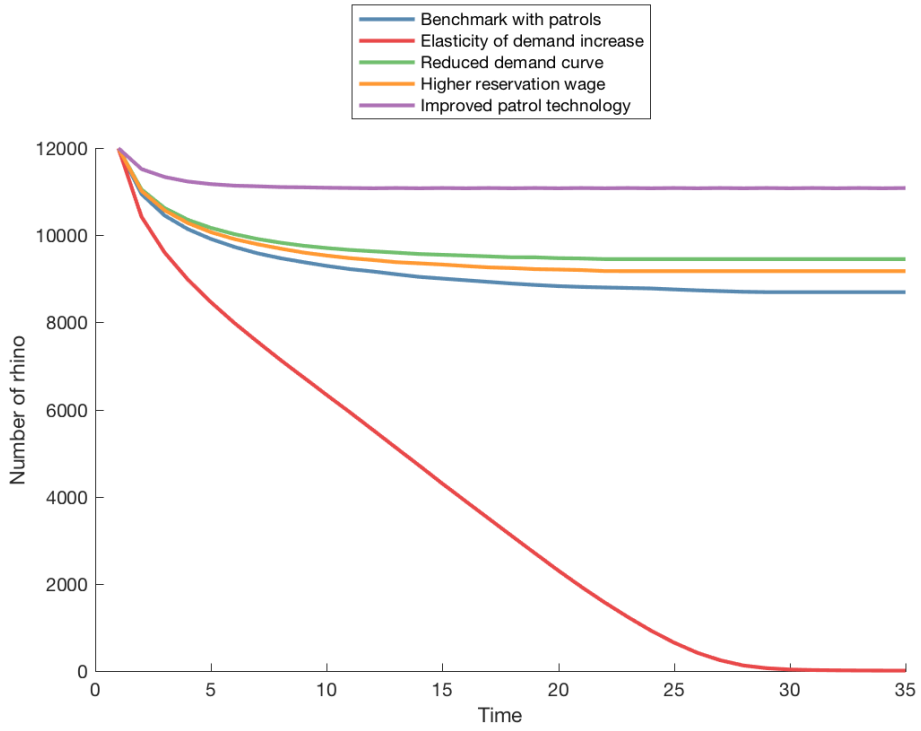


Figure 1.6: Rhino population simulations showing convergence to a steady state with varying parameters ($x_0 = K$).

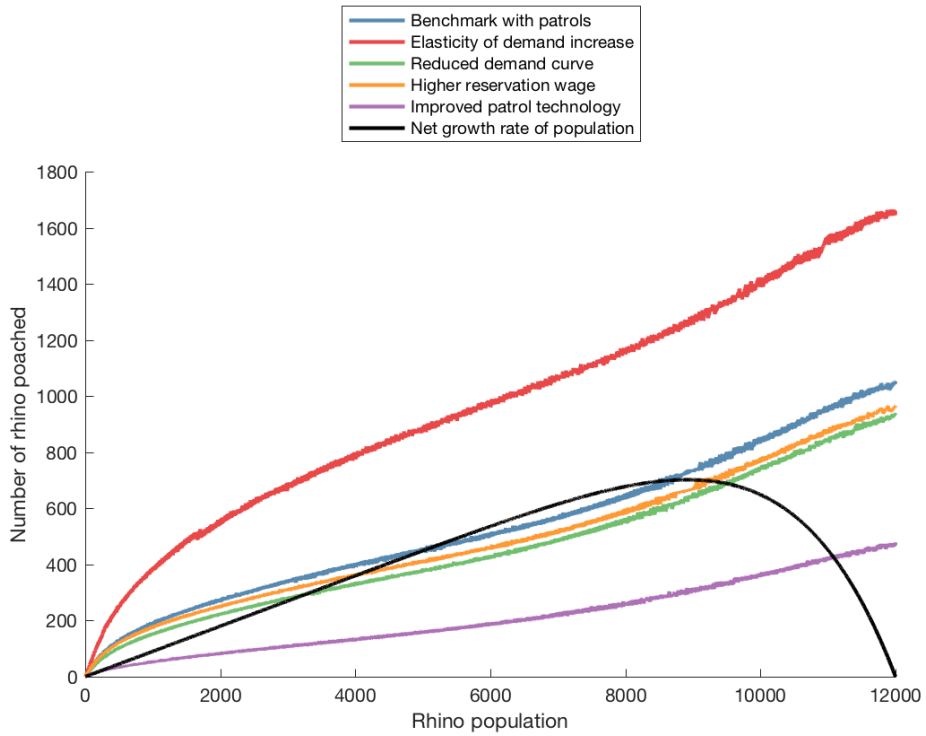


Figure 1.7: Simulated 'optimal' rhino poaching by cartels in an open access population of rhino with varying parameters. Steady state occurs when the net growth rate of the population equals the number of rhino poached.

tourism to local communities in return for wildlife protection, have proven to be a success (Fischer et al., 2011).[38] These funds can be conditioned on the number of rhino poached from the population in a given period of time. Hence, local people have an incentive to conserve the resource. Assuming cartels originate in these communities, the redistribution of funds can be thought to increase the reservation wage, $\bar{w_c} > \bar{w}$.

The model is simulated with $\bar{w_c} = 400,000$. The rise in the reservation wage reduces poaching incentives for every population level. Thus, the steady state population of rhino is 5.5% higher. The optimal spending schedule for the owner shifts downwards and spending falls at the steady state. This is because the 'optimal' number of poaching attempts falls, and thus the owner does not need to defend the population as fiercely. Hence, the owner benefit increases by 16%. Cartel profit per unit of labour rises to the new reservation wage.

Thus, there is credence to the policy of raising local incomes and reservation wages through community projects. However, this is impractical in larger communities surrounding larger reserves. In the case of the KNP it is also difficult because communities lie on the Mozambique border with the park, so funds would have to be transferred internationally. Furthermore, it does not account for moral hazard problems from poachers in these communities or general equilibrium effects of encouraging migration to these areas.

1.4.2 Demand Reduction Strategies

Historically, demand reduction strategies have worked for rhino horn. Milliken and Shaw (2012) note that South Korea, Yemen, and Japan all consumed rhino horn in the late 20th century but no longer significantly demand horn. Unfortunately, the current consumer market in Vietnam and China is poorly understood. This is because the trade is illicit and the data that exist, especially price data, are guarded closely for fear of incentivising further poaching. Published research is largely limited to interview evidence and reports from

[38] Similar projects exist in Kenya with the Maasai (ZSL, 2016), India (Save the Rhino, 2016), and Indonesia (Save the Rhino, 2016).

seizures.[39] Milner-Gulland (1993) uses pre-ban data but it is unclear how relevant these conclusions remain. For ivory, demand reduction strategies are more complex, given the legal trade in antique ivory. However, consumption of ivory is often for decorative pieces and not medicinal belief so the prospect of finding a substitute for ivory is promising. For example, Boyce and Farah (2015) suggest that mammoth ivory could be used as a substitute for elephant ivory and can therefore alleviate poaching.

There are two main types of demand reduction strategy. Education programmes (e.g. explaining that rhino horn has no medicinal benefits) directly shift the demand curve for rhino horn inwards. Alternatively, providing substitute goods (e.g. synthetic horn) increases the price elasticity of demand. In reality, these two effects happen simultaneously. However, to decompose the relevant effects, each are analysed separated.

Increasing the Demand Elasticity

The model is simulated with an increased demand elasticity of $\eta = 1.4$. Price is now less responsive to the quantity sold and hence poachers will sell more each period to maximise profits. In other words, the mark-up over costs is smaller for the cartel. The 'optimal' number of poaching attempts by cartels increases at all population levels. In response, the owner finds it optimal to defend the rhino more fiercely, and so spending on patrols rises. Whilst the shape of the schedule remains an inverse parabola, the peak shifts to a higher population level. This is because, for the same flow of utility, the cost of maintaining any population level rises. Hence, the point where increasing spending costs begin to crowd out net utility occurs at a higher population level.

Due to this, the population becomes approximately extinct. Owner net benefit falls 99% at the steady state. From this perspective alone, the quest to find substitute goods may harm the conservation effort. However, substitute goods also lead to a shift in the demand curve and this is examined now.

[39]The most comprehensive study on the rise in contemporary demand is by Milliken and Shaw (2012) .

Inwards Shift in Demand

The model is simulated with a reduced (by 20%) demand curve, $q = 2,400,000$, but the same original elasticity of demand, $\eta = 1.2$. The 'optimal' number of poaching attempts falls, as does optimal owner spending in the face of weaker poaching incentives. The shape of these schedules remains unaffected. Hence, the steady state population of rhino increases by 8.7% and owner net benefit at the steady state rises by 16%. Therefore, for a substitute good for horn to aid rhino conservation, the effects of the inwards shift in demand for horn need to outweigh the effects of increasing the demand elasticity.

1.4.3 Habitat Loss

Habitat loss is the second largest threat to rhino after poaching, and can occur because the security costs of protecting rhino are prohibitively high. The effects of an exogenous reduction in the habitat size to $K = 8000$ are examined. The shape of both the 'optimal' poaching attempts schedule and the optimal owner spending schedule remain largely unchanged. The steady state is lower because the habitat supports fewer rhino. However, the population at the steady state relative to the carrying capacity is 5 percentage points larger than before. Furthermore, the poaching rate at the steady state falls from 8.07% to 7.52% and the owner benefit per rhino increases by 8%.

As the carrying capacity falls, patrols become more effective as they guard a smaller area. Hence, optimal spending on patrols per rhino increases and the probability of capture rises 3 percentage points. The owner benefits from guarding a smaller population of rhino. This suggests that conserving multiple smaller populations of rhino might be more efficient than guarding larger habitats.[40]

[40]This ignores any ecological effects on other species which often share the same habitat. This result is also reliant on the assumption over patrol spending technology. If owners can benefit from increasing returns to scale when providing patrols, this may no longer be true.

1.4.4 Improved Patrol Technology

In the face of rising poaching threats, owners have invested in technology to improve the effectiveness of patrols. Drone technology, training, and improved equipment all work to increase the effectiveness of patrols for the same level of spending. To reflect this, the specification for the probability of capture is augmented with a technology parameter, ω,

$$\lambda_\tau(s_\tau, x_\tau, K) = \frac{\omega s_\tau}{\omega s_\tau + K x_\tau} \tag{1.15}$$

The model is simulated with $\omega = 5$. The rhino population converges to a higher steady state. Given patrols are more effective, the owner optimally chooses to spend less. Furthermore, the spending schedule peak occurs at a much lower population level. This is because the owner can afford to protect the marginal rhino for longer (because spending is more effective) before the marginal cost of patrols outweighs the marginal benefit. The 'optimal' poaching schedule for cartels shifts downwards as the probability of capture, and hence expected cost of poaching rises.

1.5 Conclusion

A key characteristic of the rapid increase in poaching since 2008 has been the development of market power by the criminal cartels orchestrating the operation. This has important consequences for owners defending their rhino using patrols. This chapter has examined these implications and how the owner should optimally protect their resource.

Optimal spending on patrols is found to rise and then fall with the rhino population. A higher steady state rhino population was maintained compared to the case where the owner was unable to invest in patrols. This steady state was falling in the degree of competition amongst poachers. Therefore, conservation policy should attempt to shut down the marginal cartel rather than strive for unilateral deterrence to poachers. This will result in a more than proportionate reduction in poaching.

The strategic effect is significant in magnitude. Anticipated future scarcity of rhino works to increase the current number of poaching attempts resulting in fewer rhino at the steady state. The strategic effect has surprising consequences for optimal owner behaviour. Owner spending on patrols falls because perversely, patrol spending works to increase the strategic effect between cartels. The importance for owners to understand the industrial organisation of poachers facing them is paramount in designing optimal policy.

The main qualification to these results is that, in this chapter, rhino horn was not considered a storable commodity. In reality, large stockpiles of rhino horn are maintained by owners and it has been argued that these could be used to lower prices and incentives to poach. Furthermore, there is evidence that private speculative stockpiles already exist in illicit markets which may work to undermine this mechanism. In any case, storing rhino horn has further consequences for optimal spending on patrols and for poacher behaviour. These will be examined in Chapter Two.

1.6 Appendix I

1.6.1 Numerical Solution

Discretisation

In order to simulate the model numerically, a discretisation must be made. The timeline of events occurring each time period (thought of as a year) is as follows. At the start of each period there are x_{t-1} rhino. The rhino population immediately grows by $g(x_{\tau-1})$ to x_{τ}^{max}. Then owner spending is chosen, s^*, which determines the probability of capture for poachers, $\lambda_{\tau}(x_{\tau}^{max}, s^*, K)$. Poachers then choose how much labour to commit to poaching, $l_{i\tau}^*$. This determines the poaching rate, $T^* = (1 - \lambda_{\tau}(x_{\tau}^{max}, s^*, K))\phi L^*$. The remaining population of rhino is determined using the state transition rule, $x_{\tau+1} = x_{\tau}^{max} - T^*$. The owner gets a contemporary benefit from the remaining rhino, $W(x_{\tau+1})$, and these rhino constitute the starting population in the next time period.[41]

Discretisation Error

Discretisation error enters into the simulation procedure in four ways.

1. Scaling in the population.
2. Rounding of poaching options to the nearest rhino.
3. The grid of spending nodes over which the owner optimises.
4. Rounding after growth to the appropriate value function node.

All of these discretisation errors create volatility in the optimal behaviour schedules derived. Errors are particularly prevalent during models of monopoly and duopoly cartel behaviour, as solving the cartel's value function requires additional discretisation. For the most part, these errors are ignored and results are reported with the errors included. When smoothing has been used to display the results, this was reported alongside the relevant data.

[41] This is an odd sequence of events which may contradict the algebra in the continuous time model, particularly with respect to when growth in the rhino population occurs. However, in solving the model numerically these assumptions simplify the process and reduce rounding errors considerably.

Calibration

An exact calibration to the rhino poaching situation in the Kruger National Park (KNP) is difficult because of the lack of available data. However, a rough calibration may be possible. The choice of parameters and functional forms are summarised in Table 1.1.

In the case of rhino, a logistic functional form for $g(x_\tau)$ is used, where r is the intrinsic growth rate of the rhino population.[42] z is a parameter determining the density dependent response: growth is not symmetric around 50% of the carrying capacity. This implies population dynamics without poaching of the form shown in Figure 1.1. A value of $r = 0.09$ and $z = 7$ is chosen for the intrinsic growth rate and density dependent response respectively. This corresponds to a maximum growth rate occurring at approximately 75% of the carrying capacity of the habitat and is supported by ecological studies (Emslie and Brooks, 1999; and Owen-Smith, 1988).

Currently, the KNP contains around 9000 rhino but the carrying capacity is thought to be much larger with space for another 2500 black rhino (Department of Environmental Affairs, 2018). Hence, a carrying capacity of $K = 12,000$ rhino is chosen. The penalty if caught is set to the fine for poaching a rhino in South Africa, \$120,000. It is recognised that the penalty for poaching may be much higher with jail time or even loss of life. However, given this model considers the decisions of the cartel and not the individual poacher, it is argued that the relevant punishment is the monetary fine in this case.

Discount factors are subjective and difficult to measure. The relevant owner here is the South African government and not an investor with profit motives. Indeed, the majority of the benefit accruing to the government from rhino is tourism income and existence value. In this sense, the owner is a social planner who should look forward and conserve the resource on behalf of future generations. Hence, a relatively high discount factor of $\beta = 0.8$ is

[42]This corresponds to $r = br - dr$, where br is the birth rate and dr the death rate.

adopted. Poachers are likely to discount the future more heavily. The cartels who poach in South Africa are international syndicates involved in numerous illicit activities. Given this, they are unlikely to be patient with profits accruing from rhino poaching. The discount factor adopted for poachers is $\rho = 0.5$.

The value of a rhino to the owner can be estimated. The sale of a single live rhino to a zoo or another reserve fetches around $29,000 (Shange, 2015). However, trophy hunts for rhino can fetch around $290,000 at auction. Thus, the figure of $a = 290,000$ is adopted. The parameter b explains how the owner values the marginal rhino. It is clear that $b < 1$ as the value of rhino increase with their rarity. Hence, the model is calibrated with $b = 0.9$.

The cost of increasing anti-poaching patrols is hard to observe as the data on patrols and expenditure is guarded closely. It would be expected that increasing patrols becomes increasingly more expensive for the owner and so $c > 1$. However, given the abundance of cheap labour in surrounding communities, it is expected that the cost will not be increasing quickly. Hence, a value of $c = 1.2$ is adopted.

The elasticity of demand is particularly difficult to determine. Given the lack of substitutes for rhino horn, it is widely accepted that the demand for horn is inelastic. However, this model examines the poaching of rhino from a single population. Given that there are multiple populations of rhino which could be poached from, the demand curve facing cartels poaching from this population is likely to be more elastic. Hence, an initial price elasticity of demand for rhino horn of $\eta = 1.2$ is adopted. q is found by solving the demand curve for the price/poaching pairing currently observed in the KNP. There were approximately 1300 rhino poached in 2016 and rhino horn conservatively sells for $30,000/kg. Hence, given the average horn is 3kg and assuming rhino are assumed to be homogenous, the demand curve can be solved to find $q = 3,000,000$. The cost of poaching parameter, d, is found by calculating a 10% margin between poaching cartel revenue and costs at the current price/quantity pairing. This results in $d = 9,000,000$. It is recognised that as the rhino population approaches zero, it is unlikely that this cost is realistic.

ϕ is virtually impossible to observe. However, given the difficulty in poaching rhino, a value of $\phi = 100$ is used. This means that the poaching cartel can attempt to poach 100 rhino in each time period (thought of as a year). The reservation wage is calibrated to the ivory market. The average sized tusk fetches around \$50,000 on the illicit market (Martin and Vigne, 2015). Given each elephant has two tusks, applying the same profit margin of 10% and the same technology of ϕ, a reservation wage of $\bar{w} = 100,000$ is used.

1.7 Appendix II

1.7.1 Summary of Results

Specification	**Population**	**Poaching (% of x_{ss})**	λ_{ss}	**Owner net benefit (% change from baseline case)**	
				Total	**Per rhino**
No Patrols	0	0%	0%	-100%	228%
Patrols (baseline case)	8,696	8.07%	8%	0%	0%
Higher reservation wage, $\bar{w} = 400,000$	9,178	7.63%	6%	16%	10%
Higher elasticity of demand, $\eta = 1.4$	6	23.57%	43%	-99%	66%
Lower demand curve, $q = 2,400,000$	9,454	7.31%	6%	16%	7%
Lower carrying capacity, $K = 8,000$	6,193	7.52%	11%	-23%	8%
Improved poaching technology, $\omega = 5$	11,083	3.84%	13%	55%	21%

Table 1.2: Summary of results across specifications with varying parameters. Calculations are made at the stable steady state in each case.

Chapter Two

Rhino Horn Stockpiles

Abstract

This chapter establishes a framework prescribing how stockpiled wildlife products might be used to increase wild populations. Whilst existing research has focussed on optimal stockpile management with a goal of profit maximisation, the framework developed here focusses on animal conservation instead. In this model, the rhino owner sells stockpile in each period to lower prices, and therefore incentives to poach. It is found that, even if the institutional arrangements are robust enough to support legalised trade, the economics suggest trade is not guaranteed to improve the conservation prospects of the species. In the absence of private sector speculation, a legalised trade could be used to sustainably conserve a rhino population when extinction would otherwise occur. However, with the introduction of speculation, there comes a point where speculative attack on the remaining stockpile is highly profitable, leading to extinction of the species.

2.1 Introduction

Legalising an international trade in rhino horn or ivory is the most contentious issue in international wildlife conservation policy. Owners of rhino and elephant have accumulated large stockpiles in these commodities which could be sold to consumer markets. Proponents argue that selling stockpiled horn could reduce prices and poaching incentives. Meanwhile, revenue from sales could be channelled back into species protection. Opponents argue that trade will reduce poaching costs by providing a channel to launder goods to market, undermine demand-reduction programmes in consuming nations, and increase total demand by allowing law-abiding consumers to purchase the products. Instead, burning the stockpiles will send a clear signal to consumers that these products should not be consumed.

This chapter establishes a framework prescribing how stockpiled wildlife products might be used to increase wild animal populations. Whilst existing research has focussed on optimal stockpile management with a goal of profit maximisation, the framework developed here focusses on animal conservation instead. It is found that, even with the assumption that institutional arrangements could be robust enough to support a legalised trade, the economics suggest trade is not guaranteed to improve the long term conservation prospects of the species. In the absence of private sector speculation, a legalised trade could be used to sustainably conserve a rhino population when extinction would otherwise occur. Using revenue from stockpile sales to fund patrols strengthens this mechanism. However, with the introduction of speculation, there comes a point where, for reasonable parameters, speculative attack on the remaining stockpile is highly profitable, leading to extinction of the species. The timing of this attack is inversely related to the size of the initial population. In this case, a legalised trade only buys time.

Illicit wildlife trades and poaching occur across many species with storable products. The most publicised and contentiously debated are elephant and rhino. Rhino and elephant are megaherbivores, ecological keystone species capable of a disproportionately large impact on the ecosystem relative to their abundance. The cost of protecting these animals has risen dramatically in recent years as poaching pressure has increased.

Nearly three quarters over the world's rhino reside in South Africa where poaching has risen by 7800% since 2007 (Department for Environmental Affairs, 2018). Rhino are poached for their horn, which can trade for up to $180,000 on the black market (Carrington, 2014). In Vietnam and China, rhino horn is falsely believed to be an anti-inflammatory in traditional 'medicine', and is a status symbol for the elite. In fact, rhino horn is comprised of keratin, the same protein comprising human fingernails. The recent rise in poaching has already decimated the Javan and Sumatran rhino populations and now seriously threatens African white and black rhino with extinction.

African savannah and forest elephant populations number around 350,000 and 120,000 respectively (Chase et al., 2016). The savannah elephant population is declining at 8%/year with 30% of the species lost from 2007-2014 due to poaching and habitat destruction. The rise in demand for ivory is attributed to the growth in purchasing power in South East Asia, where China is the largest consumer. Ivory can now trade for up to $660/kg and is purchased as a status symbol and for ornamental pieces (Larsson, 2017).

Currently, it is commonplace for owners of rhino and elephant to collect and store horn and ivory from naturally deceased animals. This prevents the commodities falling into the illicit trade. Furthermore, stockpiles increase due to confiscations from smugglers. These stockpiles are substantial: around 15 tonnes of rhino horn are currently held in South Africa (88% by the government, Milliken and Shaw, 2012). For ivory, the current policy is to burn stockpiles. Around 210 tonnes of ivory have been burned since 2011 (see Appendix I for details). However, large stockpiles remain.

International bans on ivory and rhino horn trade are governed by CITES (Convention on International Trade in Endangered Species). Domestic trade is not governed by this agreement. However, given consumer markets are international, the CITES agreement dictates the viability of using stockpiles to reduce prices. At the latest CITES meeting, Swaziland put forward a motion to allow legal sales of rhino horn to consumer markets. The mo-

tion was rejected. Regulation of international trade in ivory is more complicated than that of rhino horn due to the use of ivory in durable products. Whilst international trade in new ivory is illegal, two 'one-off' sales have been permitted since the start of the ban. In 1997, Japan bought 49,574kg of government stockpiled ivory at $\sim$ \$100/kg from Zimbabwe, Botswana, and Namibia. In 2008, China bought 107,740kg of government stockpiled ivory at $\sim$ \$140/kg from the same countries and South Africa.

2.1.1 The Proposed Trade

Current proposals to legalise an international trade fail to identify a framework for how the trade might work in practice. There are two sides to this. The institutional side considers how the logistics of the trade might work. This includes identifying official retailers in markets, how to securely transport, track, and document the approved products to distinguish them from illicit items, and how to police the trade. The institutional workings shall be briefly discussed in Section 2.11 but are largely beyond the scope of this study. Instead, the focus is on the economics of the proposed trade, asking how should an owner optimally sell stockpile in order to protect the species?

The basic intuition for a legalised trade is that by selling stockpiles, the owner can sustainably maintain a lower price of horn or ivory, which reduces poaching and leads to a larger long term animal population. There are distinct parallels between this and the mechanism by which a central bank uses foreign reserves to target a fixed exchange rate. Later, when private sector speculation on the owner's stockpile is introduced, direct comparisons can be made to the currency crises literature. Like first generation currency crises models, unsustainable stockpiling policy causes a speculative attack in this model, see Krugman (1979), Halant and Senderson (1978), and Flood and Garber (1984). Yet, the owner has no direct objective to fix a price, and as the Stackelberg leader is aware of the incentives of the speculator. This behaviour, and the ability for sunspot shocks to create incentives for speculation despite sustainable policy (though not explicitly analysed in this chapter), align the model with the second generation currency crises models, see Obstfeld (1984).

However, there are a number of complications to the story of a legalised trade in horn or ivory. Firstly, there are unusual interactions between the state (the population of animals) and the stockpiling rule. Most importantly, the number of animals is the objective of the owner, not profit as in the majority of stockpiling models. Furthermore, the stockpiling decision of the owner today affects the accumulation rate to the stockpile in the future. Secondly, speculation may occur on the owner's stockpile but there is not a direct commitment from the owner to maintain a particular price, unlike a fixed exchange rate model. Thirdly, there is the possibility of a double dividend from selling stockpiled horn because revenue can be channelled back into other forms of species protection, for example anti-poaching patrols. Fourthly, for rhino, intensive farming through de-horning may be possible. These rhino would generate horn for sale at a greater rate than the wild population but are not the objective for the owner wishing to conserve wild rhino. Lastly, because of the movement from an illicit to legalised market, there are interactions with demand and demand-reduction programmes in consuming nations which require attention when evaluating the effectiveness of the policy. These will all be considered in the main model developed in this chapter or as extensions detailed in later sections.

Some existing work examines wildlife stockpiles directly. Kremer and Morcom (2000) allow for storage in an open access harvesting model. They find that anticipated future scarcity of the resource leads to faster poaching rates and higher prices. Hence, there is a dynamic between poaching incentives and expectations leading to multiple rational expectations paths of prices and animal populations. Stockpile management is not explicitly considered as a policy tool for conservation.

Mason et al. (2012) recognise that stockpiles are already held by profit maximising private speculators who compete with poachers. The speculators find it optimal to either depress prices and deter poaching or bid up prices to encourage poaching, acting as a monopolist seller after extinction: the 'banking on extinction' strategy. Which strategy is followed depends on the initial animal population and stockpile. 'Banking on extinction' is an important consideration, especially given the institutional background to the proposed trade.

Numerous models include storage in the context of examining whether legalising trade and farming rhino, through de-horning, may act to save rhino from extinction. Brown and Layton (2001), Damania and Bulte (2007), and 't Sas-Rolfes and Fitzgerald (2013) all incorporate de-horning into a dynamic model. Generally, the rhino farmer acts to farm, store, and sell horn in order to maximise profits across time.

This chapter builds on these models in Section 2.7, recognising that de-horning may provide a fruitful way of increasing supply and reducing poaching pressure on rhino. However, farming is not possible for many species, including elephant. Furthermore, it is not clear whether farmed rhino populations could be considered the objective for conservation policy.[1] Thus, there is a need to examine a stockpiling solution which can be maintained through an extensively managed species, and with the direct objective of conservation rather than profit maximisation.

The model in this chapter is most comparable to that of Kremer and Morcom (2000). However, the analysis here substantially differs. Kremer and Morcom's focus is on the multiple rational expectations equilibrium paths generated by allowing poachers to extract and store the good. Whilst an important area of concern, which this chapter addresses using a speculating agent, the focus here is on the legalisation of trade and the subsequent use of a stockpile to conserve the resource.

This chapter recognises that the owner of the resource is not necessarily motivated by profit but instead wishes to conserve the animal population. Stockpile use for conservation, whilst debated heavily in policy, has not been examined using economic theory in this context, so no proposed optimal stockpiling strategy exists. The model here develops the theory of how such a trade might work in practice and derives an optimal stockpiling rule. This is

[1] A subset of these studies, including 't Sas-Rolfes and Fitzgerald (2013) examine two populations of rhino, one extensively managed and the other intensively managed, to address this concern.

motivated with reference to a rhino population and stockpile of horn, however, the model is directly translatable to any species with storable product.

2.1.2 This Chapter

This chapter is structured as follows. To begin, a basic two-period model is derived and examined to understand the fundamental mechanics of how stockpiles may be used to reduce poaching. Then in Section 3, an infinite time model is formulated, based on the two-period model. This is the model that is simulated in later sections. Details of this simulation are provided in Section 4. Sections 5 and 6 examine the cases of prohibited and legalised trade respectively. Here, the stockpiling rule for the owner is established and it is shown that stockpile sales may maintain a larger long run population of rhino. In Section 7, the owner objectives of profit maximisation and conservation are contrasted and it is shown that profit maximisation is inconsistent with long term conservation. In Section 8, patrol spending is introduced, allowing for a double dividend of stockpile sales. In Section 9, the existence of private speculators is allowed. This places a large constraint on owner actions which may result in the failure of the legalised trade. In Section 10, population growth shocks are shown to undermine the use of stockpiles whilst providing opportunities for speculators to attack. Finally in Section 11, the institutional issues surrounding a legalised trade are discussed before the conclusion in Section 12.

2.2 A Two-Period Model

To begin, a two-period model will be developed and analysed. The core model mechanism is that the owner of the rhino sells stockpiled horn to lower prices and incentives to poach, and therefore conserves the rhino population.

2.2.1 The Rhino Population

There are two time periods, $\tau \in (1, 2)$ and an initial population of rhino denoted x_0. Similarly to Chapter One, the population of rhino at the end of each period x_τ is given by,

$$\begin{aligned} x_1 &= x_0 + g(x_0) - T_1 \\ x_2 &= x_1 + g(x_1) - T_2 \end{aligned} \tag{2.1}$$

where $g(x_{\tau-1})$ is the net growth in the rhino population from the previous period and T_τ is the total number of rhino poached during the current period.[2] In the absence of owner stockpile sales, the steady state population of rhino x^{ss} is dictated by the condition $g(x^{ss}) = T^{ss}$, assuming extinction does not occur. Here, net growth is exactly offset by poaching.[3]

2.2.2 Stockpile Dynamics

The rhino owner enters the first period with an initial stockpile of horns z_0. It is common practice to remove horns from naturally deceased rhino to prevent them entering the illicit trade. Therefore, every period the owner accumulates horns from naturally deceased animals at the rate ϕ.[4] The owner can choose to sell part of their stockpile to the market in each period. The number of horns sold is denoted z^*_τ. It is costly for the owner to store horns, as rhino horns are degradable e.g. through weevil infestation. Hence, there is an iceberg cost of storage γ, so one horn stored today yields $(1 - \gamma)$ horns tomorrow. The stockpile at the

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[2] Typically a logistical growth model is used,

$$g(x_{\tau-1}) = r\left[1 - (\frac{x_{\tau-1}}{K})^\theta\right]$$

where r is the intrinsic growth rate of the population, K is the carrying capacity of the habitat, and θ is a density dependent response which shifts the peak of the growth function with respect to K. $g(0) = 0$, $g'(0) > 0$, $g(K) = 0$, and $g'(K) < 0$.

[3] The stability of this steady state depends on $g'(x^{ss})$. In most cases, three steady states exist. Two of these are often ignored in analysis - the stable steady state at $x^{ss} = 0$ and an unstable steady state $x^{ss} > 0$. The analysis instead focuses on the stable steady state where $x^{ss} > 0$.

[4] The accumulation rate is exogenous to the model.

end of each period is given,

$$\begin{aligned} z_1 &= (1-\gamma)z_0 + \phi x_1 - z_1^* \\ z_2 &= (1-\gamma)z_1 + \phi x_2 - z_2^* \end{aligned} \tag{2.2}$$

The steady state stockpile is dictated by the condition $z^{*ss} = \phi x^{ss} - \gamma z^{ss}$. Here, stockpile sales each period are exactly offset by natural accumulation to the stockpile net of the iceberg storage cost.

2.2.3 Poaching

The population of rhino is assumed to be an open access resource. There is substantial evidence that this is not the case but for simplicity this is assumed here (Milliken and Shaw, 2012).[5] Hence, poacher profit is zero in equilibrium and poachers are not forward looking in their decision making. Each poacher i chooses the number of rhino to poach $t_{i\tau}$ in order to maximise profits $\pi_{i\tau}$. Poachers are price takers in a single market where aggregate poaching is denoted $T_\tau = \sum_i t_{i\tau}$. The poacher problem is written,

$$\max_{t_\tau} \quad \pi_{i\tau} = \left[p(T_\tau, z_\tau^*) - c(x_\tau)\right] t_{i\tau} \tag{2.3}$$

where $c(x_\tau)$ is the cost of finding and poaching one rhino in period τ. As rhino become more abundant, the marginal cost of finding and poaching one falls.[6] The poached horn is sold in the same period to a single illicit market where $p(T_\tau, z_\tau^*)$ is the inverse demand function.[7] From the first order condition, aggregate equilibrium poaching in each period is found,

$$\begin{aligned} T_1^* &= q(x_1) - z_1^* \\ T_2^* &= q(x_2) - z_2^* \end{aligned} \tag{2.4}$$

where $q(x_\tau) \equiv p^{-1}\left[c(x_\tau)\right]$. This is the poacher's reaction function to stockpile sales by the

[5] In Chapter One of this thesis, the notion of imperfect and strategic competition between poaching cartels is analysed in detail.

[6] $c'(x_\tau) < 0$, $c''(x_\tau) < 0$.

[7] $p'(T_\tau, z_\tau^*) < 0$ in both T_τ and z_τ^*. As $T_\tau + z_\tau^* \to 0$, $p(T_\tau, z_\tau^*) \to a > 0$ where a is a constant.

owner. One horn sold from the stockpile reduces poaching by one rhino. This is because equilibrium poaching is tied down by the intersection of marginal revenue and marginal cost which, in turn, is determined by the size of the rhino population.

2.2.4 The Owner's Problem

The owner wants to protect the rhino because they receive a non-consumptive flow of utility from the population, $W(x_\tau)$. This flow of utility is increasing in the size of the rhino population but at a diminishing rate.[8] This benefit encapsulates the conservation value from maintaining a larger rhino population as well as tourism income that might accrue to the owner. The owner chooses the number of horns to sell from their stockpile in each period in order to maximise their benefit from owning rhino. As the Stackelberg leader, the owner anticipates the poaching functions derived in (2.4).

$$\max_{z_1^*, z_2^*} \; W(x_1) + \beta W(x_2) \tag{2.5}$$

where β is the owner's discount factor applied to benefits accrued in the future. In addition, the owner is constrained by the equations of motion for both state variables: the rhino population (2.1) and the stockpile (2.2). Given that a horn sold from the stockpile can never increase poaching, the owner will find it optimal to ensure that $z_2 = 0$.[9] Combining these, the constraint facing the owner is,

$$x_1 + q(x_1) + \frac{x_2 - x_1}{1-\gamma} + \frac{q(x_2)}{1-\gamma} = (1-\gamma)z_0 + \phi x_1 + \frac{\phi x_2}{1-\gamma} + x_0 + g(x_0) + \frac{g(x_1)}{1-\gamma} \tag{2.6}$$

This is the conservation of animals constraint. It states that the total number of rhino remaining in the population each period and horns consumed in the market (the left hand side) cannot exceed the total number of horns accumulating to the owner's stockpile plus the total number of rhino (including growth) in the population (the right hand side). In other words, this is an accounting constraint ensuring that all horns sold in the market by

[8] $W'(x_\tau) > 0$, $W''(x_\tau) < 0$.

[9] The maximum number of horns available for sale in period τ is given $(1-\gamma)z_{\tau-1} + \phi x_\tau$.

the owner or poacher must be accounted for by a corresponding change in owner stockpile or rhino population throughout time. The owner maximises their utility from the rhino population (2.5) subject to the conservation of animals constraint (2.6). The result of this optimisation is,

$$W'(x_1) = \beta(1-\gamma)\left[\frac{(1-\phi-\frac{1}{1-\gamma})+q'(x_1)-\frac{g'(x_1)}{1-\gamma}}{(1-\phi)+q'(x_2)}\right]W'(x_2) \tag{2.7}$$

which is an Euler Equation describing the owner's optimal behaviour. The marginal benefit from using a stockpiled horn to save a rhino in the first period is equalised with the discounted marginal benefit of using the horn to save a rhino in the second period, adjusted for the intertemporal rate of exchange $1+\zeta$ defined,

$$1+\zeta \equiv (1-\gamma)\left[\frac{(1-\phi-\frac{1}{1-\gamma})+q'(x_1)-\frac{g'(x_1)}{1-\gamma}}{(1-\phi)+q'(x_2)}\right] \tag{2.8}$$

This is the intertemporal rate of exchange relevant for the owner stockpiling horns between periods. It is the technology by which one rhino can be 'transferred' between periods through stored horn. It is generally negative because, instead of earning interest, the owner pays a storage cost plus the forgone impact on the population growth rate of saving an additional rhino in the first period. In addition, the rate of exchange adjusts for how much demand changes in response to the owner selling a marginal horn in each period. If demand changes more in period one, then horns are more effective, and it becomes more costly to 'transfer' a rhino into period two.

The two-period system can be analytically solved for certain functional forms. In this case, linear cost and demand functions are adopted. In addition, growth is linear and proportional to the population size, $g(x_{\tau-1}) = gx_{\tau-1}$. More details of these functional forms can be found in Appendix II. From the analytical solution, two schedules are derived: the conservation

of animals constraint (COA), from (2.6), and the Euler equation (EE), from (2.7).[10]

$$EE: \;\; x_2 = [\beta(1+\zeta)]^{\frac{1}{1-\epsilon}} \, x_1 \tag{2.9}$$

$$COA: \;\; x_2 = \alpha - (1+\zeta)x_1 \tag{2.10}$$

where α is the intercept of the conservation of animals constraint plotted in (x_1, x_2) space.[11] Note that the conservation of animals constraint dictates the intertemporal rate of exchange in the model by which one rhino can be 'transferred' between periods through stored horn. However, given the owner cannot 'borrow' a horn from the second period, they are in effect borrowing constrained. For clarity, imagine the case that the owner sells all of their stockpile in period one. In period two, the owner receives ϕx_2 horns. The owner could not borrow these horns in period one but now has a choice of how many of the ϕx_2 to sell in the second period. Graphically, this is depicted in the non-linearity of the COA schedule.

In equilibrium the EE schedule and COA schedule intersect to determine the rhino population in each period. The policy function for optimal stockpile sales is shown to be of the form,

$$z_\tau^* = \lambda_{0\tau} + \lambda_{1\tau} x_0 + \lambda_{2\tau} z_0 \tag{2.11}$$

where $\lambda_{0\tau}, \lambda_{1\tau}$, and $\lambda_{2\tau}$ are constants comprised of parameters in the model which vary across time. These are derived in Appendix II.

2.2.5 Comparative Statics

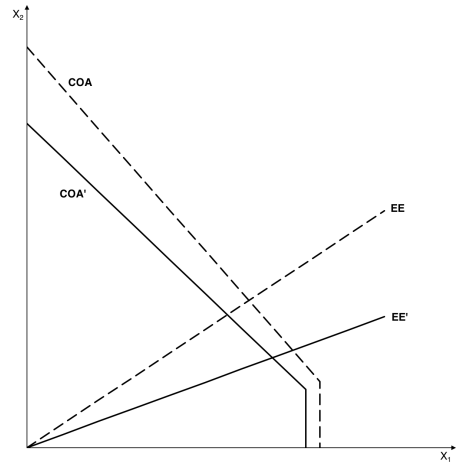
The effects of changing the parameters which feature in the Euler equation (EE) and conservation of animals constraint (COA) are now examined.

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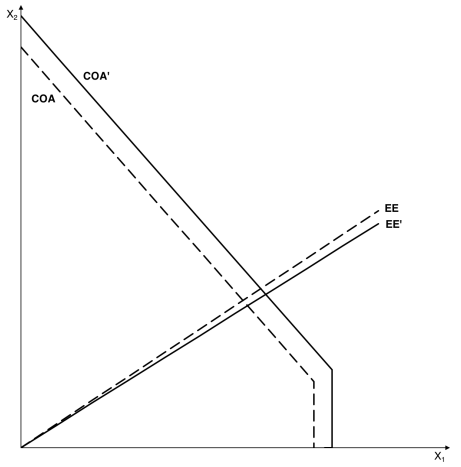
[10] ϵ in the Euler equation refers to the curvature of the owner utility function $W(x_\tau)$, see Appendix II.

[11] The intercept is found:

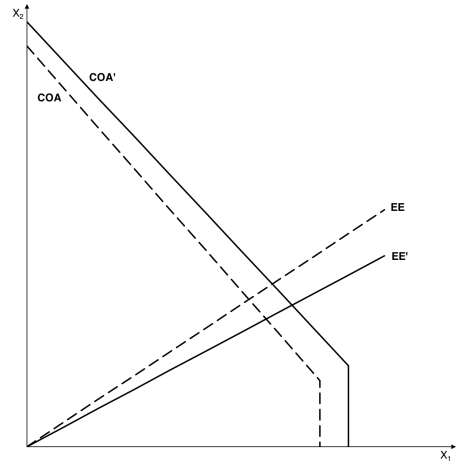
$$\alpha \equiv \frac{(1-\gamma)^2 z_0 + (1+g)(1-\gamma)x_0 + (2-\gamma)(\frac{y-a}{b})}{1-\phi+\frac{c}{b}}$$



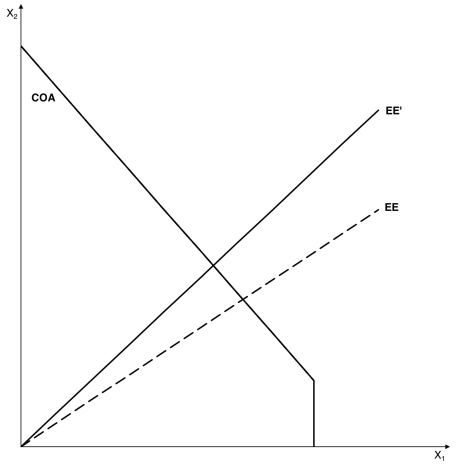
(a) Increased storage cost $\gamma \uparrow$



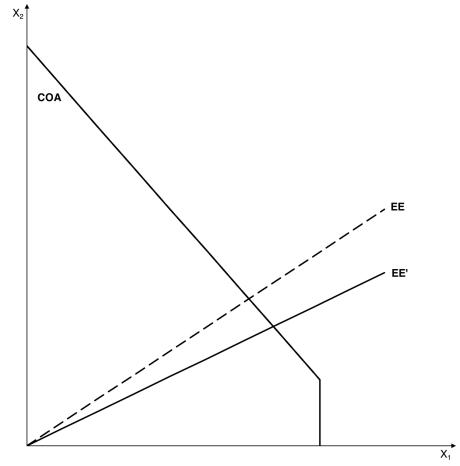
(b) Increased accumulation rate $\phi \uparrow$



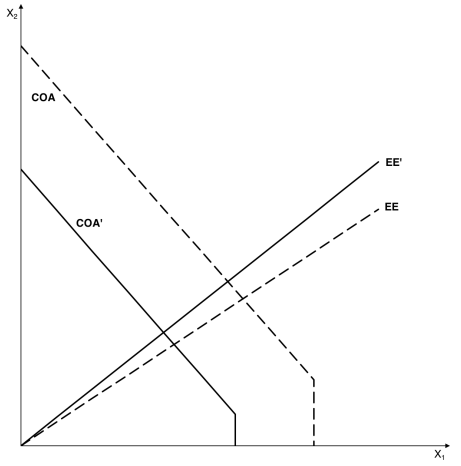
(c) Increased growth rate $g \uparrow$



(d) Increased discount factor $\beta \uparrow$



(e) Increased value of the marginal rhino $\epsilon \uparrow$



(f) Changing demand and cost functions

Figure 2.1: Comparative statics in the two-period model.

Increased storage cost $\gamma \uparrow$

Increasing the iceberg storage cost means, for a given level of storage, fewer horns are available to the owner for sale in the second period. Given the fall in the intertemporal rate of exchange, the COA constraint pivots inwards, see Figure 2.1a. Furthermore, given the iceberg storage cost applies to z_0, fewer horns are available for use in the first period. This results in a shift inwards of the COA schedule. Meanwhile, the owner wishes to sell more horns in the first period because each horn is now relatively more effective at reducing poaching (as the opportunity cost, storage for use in period two, falls). Therefore, the EE schedule pivots downwards. As a result, the rhino population in period one rises and falls in period two.

Increased accumulation rate $\phi \uparrow$

Suppose that the accumulation rate from naturally deceased animals increases (Figure 2.1b). The number of horns accumulating to the owner's stockpile increases in both periods. Hence, the COA shifts outwards. However, given some of these horns only accumulate in the second period and cannot be 'borrowed' by the owner, the vertical, 'credit constrained', section of the COA constraint also shifts upwards. Given each rhino in the period two population provides more horns to the owner through natural accumulation, the owner is incentivised to increase the initial population of period two. Therefore, the owner sells more horns in period one relative to period two. Hence, the EE schedule pivots downwards. As a result of the change, the end of period rhino population increases in both periods, but by more in period one.

Increased population growth rate $g \uparrow$

The effects of increasing the population growth rate are similar to increasing the accumulation rate (Figure 2.1c). However, growth works to greatly increase the relative abundance of horns in period two, as a given population will grow more between periods and hence increase the accumulation to the owner in the second period. Therefore, the intertemporal rate of exchange rises, increasing the slope of the COA. Meanwhile, the owner wishes to defend the marginal rhino more in period one because it results in more rhino in period two

through the increased growth. Therefore the EE schedule pivots downwards. The population of rhino in period one unambiguously increases but the change in population at the end of period two is ambiguous, depending on the owner's preferences (dictated by ϵ and β).

Increased discount factor $\beta \uparrow$

The owner now cares more about the marginal rhino in the future and so uses less stockpile in period one, saving the horns to sell and defend the population more fiercely in period two, see Figure 2.1d. The EE schedule pivots upwards and demonstrates the more equitable distribution in population across the two periods. Hence, the population in period one falls, and rises in period two.

Increased value of the marginal rhino $\epsilon \uparrow$

Increasing the parameter ϵ has two effects on the owner benefit function, see Figure 2.1e. Firstly, it increases the marginal value of a rhino for all population sizes. Secondly, it acts to increase the marginal value of a rhino at a high population relative to the marginal value of a rhino at a low population. Hence, the owner is incentivised to defend the higher population of rhino in period one more fiercely, relative to the lower rhino population in period two. In other words, because the population size has less impact on the value of a marginal rhino, the owner uses the stockpile where it can generate the largest impact. Given transfer is costly, this is in period one. Thus the EE schedule flattens and the population in period one rises, and falls in period two.

Changing demand and cost functions

Finally, the impact of increasing demand relative to the cost function of poachers is analysed, see Figure 2.1f. There are two possible cases here. Firstly, the relative magnitude of demand to the cost of poaching is determined by the difference $a - y$. Increasing demand a relative to the cost y results in the parallel shift inwards of the COA constraint as poaching rises proportionally in both periods. Hence, for a given stockpile, fewer rhino can be defended.

Secondly, demand might rise relative to poaching cost across different rhino populations.

This is the case when $\frac{c}{b}$ increases. Now, poaching is relatively more profitable in larger populations. This shifts the COA constraint inwards. Due to the relative scarcity of rhino in period two, the effect of rising poaching is proportionally greater in period two. Therefore, the owner is incentivised to save more stockpile to defend the second period population more fiercely. Thus the EE schedule pivots upwards. However, the population of rhino in both periods falls.

2.3 An Infinite-Time Model

Whilst analytically advantageous, the two-period model does have downsides in answering the policy question at hand. Most importantly, the terminal condition acts strongly on the owner's optimal stockpiling policy. Instead, there is a need to examine how such a policy might work over time to ensure that extinction does not occur. In particular, the interaction between current stockpile sales, growth in the species and accumulation of stockpile in future periods is not adequately modelled in the two-period environment. Hence, the model is adjusted into infinite time. Whilst the majority of the two-period model intuition holds, infinite time and simulation of the model will allow examination of the lasting impacts of the policy rule.

2.3.1 State Dynamics

The model is in infinite discrete time. However, the dynamics of the rhino population and the owner's stockpile are analogous to the two-period model. For an initial population of rhino denoted x_0, the population of rhino in the period τ is given,

$$x_\tau = x_{\tau-1} + g(x_{\tau-1}) - T_\tau \tag{2.12}$$

Likewise for an initial stockpile z_0, the stockpile remaining at the end of period τ is given,

$$z_\tau = (1-\gamma)z_{\tau-1} + \phi x_\tau - z^*_\tau \tag{2.13}$$

where z^*_τ denotes the stockpile sold in period τ.

2.3.2 Poaching

The problem facing poachers in infinite time is to choose poaching $t_{i\tau}$ (where again $T_\tau = \sum_i t_{i\tau}$) to maximise profits $\pi_{i\tau}$,

$$\max_{t_\tau} \quad \pi_{i\tau} = \sum_{\tau=1}^{\infty} \delta^{\tau-1} \left[p(T_\tau, z_\tau^*) - c(x_\tau) \right] t_{i\tau} \tag{2.14}$$

where δ is the poacher's discount factor. Aggregate poaching is analogous to the two-period case and, for a period τ, is defined,

$$T_\tau^* = q(x_\tau) - z_\tau^* \tag{2.15}$$

where, as before, $q(x_\tau) \equiv p^{-1}\left[c(x_\tau)\right]$. Again, a horn sold from the owner's stockpile perfectly substitutes for a poached horn.

2.3.3 The Owner's Problem

The owner wishes to protect the rhino and receives a non-consumptive flow of utility from the rhino population today and into the future. The owner problem in infinite time is written as a Bellman equation where $V(x_\tau, z_\tau)$ is the value of carrying the end of period population x_τ and end of period stockpile z_τ into the future. Hence, the owner problem is written,

$$\max_{z_\tau^*} \quad V(x_{\tau-1}, z_{\tau-1}) = W(x_\tau) + \beta V(x_\tau, z_\tau) \tag{2.16}$$

where β is the owner's discount factor. The owner's optimisation is constrained by the equations of motion for both state variables: the rhino population (2.12) and the stockpile (2.13). In addition, because the owner is the Stackelberg leader, they perfectly anticipate the poaching reaction function to stockpile sales (2.15). The terminal condition in the two-period problem is replaced by a transversality condition stating that the stockpile should diminish to zero as time extends to infinity. The intuition is similar to before; because a unit of stockpile sold can never increase poaching, the owner should use all the stockpile to

reduce poaching.

$$\lim_{\tau \to \infty} \quad \beta^{\tau} z_{\tau+1} = 0 \tag{2.17}$$

Maximising with respect to these constraints, an Euler Equation reminiscent of the two-period Euler is derived,

$$W'(x_\tau) = \beta(1-\gamma) \left[\frac{(1-\phi-\frac{1}{1-\gamma}) + q'(x_\tau) - \frac{g'(x_\tau)}{1-\gamma}}{(1-\phi) + q'(x_{\tau+1}) - \frac{g'(x_{\tau+1})}{1-\gamma}} \right] W'(x_{\tau+1}) \tag{2.18}$$

The only difference from the two-period case is the addition of a term which adjusts the incentives to save a marginal rhino by the change in the population growth rate in the period after next. This was not necessary in the two-period case because a third period did not exist. Again, this reduces to an optimal choice of the rhino population each period by the owner, given the intertemporal rate of exchange,

$$x_\tau = W'^{-1} \left[\beta(1+\zeta_\tau) \right] x_{\tau+1} \tag{2.19}$$

where,

$$1+\zeta_\tau = (1-\gamma) \left[\frac{(1-\phi-\frac{1}{1-\gamma}) + q'(x_\tau) - \frac{g'(x_\tau)}{1-\gamma}}{(1-\phi) + q'(x_{\tau+1}) - \frac{g'(x_{\tau+1})}{1-\gamma}} \right]$$

The effects of changing these parameters on the optimal stockpiling rule are largely analogous to the two-period case. However, to examine the impact on the steady state population, the model must be simulated.

2.4 Model Simulation

In order to simulate the model, functional forms and parameter values must be adopted. These are detailed in Table 2.1. Sensitivity to the parameters adopted will become a key part of the analysis. There are four functional forms to discuss:

1. Owner benefit: the owner benefit function encompasses tourism income as well as the conservation value from maintaining a population of rhino. It is clear that there are diminishing marginal returns to the size of a rhino population. When rhino are rare,

Variable/Function	Parameter/Functional form	Value adopted
K	Carrying capacity of land	$K = 100$
β	Owner discount factor	$\beta = 0.9$
ϕ	Stockpile accumulation rate	$\phi = 0.1$
γ	Iceberg storage cost	$\gamma = 0.05$
$W(x_\tau) = x_\tau^\epsilon$	Owner benefit from rhino population	$\epsilon = 0.8$
$p(T_\tau, z_\tau^*) = a(T_\tau + z_\tau^* + e)^{-1/\eta}$	Isoelastic demand curve	$a = 400$, $\eta = 0.8$, $e = 10$
$c(x_\tau) = y(x_\tau + e)^{-1/c} - d$	Cost of poaching	$y = 400$, $c = 0.8$, $d = 0.75$
$g(x_{\tau-1}) = rx_{\tau-1}(1 - (x_{\tau-1}/K)^\theta)$	Population growth	$r = 0.07$, $\theta = 7$

Table 2.1: Parameter Values and Functional Forms Adopted for the Numerical Simulation.

they attract more tourism income and have greater conservation value. When they are abundant, the conservation value of the marginal rhino falls.[12] Hence, $0 < \epsilon < 1$.

2. Demand curve: adopting an isoelastic demand curve is a strong assumption given the lack of data on the demand side of the market. However, it allows for a direct examination of the effects of changing the elasticity of demand. This is an important part of the story because prices determine how stockpile sales affect poaching.

3. Cost of poaching: this function is adopted for computational ease. The main dynamic is that a rarer population becomes harder to poach. In this case, the population can be poached until extinction because $p(x_\tau) > c(x_\tau), \forall x_\tau \geq 0$.

4. Population growth: in the case of rhino, a logistic functional form for $g(x_{\tau-1})$ is used, where r is the intrinsic growth rate of the rhino population.[13] z is a parameter determining the density dependent response. A value of $r = 0.07$ and $z = 7$ is chosen for the intrinsic growth rate and density dependent response respectively. This corresponds to a maximum growth rate occurring at approximately 75% of the carrying capacity of the habitat. This value is supported by ecological studies (Emslie and Brooks, 1999; and Owen-Smith, 1988).

[12] A scenario where increasing the population could decrease marginal returns is discounted given the current situation facing rhino.

[13] This corresponds to $r = br - dr$, where br is the birth rate and dr the death rate.

2.5 Prohibited Trade

Currently, most rhino are listed under Appendix I of CITES which prohibits any trade in rhino horn internationally. Therefore, owners of rhino and stockpiled horn cannot sell their horn in an attempt to reduce poaching. This is a specialised case of the model outlined above where $z_0 = 0$ and $\phi = 0$. Given the open access condition for poachers and that poaching is always profitable for all rhino population sizes, in the absence of owner intervention the population is immediately poached to extinction. In reality, it is possible that costs associated with poaching rise substantially as rhino become very rare which may result in a positive steady state population without owner intervention.

2.6 Legalised Trade

If a legalised international trade in rhino horn is enacted, the owner can use their stockpile of horn to influence prices in the market. To examine the potential effects of a legalised trade, the model is simulated for the same initial population of rhino and an initial owner stockpile of horn $z_0 = 100$. The owner accumulates horn from the population of animals at a rate of $\phi = 0.1$. The results are shown in Figure 2.2.

Crucially, extinction is avoided for the same parameters and the population stabilises at a steady state of around 14 rhino. The movement to this steady state is characterised by the following four phases:

1. At first, rhino are abundant and therefore the cost of poaching is low. The owner balances the value of saving the marginal rhino when poaching costs are low with the marginal value of saving a rhino in the future when they are rarer, and hence poaching is more costly. As a result there is a large drop in the population and the owner stockpile. Given their relative abundance, the price of rhino horn is low.

2. What follows is a running down of the owner stockpile, disincentivising poaching each period. However, the owner does not find it optimal to totally crowd out poaching which leads to a consistent fall in the rhino population. As rhino become rarer, the

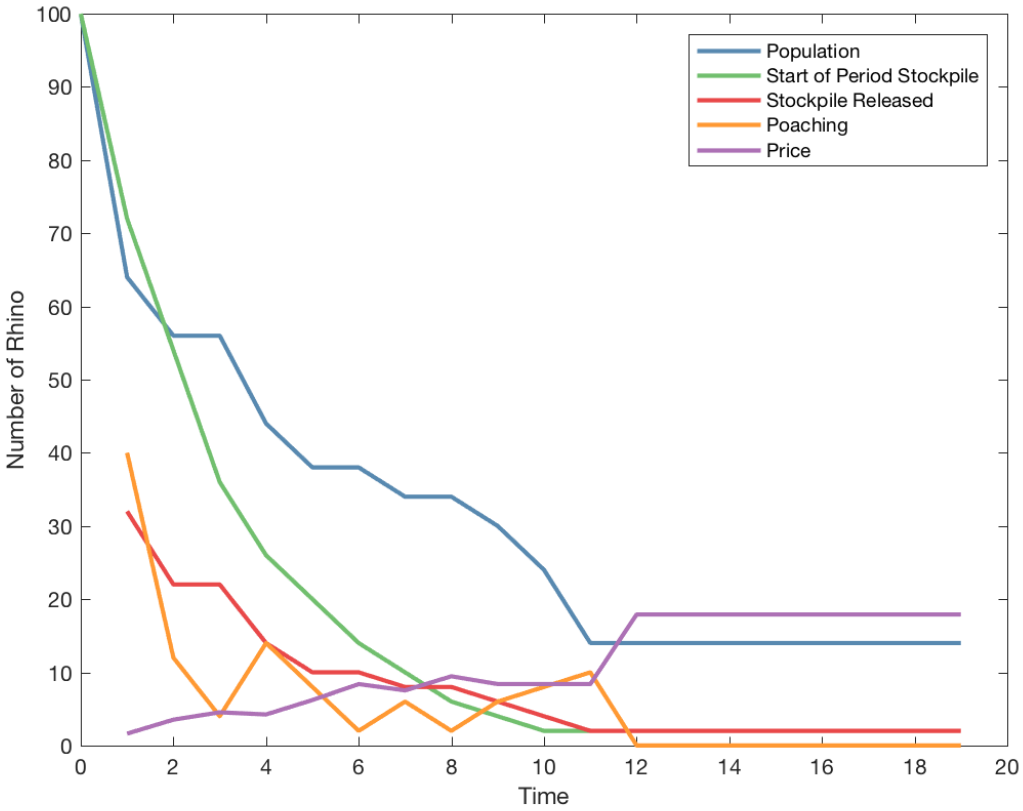


Figure 2.2: Rhino poaching and population simulation with a legalised trade ($x_0 = K$ and $z_0 = 100$). At first, rhino are abundant and therefore the cost of poaching is low. Thus, there is a large drop in the population and the owner stockpile. Then there is a running down of the owner stockpile, disincentivising poaching each period. At the steady state, the number of horns accumulating to the stockpile and sold each period plus the natural growth rate in the population offset poaching.

price of rhino horn rises, but poaching becomes more costly so the owner needs to sell fewer horns to protect the same number of rhino each period.

3. There comes a point where the owner stockpile is exhausted. However, because of accumulation from naturally deceased animals, there is a constant stream of horns accruing to the owner. These are immediately sold into the market. Hence, some poaching is still being crowded out through stockpile sales, but there are no stores between periods. During this phase, the population continues to fall as the stockpile sold each period is not sufficient to reduce poaching below the level of replenishment through population growth. As the population falls there are two opposing dynamics. On one hand, the growth rate in the population increases due to the dynamics of $g(x_\tau)$. There are fewer rhino bulls competing so breeding becomes more efficient for the same number of animals. Furthermore, as the population falls the cost of poaching rises (as rhino are rarer), reducing the incentives to poach. On the other hand, as the population continues to fall, fewer horns accumulate to the owner's stockpile each period, reducing sales. When these two dynamics balance the system enters the final stage.

4. In the final stage, the number of horns accumulating to the stockpile and sold each period plus the natural growth rate in the population offset poaching. Hence, the population stabilises at a steady state. The owner does not store horns between periods but instead sells all horns naturally accruing from the population each period. It follows intuitively that the number of horns sold, the price of rhino horn, and poaching are constant.

The steady state population depends on the parameters in the model. These effects are summarised in Table 2.2. The majority of these follow directly from the analysis in the two-period case. However, it is worth highlighting a couple of important parameters. Most importantly, the effect of changing the rate of accumulation to the owner stockpile ϕ. This is because it determines steady state owner sales and thus the amount of poaching that can be sustainably discouraged. If ϕ is too low, relative to the profitability of poaching, then sustainable sales will not be enough to prevent extinction in the population. Therefore,

Parameter increase	γ	ϕ	g	β	ϵ	η
Steady state population	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$

Table 2.2: Parameter effects on the steady state population

the long-term effectiveness of a legalised trade is largely determined by whether the owner can gather horn from naturally deceased animals at a sufficient rate to sustainably prevent extinction.

The second key parameter is the elasticity of demand η. As demand becomes more elastic, the owner must sell more horns to bring about a given price change. Therefore, the owner's ability to affect poaching diminishes, for a given size of stockpile. This results in a lower steady state population and reduced effectiveness of a legalised trade. However, the current illicit elasticity of demand is thought to be inelastic. What remains unclear is how a legalised trade may change the demand side elasticity, especially if legally abiding consumers enter the market. This demand side interaction of the policy is discussed in Section 2.11.3 and 2.11.2.

In general, the results suggest that a legalised trade in rhino horn may be effective in conserving the rhino population. However, the mechanism here is simplistic: each rhino horn sold from the owner's stockpile 'crowds out' a poached horn in the consumer market, reducing poaching and conserving the population. Often, when policy makers discuss the economics of this proposed trade, the analysis is left here and the discussion turns to the institutional mechanisms behind the trade. This neglects a number of complications to the story, which may work to increase or decrease the effectiveness of this policy. Some of these complications are analysed now.

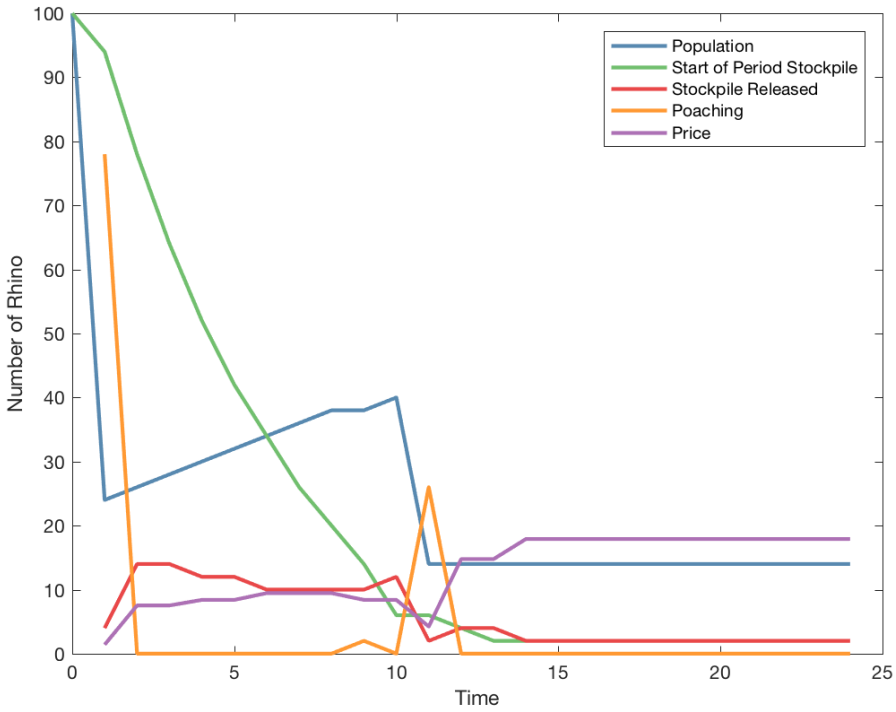


Figure 2.3: Rhino poaching and population simulation with legalised trade and a profit maximising owner ($x_0 = K$ and $z_0 = 100$). The owner allows an initial pulse harvest to increase the rarity of horn and the value of their stockpile sales. Their behaviour is not consistent with a goal of long term conservation.

2.7 A Profit Motive and Rhino Farming

Typically, previous studies have assumed that the owner of the stockpile has an objective to maximise profit rather than maximising the size of the rhino population.[14] The model is simulated with the same parameters but where the owner wishes to maximise the profit from rhino horn sales.[15] The result is shown in Figure 2.3.

The first thing to notice is the larger immediate drop in the rhino population allowed by the owner. This is because the rarer rhino are, the more valuable they are. Thus, by allowing poachers to reduce the rhino population, the owner increases the value of their stockpile. Furthermore, with a lower population the cost of poaching rises, resulting in fewer poached

[14]Studies include: Kremer and Morcom (2000), Brown and Layton (2001), and Mason et al. (2012).

[15]This new objective function could be amended so owners maximise revenue from sales net of costs of storage. This is not assumed here for simplicity and because the cost of storage is thought of as a natural degradation in stored horn rather than a cost to store horn.

horns entering the market each period and less competition with the owner's sales. The owner does not allow extinction as they still receive an accumulation to their stockpile from a positive population. This is the key difference between the behaviour of the conserving owner and the profit motivated owner: the latter has a direct incentive to maintain a lower (albeit positive) rhino population so as to increase the profit from their stockpile sales.

From this lower population, the owner sells a diminishing number of horns over time, balancing discounted future profit with current profit. This results in a gradual rise in prices over time. Initially, these stockpile sales crowd out all poaching in the market, allowing the population to recover. This recovery actually results in a slightly higher rhino population in the medium term than with the conserving owner. However, when the owner's stockpile has fallen substantially, poachers re-enter the market and the same steady state is reached as the case of the conserving owner.

There is an additional difference in behaviour between the profiteering owner and the conserving owner. This is analysed for an alternative set of baseline parameters where, despite owner intervention, the population eventually becomes extinct. Given the conserving owner only receives benefit from a positive population of rhino, they are incentivised to fight extinction as strongly as possible, exhausting their stockpile before the population becomes extinct. On the other hand, the profiteering owner defends extinction less strongly because they can continue to profit (in the absence of poaching) after the wild population has become extinct. This is a similar dynamic to the notion of 'banking on extinction' analysed by Mason et al. (2012).

In reality, some proponents of the legalised trade have argued that rhino owners who can de-horn their rhino could be the main supplier of horn to market. The problem is that these farmers are more likely to be motivated by profit. Therefore, there is a danger that they do not have incentives which are aligned with maximising the long term rhino population. Competition between owners might offset this. However, imperfect competition is likely because of the cost structure, expertise, and licenses required to operate the rhino farms.

Nevertheless, this issue is more complicated. There is a key relationship between farming horn and the accumulation rate ϕ. The accumulation rate will be higher with rhino farming, which might result in a higher steady state than if the population was left to extensive management. In addition, there is a normative judgement over whether the conservation value of a rhino in an intensively farmed population is the same as in an extensively managed population. These considerations are outside the scope of this chapter but are explored in Fitzgerald and 't Sas-Rolfes (2013).

Overall, it is clear that a profiteering owner has an incentive to maintain a lower population of rhino so as to increase the value of their horn sales. Whether this is beneficial for the population depends on whether farming owners can accumulate horn at a sufficiently high rate ϕ to offset this incentive at the steady state. Even if true, the interactions between intensively and extensively managed populations and the conservation value of a rhino in either population need consideration before concluding whether farming could benefit rhino conservation.

2.8 Patrol Spending

Proponents of the trade argue that one of the key advantages of a legalised trade is to generate funding for conservation. Security costs of holding rhino have increased dramatically with rising poaching pressure. Given the expense of funding anti-poaching patrols, selling these stockpiles is argued to generate revenue which can be directly channelled back into protecting the population.

This mechanism is incorporated into the model through anti-poaching patrols. The owner uses the revenue generated from selling horn each period to fund these patrols. Patrols increase the marginal cost of poaching because there is a chance that the poacher gets caught attempting to poach a rhino. If caught, the poacher pays a penalty χ. This probability of capture is the same as discussed in Chapter One and is endogenously determined by three

variables. It is increasing in spending on anti-poaching patrols, s_τ.[16] Each period this spending is determined by an exogenous amount of funding f_τ, thought to be from NGOs and international aid to support conservation. In addition, money from stockpile sales, $p_\tau z_\tau^*$ is also used to fund patrols. Hence,

$$s_\tau = p_\tau z_\tau^* + f_\tau \tag{2.20}$$

The simplifying assumption is that the owner cannot save the money from sold stockpiled horn today to fund patrols tomorrow. Hence, to transfer this income between periods the owner must store a horn for sale in the future. In reality, it might be optimal for owners to save the income from initially high sales to fund patrols when the population is lower. Alternatively, total sales could be invested into the equivalent of a sovereign wealth fund, and the annuity value of the fund spent on patrols each period. However, this analysis is beyond the scope of this chapter.

The probability of capture is decreasing in the carrying capacity or size of the habitat, K. Rhino spread themselves out over the habitat so a given number of patrols need to cover a greater distance, reducing their effectiveness.[17] Finally, the probability of capture is decreasing in the size of the rhino population, x_τ. As the number of rhino increase, patrols becomes less effective at tracking and guarding individual rhino.[18] For clarity, the functional form for the determination of λ_τ is chosen to be,

$$\lambda_\tau(s_\tau, x_\tau, K) = \frac{s_\tau}{s_\tau + K x_\tau} \tag{2.21}$$

In other words, the probability of capture is increasing in anti-poaching patrol spending,

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[16] $\frac{d\lambda_\tau(s_\tau, x_\tau, K)}{ds_\tau} > 0$ as $\lim_{s_\tau \to \infty} \lambda_\tau(s_\tau, x_\tau, K) = 1$, and as $\lim_{s_\tau \to 0} \lambda_\tau(s_\tau, x_\tau, K) = 0$.

[17] $\frac{d\lambda_\tau(s_\tau, x_\tau, K)}{dK} < 0$, as $\lim_{K \to \infty} \lambda_\tau(s_\tau, x_\tau, K) = 0$, and as $\lim_{K \to 0} \lambda_\tau(s_\tau, x_\tau, K) = 1$. In reality, increasing K can be achieved without increasing the acreage of the habitat e.g. by installing new waterholes. However, with a goal of interfering with ecological dynamics as little as possible, K is thought of as just the acreage here.

[18] $\frac{d\lambda_\tau(s_\tau, x_\tau, K)}{dx_\tau} < 0$, as $\lim_{x_t \to \infty} \lambda_t(s, x, K) = 0$, and as $\lim_{x_\tau \to 0} \lambda_\tau(s_\tau, x_t, K) = 1$.

per rhino, per square acre. For the remainder of this chapter, $\lambda_\tau(s_\tau, x_\tau, K)$ is denoted λ_τ for brevity. In addition, whilst the probability of capture presents a risk to poaching, the expectations operator for the poacher and owner is omitted for brevity. Given poachers and owner are risk neutral this has little consequence.

The poacher's problem becomes a choice over the number of poaching attempts, h_{it} to make each period in order to maximise profits $\pi_{i\tau}$,

$$\max_{h_{i\tau}} \quad \pi_{i\tau} = \sum_{\tau=1}^{\infty} \delta^{\tau-1} \left[(1-\lambda_\tau)p(T_\tau, z_\tau^*) - \lambda_\tau \chi - c(x_\tau)\right] h_{i\tau} \tag{2.22}$$

where the number of poached rhino is related to the number of poaching attempts, $t_{i\tau} = (1-\lambda_\tau)h_{i\tau}$, and δ is the poacher's discount factor. Poachers take spending on patrols (and the probability of capture) as given when choosing the number of poaching attempts. Equilibrium aggregate poaching is given,

$$T_\tau^* = q(x_\tau, s_\tau) - z_\tau^* \tag{2.23}$$

where, analogously to before, $q(x_\tau, s_\tau) \equiv p^{-1}\left[\frac{\lambda_\tau}{1-\lambda_\tau}\chi + \frac{c(x_\tau)}{1-\lambda_\tau}\right]$. Now, the double dividend of selling the stockpile is witnessed. Selling horn crowds out poaching each period. In addition, the revenue generated from sales is spent on anti-poaching patrols, increasing the probability of capture for poachers. This raises the expected cost of poaching and further reduces the number of poached rhino.

The model is simulated with the same parameters and patrols, see Figure 2.4. External funding is set $f_\tau = 0$. The steady state population is higher because of the double dividend generated by patrol spending. The dynamics to this steady state remain similar to the four stages described previously, but the owner changes their optimal stockpiling rule subtly. Now a horn sold crowds out more poaching and so the owner redistributes sales from mid-rhino populations to high and low rhino populations. Previously, it was relatively harder for the owner to crowd out poaching when the population was high, because the poaching cost was relatively low. Hence, the owner opted to let the population fall and work to crowd out

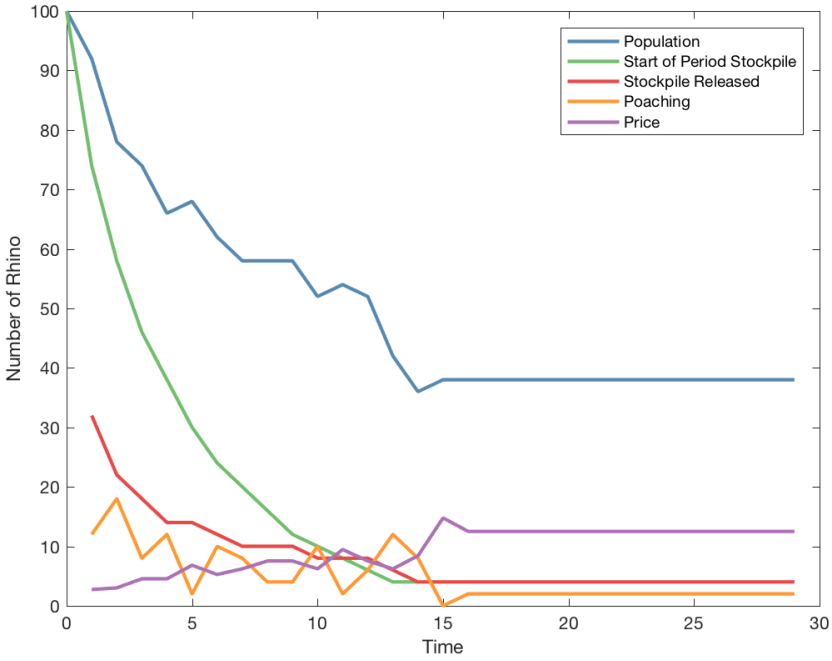


Figure 2.4: Rhino poaching and population simulation with legalised trade and owner spending on patrols ($x_0 = K$ and $z_0 = 100$). The steady state population is higher because of the double dividend generated by patrol spending. Now a horn sold crowds out more poaching and so the owner redistributes sales from mid-rhino populations to high and low rhino populations.

poaching at mid-level populations. Now, because the owner can sell fewer horns at these mid-level populations to achieve the same reduction in poaching, they can fight harder to protect the population at higher and lower populations. Therefore, there are more sales and less poaching in early periods, and a larger rhino population at the steady state compared to the case without patrols.

2.9 Speculation

If owners of rhino populations can stockpile horn, why wouldn't consumers too? In fact, there is substantial evidence that (even without a legalised trade) speculators are already storing horn in anticipation of higher future prices (Milliken and Shaw, 2012). These speculators, motivated by profit, could potentially place a large constraint on an owner attempting to use a stockpile to crowd out poaching. Yet policy debate to date has largely failed to identify this possible constraint on the mechanism of the trade.

To introduce private speculation into the model, an additional agent is introduced to the baseline model: the speculator. A speculator enters the market if the owner tries to suppress the price of horn in period τ relative to the price in τ+1 'too much'. If this occurs, speculators buy up the horn in period τ to store and sell in $\tau + 1$ at a profit. Storage is costly for the speculator who loses a fraction ω of the speculative stockpile $I_{\tau+1}$ across periods. This is analogous to the iceberg storage cost facing the owner. Speculators discount the future with factor δ (which includes an opportunity cost of funds). Free entry into speculation ensures there is no budget constraint facing the speculators. The objective of speculators is to choose $I_{\tau+1}$ each period to maximise profits π^s_τ,

$$\max_{I_{\tau+1}} \ \pi^s_\tau = \sum_{\tau=1}^{\infty} \delta^{\tau-1} p(T_\tau, z^*_\tau, (1-\omega)I_\tau, I_{\tau+1}) \tag{2.24}$$

In any given period, the supply of horns to the market comes from poaching T_τ, stockpile sales by the owner z^*_τ, and speculative holdings bought in the previous period, adjusted for the iceberg loss of storage $(1-\omega)I_\tau$, net of new speculative holdings $I_{\tau+1}$. Speculative holdings of horn adjust to fulfil this set of complementary inequalities,

$$\begin{aligned} p_\tau(T_\tau, z^*_\tau, (1-\omega)I_\tau, I_{\tau+1}) &\geq \delta(1-\omega)p_{\tau+1}(T_{\tau+1}, z^*_{\tau+1}, (1-\omega)I_{\tau+1}, I_{\tau+2}) \\ I_{\tau+1} &\geq 0 \end{aligned} \tag{2.25}$$

This states that if the price today is low enough such that a horn could be bought and sold tomorrow at a profit, net of storage loss, then speculative holdings must be positive. Otherwise, speculative holdings must be zero. Thus, speculation places a restriction on the price in period τ relative to $\tau + 1$. This constrains the owner's ability to influence prices using their stockpile. If the owner wishes to highly deter poaching today, they may be unable to do so. This is because as the price falls relative to the price tomorrow, speculators begin to enter the market, bidding up the price of horn and storing it for sale tomorrow. Hence, speculative holdings (2.25) are an additional constraint on the owner's optimisation in (2.16).

Speculators are introduced into the model simulation and have no initial holdings of horn

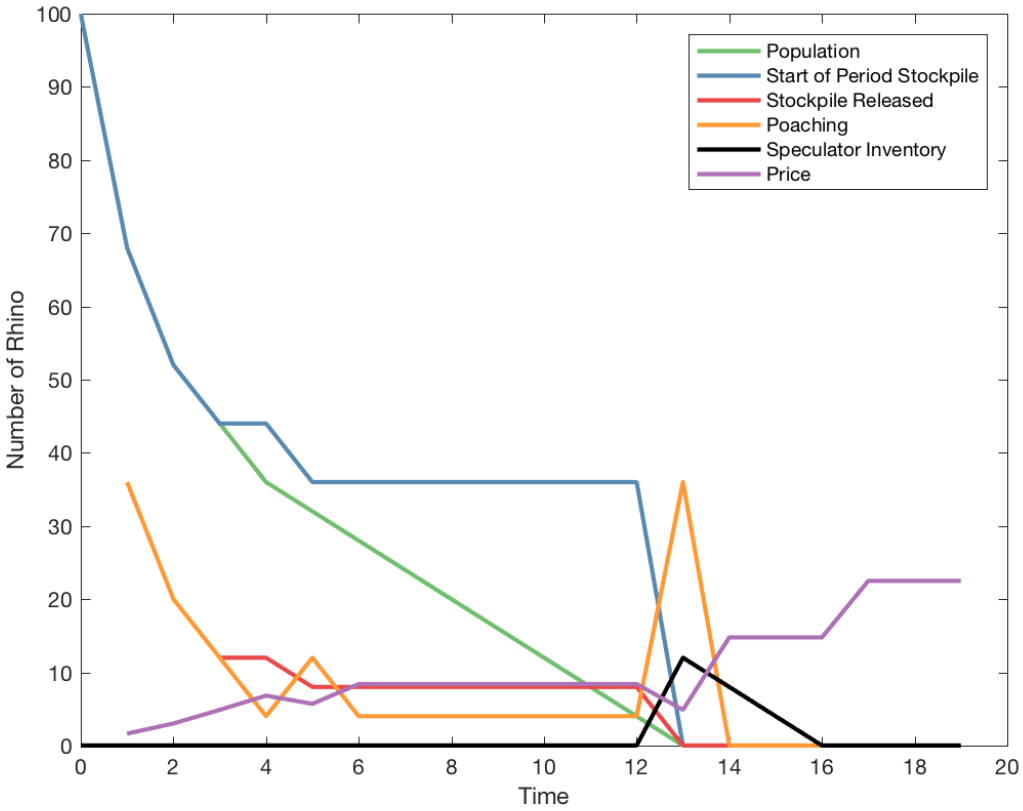


Figure 2.5: Rhino poaching and population simulation with legalised trade and speculation ($x_0 = K$, $z_0 = 100$, and $I_0 = 0$). There comes a point where the owner stockpile is small enough that speculators understand the policy cannot be maintained (in this case the stockpile is exhausted). At this point speculators rush to buy up the remaining horns in the market. This increases the poaching rate. However, given the timing of the attack, the owner cannot defend the population, which becomes extinct.

$I_1 = 0$. They are more impatient than owners $\delta = 0.6$ and have inferior storage technology $\omega = 0.14$. The remaining parameters remain unchanged and there is no owner spending on patrols.[19] Begin with a case where the starting population is $x_0 = 100$ (see Figure 2.5). As before, there is an initial fall in the population because the cost of poaching is low and the owner is forced to sell a large proportion of their stockpile to crowd out poaching. Then a period of relative stability occurs where the population remains constant whilst the owner runs down their stockpile. There comes a point where the owner stockpile is small enough that speculators understand the policy cannot be maintained (in this case the stockpile is exhausted). At this point speculators rush to buy up the remaining horns in the market. This increases the poaching rate. However, given the timing of the attack, the owner cannot defend the population, which becomes extinct. Therefore, there is a spike in poaching (driven by speculative demand) and speculators buy up and store the remaining horns. The system concludes with the speculators selling off these horns in accordance with (2.25) above.

Turn to the case where $x_0 = 40$ (see Figure 2.6). In this case, because the starting population is smaller, the cost of poaching is already relatively high, and so the owner can completely crowd out poaching. This period of stability is maintained for longer because the owner has a larger stockpile remaining for the population level. This is because they did not have to defend the population when the cost of poaching was low. Hence, the timing of the speculative attack is much later than in the case where the system starts with a higher initial population and the same owner stockpile. Subsequently, the dynamics are similar to that of the previous simulation, with a running down of owner stockpiles until speculative attack occurs.

The actions of the speculator directly constrain the owner. However, the owner is akin to the government in a second generation currency crisis model, changing their behaviour with complete knowledge of the speculative constraint on the system. With speculation,

[19] In addition, the model is run at a discretised state space rounded to the nearest ten rhino. This is to increase simulation speed as the model has three state variables, rather than two previously. The resulting policy matrices are then interpolated and smoothed to rescale to a one rhino grid as used previously.

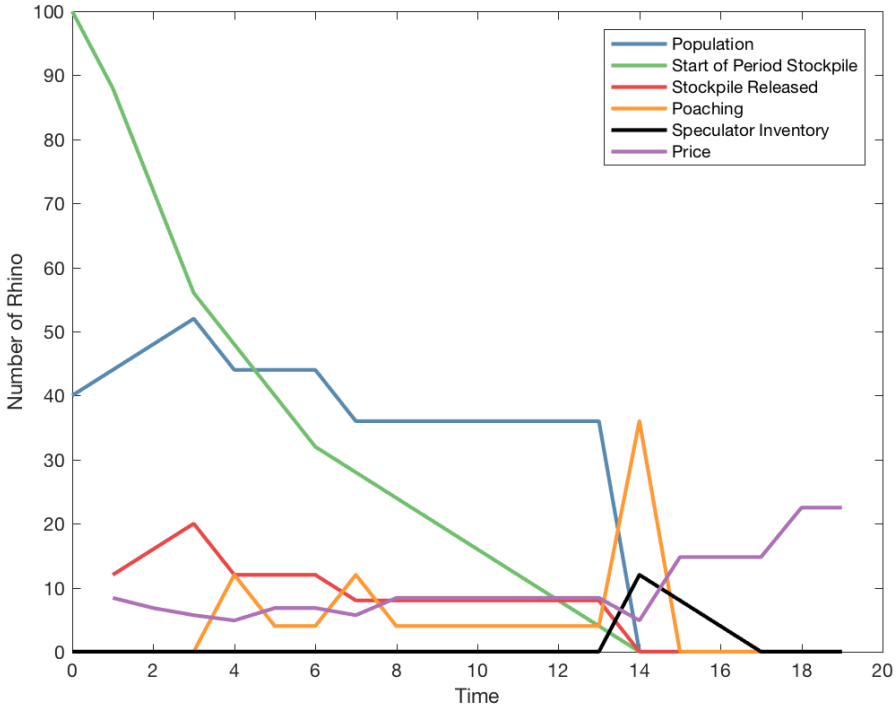


Figure 2.6: Rhino poaching and population simulation with legalised trade and speculation ($x_0 = 40$, $z_0 = 100$, and $I_0 = 0$). In this case, because the starting population is smaller, the cost of poaching is already relatively high, and so the owner can completely crowd out poaching. This period of stability is maintained for longer because the owner has a larger stockpile remaining for the population level.

the owner optimally sells more horns when both the population and stockpile are large. However, the owner is worse off when constrained by the actions of the speculator. This is particularly true when (i) the population of rhino is low and so susceptible to extinction through speculation and (ii) when the owner stockpile is small and susceptible to speculative attack. The effects of changing the speculator's storage technology ω and discount factor δ are intuitive. As storage technology improves (ω falls) or the speculator becomes more patient (δ rises), speculation places a larger constraint on owner actions. This is because speculators are willing to hold inventories for a smaller price differential between periods.

The ability for private agents to store rhino horn has the potential to seriously constrain owner actions and therefore undermine the benefits of a legalised trade. This result occurs without consideration of how sunspot shocks might affect speculator behaviour, which in turn may result in earlier speculative attack on the owner stockpile. It is shown that for the same system, extinction is inevitable with speculation. It is also shown that the timing of the speculative attack, for a given owner stockpile, is inversely related to the size of the initial population. This suggests that if a legalised trade is simply a measure to bide time, then it should be used only when rhino populations are small.

2.10 Population Growth Shocks

Now consider a non-deterministic setting and allow the rhino population to be susceptible to a drought. A drought occurs between periods with a constant probability ι, and augments the dynamics of the rhino population in two ways. Firstly, a given percentage of the rhino population is lost due to the drought μ. Secondly, the growth rate of the population falls to a fraction ν of the original rate. Therefore, the dynamics of the rhino population during a drought are determined,

$$x_{\tau+1} = (1-\mu)(x_\tau + \nu g(x_\tau)) - T_\tau \tag{2.26}$$

The consequences of a drought depend on the extent to which it is anticipated by the owner of rhino and the speculators. Poachers are not forward looking and so their behaviour

continues to be determined by the open access condition. Three cases are considered.

2.10.1 Unanticipated Drought

To begin, assume the owner does not recognise that a drought could occur and that there is no speculation. In other words, not only are droughts unpredictable, but the owner takes the probability of drought to be zero. Therefore, the policy functions for each agent remain the same. The effect of a drought is shown in Figure 2.7. In this simulation, a drought occurs for two consecutive periods: in $\tau = 4, 5$.[20] Not surprisingly, the rhino population falls substantially during this drought period. After the drought period, the owner sells more horns for the (lower) population level than it did in the no drought case. This leads to some population recovery before the stockpile is exhausted and the steady state is reached. The same steady state population is reached but the owner is worse off along the path to this steady state.

2.10.2 Anticipated Drought

Now assume the opposite and that any drought is perfectly anticipated by the owner but there remains no speculation.[21] As can be seen in Figure 2.8, the owner sells more horns in a period where a drought occurs to crowd out poaching and partially offset the effect of the drought. This results in a longer period of higher population, compared to the case of unanticipated drought. However, the owner is still worse off relative to the no drought case. The result here is clear: stockpiled horn can be used to smooth rhino population shocks.

2.10.3 Constant Probability of Drought

Lastly, assume that owners and speculators recognise that a drought could occur with the constant probability ι. They are risk neutral towards this possibility although their derived utility is risk averse. Therefore, the dynamics of the rhino population can be written,

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[20] A drought remains a random event in the simulation but the random number sequence is held fixed for ease of comparison across simulations.

[21] It is then assumed that no further drought will occur and so the system reverts to the case without drought. This allows for a simpler solve of the value function for the rhino owner.

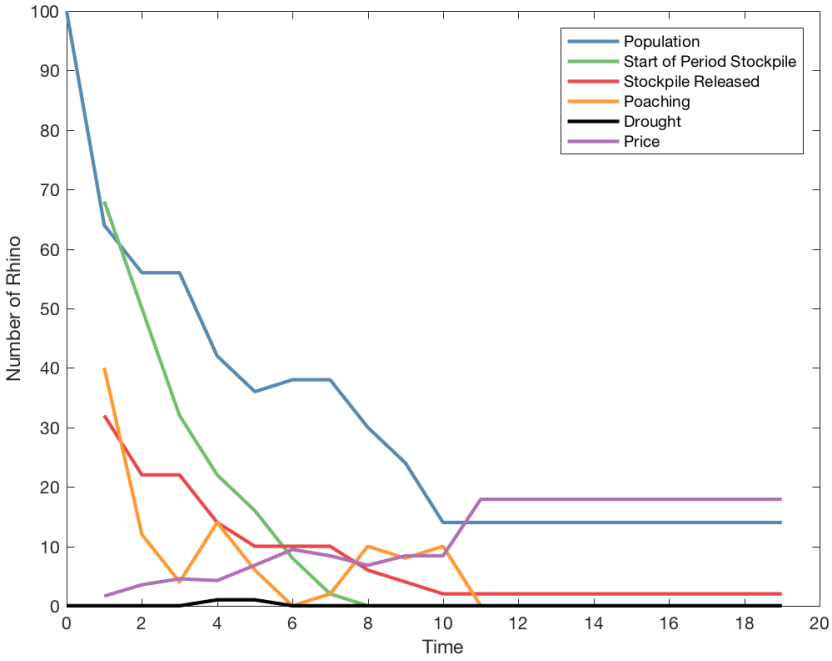


Figure 2.7: Rhino poaching and population simulation with legalised trade, no speculation, and unanticipated droughts ($x_0 = K$ and $z_0 = 100$). The rhino population falls substantially during the drought period. Afterwards, the owner sells more horns for the (lower) population level than it did in the no drought case.

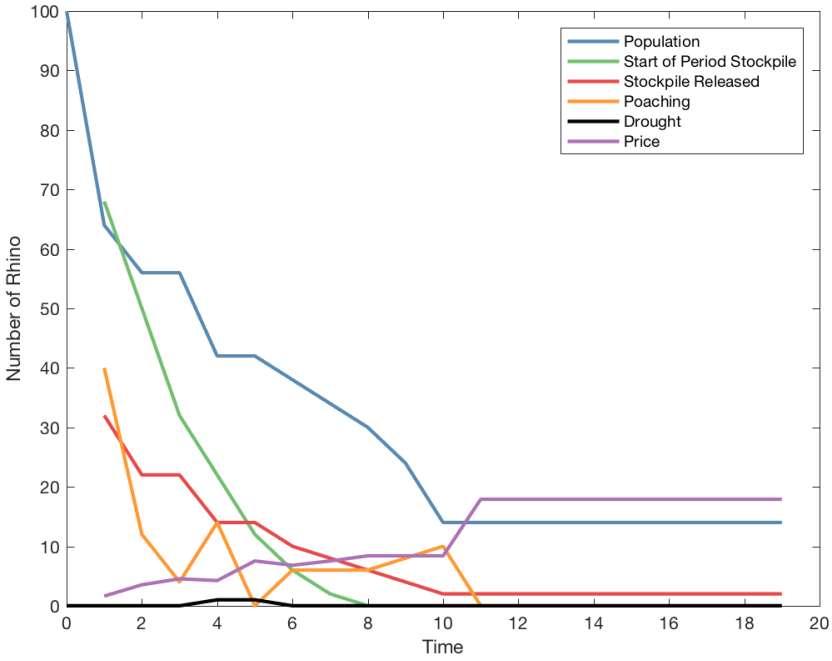


Figure 2.8: Rhino poaching and population simulation with legalised trade, no speculation, and anticipated droughts ($x_0 = K$ and $z_0 = 100$). The owner sells more horns in a period where a drought occurs to crowd out poaching and partially offset the effect of the drought.

$$x_{\tau+1} = (1-\iota)\left[(x_\tau + g(x_\tau)) - T_\tau\right] + \iota\left[(1-\mu)(x_\tau + \nu g(x_\tau)) - T_\tau\right] \tag{2.27}$$

The permanent risk of drought means that owners act more aggressively with their stockpiles, selling more horns at higher rhino populations compared to the case without drought, see Figure 2.9. The owner is attempting to avoid the risk that a drought sends the population beyond the unstable steady state towards extinction. Therefore, whilst the simulation reaches the same steady state as the case without drought, the owner benefit is reduced.

Introducing speculation adds another dimension, see Figure 2.10. Speculators are more likely to attack when there is a risk of drought, taking advantage of the fall in population without a corresponding increase in sold stockpiled horn. Therefore speculative attack can occur sooner than the case without drought (*ceteris paribus*). This underlines further fragility in the policy to sustainably use rhino horn to undermine poaching incentives and maintain a higher population of rhino.

It is possible that a drought could shock the rhino population off the stable steady state. At the steady state the naturally accruing horns and the growth in the rhino population exactly offset poaching. If a drought occurs, growth is negatively impacted resulting in fewer animals the following period. In turn, this results in fewer horns naturally accruing to the owner which may mean that poaching cannot be offset and the population collapses. However, this depends on the shape of the poaching cost function (as rhino become rarer the cost increases). It was also found to require an unreasonably large drought under the current simulation.

2.11 Institutional Issues of a Legalised Trade

What has been presented so far is an analysis of how the economics of a legalised trade might work with the constraints and issues facing the owner trying to defend a population of rhino. This analysis has deliberately ignored the institutional issues surrounding the design of a legalised trade. These difficulties are briefly discussed now.

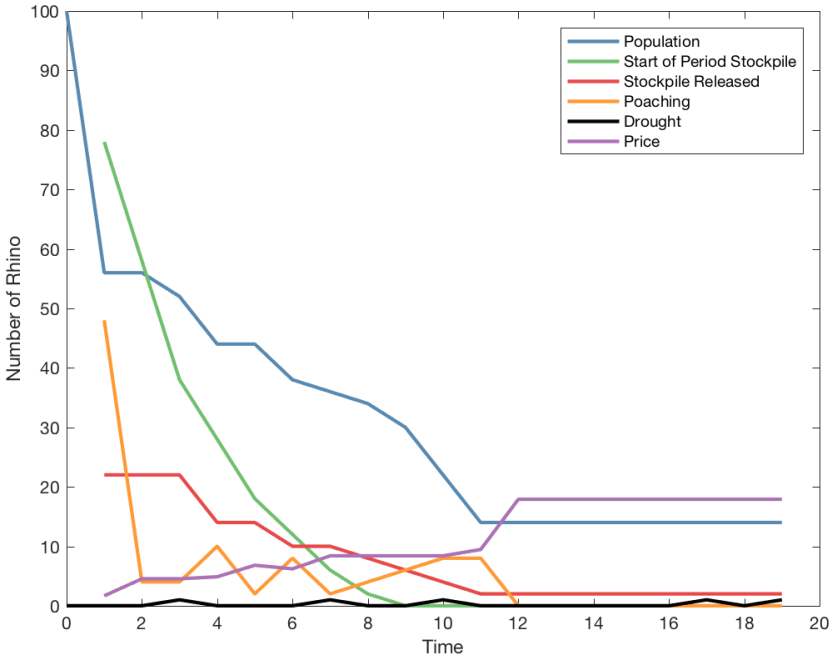


Figure 2.9: Rhino poaching and population simulation with legalised trade, no speculation, and a constant probability of drought ($x_0 = K$ and $z_0 = 100$). The permanent risk of drought means that owners act more aggressively with their stockpiles, selling more horns at higher rhino populations compared to the case without drought.

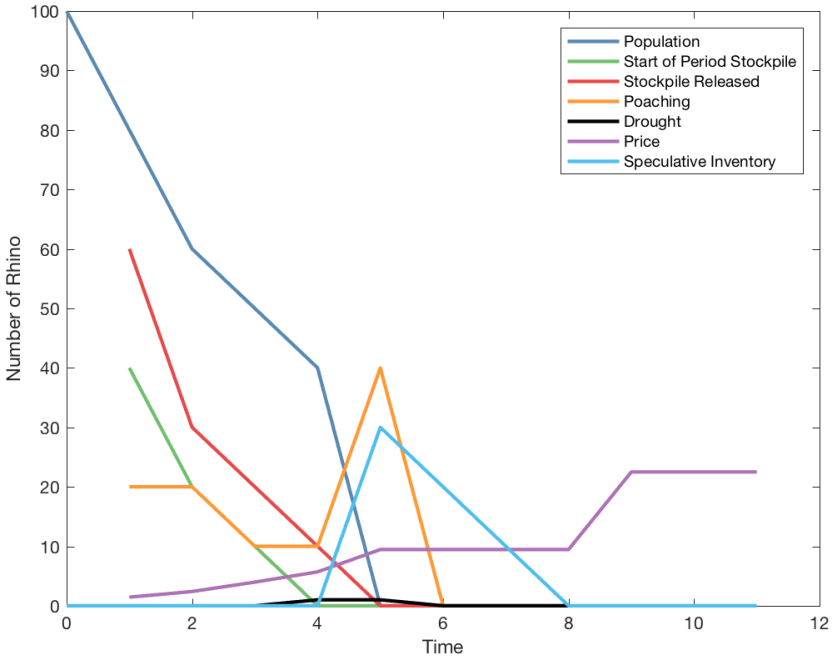


Figure 2.10: Rhino poaching and population simulation with legalised trade, speculation, and a constant probability of drought ($x_0 = K$, $z_0 = 100$, and $I_0 = 0$). Speculators are more likely to attack when there is a risk of drought, taking advantage of the potential drop in population without a corresponding increase in sold stockpiled horn.

2.11.1 Owner Coordination

A simplistic assumption made in the model is the existence of a single owner who can sell horns directly to market. In reality this is untrue; many owners own stockpiles of varying sizes and have varying objectives. Some care only about conservation, whilst others may care about profit. Despite many owners and rhino populations, there is a single price of rhino horn in consumer markets which dictates poaching incentives for all populations.[22] Therefore, the incentives for each owner to sell their stockpile are complicated and depend on the expected stockpile sales of other owners. Whilst it may be plausible that a coordinated mechanism of stockpile sales could be negotiated, there is always an incentive to wait for other owners to sell stockpiled horn first. If profiteering rhino farmers are part of a legalised trade, as has been suggested in South Africa, these incentives are strong and tie in with the optimal profiteering behaviour discussed previously. However, these incentives do not just apply to profiteering owners, as an owner who cared purely about conservation but could use revenue from sales to spend on patrols would still have an incentive to wait. Nevertheless, to achieve optimal protection through stockpile management in practice, a coordinated agreement between the owners must be reached. This is not an easy task given the international scale, heterogeneity in stockpiles and populations, and the involvement of both public and private sector agents.

2.11.2 Moving the Horns to Market

Even if a stockpiling rule could be agreed and implemented, the institutional mechanism to bring the horns to market is still complex, see Fischer (2004). Firstly, approved sellers in consumer markets would have to be identified. The adoption of approved sellers would necessarily introduce an element of price making behaviour. The potential for large mark ups on horns, whilst aiding profiteering owners and approved sellers, would drive a wedge in the mechanism to final consumer prices. If an illegal trade could undercut these prices,

[22]The assumption of a single price and market is also a strong one. This is somewhat discussed in Sections 2.11.3 and 2.11.2 but the truth is that little is understood about the demand side of the market. Nevertheless, the discussion here remains appropriate.

then demand for poached horn may still flourish. As a result, the market would end up segmented. Secondly, identification of the approved horns must be easily verifiable along the supply chain to prevent laundering of illegally poached horns through the same channel. There is a significant concern that this would be impossible. Whilst DNA verification of each horn may be possible (and has been suggested), this process is time consuming and costly. Thirdly, there is high potential for corruption along the supply chain. Given government officials in both consumer markets and source countries have been implicated in the illicit trade, it is highly likely that a legalised trade would generate the same incentives for rent seeking. This would undermine the mechanics of the legalised trade but also allow a potential avenue for laundering illegal horn to the legal market.

2.11.3 Demand Side Interactions

Given the potential benefits of using stockpiled horn to reduce poaching, why do owners consistently publicly burn stockpiles? There is a worry that legalising trade from stockpiled horn legitimises consumption of rhino horn for traditional 'medicinal' purposes. This, combined with the movement to a legal market, has the potential for two negative impacts. Firstly, legalising trade increases demand as law-abiding consumers enter the market. Secondly, legitimising consumption increases demand and undermines 'demand-reduction programmes' in consumer markets. These programmes have worked in other markets (as the historical demand for rhino horn has changed geographically over time), and are the long term solution to the poaching problem. On the other hand, burning the stockpile is thought to support these programmes, signalling that these products are not for consumption. The questions here become, to what extent will legalising trade increase demand? And can owners afford to wait for the demand reduction programmes to take hold?

Lastly, there is the potential that consumers will pay a premium for 'wild' horn (i.e. from extensively managed populations), rather than for 'farmed horn'. If de-horning farmed rhino is the only possible sustainable supply of a legalised trade (in order to achieve a high enough accumulation rate ϕ) then this premium would still encourage poaching of extensively managed populations which are the goal for conservationists.

2.11.4 Summary

Thus, whilst this chapter has outlined the economic rationale and potential pitfalls of a legalised trade in rhino horn, to achieve such a trade in practice, one would still require numerous complex institutional arrangements to be made. Further research on the demand side of the market and consumer preferences would need to occur to legitimise a legalised trade as a sensible policy. It is certainly unclear at the moment that the institutional mechanisms of a legalised trade could be rigorous enough to advocate it as conservation policy.

2.12 Conclusion

This chapter examines the economics of using stockpiled horn to reduce poaching pressure on wild populations. Even assuming that institutional arrangements could be robust enough to support a legalised trade, the economics suggest that it is not certain that stockpile management could improve the long term conservation prospects of the species.

In the absence of private sector speculation, a legalised trade could be used to save and maintain a rhino population in the long term when extinction would otherwise occur. Using revenue from stockpile sales to fund patrols would strengthen this mechanism. However, with the introduction of speculation, there comes a point where, for reasonable parameters, speculative attack on the remaining stockpile is highly profitable, leading to extinction of the species. This speculation was shown to be more likely in drought periods.

The possibility of farming rhino horn may alleviate this issue, if the rate of accumulation to the owner stockpile is high enough. However, the objectives of a profiteering rhino farmer are not consistent with a long run recovery in the population numbers. The profiteering owner has a direct incentive to maintain a lower population so as to increase the value of their stockpile. Furthermore, the institutional issues surrounding coordination between owners of extensive and intensive rhino populations are much more complex than between extensive owners only.

2.13 Appendix I

2.13.1 Historic Ivory Stockpile Burnings

Date	Country	Amount	Notes
03/08/2017	USA	1,800kg	From seizures. Represents at least 100 elephant.
12/11/2016	Vietnam	2,200kg	Represents an estimated 330 elephant. Also burned: 70kg of rhino horn, from an estimated 23 rhino.
13/06/2016	Singapore	7,900kg	-
30/04/2016	Kenya	105,000kg	Represents an estimated 8,000 poached elephant. Also burned: 1,000kg of rhino horn, from an estimated 343 rhino.
19/04/2016	Cameroon	2,000kg	-
14/04/2016	Malaysia	9,550kg	Represents 60% of country's stockpile from seizures.
31/03/2016	Italy	400kg	-
14/03/2016	Malawi	2,600kg	-
26/01/2016	Sri Lanka	1,500kg	A shipment of 359 tusks confiscated.
26/08/2015	Thailand	2,100kg	-
06/07/2015	Mozambique	2,434.6kg	193.5kg of rhino horn also burned.
19/06/2015	USA	909kg	-
29/05/2015	China	662kg	-
29/04/2015	UAE	10,000kg	-
25/04/2015	Republic of Congo	4,700kg	-
20/03/2015	Ethiopia	6,100kg	-
03/03/2015	Kenya	15,000kg	-
09/04/2014	Belgium	1,500kg	-
21/02/2014	Chad	1,100kg	-
06/02/2014	France	3,500kg	-
06/01/2014	China	6,150kg	-
23/11/2013	USA	5,400kg	-
21/06/2013	Philippines	5,000kg	-

Table 2.3: Historic ivory stockpile burnings 2013-2017 (Amended from: Poaching Facts, 2018).

2.14 Appendix II

2.14.1 Solving the Two-Period Model

For ease of analysis, functional forms listed in Table 2.4 are adopted.

Function	Description	Functional form adopted	Parameter restrictions
$W(x_\tau)$	Owner utility function	mx_τ^ϵ	$m > 0$, $0 < \epsilon < 1$
$c(x_\tau)$	Poacher marginal cost function	$y - cx_\tau$	$y > 0$, $c > 0$
$p(T_\tau, z_\tau^*)$	Demand curve	$a - b(T_\tau + z_\tau^*)$	$a > 0$, $b > 0$
$g(x_\tau)$	Population net growth rate	gx_τ	$0 \leq g < 1$

Table 2.4: Functional forms adopted in the two-period model

Given these functional forms, poaching each period solves,

$$T_\tau = \frac{a-y}{b} + \frac{c}{b}x_\tau - z_\tau^* \tag{2.28}$$

The Euler equation for the cartel can now be written,

$$x_2 = \left[\beta(1-\gamma)\left(\sigma - \frac{1+g}{1-\gamma}\right)\right]^{\frac{1}{1-\epsilon}} x_1$$

$$x_2 = \kappa x_1$$

where $\kappa \equiv \left[\beta(1-\gamma)\left(\sigma - \frac{1+g}{1-\gamma}\right)\right]^{\frac{1}{1-\epsilon}}$ and $\sigma \equiv 1 - \phi + \frac{c}{b}$. Combine with the conservation of animals constraint (2.6) to solve for the optimal choice of rhino population across the two periods by the owner.

$$x_1^* = \frac{(1-\gamma)^2}{\sigma(1-\gamma+\kappa)-(1+g)}z_0 + \frac{(1+g)(1-\gamma)}{\sigma(1-\gamma+\kappa)-(1+g)}x_0 + \frac{(2-\gamma)(y-a)}{b[\sigma(1-\gamma+\kappa)-(1+g)]}$$

$$x_2^* = \frac{\kappa(1-\gamma)^2}{\sigma(1-\gamma+\kappa)-(1+g)}z_0 + \frac{\kappa(1+g)(1-\gamma)}{\sigma(1-\gamma+\kappa)-(1+g)}x_0 + \frac{\kappa(2-\gamma)(y-a)}{b[\sigma(1-\gamma+\kappa)-(1+g)]}$$

Optimal sales of stockpile each period is found by substituting these optimality conditions

into the equation dictating population dynamics, (2.1), together with the open access solution for poaching (2.28).

$$z_1^* = \left(\frac{b+c}{b}\right) x_1^* - (1+g)x_0 + \left(\frac{a-y}{b}\right)$$
$$z_2^* = \left(\frac{b+c}{b}\right) x_2^* - (1+g)x_1^* + \left(\frac{a-y}{b}\right)$$

Lastly, stockpile dynamics are given,

$$z_1 = (1-\gamma)z_0 + \phi x_1^* - z_1^*$$
$$z_2 = 0$$

This solves the system entirely assuming interior solutions.

Chapter Three

Elephant Poaching Across Borders

Abstract

As poaching continues at unsustainable levels, elephant populations and conservation policy are becoming increasingly fragmented. A new panel of elephant census data for 1,262 reserves across 37 countries in Africa is used to examine the effect of varying anti-poaching policy across borders. Border effects are found to be statistically significant and an international border results in an elephant population up to 2.5 times smaller than a reserve without a border. In addition, evidence that poachers arbitrage across reserves is found. A 1% increase in the bordering population increases the elephant population in a reserve by 0.26%. Conflict significantly reduces elephant populations across borders. The policy consequence is clear: as populations become increasingly fragmented, transfrontier conservation policy becomes more important.

3.1 Introduction

Elephant populations are becoming increasingly fractionalised. The recent increase in poaching has targeted populations outside formal protection. With divided populations comes varying degrees of intensive management and anti-poaching protection. This has led to a fragmented policy landscape. Now, there exist opportunities for highly organised poachers to arbitrage across reserve populations. However, whilst cross-border trade of ivory to South East Asian markets is well documented, cross-border poaching is rarely discussed.

This chapter seeks to empirically examine this, determining the extent to which different types of borders, and the differences in policy across these borders, affect poaching. A new panel of data detailing elephant populations on a reserve-level across Africa is assembled. Using this new panel of data, the first empirical estimates of the magnitude of these border effects are made. It is found that borders do matter for elephant populations and that poachers arbitrage across reserves. This has clear policy implications for transfrontier conservation policy, even for countries that have few elephant of their own.

Poaching of elephant and rhino occurs across international borders. It is estimated that 90% of all rhino poached in the Kruger National Park, South Africa, are killed by Mozambicans crossing the border (PBS, 2014; Goba, 2017). In the Central African Republic, Sudanese and Chadian poachers are suspected to operate (Hicks, 2013). In the Minkébé National Park in Gabon, 25,000 forest elephant have been lost between 2004-2014, due to poaching near the Cameroon border (Dvorsky, 2017). Given 45% of African reserves containing elephant populations are situated on international borders, cross-border poaching is an important consideration when designing conservation policy.[1] Not only does cross-border poaching occur, but poachers arbitrage across reserves within countries. Recently rhino poachers have moved from operating in the heavily patrolled Kruger National Park to other parks in South Africa e.g. the Hluhluwe-iMfolozi Reserve which are less well funded (Sommerville, 2018).

[1] According to the panel assembled in this chapter.

Despite a long standing recognition that transfrontier management of wildlife is the gold standard for conservation policy, existing practices remain uncommon and underdeveloped (Vasilijević et al., 2015). Transfrontier management of elephant is particularly important, as not only do the animals migrate long distances across borders but illicit trade sees ivory smuggled from Africa to the consumer market in South East Asia (Lindsay et al., 2017). Whilst The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) governs international conservation policy on cross-border trade of ivory or rhino horn, it does not stipulate domestic trade policy nor the severity of punishments levied against poachers. As a result, large differences occur across international borders, especially when neighbouring nations have small or no elephant populations. This has exacerbated the law enforcement problem of defending reserves on borders. For example, in South Africa poachers can be shot on sight but in neighbouring Mozambique poaching was considered a misdemeanour offence until 2015.

The empirical consequences of transfrontier wildlife management are less well understood, mainly due to the lack of data. Estimating elephant populations is difficult and costly so censuses occur infrequently in the majority of reserves in Africa. Those reserves that census regularly rarely release the data publicly, for fear of signalling abundance and migration patterns to poachers. Therefore, previous research on elephant transfrontier conservation has often been limited to case study evidence or descriptive statistics.

In this chapter, a new panel of data detailing elephant populations for 1,262 reserves across 37 countries in Africa is assembled from Elephant Status Reports. Using this panel, the effects of reserve borders on elephant population trends in Africa is examined. To the author's knowledge, this is the first reserve-level panel of elephant population data empirically examined in the field since the ivory trade ban. Significant border effects are found. An international border results in an elephant population up to 2.5 times smaller than a reserve without a border. In addition, evidence that poachers arbitrage across reserves within the same country is found. The effect of conflict is also analysed. It is found that conflict

significantly reduces elephant populations, particularly across international borders.

3.2 The Model

In this section, a model describing the evolution of an elephant population is developed, which will then be taken to the data. In Chapters One and Two, a single owner and population of animals was considered. Now, multiple separable elephant populations subject to varying levels of management are examined. It is worth emphasising that throughout this chapter, expressions such as 'beneficial to', 'increasing the population', or 'a negative effect' are made with reference to a single reserve, and are not necessarily translatable to the aggregate level of poaching across reserves.

3.2.1 The Elephant Population

An elephant population x_τ grows over time $\tau = 0, 1, 2..., \infty$ up to the carrying capacity of the habitat K. This growth is modelled with a logistic growth function,

$$x_{\tau+1} = x_\tau + r\left[1 - \frac{x_\tau}{K}\right]^\theta \tag{3.1}$$

where r is the intrinsic growth rate of the population, and θ is a density dependent response, which shifts the peak of the growth function with respect to the carrying capacity.[2] Without poaching, the population will reach the steady state of the carrying capacity where natural births offset deaths each period.

Now, introduce poaching T_τ. It is clear that the new steady state will be below the carrying capacity of the habitat if poaching is profitable.[3] Here, natural deaths and poaching exactly offset the number of new animals born each period. Therefore, the evolution of the elephant

[2]Where $g(0) = 0$, $g'(0) > 0$, $g(K) = 0$, and $g'(K) < 0$.

[3]In fact, three steady states exist. The first corresponds to the case where the elephant population is zero and is ignored throughout. The second is an unstable steady state at a positive elephant population. This is also ignored. The last is where natural deaths and poaching exactly offset the number of new animals born each period. This is considered the relevant sustainable outcome to evaluate conservation policy.

population is dictated by,

$$x_{\tau+1} = x_\tau + r\left[1 - (\frac{x_\tau}{K})\right]^\theta - T_\tau \tag{3.2}$$

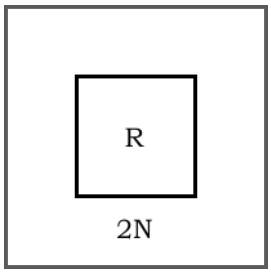
The remainder of this model works to determine T_τ in (3.2). Crucially, T_τ will systematically vary with the type of border that the reserve possesses.

3.2.2 Poaching

The population of elephant is assumed to be an open access resource.[4] Poachers are price takers in a single market and cannot store ivory. Begin with the case of a reserve without an international border or bordering reserve.

Case 1: Poaching Without Borders

Consider a number of identical poachers $2N$ surrounding a single elephant population in reserve R.



Case 1: A single elephant population in reserve R surrounded by $2N$ poachers.

Each poacher can make up to $\bar{h}$ poaching attempts every time period. With each poaching attempt there is a probability λ_R that they are caught by the reserve owner and are forced to pay a penalty χh_R. This penalty is increasing in the number of poaching attempts made by the poacher in the period h_R.[5] The probability of capture is increasing in anti-poaching

[4]There is evidence this might not be the case, see Chapter One, but for simplicity this is assumed here.

[5]The penalty is modelled in the same way in Milner-Gulland and Leader-Williams (1992). Time subscripts are dropped for simplicity and because the poachers are not forward looking.

patrol spending by the owner. This is exogenous here but is explicitly modelled in Chapter One. The poachers take this patrol spending as given.

If the poachers are caught, the poaching attempt is unsuccessful and the elephant lives. If they are not caught, they successfully poach an elephant and sell the ivory in the market, receiving price p. Regardless of the outcome, the poacher pays a cost to make the poaching attempt c_R. This includes the cost of acquiring weapons and the search cost of finding the elephant. Therefore, c_R is decreasing in the abundance of elephant in the reserve x_R.

Assume that some poaching is profitable so the zero poaching solution can be ignored.[6] The poacher chooses the number of poaching attempts to maximise expected contemporaneous profit each period. For simplicity, and given the risk neutrality of poachers, the expectations operator is left out of algebraic expressions throughout this model.

$$\begin{aligned} \max_{h_R} \quad & \left[p(1-\lambda_R) - \lambda_R \chi h_R - c_R\right] h_R \\ s.t. \quad & h_R \leq \bar{h} \end{aligned} \tag{3.3}$$

Therefore, the 'optimal' number of poaching attempts made by each poacher, assuming the constraint is not binding, is given,

$$h_R = \frac{p(1-\lambda_R) - c_R}{2\lambda_R \chi} \quad \equiv \quad \frac{\pi_R}{2\lambda_R \chi} \tag{3.4}$$

Or, if the constraint is binding, $h_R = \bar{h}$. This is a profit maximising condition where marginal revenue, $p(1-\lambda_R)$, equals marginal cost, $2\chi\lambda_R h_R + c_R$. The marginal cost is increasing in the probability of capture and number of poaching attempts due to the structure of the fine payable when caught. Marginal revenue is decreasing in the probability of capture. Poachers attempt to poach up to the point where these are equal or their time endowment constraint binds. The number of poaching attempts is increasing in the price of ivory p, and decreasing in the cost of a poaching attempt c_R, the probability of capture λ_R, and the fine

[6] In other words that $p(1-\lambda_R) > \chi\lambda_R + c_R$.

χh_R. Given total poaching is equal to the number of successful attempts,

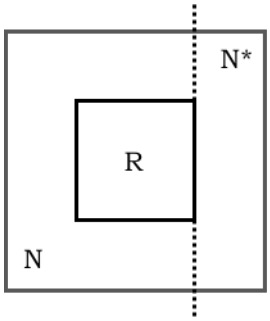
$$T_R = (1 - \lambda_R)H_R \tag{3.5}$$

where $H_R = 2Nh_R$ and $2N$ is the number of poachers. Therefore, aggregate poaching can be written,

$$T_R = \begin{cases} \dfrac{2N(1-\lambda_R)}{2\lambda_R\chi}\pi_R & \text{if } h_R \leq \bar{h}. \\ 2N(1-\lambda_R)\bar{h}, & \text{if } h_R = \bar{h}. \end{cases} \tag{3.6}$$

This is simply the aggregation of the choice of poaching attempts across the poachers and is increasing in the number of poachers surrounding the reserve.

Case 2 (IB): Poaching with an International Border



Case 2: A single elephant population in reserve R surrounded by N home poachers and N^* foreign poachers across an international border (denoted by the dotted line).

Now consider a reserve R which lies on an international border IB. The structure of the population surrounding the reserve changes. There are now N home poachers surrounding the reserve and N^* foreign poachers (instead of $2N$ home poachers). Aggregate poaching from domestic poachers T_R^{IB} remains the same as Case 1 and can be written,

$$T_R^{IB} = \begin{cases} \dfrac{N(1-\lambda_R)}{2\lambda_R\chi}\pi_R & \text{if } h_R \leq \bar{h}. \\ N(1-\lambda_R)\bar{h}, & \text{if } h_R = \bar{h}. \end{cases} \tag{3.7}$$

where in T_R^{IB} the superscript denotes the border type IB, and the subscript denotes the

reserve where the poaching attempt is made R. The foreign country has N^* poachers who have the same time endowment as domestic poachers $\bar{h}$. However, as law enforcement is harder across the border (patrols cannot chase poachers across the border), the probability of capture for foreign poachers is lower $\lambda_R^* < \lambda_R$. Foreign poachers maximise a symmetric problem and choose the number of poaching attempts h_R^* to make each period. Therefore aggregate poaching from foreign poachers T_R^{IB*} can be written,

$$T_R^{IB*} = \begin{cases} \dfrac{N^*(1-\lambda_R^*)}{2\lambda_R^*\chi}\pi_R & \text{if } h_R^* \leq \bar{h}. \\ N^*(1-\lambda_R^*)\bar{h}, & \text{if } h_R^* = \bar{h}. \end{cases} \tag{3.8}$$

These two aggregate poaching results have analogous interpretations to the no border case (3.6). However, poaching is greater with an international border than without when,

$$\frac{N^*}{N} > \frac{\lambda_R^*}{(1-\lambda_R^*)}\frac{(1-\lambda_R)}{\lambda_R} \tag{3.9}$$

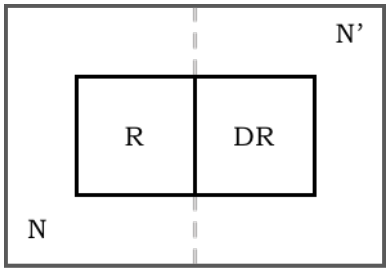
Which is true when $N = N^*$ as $\lambda_R^* < \lambda_R$. This leads to the first hypothesis.

Proposition 1: *Poaching will be greater in reserves on an international border (ceteris paribus) than reserves within a country i.e.* $T_R^{IB} + T_R^{IB*} \geq T_R$.

As anti-poaching patrols are less effective at catching poachers crossing the international border, then the expected cost of poaching for the poacher falls. Therefore, the only way aggregate poaching can fall is when there are fewer poachers in total.

Case 3 (DR): Poaching with a Bordering Domestic Reserve

Now consider two bordering reserves. Neither reserve lies on an international border. The elephant population cannot migrate between reserves and so can be treated as two separate populations. In reality, one can think that these reserves are sufficiently close to each other so poachers may choose to poach from either reserve. Denote the population of poachers around the reserve R and bordering reserve DR, N and N' respectively. Does poaching fall in R relative to Case 1?



Case 3: An elephant population in reserve R surrounded by N poachers borders a separate elephant population in reserve DR in the same country surrounded by N' poachers (the grey dotted line denotes the separation of the two poacher populations N and N'.)

Each poacher chooses the number of poaching attempts to make in each reserve. The penalty χ remains the same across reserves (this is dictated by national law). However, the probability of being caught and the cost of poaching is allowed to differ across reserves. The poacher remains constrained by their time endowment as they maximise,

$$\begin{aligned} \max_{h_R, h_{DR}} \quad & \left[p(1-\lambda_R) - \lambda_R \chi h_R - c_R\right] h_R + \left[p(1-\lambda_{DR}) - \lambda_{DR}\chi h_{DR} - c_{DR}\right] h_{DR} \\ & s.t. \quad h_R + h_{DR} \leq \bar{h} \end{aligned} \tag{3.10}$$

Assuming the constraint is binding, the 'optimal' number of poaching attempts made in reserve R by each poacher is found,

$$h_R^{DR} = \frac{1}{2\chi(\lambda_R + \lambda_{DR})}\left[\pi_R - \pi_{DR} + 2\chi\lambda_{DR}\bar{h}\right] \tag{3.11}$$

Poachers choose poaching in R to equalise the marginal revenue with the marginal cost of a poaching attempt in R plus the opportunity cost of a marginal poaching attempt in DR. This opportunity cost is defined as the difference between marginal revenue and marginal cost of a poaching attempt in DR. Therefore, the number of poaching attempts in R is falling in the profitability of poaching in DR. Poachers attempt to poach more in R when the cost of poaching in DR (c_{DR}) or the probability of capture in DR (λ_{DR}) is higher.

Due to symmetry in the N and N' populations of poachers, aggregate poaching is derived,

$$T_R^{DR} = \begin{cases} \dfrac{(N+N')(1-\lambda_R)}{2\chi(\lambda_R+\lambda_{DR})}\left[\pi_R - \pi_{DR} + 2\chi\lambda_{DR}\bar{h}\right] & \text{if } h_R \leq \bar{h}. \\ (N+N')(1-\lambda_R)\bar{h}, & \text{if } h_R = \bar{h}. \end{cases} \tag{3.12}$$

For the case where $N = N'$, poaching can only decrease relative to the no border case (Case 1). To see why, consider when all poachers (from both N and N') dedicate their entire time endowment to poaching in reserve R. If this was profitable, then this solution was also available to the poachers in Case 1. Therefore poaching will remain the same when $N = N'$. For a formal proof see Appendix I.

Proposition 2: *Poaching will be lower in reserves bordering another domestic reserve compared to a single reserve (ceteris paribus) i.e.* $T_R^{DR} \leq T_R$.

If poaching in both reserves is profitable then the poacher population N' can be greater than the population N and poaching in the reserve R can still fall. When poaching in Case 1 is unconstrained by $\bar{h}$, the necessary condition for this is,

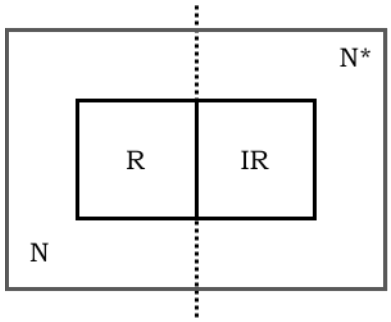
$$\frac{N'}{N} > \frac{\pi_R\left(1 + 2\frac{\lambda_{DR}}{\lambda_R}\right) + \pi_{DR} - 2\lambda_{DR}\chi\bar{h}}{\pi_R - \pi_{DR} + 2\lambda_{DR}\chi\bar{h}} \tag{3.13}$$

And when it is constrained by $\bar{h}$,

$$\frac{N'}{N} > \frac{4\chi\bar{h}(\lambda_R + \lambda_{DR})}{\pi_R - \pi_{DR} + 2\lambda_{DR}\chi\bar{h}} - 1 \tag{3.14}$$

The degree to which the population N' can be greater than the population N is dictated by the relative profitability of the reserve DR to the reserve R. The more profitable the reserve DR, the fewer poaching attempts made in the reserve R for the same total population of poachers. Crucially, one of the parameters determining this is the relative probability of capture in each reserve. Therefore, it can be seen how differences in anti-poaching policy can dictate arbitrage by poachers across reserves.

Case 4 (IR): Poaching with a Bordering International Reserve



Case 4: An elephant population in reserve R surrounded by N home poachers borders a separate elephant population in reserve IR surrounded by N^* foreign poachers across an international border (denoted by the dotted line).

This case is similar to the case of a bordering domestic reserve (Case 3). N poachers in the home country can choose to make a poaching attempt in reserve R or cross the border and attempt to poach from the international reserve IR. Like Case 2, they face a lower probability of capture $\lambda^*_{IR} < \lambda_{IR}$ when poaching in IR relative to a foreign poacher. This is because law enforcement is harder across international borders. This logic is symmetric as N^* foreign poachers face a lower probability of capture in R than home poachers $\lambda^*_R < \lambda_R$. In addition, the penalty if caught is allowed to differ across countries. Let χ^* denote the penalty paid if caught poaching in IR and χ the penalty in R as before. The problem facing poachers in N is,

$$\begin{aligned} \max_{h_R, h_{IR}} \quad & \left[p(1-\lambda_R) - \lambda_R \chi h_R - c_R\right] h_R + \left[p(1-\lambda^*_{IR}) - \lambda^*_{IR}\chi^* h_{IR} - c_{IR}\right] h_{IR} \\ & s.t. \quad h_R + h_{IR} \leq \bar{h} \end{aligned} \tag{3.15}$$

Assuming the time constraint is binding, the 'optimal' number of poaching attempts made in the reserve R by each home poacher is found,

$$h^{IR}_R = \frac{1}{2(\chi\lambda_R + \chi^*\lambda_{IR})}\left[\pi_R - \pi^*_{IR} + 2\chi^*\lambda^*_{IR}\bar{h}\right] \tag{3.16}$$

where $\pi^*_{IR} \equiv p(1-\lambda^*_{IR}) - c_{IR}$. The interpretation here is analogous to Case 3 with a domestic reserve. Home poachers increase the number of poaching attempts in R up to

the point where the marginal revenue of a poaching attempt equals the marginal cost plus the opportunity cost of using that attempt to poach in the reserve IR. Thus, the number of poaching attempts in the reserve R is decreasing in the profitability of poaching in the reserve IR. In turn, the more the border reduces the effectiveness of anti-poaching patrols, i.e. as λ^*_{IR} falls relative to λ_{IR}, the higher the relative profitability of poaching in IR.

Therefore aggregate poaching in the reserve R by home poachers is derived,

$$T_R^{IR} = \begin{cases} \dfrac{N(1-\lambda_R)}{2(\chi\lambda_R + \chi^*\lambda^*_{IR})}\left[\pi_R - \pi^*_{IR} + 2\chi^*\lambda^*_{IR}\bar{h}\right] & \text{if } h_R \leq \bar{h}. \\ N(1-\lambda_R)\bar{h}, & \text{if } h_R = \bar{h}. \end{cases} \tag{3.17}$$

Through a symmetric problem aggregate poaching in the reserve R by foreign poachers is found. The probability of capture in R facing foreign poachers is lower because of the international border.

$$T_R^{IR*} = \begin{cases} \dfrac{N^*(1-\lambda^*_R)}{2(\chi\lambda^*_R + \chi^*\lambda_{IR})}\left[\pi^*_R - \pi_{IR} + 2\chi^*\lambda_{IR}\bar{h}\right] & \text{if } h^*_R \leq \bar{h}. \\ N^*(1-\lambda^*_R)\bar{h}, & \text{if } h^*_R = \bar{h}. \end{cases} \tag{3.18}$$

Is poaching in R greater than in Case 1 i.e. $T_R^{IR*} + T_R^{IR} > T_R$? Consider a scenario where poaching only occurs in the reserve R and the time endowment is binding. For poaching to increase relative to Case 1,

$$\begin{aligned} \left[N^*(1-\lambda^*_R) + N(1-\lambda_R)\right]\bar{h} &> 2N(1-\lambda_R)\bar{h} \\ \Leftrightarrow N^*(1-\lambda^*_R) &> N(1-\lambda_R) \end{aligned} \tag{3.19}$$

Which is true when $N = N^*$ as $\lambda^*_R < \lambda_R$. The logic here is the same as in Case 2 (with an international border IB and no bordering reserve). Given anti-poaching patrols are less effective at catching foreign poachers, the same number of poaching attempts results in more elephant poached.

Now assume that poaching occurs in both reserves. To see if poaching is greater in the reserve R relative to Case 1 consider the following:

1. Assume the border does not alter the probability of capture $\lambda_R = \lambda_R^*$, $\lambda_{IR} = \lambda_{IR}^*$, and that there is the same punishment across the border $\chi = \chi^*$. In this case, the international border has no impact. Therefore the international reserve IR is analagous to a bordering domestic reserve DR and poachers arbitrage across the two. If poachers choose to only poach in the reserve R poaching will remain the same as in Case 1. Therefore, poaching can only increase in R when $N^* > N$.[7]

2. Instead, assume now the same population of poachers in each country $N = N^*$ and the same punishment across the border $\chi = \chi^*$, but allow for the probability of capture to be lower for poachers crossing the border. It can be shown that poaching increases in the reserve R when,

$$\frac{(1-\lambda_R^*)}{(\lambda_R^*+\lambda_{IR})}\left[\pi_R^* - \pi_{IR} + 2\chi\lambda_{IR}\bar{h}\right] > \frac{(1-\lambda_R)}{(\lambda_R+\lambda_{IR}^*)}\left[\pi_R\left(1+\frac{2\lambda_{IR}^*}{\lambda_R}\right) + \pi_{IR}^* - 2\chi\lambda_{IR}^*\bar{h}\right] \quad (3.20)$$

   At this point, the disadvantage of reduced effectiveness of anti-poaching patrols outweighs the advantage of having poachers arbitrage across multiple elephant populations. Therefore, aggregate poaching in R increases. The left hand side dictates the relative incentive to poach in the reserve R compared to the reserve IR facing a foreign poacher. They face a reduced probability of capture from poaching in R, λ_R^*. As the left hand side increases, poaching in R becomes more attractive for the foreign poacher. The right hand side is the mirror relative incentive for a home poacher. They face a reduced probability of capture from poaching in IR, λ_{IR}^*. As this rises, it is relatively more profitable to poach in IR and so poacher arbitrage across reserves works to reduce poaching in R.

3. Lastly, assume the border does not alter the probability of capture $\lambda_R = \lambda_R^*$, $\lambda_{IR} = \lambda_{IR}^*$, and that there is the same population of poachers in each country $N = N^*$. This is similar to the case of a bordering domestic reserve (Case 3), however the penalty is allowed to vary across reserves $\chi \neq \chi^*$. Again, it is found that poaching cannot

[7]The proof is also analogous and contained in Appendix I.

increase in R. The worst case for poaching in R is that poachers do not operate in IR. However, this action was available to the poachers under Case 1 and therefore poaching cannot increase. Hence, varying penalties for poachers across reserves is not enough to remove the 'benefit' to reserve R of having a bordering reserve. However, it does affect the marginal incentive for poachers to poach in IR instead of R. This theory corroborates Milner-Gulland and Leader-Williams (1992), the probability of capture is the most significant factor for altering poacher behaviour.

Overall, the impact of a bordering international reserve on the number of poaching attempts in the reserve R is ambiguous. On the one hand, home poachers may choose to poach in the reserve IR instead of R, reducing poaching. This incentive is dictated by the relative profitability of poaching in IR to R. The incentive is increased because home poachers are less likely to be caught in IR as enforcement is harder across the border $\lambda^*_{IR} < \lambda_{IR}$. On the other hand, the border effect works to increase poaching in R as anti-poaching patrols are less effective at catching foreign poachers. This leads to the final hypothesis,

Proposition 3: *Poaching will be higher in reserves bordering another reserve across an international border i.e.* $T_R^{IR*} + T_R^{IR} > T_R$*, when either, (i) the relative foreign poacher population size is greater, or (ii) the anti-poaching patrol effectiveness at the border is lower, or (iii) the cost of poaching is sufficiently low in the reserve* R *relative to the bordering international reserve* IR*.*

3.2.3 Elephant Population Dynamics

The results in the previous subsections can be combined to find the evolution of the elephant population in a reserve R over time. The relevant aggregate poaching rate T_R^B, for a reserve with border type B, is substituted into (3.2),

$$x_{R,\tau+1} = x_{R,\tau} + r\left[1 - \frac{x_{R,\tau}}{K_R}\right]^{\theta} - T^B_{R,\tau} \tag{3.21}$$

In practice, it is possible that a reserve R borders both a reserve in the same country DR as well as a reserve across an international border IR. Therefore the border type,

and subsequent aggregate poaching rate, does not fall cleanly into one of the previous cases. However, the implications for poaching incentives can be extended directly: poachers equalise the marginal incentives to attempt to poach across the three reserves. This is the model that is taken to the data in the following sections.

3.3 Data

The empirical literature on elephant poaching is small because data is scarce. Monitoring elephant populations over time is difficult and expensive. Furthermore, whilst reserves might keep regular records of their number of elephant and poaching trends, these records are often not publicly shared. Only recently has there been a concerted effort to maintain more detailed and frequent records across Africa. This effort has been led by the MIKE (Monitoring the Illegal Killing of Elephants) database maintained by CITES. Indeed, this is the database which has been most commonly used in the literature.

There are two problems with poaching data. Firstly, programmes like MIKE only record data for a subset of reserves in Africa. Secondly, it is highly influenced by the degree of anti-poaching enforcement: more carcasses are found when enforcement is higher. To attempt to circumvent this problem, the Proportion of Illegally Killed Elephants (PIKE) is used. In other words, what proportion of all carcasses found are because of poaching? Yet enforcement is likely to focus on tracking down these carcasses or working in areas most under the threat of poachers, continuing to bias the results (see Underwood et al., 2013).

In this chapter, elephant population census data is used. This provides a more comprehensive account of elephant numbers on a reserve-level, over a longer period of time. The predominant threats to elephant populations in Africa are poaching and habitat loss. Given census areas are recorded and can be tracked over time, habitat loss can be somewhat controlled for. Therefore, it is argued that the remaining movements in elephant populations will be largely due to poaching as modelled previously. Hence throughout the analysis, a

factor which reduces the elephant population will be said to increase elephant poaching.[8]

3.3.1 Elephant Population Numbers

The IUCN African Elephant Specialist Group (AfESG) has produced reports tracking the estimated number of elephant in reserves in Africa over time.[9] These reports compile census data from individual researchers, reserve owners, and governments into a centralised database, the African Elephant Database (AED). Each entry documents the most recent census of the elephant population in question, the method of the census, the reliability of the estimate, and the area of range surveyed.

Census methods vary across reserves, over time, and in accuracy. Generally there are three types of estimates: total counts, sample counts, or informed guesses. These are declining in reliability. Total counts aim to identify every individual elephant in a given range. Typically, aircraft are used. However, ground counts using vehicles are possible depending on terrain and habitat. These counts are generally expensive and are only used when funding allows or populations are small or densely located. Sample counts aim to count elephant in a subset of their entire population range and then scale up the resulting estimate. They are less accurate than total counts due to the assumptions made over the difference in elephant density between the sampled and non-sampled area. The same methods of aerial and ground counts can be used on the sample area. Alternatively, particularly in heavily forested areas, dung counts are often used to attain a measure of elephant density. However, this is less reliable. Finally, informed guesses are the least reliable census method. At best, these include sample counts without methodological scaling (without confidence intervals). At worst these include extrapolations from models of the population or old data points.

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[8] Having said this, it is clear that there are other factors which may result in a decline in the elephant population, other than poaching. Robustness to climate shocks is tested. Hunting of elephant for bush meat can be viewed as a form of poaching where p in the model now reflects the value for the meat rather than ivory. Lastly, revenge killings for damage to agriculture are common in certain reserves. Again, robustness to agricultural land use is tested.

[9] Reports used are Said et al. (1995), Barnes et al. (1998), Blanc et al. (2002), Blanc et al. (2007), and Thouless et al. (2016).

The censuses detailed in the AfESG reports are the data used in this chapter. However, despite making the reports publicly available, the authors were unable to send through the original geo-coded data despite requests. Therefore, the borders for each elephant population were manually mapped using the range maps in each report. Substantial corrections were made to the census data when it had been incorrectly converted into the publicly available reports. Manually tracking the data also allowed for following the same elephant populations across time, even when the reserve name changed. In certain cases, censuses were aggregated to create a comparable population range to historically recorded ranges.

This data work has produced an unbalanced panel of data tracking elephant population numbers on a reserve-level throughout Africa since 1985. The panel is unbalanced across the timing of the censuses in each reserve but also in the number of censuses taken in each reserve. This presents econometric challenges which are discussed later. At the time of writing, this is the only panel data work with elephant population numbers on a reserve-level since the 1989 ivory ban that exists in the literature.[10]

In total, the panel contains data on elephant populations for 1,262 reserves across 37 countries in Africa. 685 of these reserves have data spanning more than one elephant status report. Given the dynamic specification, it is this number which represents the sample size. The maximum number of observations in time for any reserve is 5 (there are only 5 status reports) and there is an average of approximately 3 data points for these remaining reserves. The average observation period is 7.5 years and the median is 7 years. Sensitivity of the results to the observation period is examined in the robustness section.

Treating the data as a pooled cross-section, the average number of elephant found in a reserve is 1872. The distribution of elephant across reserves is shown in Figure 3.2 (Appendix

[10]To the author's knowledge. It is also worth noting that very few observations occur pre-1989 and the results are robust to the exclusion of these observations.

Border Type	Mean	Variance	CV	N	P5	P25	P50	P75	P95
No Border	417	1.81e+06	3.22	240	1	15	58	200	2111
DR	1489	1.49e+07	2.58	440	0	54	264	1131	6318
DR and IR	5960	2.95e+08	2.87	216	0	64	781	3016	31613
DR and IB	1877	1.81e+07	2.26	101	0	58	488	1850	9292
IR	280	3.85e+05	2.22	136	0	33	78	261	1114
IB	458	9.21e+05	2.09	90	2	21	60	455	1966
IR and IB	1805	1.40e+07	2.07	5	34	39	88	365	8500
DR, IB and IR	601	3.63e+05	1.00	17	33	237	469	740	2260
All Reserves	1872	6.19e+07	4.20	1245	0	37	185	876	7371

Table 3.1: Summary statistics for elephant populations across reserves, sorted by border type.

II). The distribution is positively skewed with a small number of reserves with large elephant populations. These increase the mean substantially. The 95^{th} percentile is at 7300 elephant with a maximum of approximately 130,000. Therefore, for the majority of the analysis, observations from reserves with more than 7000 elephant are not used.[11]

The overall mean masks significant variation in the average number of elephant across reserves with differing border types. Table 3.1 exhibits this. Overall, 81% of all reserves have a bordering reserve or international border. 62% of reserves border a domestic reserve DR. 45% lie on an international border of which 65% border an international reserve IR. The mean elephant population tends to be highest in reserves which border another reserve domestically DR and lowest on an international border IR and IB. Whilst identifying the type of reserve border is possible, identifying the nature of the border is not. In particular, whether the border is fenced or whether populations are free to migrate are key variables which are not available here. As such, the reserve populations in the dataset are treated as individual populations where migration to other reserves is not possible.

Despite clear deficiencies in the accuracy of the data, this new panel is the best currently

[11]Robustness of results to this choice is examined in later sections.

available for analysis of poaching across Africa. This examination is novel and exploiting the panel structure of the data allows control over unobserved fixed effects which has previously been impossible.

3.3.2 Control Variables

It was found that the elephant population evolves over time due to,

$$x_{R,\tau+1} = x_{R,\tau} + r\left[1 - \frac{x_{R,\tau}}{K_R}\right]^{\theta} - T^{B}_{R,\tau} \tag{3.21}$$

In turn, $T^{B}_{R,\tau}$ was a function of the cost of poaching c, probability of capture λ, price p, time endowment of poachers $\bar{h}$, number of poachers N, and penalty if caught χ for reserve R relative to bordering reserves. These are the variables that require controls in the estimation framework. The majority of controls used are on a country-level as regional data local to the reserve was unavailable.

Controlling for price p is the most straightforward. Given the majority of ivory is sold to a single market in South East Asia, including time dummies in the regression will control for changes in ivory demand and price over time. Controlling for the penalty if caught χ requires data on historical poaching sentences which is hard to obtain for the panel. Given that these penalties are largely unchanged over time, country-level fixed effects should account for differences across countries.

The cost of poaching is dictated by elephant abundance. Therefore, the lagged elephant population and bordering elephant population are included as explanatory variables.

At its simplest, the remaining parameters (the probability of capture, and the time endowment of poachers) are both captured by the average income per capita in the country of question. The higher this income, the less time poachers devote to poaching $\bar{h}$ as the higher the opportunity cost of poaching. In addition, the higher the income, the more resources invested in anti-poaching patrols by the reserve owner. Data for GDP per capita is taken

Border Type	Mean	Variance	CV	N	P5	P25	P50	P75	P95
No Border	2483	6.19e+07	2.77	240	65	218	650	2018	11700
DR	10484	4.10e+09	6.11	440	145	596	2171	6028	37106
DR and IR	10555	4.76e+08	2.07	392	1581	4105	64	11547	42168
DR and IB	11869	1.52e+09	3.28	221	1366	3100	58	7845	37200
IR	4445	2.44e+08	3.51	136	66	330	986	3509	19366
IB	3316	2.48e+07	1.50	90	136	506	1424	3300	12844
IR and IB	10541	2.85e+08	1.60	5	1087	3120	3463	4390	40643
DR, IB and IR	9598	5.63e+08	2.47	17	10	1970	2597	5079	100743
All Reserves	7946	1.71e+09	5.21	1245	126	537	1920	5142	27000

Table 3.2: Summary statistics for reserve area, sorted by border type.

from the World Development Indicators and is measured at constant 2010 US$ prices (World Bank, 2018b).

The number of poachers N is captured by country fixed effects and population growth data. This data is also taken from the World Development Indicators (World Bank, 2018b).[12] Finally, for elephant populations in Sudan, data for Sudan is used up to the independence of the Republic of South Sudan in 2011. Thereafter, data for South Sudan is used (as this is where all of the elephant populations are located).

The distribution of reserve area is also heavily positively skewed. Distribution statistics for reserve area, sorted by border type, are displayed in Table 3.2. In the estimation that follows, elephant density is not used as the dependent variable. To do so would be to restrict the coefficient on reserve area to unity. However, there are numerous effects of area. Smaller reserve areas are thought to be correlated with lower carrying capacities, reducing the population growth rate. On the other hand, a given level of patrol spending is more effective over a smaller reserve area. Bordering reserve areas have symmetric effects. Thus, it is hard to find theoretical reasoning to restrict the coefficient and examine elephant density.

[12]This data was unavailable for Eritrea from 2012 to present due to the end of its relationship with the World Bank.

There is still concern that reserve area outliers may drive the results. However, the results are found to be robust to eliminating large or small reserves.

3.3.3 Estimation Framework

For each reserve i in country j the population of elephant evolves over time τ according to (3.21). Allowing reserve i to border k domestic reserves (DR as in Case 3), and m international reserves (IR as in Case 4) in n foreign countries, the regression model to be fitted is written,

$$\begin{aligned} x_{ij\tau} = \; & r + \beta_1 x_{ij\tau-1} + \beta_2 Area_{ij} + \beta_3 GDP_{j\tau} + \beta_4 Pop_{j\tau} + \beta_5 IB_{ij} \\ & + \beta_6 ({IB_{ij}}^* Pop_{n\tau}) + \beta_7 ({IB_{ij}}^* GDP_{n\tau}) + \beta_8 DR_{ij} + \beta_9 ({DR_{ij}}^* x_{kj\tau}) \\ & + \beta_{10} ({DR_{ij}}^* Area_{kj}) + \beta_{11} IR_{ij} + \beta_{12} ({IR_{ij}}^* x_{mn\tau}) + \beta_{13} ({IR_{ij}}^* Area_{mn}) \\ & + \beta_{14} ({IR_{ij}}^* GDP_{n\tau}) + \beta_{15} ({IR_{ij}}^* Pop_{n\tau}) + \alpha_j + \zeta_\tau + \epsilon_{ij\tau} \end{aligned} \tag{3.22}$$

where,

- $x_{ij\tau}$ is the log of the elephant population in reserve i in country j in year τ.
- $Area_{ij}$ is the log of the census area in reserve i in country j.
- $GDP_{j\tau}$ is log GDP per capita of country j in year τ.
- $Pop_{j\tau}$ is log population growth of country j in year τ.
- DR_{ij} is a dummy variable taking the value of 1 if reserve i borders another reserve k in the same country j, as in Case 3 above.
- IB_{ij} is a dummy variable taking the value of 1 if reserve i in country j lies on an international border with country n but does not border a reserve internationally, as in Case 2 above.
- IR_{ij} is a dummy variable taking the value of 1 if reserve i in country j borders another reserve m in a foreign country n, as in Case 4 above.

- r is a constant term.
- α_j is a country j level fixed effect.
- ζ_τ are a set of time (year) dummies.
- $\epsilon_{ij\tau}$ is a residual term. In estimation, these are clustered on the reserve-level.

In the case where multiple borders exist, an average of bordering variables is taken for each border type. As discussed, the lag of the elephant population census estimate is often missing and therefore the last available lag is used. For control variables, data is largely available for every time period. Therefore, an average of the control variable is taken across the elephant population observation period. Data for the neighbouring elephant population is taken to be the last observation that occurred before τ.

3.3.4 Hypotheses

The hypotheses derived from the model are now re-written using the coefficients in the above specification.

Hypothesis 1: *Poaching will be greater in reserves on an international border (ceteris paribus) than reserves within a country i.e.* $T_R^{IB} + T_R^{IB*} \geq T_R$. *This implies* $\beta_5 < 0$.

This effect is exacerbated if the number of poachers in the bordering country is large, $\beta_6 < 0$, or the time endowment of these poachers is higher. Given the link between time endowment and income, it is expected $\beta_7 > 0$.

Now, consider the case where a reserve R borders another reserve DR in the same country.

Hypothesis 2: *Poaching will be lower in reserves bordering another domestic reserve compared to a single reserve (ceteris paribus) i.e.* $T_R^{DR} \leq T_R$. *This implies* $\beta_8 > 0$.

In addition to the effects of income and population (which cannot be measured for the case of a domestic reserve as only country-level data is available), the larger the elephant

in the neighbouring domestic reserve DR, the lower the cost of poaching c_{DR}. Therefore, the larger the reduction in poaching in R as poachers choose to poach in DR instead, $\beta_9 > 0$.

Now, consider the case where a reserve R borders a reserve IR across an international border,

Hypothesis 3: *Poaching will be higher in reserves bordering another reserve across an international border i.e.* $T_R^{IR*} + T_R^{IR} > T_R$*, when either, (i) the relative foreign poacher population size is greater,* $\beta_{15} < 0$*, or (ii) the anti-poaching patrol effectiveness at the border is lower,* $\beta_{14} > 0$*, or (iii) the cost of poaching is sufficiently low in the reserve* R *relative to the bordering reserve* IR*,* $\beta_{12} > 0$.[13]

In addition, a fourth hypothesis is added. The population surrounding R increases poaching as there are more poachers. However, poaching falls as the income of poachers increases, because the opportunity cost of poaching is higher. Furthermore, reserves with higher income are expected to have more anti-poaching patrols.

Hypothesis 4: *Poaching in a reserve* R *is increasing in the surrounding population,* $\beta_4 < 0$*, and decreasing in the income of the surrounding population,* $\beta_3 > 0$.

It is harder to determine the sign of β_1. Whilst a larger population of elephant in R reduces the cost of poaching c_R, a larger population of elephant in the previous period will correlate to a larger population today. It is this second effect which is expected to dominate, $\beta_1 > 0$.

Finally, consider the effect of reserve area on the elephant population. Larger reserves tend to have higher carrying capacities supporting larger elephant populations. In addition, the same number of elephant spread over a larger area increasing the cost of poaching, $\beta_2 > 0$. The area of bordering reserves works with opposite effect. The larger the bordering reserve,

[13] No hypothesis is made on the coefficient β_{11} as poaching in R depends solely on the relative characteristics of the bordering international reserve.

the higher the cost of poaching, and therefore poaching in R becomes more profitable. This reduces the elephant population, $\beta_{13} < 0$ and $\beta_{10} < 0$.

3.3.5 Econometric Issues

The novelty in this work is through the assembly and use of a new panel of data to find empirical evidence for poaching across borders. This goes beyond existing studies which are often limited to descriptive statistics or case study evidence. The aim with this work is to use the best identification framework given the dataset at hand. Nevertheless there is no claim that the results represent 'clean identification'. A number of econometric issues remain with the specification. Often the data is not extensive enough to allow for the use of more complex econometric methods. Instead, in each case, a number of solutions are suggested in order to argue that the results found are robust. Additional details can be found in Appendix IV.

Unbalanced Panel Problem

As previously stated, the data is unbalanced across both the timing and the number of censuses in each reserve. Therefore problems summarised in Millimet and McDonough (2016) are encountered. For the large part, the unbalanced panel and associated issues are ignored. The unbalanced nature of the panel stems only from the elephant census data points. The majority of control variables are available in every year. Robustness of the results to the size of this observation period will be examined and ensured.

Dynamic Panel Problem

The specification entails a dynamic model of elephant populations which can lead to Nickell bias (Nickell, 1981). The dynamic specification allows for control of the demand side of the ivory market for which little data exists. Furthermore, exploiting dynamic variation allows for control of fixed effects. Nickell bias leads to an underestimation of the persistence in the dependent variable (the elephant population). In turn, this may lead to inconsistency in other estimators. The solutions suggested by Anderson and Hsiao (1981), Arellano and Bond (1990), Arellano and Bover (1995), and Blundell and Bond (1998), are not viable here,

for details see Appendix IV. Instead, the dynamic panel problem is mitigated (through the use of country-level instead of reserve-level fixed effects) but not explicitly treated.[14]

Spatial Simultaneity Bias

Given the specification suggested, there is a possibility of bias arising due to simultaneity in the model. This is because the reserve's population of elephant is a function of the bordering reserve's population of elephant. To a large degree this simultaneity bias is solved by the large observation periods in the data. Very rarely is the contemporaneous or lagged data point for the bordering elephant population available, and hence the last available observation is used. Whilst it is acknowledged that inconsistency may remain, the large part of the simultaneous bias is reduced.

3.4 Results

Table 3.3 displays the results from the main specification. Three variants are run: (A) has no control for neighbouring reserve elephant populations, (B) is the baseline specification as detailed in (3.22), and (C) excludes data from two ecosystems: the Okavango Delta, and the Maasai Mara and Serengeti. The reason for excluding these two ecosystems is due to the large amount migration between reserves (Thouless et al., 2016; Poole et al., 2016). This seasonal migration is in contrast with the assumptions of the model and presents issues when tracking reserve populations over time.

Significant border effects are found. In all three specifications, a reserve on an international border with no bordering reserve IB, experiences a statistically significant loss of elephant population over time compared to an identical reserve with no international border. The

[14] In order to clearly see border effects, a fixed effects specification on the reserve-level is not analysed and country-level fixed effects are used instead. One could obtain reserve-level fixed effects from a fixed effects specification and in turn regress these on the border variables. However, in this case the effect being measured would be whether a border type leads to a larger population of elephant in the reserve, not how the border type affects the evolution of the elephant population over time. For example, it might be that reserves with an international border have larger than average elephant populations to begin with. Thus, the effect of the border is positive when regressed on the fixed effect. However, if poaching is made easier due to the border then the effect of the border is negative when included in the specification above.

	(A) No Population		(B) Baseline		(C) No Okv/Mas	
$x_{ij\tau-1}$	0.496***	(0.000)	0.472***	(0.000)	0.493***	(0.000)
$Area_{ij}$	0.259**	(0.021)	0.306**	(0.011)	0.256**	(0.037)
$GDP_{j\tau}$	1.196+	(0.165)	0.906	(0.312)	1.324+	(0.101)
$Pop_{j\tau}$	-0.572+	(0.190)	-0.476	(0.251)	-0.447	(0.280)
IB_{ij}	-3.613**	(0.039)	-3.602*	(0.066)	-4.137**	(0.035)
$IB_{ij}{}^{*}GDP_{n\tau}$	0.434**	(0.038)	0.432*	(0.063)	0.506**	(0.034)
$IB_{ij}{}^{*}Pop_{n\tau}$	0.298	(0.572)	0.337	(0.547)	0.361	(0.498)
DR_{ij}	0.881	(0.292)	1.095+	(0.182)	1.024	(0.217)
$DR_{ij}{}^{*}x_{kj\tau}$			0.262***	(0.005)	0.227**	(0.014)
$DR_{ij}{}^{*}Area_{kj}$	-0.0776	(0.440)	-0.286**	(0.011)	-0.256**	(0.022)
IR_{ij}	2.246	(0.367)	2.725	(0.331)	2.000	(0.502)
$IR_{ij}{}^{*}x_{mn\tau}$			0.00318	(0.986)	0.0430	(0.828)
$IR_{ij}{}^{*}Area_{mn}$	-0.328**	(0.032)	-0.360+	(0.144)	-0.445+	(0.109)
$IR_{ij}{}^{*}GDP_{n\tau}$	0.112	(0.642)	0.102	(0.694)	0.171	(0.517)
$IR_{ij}{}^{*}Pop_{n\tau}$	-0.348	(0.728)	-0.495	(0.620)	0.311	(0.662)
Observations	433		433		423	
R^2 Overall	0.574		0.574		0.589	
R^2 Between	0.659		0.648		0.651	
R^2 Within	0.0424		0.0769		0.113	

Time effects and country fixed effects not shown.

Standard errors clustered on the reserve-level.

p-values in parentheses: $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.3: Baseline specification regression results. Dependent variable is log of the elephant population $x_{ij\tau}$. Statistically significant border effects are found. In all three specifications, a reserve on an international border with no bordering reserve IB experiences a significant loss of elephant population over time compared to an identical reserve with no international border. On the other hand, a reserve with a bordering domestic reserve DR loses fewer elephant over time relative to an identical reserve with no border. Whilst bordering an international reserve IR is found to have a positive effect on the elephant population (which is increasing in the population of elephant in the neighbouring reserve), this effect is statistically insignificant.

magnitude of this effect is large: an identical reserve with no border would on average expect to have an elephant population 2.5 times the size of a population in a reserve with an international border, controlling for past population levels. Therefore, from Hypothesis 1,

Empirical Result 1: *Poaching is greater in reserves on an international border (ceteris paribus) than reserves within a country i.e.* $T_R^{IB} + T_R^{IB*} \geq T_R$. *The magnitude of this effect is large: the reserve with no border would on average expect to have an elephant population 2.5 times the size of a population in a reserve with an international border.*

On the other hand, a reserve with a bordering domestic reserve DR loses fewer elephant over time compared to an identical reserve with no border. This beneficial effect is increasing in the elephant population of the bordering reserve. A 1% increase in the bordering reserve's population increases the elephant population in the reserve R by 0.26%. When the elephant population in DR is small, the effect is statistically insignificant. This was expected. When the bordering population is low, the cost of poaching is higher, and so poachers are more likely to poach in R. However, poaching will not increase unless there is an increase in the number of poachers. This can be seen in Figure 3.1. Therefore, from Hypothesis 2,

Empirical Result 2: *Poaching will be lower in reserves bordering another domestic reserve ceteris paribus i.e.* $T_R^{DR} \leq T_R$. *This suggests that poachers arbitrage across reserves. A 1% increase in the bordering reserve's DR population increases the elephant population in the reserve R by 0.26%.*

Finally, bordering an international reserve IR is found to have a positive effect on the elephant population (which is increasing in the population of elephant in the neighbouring reserve). Whilst the coefficients have the expected signs (with the exception of the population growth of the neighbouring country in Specification (C)) all are statistically insignificant at the 10% level. Therefore, Hypothesis 3 cannot be rejected.

Empirical Result 3: *The relevant coefficients were statistically insignificant and so it is*

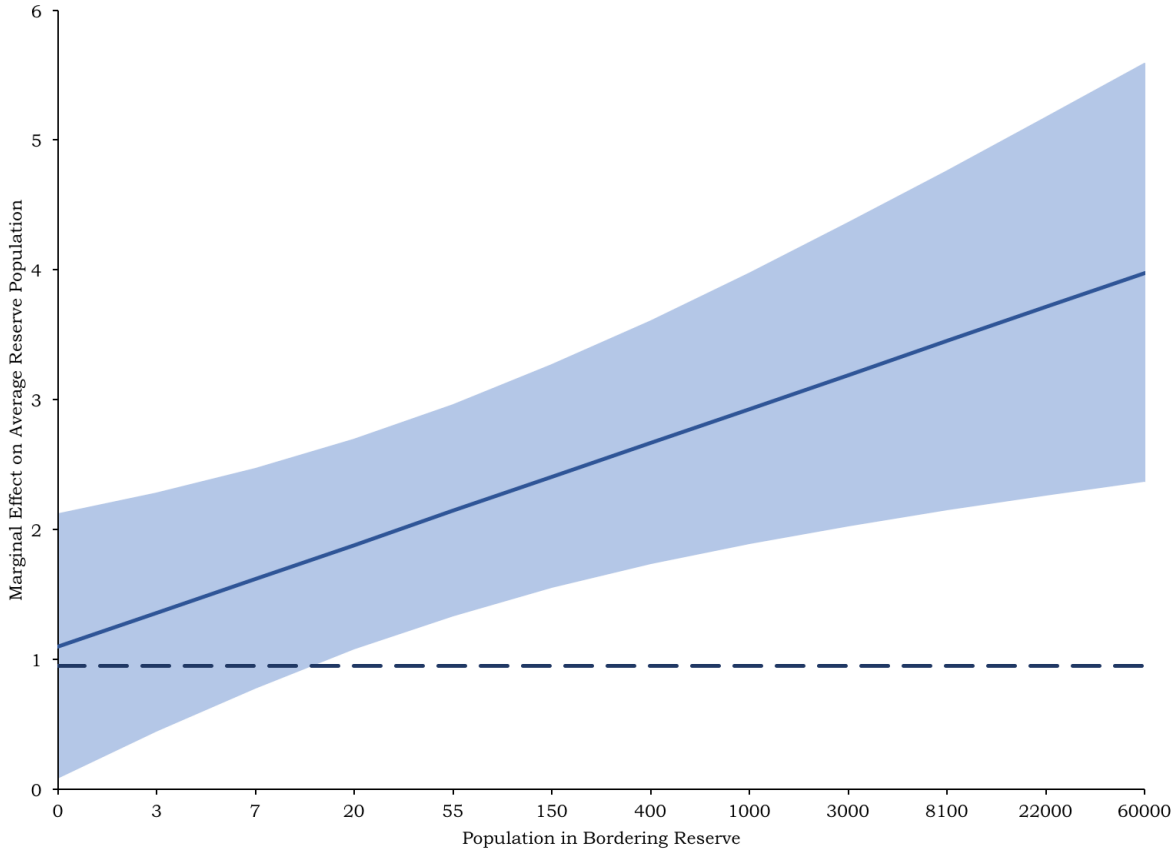


Figure 3.1: Marginal effects plot showing how the average population of a reserve is affected by the population of elephant in a bordering reserve. The marginal effect is the solid line (with shaded 95% confidence bound). The dotted line dictates significance over a no border case. A border with DR results in higher average elephant populations than a reserve without borders, but only when the elephant population in DR is sufficiently high. In other words, when poaching is profitable across the two reserves, there is an arbitrage option for poachers.

unclear as to whether poaching may be lower or greater in reserves bordering an international reserve (ceteris paribus) i.e. $T_R^{IR} + T_R^{IR*} \gtrless T_R$. *This ambiguity was predicted by the model.*

The negative effect of an international border IB can be mitigated by the wealth of the bordering nation. A 1% increase in the bordering nation's GDP per capita increases the elephant population in R by 0.43%.[15] However, for the mean GDP per capita of a bordering nation in the sample, this is not enough to offset the negative effect of the border. In addition, a 1% increase in GDP per capita of a nation with reserve R increases the elephant population by 0.9%.[16] Finally, wealth works to increase the benefit of a border with an international reserve. This suggests that, as wealth increases, the effect of reducing foreign poacher's time dedicated to poaching outweighs the effect of increasing anti-poaching patrols in IR (making R more profitable for poachers). Overall this effect is statistically insignificant.

Increasing population growth by 1% reduces the elephant population by 0.47%.[17] The direction and magnitude is similar when examining the effect of a foreign population on a reserve with a bordering international reserve. Across international borders with no reserve, population growth has a puzzling positive effect. However, in all cases the effect is rarely statistically significant. Tentatively, this provides some support to Hypothesis 4,

Empirical Result 4: *Poaching in a reserve R is increasing in the surrounding population,* β_4. *Increasing population growth by 1% reduces the elephant population by 0.47%. Poaching is decreasing in the income of the surrounding population,* β_3. *A 1% increase in GDP per capita increases the elephant population by 0.9%. However, these effects were rarely statistically significant at the 10% level.*

[15] This effect is statistically significant at the 5% level.

[16] This effect is statistically insignificant at the 10% level but statistically significant at the 20% level in all but the baseline Specification (B).

[17] This effect is statistically insignificant at the 10% level.

Reserve areas also significantly affect the elephant population. The area of the reserve has a statistically significant positive effect as the larger the area, the larger the carrying capacity, and the larger the elephant population growth. Furthermore, the larger the area, the harder it is for a poacher to find an elephant to poach, and the higher the cost of poaching. Larger areas of bordering reserves have negative effects - by increasing the poaching cost (for a given elephant population), poaching becomes relatively more attractive in R.

Whilst this model allows for estimation and identification of the key border effects, it has its limitations. The model excels at explaining why some elephant populations are large and others are small: explaining around 60% of the total variation in the data. It shows that borders play a key role in this variation. The specification does less well at explaining variation around these level effects: explaining only 10% of within variation in the model. This isn't particularly surprising given the data used. There is little regional level data, so multiple reserves in the same country have the same control variables. Furthermore, the long observation periods contribute to the lack of within variation.

3.4.1 Time Effects

An intriguing question is what drives the average changes in elephant population and poaching over time? The annual time effects derived from the baseline specification are saved and used as the dependent variable in a time series regression. They are regressed on the log of Chinese GDP per capita (World Bank, 2018b) and the log of the annual average gold price (World Bank, 2018a). Given China is the largest consumer of elephant ivory, it is expected that Chinese GDP per capita will reduce the average elephant population each period. Meanwhile, gold is an alternative commodity for investment and has been used as an instrumental variable for the black market ivory price (Do et al., 2017). Therefore it is expected to have a negative effect on the average elephant population. Both of these explanatory variables are found to follow unit root processes. Therefore, the stationary, differenced variables are used as regressors along with a time trend.

	Time Effects	
ΔLn(Chinese GDPpc)	-15.90**	(0.010)
ΔLn(Gold Price)	0.846	(0.444)
Time Trend	-0.0890***	(0.001)
Constant	2.692***	(0.000)
Observations	21	
R^2 Overall	0.551	
$F(3, 17)$	13.51	

p-values in parentheses

$^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.4: Time effects regression results. Dependent variable is the annual time effect derived from Specification (B). The change in log of Chinese GDP per capita is found to reduce the average elephant population across reserves in Africa. This effect is statistically significant at the 5% level and 55% of the variation in the time effects is explained.

The change in log of Chinese GDP per capita is found to reduce the average elephant population across reserves in Africa. This effect is statistically significant at the 5% level and 55% of the variation in the time effects is explained. This provides credence that the changes in elephant population are predominantly driven by poaching. It is unsurprising that Chinese GDP per capita should be such a significant factor. The change in log in gold price is found to be statistically insignificant.

In addition, it is argued that the two approved legal sales of ivory from stockpiles in 1999 and 2008 have worked to increase poaching, see Hsiang and Sekar (2016). Meanwhile other owners have publicly burned ivory to send the message that it should not be consumed. The quantity of ivory burned each period (and its lag) and two dummy variables noting the announcements and legal sales of stockpiled ivory respectively were included in the time effects regression. However, all were found to be statistically insignificant. Despite this, a Wald breakpoint test for a structural break in 2008 was found to be statistically significant. This corresponds to the large increase in poaching which Hsiang and Sekar (2016) argue came from the legal sale.

3.5 Conflict

Human conflict, elephant poaching, and illicit ivory sales have a long and extensive history, often with disastrous consequences for nearby elephant populations. In Zakouma National Park in Chad, Sudanese rebels on horseback have poached elephant to fund military options since 2002 (Nuwer, 2018). There is widespread evidence that Joseph Kony uses elephant poaching in Garamba National Park in the Democratic Republic of Congo to fund the Lord's Resistance Army (Agger and Hutson, 2013). Originally based in the park itself, it is now thought that the remnants of the LRA are in Kafia Kingi in South Sudan, sending poaching expeditions across the border into Garamba (Laing, 2016). In 2012, the LRA and associated rebel groups accounted for the majority of illicit trade in ivory in all of Central Africa, and were thought to be responsible for large increases in poaching in the Central African Republic, Gabon, Cameroon, Chad, The Republic of Congo, and the Democratic Republic of Congo (UN, 2013).

The association between poaching elephant and conflict is not just a case of finance. During the Rwandan civil war, the Virunga National Park saw an upsurge in poaching for bushmeat and income as 860,000 refugees settled nearby (Humphreys and Smith, 2011). Here, the consequences for elephant populations were not limited to poaching, with large scale deforestation destroying elephant habitat (Beyers et al., 2011). Surrounding the Okapi Faunal Reserve in Eastern Democratic Republic of Congo, during the conflict in 1996, hunter communities appeared, poaching elephant from the park to sell meat and ivory to local militia forces based in the area. Later, in 2000, deserters from the Ugandan backed rebels set up poaching camps in the same area (ibid.). However, the links are not always negative. Elephant populations actually rose in Rhodesia in the mid-1960s to the 1980s as militant groups fought the regime (Sommerville, 2017). Their operations in the wilderness presented danger for hunters seeking to poach elephant. However, anecdotal evidence suggests this is an exception.

The problem is that elephant habitat in game reserves and national parks provide areas of strategic value for modern guerilla warfare (Ellis, 1994). The use of national parks for mili-

tary camps is common too. For example, the Kruger National Park was used as a training camp for the South African Defence Force (SADF) to train The Mozambique Resistance Movement (RENAMO) during the Mozambique civil war (Annecke and Masubelele, 2016). In these cases, elephant populations are collateral damage. RENAMO set up headquarters in the Gorongosa National Park which as a consequence saw a 90% reduction in all wildlife during the civil war. The rebels poached elephant for bushmeat and ivory to fund munition purchases. A country-wide shortage of food meant government troops poached for bushmeat too (Barosso, 2012).

As a final example, consider the Gonarezhou Area, now a transfrontier park between Zimbabwe and Mozambique. Here, elephant (and rhino) used to be abundant. Poaching by the Shangaan people in the early 1980s was minimised as conservationists worked with the communities towards a sustainable use policy. Then the conflict in Mozambique saw large troop movements through the park. Zimbabwean soldiers poached under the pretence of counter-insurgency operations (Sommerville, 2017). RENAMO also operated under SADF training and instructions to smuggle ivory into South Africa. Other Mozambican gangs poached ivory to sell for food in nearby countries due to the famine in Mozambique. The elephant population collapsed as over 1000 were poached towards the end of the 1980s (ibid.).

Conflict is included in the specification to see if this effect manifests itself in the panel of reserves across Africa. In the context of the model, it can be thought that conflict leads to a reduction in protection for elephant and therefore the cost of poaching. In addition, conflict may work to increase the time allocated to poaching by poachers. Hence, it is expected that elephant populations will be negatively affected by domestic conflict. The border effect is harder to predict. Conflict in a neighbouring country might increase the profitability of poaching across the border, resulting in a beneficial effect to the domestic population. On the other hand, it may increase the time allocated to poaching by foreign poachers, resulting in an increase in poaching domestically. Therefore in cases where conflict occurs across a border with no reserve, the second effect dominates and poaching is expected to increase. In cases where a reserve does exist across the border, the population change due to conflict

will depend on which of these effects dominate.

Country-level conflict data from the Major Episodes of Political Violence (1946-2016) dataset by the Integrated Network for Societal Conflict Research (INSCR) is used (Center for Systemic Peace, 2018). Major episodes of violence are defined as those that cause more than 500 deaths over the span of the conflict. Each episode is classified into civil, ethnic, or international conflict categories. In turn, the magnitude of the impact of the violence is attributed a score between 0-10. This data is reported annually.[18] The raw data is simplified through aggregating civil and ethnic violence into a single variable measuring domestic conflict.

The results for conflict are exhibited in Table 3.5. Before examining the effects of conflict it is noted that the border effect results continue to hold both in magnitude and statistical significance. In Specification (D) international conflict IC and domestic conflict DC are aggregated into total conflict TC, before being separated in Specification (E). Separating conflict into domestic and international conflict shows that it is domestic conflict which is the statistically significant factor. The statistically insignificant and often positive coefficients on international conflict reflect the lack of international conflict in the data set (only three episodes occur in the data: between Uganda and Rwanda 1996-2002, Eritrea and Ethiopia 1998-2000, and Mauritania and Senegal 1989-1991). Hence, Specification (F) only contains domestic conflict.

It is shown that conflict significantly reduces elephant populations, particularly across borders. Conflict in the same country as a reserve R is found to have a negative effect on the elephant population. A one point increase on the conflict scale reduces the elephant population by approximately 6%. This was expected and ties into the case of Gorongosa National Park discussed previously. The park is of strategic value to conflict and poaching increases because conflict results in (i) less protection for elephant, (ii) increased demand

[18]If more than one episode occurs in the year then the score is aggregated.

	(D)		(E)		(F)	
	Total Conflict		Domestic and International Conflict		Domestic Conflict	
$x_{ij\tau-1}$	0.485***	(0.000)	0.492***	(0.000)	0.485***	(0.000)
$Area_{ij}$	0.258**	(0.038)	0.255**	(0.040)	0.259**	(0.037)
$GDP_{j\tau}$	1.161^{+}	(0.199)	1.186	(0.202)	1.087	(0.224)
$Pop_{j\tau}$	-0.458	(0.278)	-0.396	(0.346)	-0.421	(0.320)
$TC_{j\tau}$	-0.0669	(0.615)				
$DC_{j\tau}$			-0.137	(0.339)	-0.141	(0.317)
$IC_{j\tau}$			0.296	(0.535)		
IB_{ij}	-3.961**	(0.045)	-3.925**	(0.048)	-3.969**	(0.045)
$IB_{ij}{}^{*}GDP_{n\tau}$	0.490**	(0.043)	0.495**	(0.039)	0.497**	(0.040)
$IB_{ij}{}^{*}Pop_{n\tau}$	0.387	(0.468)	0.295	(0.616)	0.344	(0.507)
$IB_{ij}{}^{*}TC_{n\tau}$	-0.105	(0.339)				
$IB_{ij}{}^{*}DC_{n\tau}$			-0.132	(0.253)	-0.127	(0.265)
$IB_{ij}{}^{*}IC_{n\tau}$			0.156	(0.769)		
DR_{ij}	1.062	(0.207)	1.106^{+}	(0.195)	1.101^{+}	(0.193)
$DR_{ij}{}^{*}x_{kj\tau}$	0.233**	(0.012)	0.235**	(0.012)	0.236**	(0.011)
$DR_{ij}{}^{*}Area_{kj}$	-0.270**	(0.018)	-0.279**	(0.017)	-0.279**	(0.015)
IR_{ij}	2.700	(0.385)	3.044	(0.335)	3.079	(0.327)
$IR_{ij}{}^{*}x_{mn\tau}$	0.0364	(0.856)	0.0252	(0.901)	0.0289	(0.886)
$IR_{ij}{}^{*}Area_{mn}$	-0.426^{+}	(0.141)	-0.399^{+}	(0.178)	-0.404^{+}	(0.172)
$IR_{ij}{}^{*}GDP_{n\tau}$	0.0684	(0.815)	0.0260	(0.930)	0.0195	(0.947)
$IR_{ij}{}^{*}Pop_{n\tau}$	0.350	(0.567)	0.202	(0.768)	0.233	(0.717)
$IR_{ij}{}^{*}TC_{n\tau}$	-0.203	(0.204)				
$IR_{ij}{}^{*}DC_{n\tau}$			-0.326*	(0.050)	-0.322**	(0.049)
$IR_{ij}{}^{*}IC_{n\tau}$			0.0176	(0.969)		
Observations	423		423		423	
R^2 Overall	0.592		0.594		0.593	
R^2 Between	0.654		0.656		0.654	
R^2 Within	0.117		0.119		0.121	

Time effects and country fixed effects not shown.

Standard errors clustered on the reserve-level.

p-values in parentheses: $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.5: Conflict specification regression results. Dependent variable is log of the elephant population $x_{ij\tau}$. It is shown that conflict significantly reduces elephant populations, particularly across borders. Conflict in the same country as a reserve R is found to have a negative effect on the elephant population. When conflict occurs across the international border with no bordering reserve IB, a one point increase on the conflict scale reduces the elephant population in R by approximately 10% (the effect is statistically insignficant). When conflict occurs across the international border with a bordering reserve IR, a one point increase on the conflict scale reduces the elephant population in R by approximately 20% (statistically significant at the 5% level).

for bush meat when local economies collapse, and (iii) a munitions trade which illicit ivory can finance. However, this effect is statistically insignificant.

When conflict occurs across the international border with no bordering reserve IB, a one point increase on the conflict scale reduces the elephant population in R by approximately 10% (the effect is statistically insignificant). Again, this was expected as in the case of Garamba National Park. Here, the dedicated time to poaching increases as ivory is used to finance conflict across the border. Displaced populations may also contribute to the increase in poaching.

Finally, when conflict occurs across the international border with a bordering reserve IR, a one point increase on the conflict scale reduces the elephant population in R by approximately 20% (statistically significant at the 5% level). This suggests that the rise in time dedicated to poaching outweighs the substitution effect across the border. Alternatively, perhaps international enforcement is important and conflict reduces the probability of capture for crossing the border as patrols are abandoned. This was certainly the case in the Gonarezhou Area during the Mozambique civil war.

3.6 Policy Implications

Given reserves cannot be moved, what are the consequences of this analysis to the policy maker? Is the situation futile and some reserves are simply prisoners of geography? To some extent, yes. Reserves on an international border are harder to police than reserves which are not. However, the extent to which the border has a negative effect on the elephant population can be mitigated by neighbouring policy. The wealth of foreign citizens, the amount of conflict, and anti-poaching policy all affect the amount of poaching. The policy consequence here is clear: even if the neighbouring country has no elephant of its own, their domestic policy towards poaching still matters for elephant conservation.

Whilst CITES governs international conservation policy, domestic policy remains up to the

discretion of member states. The probability of capture and anti-poaching patrols are crucial in altering poacher behaviour. Elephant poaching is an international problem, the border does matter, and therefore countries need to work together to avoid the negative externality of bordering policy. This is not a novel conclusion, and it is recognised that in practice this is much easier said than done. Nevertheless, further progress in negotiations towards transfrontier policy coordination on this matter is essential to solve the problem.

In addition, there is a need for policy coordination across reserves within a country. The results suggest poachers arbitrage across reserves when profit maximising. As a result, the failure of policy coordination across owners and reserves can quickly lead to the significant loss of one elephant population. This may have been observed in South Africa. Here the large militarisation in the Kruger National Park to prevent rhino poaching has worked to reduce poaching. However, the Hluhluwe-iMfolozi Reserve nearby has experienced an increase in poaching as poachers may have arbitraged across reserves.

A final plea is made to researchers to revise their policy of restricting access to valuable elephant data. Measuring and recording elephant populations is difficult and costly, and presumably the time and budget could instead be used to increase patrols. However, analysing data helps shed light on the bigger picture for elephant. Moves have been made to this end with the implementation of MIKE and PIKE, and the Great Elephant Census. Yet, the data that does exist is still guarded closely by researchers, NGOs, or governments. It is not clear why this is. Whilst there are obvious dangers to publishing new spatial data on elephant ranges and migration patterns, historic data has little value to the poacher. However, it is the potential poacher access to the data which is often used as the excuse for concealing the data. The work here is, to the researcher's knowledge, the first to attempt to put together a panel of data across Africa on the subject. It scratches the surface on the potential empirical work which could be done to help policy makers devise a solution to the growing problem. The more research in this field, the better, and that starts with data access.

3.7 Conclusion

The recent increase in poaching has led to increasingly fragmented elephant populations. This has the consequence of generating large differences in conservation policy across reserves and national borders. In Chapters One and Two, a single owner and population of animals was considered in the design of optimal conservation policy. However, this clearly does not account for the effects of neighbouring policy. This chapter sought to empirically examine the effects of differences in conservation policy across these borders, and the consequences for poaching.

A new panel of data detailing elephant populations for 1,262 reserves across 37 countries in Africa is assembled from Elephant Status Reports. Using this panel, the effects of reserve borders on elephant population trends in Africa is examined. To the author's knowledge, this is the first reserve-level panel of elephant population data empirically examined in the field since the ivory trade ban. Significant border effects are found. An international border results in an elephant population up to 2.5 times smaller than a reserve without a border. In addition, evidence that poachers arbitrage across reserves within the same country is found. It is also found that conflict significantly reduces elephant populations, particularly across international borders.

The policy consequence is clear: as populations become increasingly fragmented, transfrontier conservation policy becomes more important. This has further implications for CITES. It is becoming increasingly apparent that CITES should be used as an institution to coordinate domestic policy, as well as international policy when it comes to endangered species. In addition, there is a need for policy coordination across reserves within a country.

It is recognised a number of econometric issues remain unaddressed in this study. However, the contribution of this work is to assemble a new panel of data and to begin to empirically estimate these effects, building on the existing literature which often uses case study or descriptive statistic evidence. A plea is made to other researchers' policy on elephant data. The more research in this field, the better, and that starts with data access.

3.8 Appendix I

3.8.1 Proof that Poaching Falls in Case 3

Poaching is higher in Case 3 than Case 1 when,

$$\frac{N'}{N} > \frac{\pi_R \left(1 + 2\frac{\lambda_{DR}}{\lambda_R}\right) + \pi_{DR} - 2\lambda_{DR}\chi\bar{h}}{\pi_R - \pi_{DR} + 2\lambda_{DR}\chi\bar{h}}$$

When $N = N'$ this collapses to,

$$\bar{h} > \frac{\pi_R}{2\chi\lambda_R} + \frac{\pi_{DR}}{2\chi\lambda_{DR}}$$

The number of poaching attempts in Case 1 is,

$$h_R = \frac{\pi_R}{2\chi\lambda_R} \leq \bar{h}$$

Therefore, the only $\bar{h}$ to make both of these choices feasible is when,

$$\bar{h} = \frac{\pi_R}{2\chi\lambda_R}$$

This corresponds to no poaching attempts in DR and the same number of poaching attempts in R as previously shown. Therefore, poaching cannot fall when $N = N'$.

3.9 Appendix II

3.9.1 Additional Figures

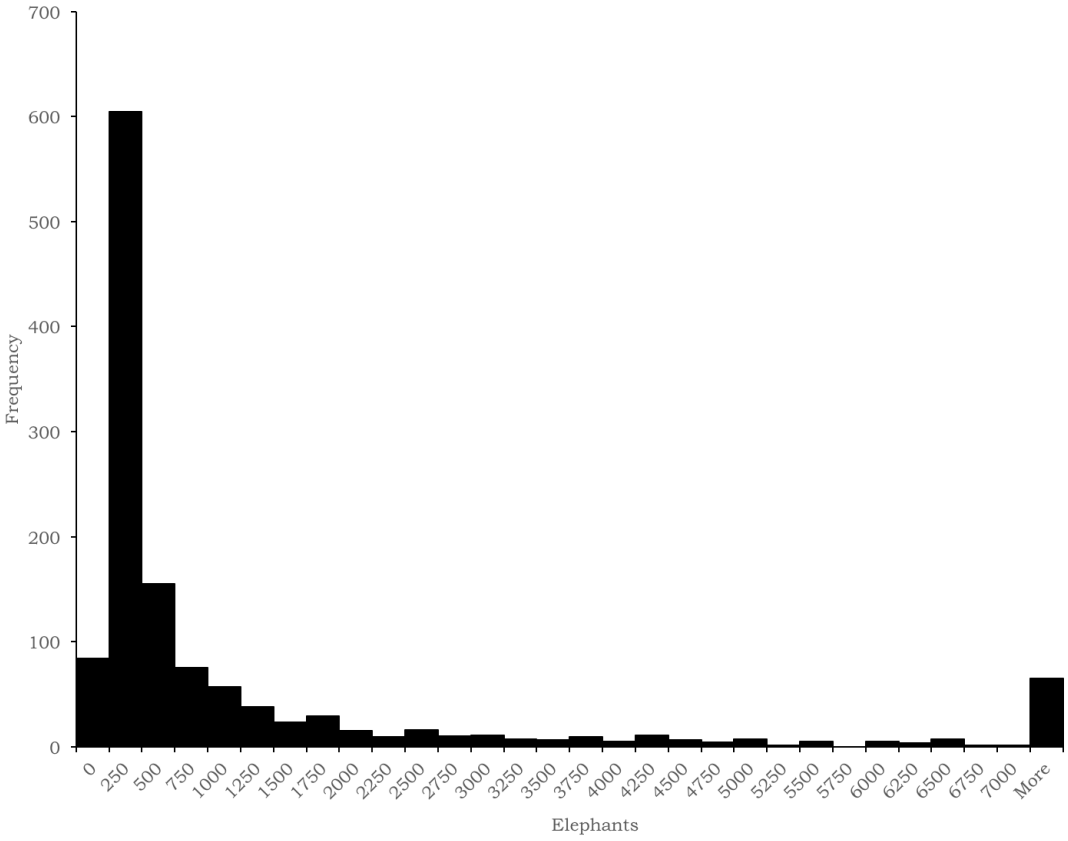


Figure 3.2: Histogram of elephant populations across reserves.

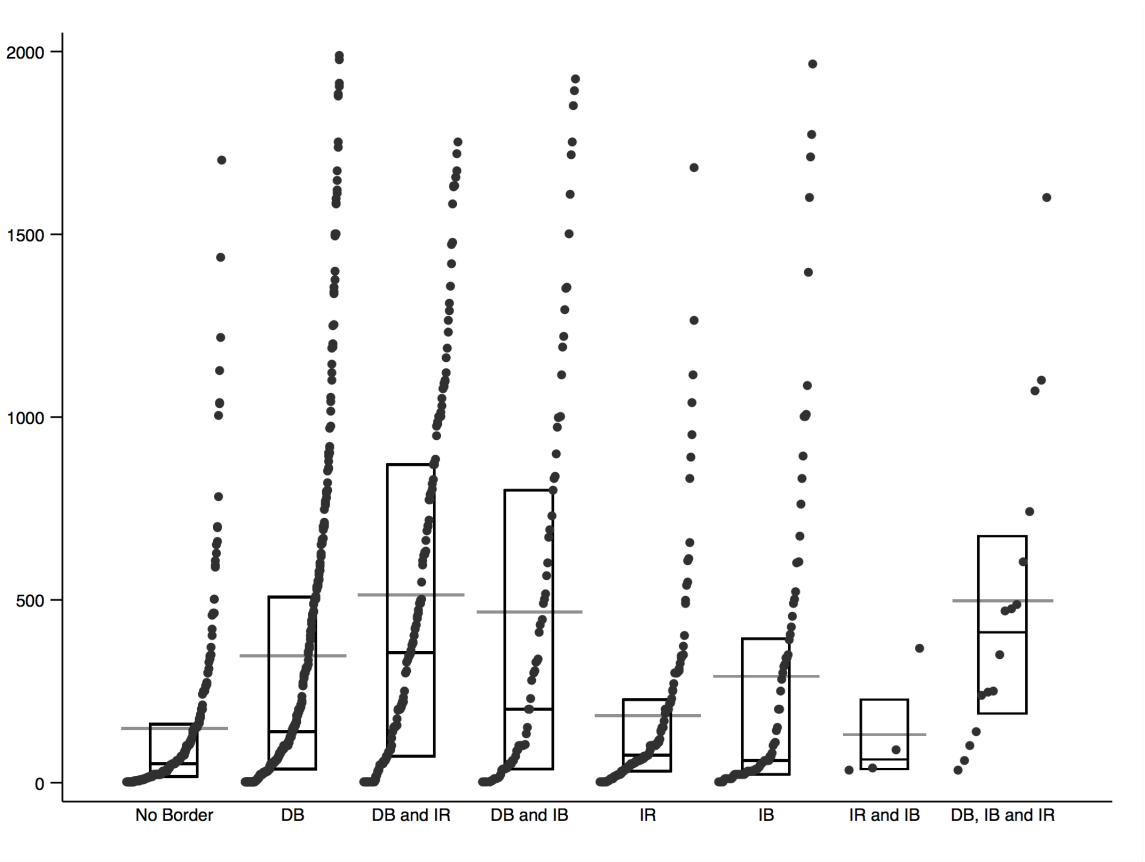


Figure 3.3: Box plot and distribution of elephant populations across reserves, categorised by border type. The wide grey line indicates the mean in each case. The y-axis is the elephant population in the reserve.

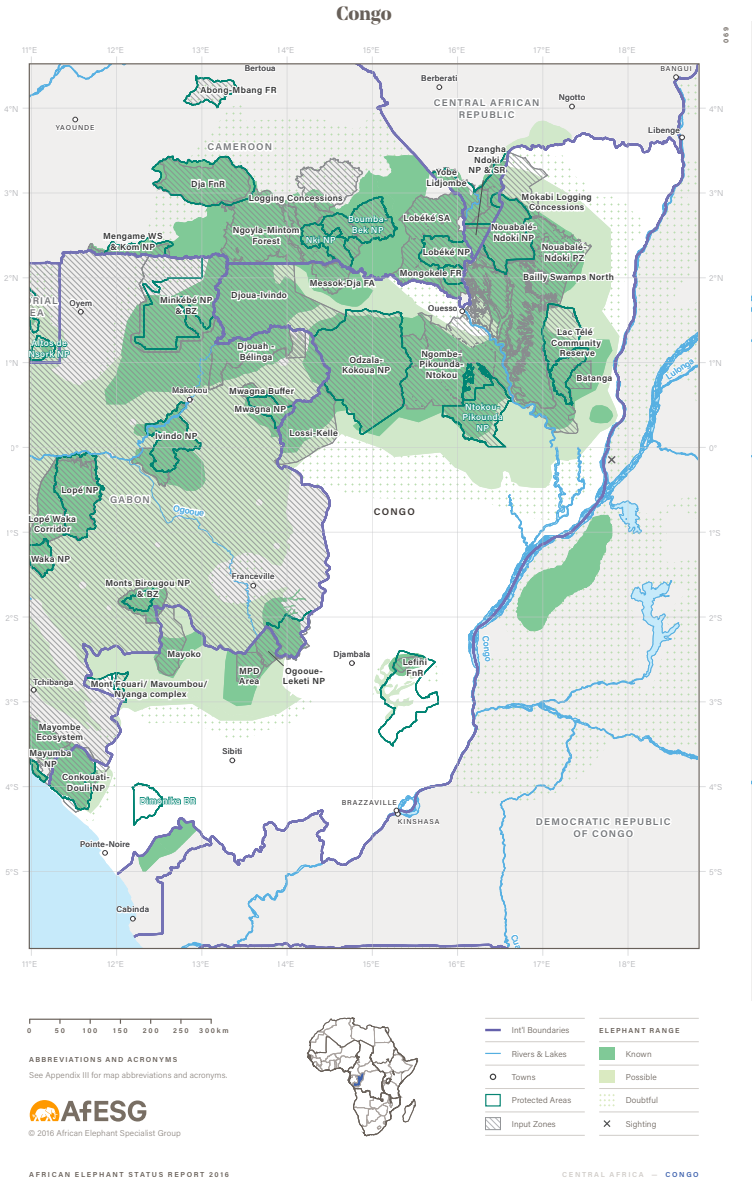


Figure 3.4: Excerpt from specialist group report showing elephant range data for Congo. (C.R. Thouless, H.T. Dublin, J.J. Blanc, D.P. Skinner, T.E. Daniel, R.D. Taylor, F. Maisels, H.L. Frederick and P. Bouché (2016). African Elephant Status Report 2016: an update from the African Elephant Database. Occasional Paper Series of the IUCN Species Survival Commission, No. 60 IUCN/SSC African Elephant Specialist Group. IUCN, Gland, Switzerland. Shared in accordance with the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License, Link: https://creativecommons.org/licenses/by/4.0/)

3.10 Appendix III

3.10.1 Further Robustness Checks

In this section the results are shown to be robust across a number of checks. As a reminder, the results are,

Empirical Result 1: *Poaching is greater in reserves on an international border (ceteris paribus) than reserves within a country i.e.* $T_R^{IB} + T_R^{IB*} \geq T_R$. *The magnitude of this effect is large: the reserve with no border would on average expect to have an elephant population 2.5 times the size of a population in a reserve with an international border.*

Empirical Result 2: *Poaching will be lower in reserves bordering another domestic reserve ceteris paribus i.e.* $T_R^{DR} \leq T_R$. *This suggests that poachers arbitrage across reserves. A 1% increase in the bordering reserve's DR population increases the elephant population in the reserve R by 0.26%.*

Empirical Result 3: *The relevant coefficients were statistically insignificant and so it is unclear as to whether poaching may be lower or greater in reserves bordering an international reserve (ceteris paribus) i.e.* $T_R^{IR} + T_R^{IR*} \gtrless T_R$. *This ambiguity was predicted by the model.*

Empirical Result 4: *Poaching in a reserve R is increasing in the surrounding population,* β_4. *Increasing population growth by 1% reduces the elephant population by 0.47%. Poaching is decreasing in the income of the surrounding population,* β_3. *A 1% increase in GDP per capita increases the elephant population by 0.9%. However, these effects were rarely statistically significant at the 10% level.*

First, consider limiting the observation period in the unbalanced panel. Limiting to ten years entirely eliminates reserves in Angola, Chad, Guinea-Bissau, Liberia, Rwanda, Sierra Leone, and South Sudan, in addition to observations in other countries. This is a total loss

of 152 observations and 95 reserves relative to the baseline case. Limiting the observation period to five years sees the further loss of all reserves in Central African Republic, Republic of Congo, Ethiopia, Nigeria, and Togo. This is a total loss of 314 observations and 157 reserves compared to the baseline case.

However, in both cases the results remain largely robust. Result 1 holds when the observation period is limited to ten years. The GDP of the bordering country remains a statistically significant factor. However, when limited to five years the coefficient is no longer statistically significant, and switches sign. This is unsurprising. Limiting the observation period removes reserves where data collection has been disrupted by conflict or is not prioritised (perhaps due to cost) which might be indicative of poorer management. Meanwhile Result 2 remains robust in both cases. The population of elephant in the bordering reserve remains statistically significant indicating that the relative profitability between reserves is the key factor. Result 3 is maintained as no statistical significance is found in any specification, including the baseline. Result 4 is also unchanged across observation period restrictions. The within explanatory power of the model unsurprisingly increases with the fall in the observation period. However, the overall R^2 falls.

Next, restrictions placed on the size of elephant population in each reserve are shown to have no effect. Due to the skew in the distribution of elephant across reserves, only reserves with fewer than 7000 elephant (corresponding to the approximate 95^{th} percentile) are used in analysis. Removing this restriction leads to no change in the magnitude or statistical significance of the coefficients. Robustness to the treatment of extinction is also analysed. Eliminating observations where the population of elephant is zero removes all observations in Angola, Guinea Bissau, and South Sudan. A total of 45 observations in 29 reserves are lost, compared to the baseline case. Result 1 remains robust in magnitude but not in statistical significance. Again, this unsurprising. The majority of reserves where extinction occurs are on an international border with no bordering reserve. Result 2 is also robust and the bordering population remains a statistically significant factor dictating relative profitability across reserves. Result 3 holds as variables relating to reserves bordering other international

reserves are still statistically insignificant.

Finally, the results are robust to the inclusion of climate and agriculture controls. Table 3.6 exhibits the results. Agriculture is included because elephant are often killed as revenge for crop damage. The inclusion of agriculture (% of GDP output) does not change the results (World Bank, 2018b). However, puzzlingly, agriculture has a positive effect on elephant populations which is statistically significant at the 10% level. This might be because the ecology that supports large elephant populations also supports productive agriculture. Specification (I) includes country-level rainfall and temperature as controls (World Bank, 2017). Again, the results remain similar. The main difference is the large change in magnitude of the negative effect of an international border with no reserve. This was found to be largely due to the reduction in observations due to missing climate data.

3.10.2 Differenced Specification

Whilst country-level fixed effects are used throughout the analysis, there is still concern that reserve-level fixed effects may exist. To remove the reserve-level fixed effect, a differenced specification shall be estimated. This specification is written,

$$\begin{aligned}\Delta x_{ij\tau} = \; & \gamma_1 \Delta GDP_{j\tau} + \gamma_2 \Delta Pop_{j\tau} + \gamma_3 ({IB_{ij}}^* \Delta GDP_{n\tau}) + \gamma_4 ({IB_{ij}}^* \Delta Pop_{n\tau}) \\ & + \gamma_5 ({DR_{ij}}^* \Delta x_{kj\tau}) + \gamma_6 ({IR_{ij}}^* \Delta x_{mn\tau}) + \gamma_7 ({IR_{ij}}^* \Delta GDP_{n\tau}) \\ & + \gamma_8 ({IR_{ij}}^* \Delta Pop_{n\tau}) + \Delta\zeta_\tau + \Delta\epsilon_{ij\tau}\end{aligned} \tag{3.23}$$

The advantage of this specification is that it removes unobserved reserve-level fixed effects, vastly improving the within fit of the model. However, the disadvantage is that the effect of the border is harder to observe as it is removed by differencing. Therefore, Result 1 cannot be examined. However, the effect of changes in variables across the border can still be estimated. Generating changes in variables for the differenced specification with the unbalanced panel is challenging. This is solved by taking the difference from the last available data point and averaging across the observation period to find the average annual difference.

	(G) Baseline		(H) Agriculture		(I) Climate Variables	
$x_{ij\tau-1}$	0.472***	(0.000)	0.471***	(0.000)	0.499***	(0.000)
$Area_{ij}$	0.306**	(0.011)	0.304**	(0.011)	0.251*	(0.053)
$GDP_{j\tau}$	0.906	(0.312)	0.801	(0.381)	0.989	(0.365)
$Pop_{j\tau}$	-0.476	(0.251)	-0.850*	(0.085)	-0.289	(0.486)
$Agric_{j\tau}$			0.104*	(0.069)		
$Rain_{j\tau}$					1.274	(0.470)
$Temp_{j\tau}$					30.97+	(0.101)
IB_{ij}	-3.602*	(0.066)	-3.697*	(0.084)	-16.03+	(0.137)
$IB_{ij}{}^{*}GDP_{n\tau}$	0.432*	(0.063)	0.416*	(0.076)	0.609*	(0.058)
$IB_{ij}{}^{*}Pop_{n\tau}$	0.337	(0.547)	0.285	(0.591)	0.998	(0.239)
$IB_{ij}{}^{*}Agric_{n\tau}$			0.00600	(0.647)		
$IB_{ij}{}^{*}Rain_{n\tau}$					-0.507	(0.523)
$IB_{ij}{}^{*}Temp_{n\tau}$					4.388+	(0.176)
DR_{ij}	1.095+	(0.182)	1.128+	(0.174)	1.169	(0.303)
$DR_{ij}{}^{*}x_{kj\tau}$	0.262***	(0.005)	0.265***	(0.005)	0.276**	(0.013)
$DR_{ij}{}^{*}Area_{kj}$	-0.286**	(0.011)	-0.289**	(0.012)	-0.302**	(0.023)
IR_{ij}	2.725	(0.331)	2.612	(0.371)	-0.0373	(0.998)
$IR_{ij}{}^{*}x_{mn\tau}$	0.00318	(0.986)	-0.0300	(0.872)	0.00746	(0.972)
$IR_{ij}{}^{*}Area_{mn}$	-0.360+	(0.144)	-0.303	(0.246)	-0.493+	(0.139)
$IR_{ij}{}^{*}GDP_{n\tau}$	0.102	(0.694)	0.126	(0.652)	0.379	(0.346)
$IR_{ij}{}^{*}Pop_{n\tau}$	-0.495	(0.620)	-0.632	(0.537)	-0.805	(0.541)
$IR_{ij}{}^{*}Agric_{n\tau}$			-0.00431	(0.740)		
$IR_{ij}{}^{*}Rain_{n\tau}$					-0.398	(0.632)
$IR_{ij}{}^{*}Temp_{n\tau}$					1.567	(0.704)
Observations	433		433		351	
R^2 Overall	0.574		0.577		0.592	
R^2 Between	0.648		0.652		0.655	
R^2 Within	0.0769		0.0831		0.135	

Time effects and country fixed effects not shown.

Standard errors clustered on the reserve-level.

p-values in parentheses: $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.6: Robustness specification regression results. Dependent variable is log of the elephant population $x_{ij\tau}$. The inclusion of agriculture (% of GDP output) does not change the results. However, puzzlingly, agriculture has a positive effect on elephant populations which is statistically significant at the 10% level.

	(J) Differenced		(K) No Okv/Mas	
$\Delta GDP_{j\tau}$	0.285	(0.791)	0.430	(0.661)
$\Delta Pop_{j\tau}$	-0.523	(0.281)	-0.557	(0.275)
$IB_{ij}{}^{*}\Delta GDP_{n\tau}$	1.208	(0.279)	0.935	(0.460)
$IB_{ij}{}^{*}\Delta Pop_{n\tau}$	0.538	(0.581)	0.898	(0.392)
$DR_{ij}{}^{*}\Delta x_{kj\tau}$	0.000312	(0.243)	0.000123	(0.233)
$IR_{ij}{}^{*}\Delta x_{mn\tau}$	-0.0000898**	(0.011)	0.00103^{+}	(0.104)
$IR_{ij}{}^{*}\Delta GDP_{n\tau}$	9.046***	(0.000)	8.520***	(0.000)
$IR_{ij}{}^{*}\Delta Pop_{n\tau}$	-1.667	(0.619)	1.675	(0.261)
Observations	281		276	
R^2 Overall	0.224		0.224	
R^2 Between	0.202		0.184	
R^2 Within	0.228		0.280	

Time effects are not shown.

Standard errors clustered on the reserve-level.

p-values in parentheses: $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.7: Differenced specification regression results. Dependent variable is differenced log of the elephant population $\Delta x_{ij\tau}$.

The results are shown in Table 3.7. The within explanation of the model trebles to around 30%. Bordering GDP per capita remains an important factor, working to increase elephant populations. Increasing wealth increases the opportunity cost of poaching and reduces poaching in IR and R. Furthermore, evidence of elephant migration is found: there is a statistically significant negative effect of a change in population in a bordering international reserve. However, after removing the Okavango and Maasai Mara and Serengeti Ecosystems this reverts to a positive effect. The negative effect might be due to migration. When the neighbouring population is high, the reserve population is low as elephant have moved across the border. Removing ecosystems where migration is high reverts the effect. Now, the evidence supports the result that poachers arbitrage across reserves. Larger populations in neighbouring reserves result in a lower cost of poaching and provide an incentive for poachers to poach across the border. This increases the elephant population in R.

3.11 Appendix IV

3.11.1 Econometric Issues

Unbalanced panel

The problem with the unbalanced panel is that the observation period does not correspond to the unit period for the underlying data generating process. Millimet and McDonough (2016) evaluate various estimation strategies to tackle the problem. These include non-linear least squares estimation using fixed effects and Chamberlain's (Chamberlain, 1984) method to correct for the missing data, quantile differencing using regression (Lee et al., 2012) or General Method of Moments (Nauges and Thomas, 2003) to attempt to remove the fixed effect, and orthogonal to backward mean transformations (Everaert, 2013).

In the case of this panel, the further complication is that the observation period varies across reserves and over time. In addition, the lags between observations (elephant population censuses) are substantial. Therefore, instrumentation that relies upon past observations is likely to be weak. Furthermore, given the panel is large in N and small in T, there is relatively little data to pursue estimation which requires orthogonal to backwards mean transformations. Lastly, it is worth noting that the estimating strategies proposed in Millimet and McDonough (2016) behave reasonably poorly in their simulations.

Therefore, as in the majority of studies, the unbalanced panel problem is ignored. The data requirements to begin to tackle the problem are too high given the data set to hand and instrumentation, given the large observation period gaps, will likely lead to weak instrumentation problems rather than presenting a solution to the problem.

Dynamic panel

The typical solution to dynamic panel problems is proposed by Arellano and Bond (1990), later refined by Arellano and Bover (1995) and Blundell and Bond (1998). Generally, these methods involve differencing the model and instrumenting for the differenced lagged dependent variable with further past lags or differenced variables using a series of moment

conditions in a GMM framework. This is not a viable solution here due to the data requirements. Firstly, differencing across observations is difficult given the unbalanced panel. Secondly, given data gaps, past lags or differences are highly likely to be weak instruments resulting in further bias. In addition, the results are compared to a differenced specification for robustness. In this specification, there is no lagged change in the dependent variable and so there is no dynamic panel problem. The reason why this is not used as the main specification is because of the difficulty in obtaining border effects from the specification and the problems encountered when differencing using the unbalanced panel.

Spatial Simultaneity

As Reed (2015) explains, simply lagging the elephant population of the bordering reserve is not enough to remove this inconsistency. Yet this is a common treatment in other research approaches. If the lagged dependent variable, in this case the lagged population of elephant, did not appear in the model, then this could be used to instrument for the bordering population of elephant. However, this is not the case. Ideally, an instrumental variable approach should be taken but, unfortunately, the data requirements for such an approach are too high for this study.

Measurement Error

Finally, consider what might be determining the observation period in the unbalanced panel. When robustness to the observation period is examined in Appendix III, it is clear that large gaps in the data may be related to conflict and poorer governance. This suggests there are links between larger observation periods (and by extension the length over which the data is interpolated) and the control variables in the model. Furthermore, the choice of census area is unlikely to be random and may lead to overestimating the population e.g. if the elephant range that is surveyed has a higher elephant population density than the surrounding area. There is also a worry that the choice of census method (and associated accuracy) is correlated with the size of the elephant population, degree of anti-poaching enforcement, or quality of governance.

Policy Consequences

This section revisits the main conservation policy debates discussed in the introduction in light of the results derived in the previous chapters.

Anti-Poaching Patrols

The recent upsurge in poaching has been characterised by more sophisticated poacher coordination and equipment. Now, poachers are part of a complex value chain run by international criminal cartels with market power. This value chain allegedly often involves corruption from the senior politician to the ranger level. It was shown in Chapter One that market power, and subsequent strategic behaviour by poaching cartels, has important consequences for owner anti-poaching patrol policy. Anticipated future scarcity of rhino worked to increase the current number of poaching attempts. This resulted in a significantly lower steady state population of rhino relative to the case with no strategic effect. Counter-intuitively, optimal owner spending on patrols should fall, because patrol spending worked to increase the size of this strategic effect between cartels. It was also shown that policy should focus on shutting down the marginal cartel.

Furthermore, as rhino and elephant populations become increasingly fractionalised, coordination in anti-poaching policy and law becomes increasingly important. In Chapter Three, evidence that poachers arbitrage across reserves (and borders) to profit maximise was found. A 1% increase in the bordering population increased the elephant population in a reserve by 0.26%. Therefore coordination in anti-poaching patrol policy is required to avoid a policy

externality on nearby reserves. Meanwhile, it was found that elephant populations on international borders are harder to protect and more susceptible to poaching. An international border resulted in an elephant population up to 2.5 times smaller than a reserve without a border. It was hypothesised that this is because anti-poaching patrols are less effective across international borders. It is therefore imperative that bordering nations work together to devise solutions to the poaching problem.

Finally, the risk to ranger life has not been discussed in this thesis. With the average poacher having access to more sophisticated and dangerous weaponry, the risk to life for rangers has increased in the new wave of poaching. Furthermore, with more severe punishments, the poacher has more reason to fight if cornered by an anti-poaching patrol. Therefore, it is important to keep in mind this additional risk when discussing anti-poaching patrol policy.

Verdict: Patrols continue to be the main conservation strategy available to owners to protect their animals. It is becoming increasingly important to understand the competition structure of poachers facing the policy maker. The degree of anti-poaching protection should change as poachers become more sophisticated in behaviour. It is also important to focus on shutting down marginal cartels, rather than a policy of unilateral deterrence across all poachers. The evolving poaching crisis places an increasing pressure on policy coordination across borders. Whilst trade is governed by CITES, there should be increased emphasis placed on patrolling reserves on international borders by both countries in question, regardless of the elephant or rhino population in each. Equally, neighbouring reserves within a country should coordinate policy to prevent arbitrage across reserves and any externalities associated with the degree of animal protection.

Legalisation of Trade

The economics of how a legalised trade might operate were examined in Chapter Two. There are three main arguments for legalisation made by policy makers.

1. Legalised trade allows farming of resources to supply the market. It is argued that

increasing supply to the market, for the same demand, lowers prices and reduces incentives to poach. It was found in Chapter Two that, with the absence of private sector speculation, a legalised trade could be used to sustainably conserve a rhino population when extinction would otherwise occur. The sustainability of this steady state was susceptible to population shocks. With the introduction of speculation, there came a point where speculative attack on the remaining stockpile is highly profitable, leading to extinction of the species. The timing of this attack was inversely related to the size of the initial population.

2. Revenue from stockpile sales could be invested into conservation. This was seen to result in a double dividend of stockpile sales, allowing the owner to reduce poaching by the same amount, despite selling fewer horns each period. Therefore, it allowed the owner to sustainably support a larger population of rhino at the steady state. However, it was found that speculation still occurred for reasonable simulation parameters.

3. A rhino's horn grows back after de-horning. Hence, owners of rhino could farm the horn and conserve the animal. The possibility of farming rhino horn may alleviate the issue of speculation, if the rate of accumulation to the owner stockpile is high enough. However, it was found that the objectives of a profiteering rhino farmer are not consistent with a long run recovery in the population numbers. The profiteering owner had a direct incentive to maintain a lower population so as to increase the value of rhino horn. Furthermore, the institutional issues surrounding coordination between owners of extensive and intensive rhino populations are much more complex than between extensive owners only.

Verdict: The rejection of motions to legalise trade in rhino horn and ivory discussed at the latest CITES convention is welcome at this stage. Currently, legalisation does not pass the precautionary principle. With the presence of speculators, a legalised sale could not be used to sustainably conserve the species unless the accumulation to the stockpile or double dividend with patrol spending is high enough. Farming rhino horn could in theory allow for fast enough accumulation of horn to sustain the sale and prevent speculation. However, it was shown that an objective of profit is not consistent with the long term recovery of the

species. It is also unclear as to whether the intensively farmed rhino would be considered the objective of conservation. Furthermore, potential demand side interactions and the institutional framework required for a legalised trade were not discussed in Chapter Two. Much more needs to be understood about the consumer market and how it might change with a legalised trade. In addition, a detailed and practical institutional framework needs to be devised to ensure that the legalised trade is regulated and managed in an effective way, should it be introduced.

Community Engagement

Often, whilst poaching operations are run by international criminal syndicates, local people are employed to poach. Raising the value of these animals to local communities reduces the incentives to turn to poaching. In Chapter One, raising the reservation wage of poachers reduced the time dedicated to poaching. This could be achieved through reinvesting tourism income back into local communities, providing incentives to conserve the animals.

Verdict: In certain cases, community engagement has proven to be highly effective. However, these projects are harder to establish in larger parks and when poaching occurs across international borders. Furthermore, as the price of horn and ivory rises, it is unclear as to whether these projects will remain financially sustainable in the face of rising poaching incentives.

Sustainable Use and Trophy Hunting

Raising the value of rhino and elephant to owners is important in the short term, especially given rising security costs. In the models in Chapters One and Two, raising the conservation benefit to the owner was seen to increase expenditure on patrols and provide incentives to conserve the population. Management practices that generate additional value for owners and prevent the loss of habitat for the species should not necessarily be removed. However, it is unclear if all practices are consistent with the goals of conservation.

Verdict: Whilst trophy hunting is ethically abhorrent, policy makers may not be able to remove these management options from owners of rhino and elephant, because these businesses may continue to provide incentives to protect populations of animals. However, trophy hunting remains a new industry and has not learned to self-regulate. Unfortunately, this has led to 'canned hunting' where animals are farmed and only released when a hunt is organised. Therefore, policy makers should work to provide suitable regulation to ensure, if possible, that these management practices are consistent with the goals of conservation.

Demand Reduction

Throughout the thesis, a reduction in demand was shown to reduce poaching incentives. This connection is trivial but how to create a reduction in demand is not. Patrols, community engagement, and a potential legalised trade are all policies which hope to conserve the animals until this change in demand is engineered. For these policies, the key is not to undermine demand reduction programmes. The challenge for demand reduction programmes is how to change the cultural beliefs of people who (falsely) view these animal products as medicinal cures.

Verdict: Reducing demand is, and must remain, the long term goal of conservation policy. Other conservation policies must not undermine this objective. Increased international pressure on consuming nations may work to engineer a change in habits. However, it is acknowledged this is difficult to achieve in practice.

Conclusion

Rhino and elephant poaching is a complex, international problem that needs to be solved. In this thesis, an attempt has been made to examine the economics of this problem and present potential solutions. Three defining characteristics of the upsurge in poaching since 2008 were identified and tackled. These are: the evolving industrial organisation and sophistication of poacher behaviour, the renewed questions and economics surrounding a legalised trade, and the increasing importance of policy coordination across reserves and borders as elephant and rhino populations become increasingly fragmented.

In Chapter One, the consequences of evolving industrial organisation and sophistication of poacher behaviour were examined for an owner using patrols to protect their rhino. Optimal spending on patrols was found to rise and then fall with the rhino population. The steady state rhino population was found to be falling in the degree of competition amongst poachers. Therefore, conservation policy should attempt to shut down the marginal cartel rather than strive for unilateral deterrence to poachers.

It was shown that market power, and subsequent strategic behaviour by poaching cartels, has important consequences for owner anti-poaching patrol policy. The strategic effect between cartels was significant in magnitude and has surprising consequences for optimal owner behaviour. Owner spending on patrols should fall because perversely, patrol spending works to increase the strategic effect between cartels. The importance for owners to understand the industrial organisation of poachers facing them is paramount in designing optimal policy.

In Chapter Two, rhino horn was a storable good and the renewed questions and economics surrounding a legalised trade were examined. Even assuming that institutional arrangements could be robust enough to support a legalised trade, the economics of the trade suggest that it is not certain that stockpile management could improve the long term conservation prospects of the species.

In the absence of private sector speculation, a legalised trade could be used to save and maintain a rhino population when extinction would otherwise occur. Using revenue from stockpile sales to fund patrols would strengthen this mechanism. However, with the introduction of speculation, there comes a point where speculative attack on the remaining stockpile is highly profitable, leading to extinction of the species. This speculation was shown to be more likely in drought periods.

The possibility of farming rhino horn may alleviate this issue, if the rate of accumulation to the owner stockpile is high enough. However, the objectives of a profiteering rhino farmer are not consistent with a long run recovery in the population numbers. The profiteering owner has a direct incentive to maintain a lower population so as to increase the value of rhino horn. Furthermore, the institutional issues surrounding coordination between owners of extensive and intensive rhino populations are much more complex than between extensive owners only.

Finally, the recent increase in poaching has led to increasingly fragmented elephant populations, and consequently large differences in conservation policy across reserves and national borders. In Chapters One and Two, a single owner and population of animals was considered in the design of optimal conservation policy. However, this does not account for the effects of neighbouring policy. Chapter Three sought to empirically examine the effects of differences in conservation policy across these borders, and the consequences for poaching.

A new panel of data detailing elephant populations for 1,262 reserves across 37 countries in Africa was assembled from Elephant Status Reports. Using this panel, the effects of

reserve borders on elephant population trends in Africa were examined. Significant border effects were found. An international border results in an elephant population up to 2.5 times smaller than a reserve without a border. In addition, evidence that poachers arbitrage across reserves within the same country was found. It was also found that conflict significantly reduces elephant populations, particularly across international borders.

The policy consequence is clear: as populations become increasingly fragmented, transfrontier conservation policy becomes more important. In addition, there is a need for policy coordination across reserves within a country. This has further implications for CITES. It is becoming increasingly apparent that CITES should be used as an institution to coordinate domestic policy, as well as international policy when it comes to endangered species.

Where does this leave the current thinking around policy? Patrols continue to be the main conservation strategy available to owners to protect their animals. It is becoming increasingly important to understand the competition structure of poachers facing the policy maker. The degree of anti-poaching protection should change as poachers become more sophisticated in behaviour. The evolving poaching crisis places an increasing pressure on policy coordination across borders. Whilst trade is governed by CITES, there should be emphasis placed on patrolling reserves on international borders by both countries in question, regardless of the elephant or rhino population in each. Equally, neighbouring reserves within a country should coordinate policy to prevent arbitrage across reserves and any externalities associated with the degree of animal protection.

The rejection of motions to legalise trade in rhino horn and ivory discussed at the latest CITES convention is welcome at this stage. Currently, legalisation does not pass the precautionary principle. With the presence of speculators, a legalised sale could not be used to sustainably conserve the species unless the accumulation to the stockpile or double dividend with patrol spending is high enough. Farming rhino horn could in theory allow for fast enough accumulation of horn to sustain the sale and prevent speculation. However, it is shown that an objective of profit is not consistent with the long term recovery of the species.

The institutional framework around conservation policy was not the focus of this thesis. However, it is recognised that this presents a significant barrier to policy makers worldwide. It is the nature of the problem that weak institutions surround both the consuming nations and source countries for animal products. Nevertheless, understanding the economic intuition around potential policy options is vital in solving the problem. On this note, a plea is made to researchers to revise their policy of restricting access to valuable elephant data. The more research in this field, the better, and that starts with data access.

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