

A Bio-economic Analysis of Community Wildlife Conservation in Zimbabwe

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Abstract

This paper uses a bio-economic model to analyze wildlife conservation in two habitats adjacent to a national park by two types of communities in the context of Southern Africa. One community is made up of peasant farmers operating under a benefit-sharing scheme (CAMPFIRE) while the other is made up of commercial farmers practising game farming in a conservancy (the Save Valley Conservancy). Both communities exploit wildlife by selling hunting licenses to foreign hunters but with different levels of success. The park agency plays a central role by authorizing the harvest quota for each community. We formulate a bio-economic model for the three agents and optimize the market problem for each agent and compare the outcomes with the social planner's solution. Our results show that the level of anti-poaching enforcement by the park agency is suboptimal while anti-poaching effort exerted by the conservancy community achieves social optimality. CAMPFIRE communities exert more poaching effort than what the social planner would recommend. Our model shows that an improvement in community institutions might have a significant impact on growth of the wildlife stock through their role in constraining behaviour. Thus, institutional reforms in benefit-sharing schemes such as CAMPFIRE could see the local community behaving like the game farming communities such as the one in the Save Valley Conservancy.

Keywords: Bioeconomic, community wildlife conservation, CAMPFIRE, private game farms

JEL codes: Q20, Q57 Q28

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1. Introduction

Integrated Conservation and Development Projects (ICDPs), commonly referred to as Community-Based Natural Resource Management (CBNRM) in the literature, are central for future rural development in Southern Africa (Munthali, 2007; and Thomson et al., 2013). Conceptually, the idea of CBNRM seems indisputable and likely to encourage conservation of wildlife resources and to improve the livelihoods of poor rural households if resources are exploited legally and commercially by local communities. Nevertheless, despite such arrangements, community wildlife conservation in the region still faces some serious challenges one of them being illegal harvesting¹ of wildlife resources by local people living adjacent to protected areas (Murombedzi, 1999; Fischer et al., 2011; and Gandiwa, 2011).

One example of CBNRM is the Communal Areas Management Programme for Indigenous Resources (CAMPFIRE) in Zimbabwe which was instituted by the government during the mid-1980s as a benefit-sharing scheme involving local communities. Previous studies have described the CAMPFIRE programme as a role model of CBNRM in Southern Africa (Murombedzi, 1999; Logan and Moseley, 2002; Muchapondwa, 2003; and Balint and Mashinya, 2006). The fundamental idea behind such an initiative is that benefits from wildlife conservation should be able to strengthen the incentive of local people in such a way that they treat wildlife as a valuable asset (Songorwa, 1999; Songorwa, 2000; and Balint and Mashinya, 2006). Viewed as an asset, wildlife has the potential to hedge local communities against agricultural risk associated with extreme weather conditions through creating employment and generating revenues (Muchapondwa and Sterner, 2012; and Poshiwa et al., 2013).

The CAMPFIRE programme enjoyed very limited success over the entire course of its establishment. Poaching subsided only temporarily after its commencement as neighbouring communities started to reap economic benefits from legal wildlife utilization and then rebounded a few years later (Fischer et al., 2011). Both human-wildlife conflict (Gandiwa et al., 2013a) and poaching incidences (Gandiwa et al., 2013b) escalated during the fast-track land reform programme (FTLP) in Zimbabwe which spanned more than a decade starting in the year 2000. The FTLP was also accompanied by severe economic hardships and human settlements encroaching wildlife habitat. Thus, the CAMPFIRE programme experienced two major setbacks. The increase in poaching incidences seems to suggest that the CAMPFIRE programme failed to generate adequate incentives for local communities to conserve wildlife and that the FTLP was disruptive, in the sense that it brought in settlers who were not interested in conservation. It is also hard to separate the economic incentives of Campfire from the general difficulties of the land reforms.

This phenomenon is not only unique to Zimbabwe, but to many other countries in the Southern Africa region (Johannesen and Skonhott, 2005). To this end, scholars argue that the impact of benefit-sharing schemes such as the CAMPFIRE programme is limited by possible dilemmas in the actual design of the scheme or trade-offs inherent in linking development and conservation objectives (Wells et al., 1999; Fischer et al., 2011; and Johannesen and Skonhott, 2014). These dilemmas are also closely intertwined with the nature of the

¹ A distinction is made in this paper between commercial and subsistence poaching. Commercial poaching is presumed to be an open access business usually conducted by outsiders but with the help of local communities while subsistence poaching is mainly done for subsistence by the local communities themselves (Fischer et al., 2011). Local communities contribute to commercial poaching or illegal trophy hunting by supplying information to outsiders about the movements of wild animals in their wilderness area and sometimes provide escort services for a very small fee.

community (i.e. the quality of local institutions that are in place) and the benefit-cost structure (incentives) associated with the property rights system.

Given the intentions of most governments in the region to improve the living standards of poor rural households living adjacent to national protected areas through wildlife-based land reform, it is imperative to understand how different types of CBNRM regimes or conservation models work and to use this information not only to take appropriate action to enhance wildlife conservation in existing communal areas but also to take pre-emptive actions or reforms to safeguard good stewardship practices in conservancies². The conservancy community has played a crucial role in protecting wildlife and biodiversity on private farmland outside of formal protected areas since their establishment in Southern Africa during the early 1970s.

This paper considers communities that are involved in wildlife conservation in the vicinity of the Gonarezhou National Park (GNP) in Zimbabwe. Two distinct CBNRM communities co-exist with each other in the same geographical location. They undertake similar activities (i.e. wildlife conservation and agricultural production) and could therefore potentially benefit from conservation. The first regime is made up of CAMPFIRE communities organized under the 'traditional' CBNRM arrangement involving peasant farmers in communal areas. Kreuter et al., (2010) identified a second CBNRM regime of landowners within the bounds of the Great Limpopo Trans-frontier Conservation Area that are organized into private nature reserves or conservancies e.g., the Save Valley Conservancy (SVC). Given these two CBNRM communities, one regime is doing very well in terms of conservation and wildlife utilization, while the other faces demise. To a larger extent, the conservancy community performs much better in both dimensions compared to the CAMPFIRE communities since the latter lack incentives to conserve wildlife (Fischer et al., 2011; and Campbell and Shackleton, 2001). This is supported by the increase in area under conservation and wildlife population on private land (Muir-Leresche and Nelson, 2000). Moreover, the conservancy community exhibit characteristics that enhance CBNRM and coordinated decision making for wildlife conservation (Krug, 2001; and Kreuter et al., 2010).

Therefore, the main objectives of this paper are to compare wildlife management and utilization under CAMPFIRE and conservancy communities, and to suggest appropriate reforms that might encourage the CAMPFIRE community to move from a seemingly suboptimal regime to one that is optimal. Unlike previous studies, this paper seeks to establish the conditions under which a CAMPFIRE community can be incentivized to behave like the conservancy community which is more successful in revenue generation and stewardship practice. Given the background above, three important questions arise; i) What are the significant differences between the two types of communities that interact with wildlife in Zimbabwe? ii) How and why do their differences affect revenue generation and steward practice? iii) Given the apparent superiority of conservancy outcomes in terms of livelihoods and conservation, how can we incentive CAMPFIRE communities to behave like the conservancy community, i.e., what reforms are necessary in CAMPFIRE for it to achieve equivalent outcomes?

The rest of the paper is organised into four sections. Section 2 analyses the similarities and differences between the CAMPFIRE and conservancy communities. Section 3 develops the bio-economic model, presents some comparative statics and computes estimates of some key parameters of the bio-economic model using data collected from communities around the Gonarezhou National Park in Zimbabwe. Section 4 provides a discussion of the results of the

² While there is no statutory definition of a conservancy in Zimbabwe, the working definition is: "Any number of properties, which are amalgamated into a single complex in order to enable more effective management, utilization and protection of the natural resources" (Waterhouse, 2004).

optimization problems and model simulation. Finally, section 5 presents the conclusions and policy implications.

2. CAMPFIRE versus the conservancy community

In Zimbabwe, community-based wildlife conservation takes place mainly under two different CBNRM arrangements, i.e., conservancies and the CAMPFIRE programme. According to Bell (1984), emphasis on formal protected areas shifted during the 1970s with the recognition that islands of protection were inadequate for maintaining spatially heterogeneous biodiversity. The Parks and Wildlife Act (1975) gave landowners property rights to wildlife on their land (Murombedzi, 1999). In the conservancy, private game farms have pulled down their fences and are managing wildlife as a common pool resource. Due to its fugitive character, wildlife is managed as a community, rather than on individual farms in order to supply the required habitat size. Kreuter et al. (2010) identified groups of landowners within the bounds of the Great Limpopo Trans-frontier Conservation Area that have incorporated their properties into conservancies or private nature reserves, thereby expanding the management scale of common pool wildlife resources. Managing wildlife as a community allows the conservancy to enjoy economies of scale and individual farms to specialize in offering services and products that are in line with the resources found on their properties.

Upon independence, the government enacted a new law, i.e., “the Parks and Wildlife Act of 1982”, which gave birth to the CAMPFIRE programme. The law aimed to provide democratically elected RDCs the appropriate authority for managing wildlife within their geographical boundaries. This new paradigm entails conferring local communities through their RDCs, (i) greater control over formerly public wildlife in communal areas in defined territories, (ii) enhanced capacities to add value to local wildlife, and (iii) specific financial rewards likened to alleged conservation value of wildlife within their territories (Gadgil and Rao 1994; and Murombedzi, 1999). Provided these commitments are forthcoming, the park agency steps back into the role of regulator and adviser, retaining the right to control wildlife harvesting quotas (Fischer et al., 2011). It is acknowledged that communities facing the same political, legal and economic environment are affected differently.

Because of the FTLRP, Zimbabwe has less than 8 conservancies (with over 100 registered private game farms) and 37 CAMPFIRE districts, 37 RDCs, 118 wards with over 121500 households participating in wildlife conservation. The eight conservancies cover an area of 1,140,688 ha in total, while the CAMPFIRE wards cover approximately 2,478,000 ha in total. Comparing how communities under CAMPFIRE operate with the conservancy communities, we observe striking similarities and differences. First, we characterize the CAMPFIRE community followed by a characterization of the conservancy community in the SVC and finally summarize the major differences in a table. Although the paper utilizes the GNP area as a case study, the results would generally apply to other areas in Zimbabwe.

2.1 The CAMPFIRE community

The CAMPFIRE projects are located on ancestral land that belongs to the whole community by traditional law. Part of the land is allocated to individual use rights where crop cultivation takes place while the remainder is allocated communal use rights such as grazing and wildlife conservation. In addition to wildlife conservation, peasant farmers under CAMPFIRE grow crops and keep livestock as part of their livelihood activities. They also suffer loss from wildlife intrusion in the process. The agricultural potential in terms of crop cultivation in the area is extremely low due to harsh climatic conditions, while the technology is predominantly

subsistence in nature. This makes livestock rearing and wildlife conservation the most viable private investment options for CAMPFIRE communities living around the national park.

The CAMPFIRE programme aimed at giving local communities co-ownership of local natural resources so that they can generate income through leasing trophy hunting concessions, harvesting resources, game cropping and tourism activities (Fischer et al., 2011; and Balint and Mashinya, 2006). However, this aim was not achieved as the government has been reluctant to continue with the devolution and decentralization exercise of natural resource management (NRM) to the community's grassroots level (Murombedzi, 1999). CAMPFIRE has only been able to devolve authority over natural resources from the central government to rural district councils. Murombedzi (1999) argues that, if the programme is to be effective, a further devolution of authority is required so that producer communities, those who live directly beside wildlife, are given full control of the natural resources on their land. This calls for policies that can result in greater devolution of managerial functions (e.g., quota setting, game cropping, patrols or monitoring and enforcement) and decision-making (e.g., harvesting, investment and how revenue is shared and utilized) into the hands of local communities, while the state maintains regulatory functions (Ntuli & Muchapondwa, 2015).

Custody of wildlife falls in the hands of the Zimbabwe National Parks and Wildlife Authority (ZNPWA) who manage it on behalf of the state and allocate hunting quotas to other players in the industry such as CAMPFIRE and the conservancy communities³. The appropriation rights to wildlife under the CAMPFIRE programme fall in the hands of the Rural District Council (RDC). This means that, to receive harvesting quota, the CAMPFIRE communities need to apply for it through their respective RDCs. This puts the local communities at a disadvantage because the major decisions about how wildlife is managed, utilized and how revenues from wildlife conservation are shared rest in the hands of state apparatus. With the present arrangement, local communities are relegated to mere spectators or beneficiaries of wildlife conservation rather than important stakeholders. The current revenue sharing plan is such that the RDC gets 47% of wildlife income from each community, 3% goes to the CAMPFIRE association, while the remainder (50%) goes to the producer community (Bond & Frost, 2005).

Local communities operate under very close supervision from both the park agency and RDC. Because park authorities are unable to carry out anti-poaching enforcement both inside the national park and on communal land due to limited resources, local communities are now tasked to continue with the conservation work in their jurisdictions outside the formal protected areas. As a result, anti-poaching enforcement under most CAMPFIRE projects is very weak, because it is done by communities that lack incentives to conserve wildlife⁴. To strengthen the incentives, we propose that the RDC should transfer wildlife management functions and benefits to sub-district producer communities. The problem of information asymmetry is also rife between state authorities and CAMPFIRE communities, such that the park agency usually has less information about poaching activities in the area than the community. Acquire such information would involve cost for the agency. This puts the CAMPFIRE community in a better position to take care or manage wildlife roaming outside the formal protected areas.

³ Note: In Zimbabwe, wildlife is the property of the state and no one community or individual owns it. This implies that the state has the authority to grant only appropriation rights (i.e. rights to use or rights to income) to certain individuals or communities, but not ownership rights (Murombedzi, 1999).

⁴ The effectiveness of anti-poaching enforcement under the CAMPFIRE programme is compromised by the fact that it is carried out on a part-time basis by either volunteers in the community (resource monitors) or the wildlife management committee who usually face resource and time limitations since they have to commit to other important household activities particularly during the agricultural season.

Local communities are supposed to satisfy a number of requirements in order for them to be recognized as conservation groups. For example, they are required to set aside land belonging to the community as a wildlife buffer zone or conservation land⁵, to have a wildlife management committee (WMC) in place, to develop a constitution, to have a wildlife management plan (WMP) and to designate resource monitors among other things. In a few areas, the RDC supplies game guards and it is only in a very few cases that these guards are either armed or trained to execute such important assignments. For example, out of many CAMPFIRE communities around the GNP, the Mahenye CAMPFIRE community is the only one with trained and armed game guards (Ntuli & Muchapondwa, 2015).

Due to the absence of an effective fence separating the national park from communal land, wildlife is free to traverse the community's conservation area. The community, however, does not carry out any meaningful investment such that wildlife simply replenishes itself partly because of the relationship with the national park. Under CAMPFIRE, the link between returns to wildlife conservation and investment is not clear. For instance, the contribution by individual members of the community in terms of effort is uncertain. Hence, the issue of shares in the wildlife enterprise is not well defined. In reality, the CAMPFIRE community treats wildlife as a common pool resource and this automatically gives members of the community equal shares in the wildlife enterprise. As a result, this presents a situation which assumes that all members of the community contribute the same in terms of their investments (e.g., labour inputs, conservation land and wild animals) so that even free-riders get equal shares on things such as labour inputs.

Wildlife harvesting under CAMPFIRE happens legally when the RDC engages the safari operator who will in turn source for clients to utilize the quota on behalf of the RDC, and illegally by community members themselves to get rid of problem animals or for selfish reasons in order to maximize individual benefits. The safari operators link the RDC with the overseas market. The RDC generate revenues by selling hunting licenses to safari operators in the area and share the proceeds with local communities. In this way, the safari operators act as some kind of middlemen, who then sell the licenses at a premium to the actual trophy hunters abroad at organized international events and also make the necessary arrangements for the clients to come.

Even though some clients may be professional hunters themselves, every kill must still be made in the presence of a certified professional hunter who is registered according to the laws of Zimbabwe. If the animal being killed is on communal land, the presence of a representative from the RDC is needed. Sometimes, in cases where the safari operator lacks adequate knowledge about animal movements in the area, a community member is recruited to assist and to witness the kill. A registered professional hunter is there to make sure that the right kind of animal is killed (e.g., female elephants should not be killed by law) and the animal is killed ethically.

2.2. The conservancy community

Some private game farms pooled land (i.e. by dissolving their internal boundaries) and other resources together and now manage wildlife as a common pool resource due to its fugitive character. This allows for economies of scale and specialization in activities that are most conducive to the type of resources present on individual farms. For example, some farmers might choose to specialize in wildlife conservation, while others combine conservation with agricultural activities, such as crop cultivation, cattle ranching and citrus, but on a limited scale. This paper considers the Save Valley Conservancy (SVC) due to its proximity to the

⁵ It should be noted that the land allocated by local communities towards conservation does not really expand the wildlife reserve. Although it expands the stock, both the land and the wildlife inside the reserve and on communal land are governed by different pieces of legislation.

GNP and the fact that the conservancy share borders or interacts with neighbouring communities. Most importantly, the farmers in the SVC are operating as a community just like in CAMPFIRE projects.

The establishment of the SVC was meant to rectify the ecological imbalances and environmental degradation caused by excessive cattle ranching during the 1920's, which subsequently forced wildlife to the outskirts of the valley. As a matter of policy, it was suggested that decreasing the number of cattle and introducing the original wildlife back to the area would help to restore the natural balance. Because of this intervention, the environment slowly recovered. Many of the indigenous plants and vegetation has been rehabilitated and the area has been successfully restocked with wildlife. The SVC was formed by combining 24 adjoining farms and measures about 3200 km². It is involved in intensive protection of rhinos, private game safaris, limited hunting concession and multi species research. Farmers in the conservancy receive most of their income from high quality and low density tourism including accommodation for travelers. It supports local communities by supplying jobs, allowing them to sell their arts and crafts, as well as improving and upgrading the Save Valley area. There is also a 330 km electric fence surrounding the conservancy to protect the wildlife animals from harm as well as the environment.

The appropriation rights to wildlife fall in the hands of the conservancy. Unlike in the communal areas, shares, labour inputs, capital contributions made by individual private game farms and provisioning rules are well defined. With the removal of fences, each farm contributed to the common pool resources in terms of land and wild animals. The contributions were noted and converted into shares, which are in turn used to allocate the hunting quota given to them as a group. The conservancy is charged to make sure that the wild animal population reaches a threshold needed for sustainable trophy hunting which will in turn benefit the whole group. If the wild animal population reduces significantly or falls below some agreed level, they all contribute to make sure that the animals reach the intended threshold. The group is also responsible for maintaining roads and other infrastructure, animal counting and anti-poaching enforcement. Anti-poaching enforcement under the conservancy is very effective because well trained and armed game guards patrol the area at regular intervals. The SVC also generates revenue through tourism activities.

The conservancy community operates with minimum state interference as they are on private land. This gives the conservancy autonomy to make important decisions such as investments. The conservancy pays tax and levies to the government and the RDC, and applies for a harvesting quota as a community directly from the ZNPWA every year. Just as in communal areas, wildlife is harvested both legally and illegally in the conservancy. The legal trophy hunting activities in both the SVC and CAMPFIRE communities are guided by quota allocations. Illegal harvesting is also carried out by the local communities living adjacent to the conservancy. Because local communities in the area constantly suffer from wildlife intrusion and are marginalized by the law to the extent that the benefits from wildlife conservation are negligible, they have greater incentives to poach.

The conservancy community sells its products to overseas markets and sometimes engages safari operators since they are more specialized for this type of business. Representatives from the conservancy travel overseas to attend organized international events where they advertise their products to interested clients. To a large extent, the clients who eventually utilize the quota under CAMPFIRE and the private game farming community are the same. In addition to getting a small margin from selling hunting quotas, farmers in the SVC also generate substantial income through the provision of accommodation, specific guns requested by the trophy hunter and each day the farm owner is traveling with the client until a kill is made. Table 1 below gives a summary of the key differences and similarities between the two communities.

Table 1: Summary of key differences and similarities

Differences	
<i>Communal farmers in CAMPFIRE projects</i>	<i>Private game farms in the conservancy</i>
<ul style="list-style-type: none"> - Degree of state interference is high - Operating on communal land - Appropriation rights belongs to RDC - Contributions/shares are not well defined - Anti-poaching enforcement is done by a community/ unpaid volunteers that lack incentives - Marketing is done by Safari operators on behalf of local communities 	<ul style="list-style-type: none"> - Minimum state interference - Operating on private land - Appropriation rights fall in the hands of the conservancy - Contributions and shares are well defined in terms of provision rules - Anti-poaching enforcement is done by trained and armed game guards - Marketing activities are carried out at both individual farm level and as a group - Income generated from non-consumptive tourism
Similarities	
<ul style="list-style-type: none"> - Same geographical region and located adjacent to GNP - Similar activities (i.e. agricultural production and wildlife conservation) - Wildlife in Zimbabwe is a property of the state and no one individual or group owns it - Wildlife is managed as a CPR due to the absence of internal boundaries - Anti-poaching enforcement is done at group level - The clients who eventually utilize the quota are the same - Income from trophy hunting 	

Source: Survey data 2013

In this section, we demonstrated that we are aware of the differences in characteristics between the CAMPFIRE community and the conservancy. Some of these differences could be responsible for driving the discrepancies in outcomes between the two communities. However, the next section will highlight and analyze only those key attributes that we think matters for conservation and welfare, and for the CAMPFIRE communities to catch up. This paper argues that since both communities are carrying out similar activities, they should potentially be able to achieve similar results. This paper argues that since both communities are carrying out similar activities⁶, they should potentially be able to achieve similar results. For instance, both communities should be able to register a positive growth in the stock of wildlife as poaching subsidizes over time. If we appeal to other activities such as cotton and

⁶ The communities are carrying out similar activities. The wildlife enterprise is governed by the Parks and Wildlife Act of 1982. This applies to wildlife both on private and communal lands. On private land, use rights and right to wildlife income follow the freehold land title, while on communal land, these rights are granted through the appropriation authority status. The uses of wildlife are comparable, for example, CAMPFIRE documents the following uses; trophy hunting, tourism, live animal sales and meat cropping, and these are the very same activities, which the conservancy is undertaking. Furthermore, the ownership rights under these two dispensations are equivalent, i.e., owning a lion or an elephant is treated the same way on private and communal land. The only differences between the two communities are: first, how automatic ownership becomes after the park agency has granted a quota – with private tenure it is automatic, but with communal, it goes through a process. Second, CAMPFIRE communities partly benefit through natural replenishment from the national park unlike in the case of the conservancy. In our view, we think the activities are identical in terms of what happens on communal land and the conservancy.

tobacco farming, we observe that both peasant and commercial farmers have achieved similar good outcomes in the past (Rukuni & Eicher, 1994; and Rukuni et al., 2006).

3.0 The bio-economic model

The analysis focuses on comparing conservation and welfare outcomes for two different communities involved in wildlife management adjacent a formal protected area: the CAMPFIRE community gets part of the proceeds from wildlife conservation which are distributed to them as cash transfers, while the conservancy community manages wildlife and generates revenues directly through hunting and tourism activities. There are three agents namely the park agency, the conservancy and the CAMPFIRE community. We formulate optimization problems for each agent representing the baseline scenarios in terms of wildlife management (stock size and anti-poaching enforcement), and wildlife utilization (harvesting effort and poaching effort). We then compare the outcomes with those of the social planner and suggest reforms required for the CAMPFIRE community to behave like the conservancy community, which produces better conservation and welfare outcomes.

We adopt the standard assumption of a homogenous community where decisions are made at group level e.g., a community can choose either to put effort in poaching or anti-poaching enforcement, depending on how it weighs the benefits and costs from wildlife conservation. This is a plausible assumption given the nature of decision-making we observe. Local communities use traditional institutions which normally involve the chief or village headmen, where they meet under a tree and make decisions together as a group. Even though rebellion often occurs in the community, social norms help ensure the prevalence of a certain course of action by all members of the community. The conservancy community has committees and boards in place that make the crucial decisions on behalf of the group.

We assume that agents are managing a single wildlife species (e.g., African Elephant) whose stock size is denoted by X_i , where the subscript $\{i = 0, 1\}$ denotes a patch of land. We agree that the issue of relative sizes of the park and various communities is an important consideration because it can enlighten us on some aspects of conservation and welfare. However, this is not the angle this paper takes into consideration and we do not think that abstracting from land size will affect our key findings and message, that is, our results are not dependent on relative size. Given the ineffectiveness of the fence between the park and communal lands, we assume that wildlife on that patch is managed as one stock. Intuitively, one could envisage the stock leaving the national park and roaming on communal land during the agricultural season being attracted by crops and returning to the protected areas after the season. Let X_0 denote the stock of wildlife shared by the park agency and CAMPFIRE communities and X_1 the stock managed by the conservancy. The following additional implicit assumptions apply $X_i(t) \geq 0$, $X_i(0) = X_i^{(0)}$ and $X_i(\infty) < \infty$. Please refer to the appendix for a summary of definitions of symbols and the functional forms used in this paper.

No hunting takes place inside the national park, but it is allowed in areas outside the park. Therefore, in the absence of natural growth X_0 potentially shrinks when roaming on communal land and is allowed to recover when it returns to the protected areas. Assuming a particular biomass at a specific point in time $X_i(t)$, the stock grows according to natural growth $F(X_i, \cdot)$ and shrinks due to trophy hunting h_i and poaching $\psi_i(\cdot)$.

$$\dot{X}_i = F(X_i, \cdot) - h_i - \psi_i(\cdot) \dots \dots \dots (1)$$

$$\dot{X}_0 = F(X_0, L) - h_0 - \psi_0(L, T_0^p) \text{ [Stock dynamics in the national park and on communal land]}$$

$$\dot{X}_1 = F(X_1, T_1^e) - h_1 - \psi_1(T_1^e, T_1^p) \text{ [Stock dynamics inside the conservancy]}$$

where L is anti-poaching effort exerted by the park agency, T_1^e denotes anti-poaching effort exerted by the conservancy and T_0^p represents the poaching effort employed by the local community. We assume that the growth function depends not only on stock size, but also on anti-poaching effort, since its application facilitates growth in the wildlife stock. The natural growth function obeys the usual conditions:

$$\frac{\partial F(X_i, \cdot)}{\partial X_i} > 0, \frac{\partial^2 F(X_i, \cdot)}{\partial X_i^2} \leq 0, \frac{\partial F(X_0, L)}{\partial L} > 0 \text{ and } \frac{\partial F(X_1, T_1^e)}{\partial T_1^e} > 0$$

In addition, we assume that $F(0, \cdot) = 0 = F(K, \cdot)$ so that there is no growth if the stock size is either zero or reaches the carrying capacity of the resources system (Fischer et al., 2011).

Unlike Fischer et al. (2011) who emphasized poaching by outsiders but with assistance from the local community and anti-poaching enforcement by a few successful CAMPFIRE communities and in line with Johannesen & Skonhøft (2014), we emphasize poaching activities by the majority of CAMPFIRE communities living adjacent to protected areas. Accordingly, we assume that it is only the park agency that carries out anti-poaching enforcement both inside the park and in the communal areas adjacent the protected area. The conservancy is responsible for anti-poaching effort in its area. The CAMPFIRE community perpetrates poaching both in its area and on the conservancy – this is motivated by the need to defray costs from the nuisance effect of wildlife (Johannesen & Skonhøft, 2014), for selfish reasons i.e. hunting for meat and trophies (Marks, 1984; Barrett and Arcese, 1998; and Fischer et al., 2011) and also protest against the establishment of conservancies in areas viewed as traditionally belonging to CAMPFIRE communities (Wels, 2000).

Poachers do not take into consideration the impact of their actions on the future stock of wildlife. It is natural to assume that the poaching function increases with poaching effort and reduces with anti-poaching enforcement by the park agency and conservancy community i.e.

$$\psi_2(L, 0) = 0, \frac{\partial \psi_2(\cdot)}{\partial T_2^p} > 0 \text{ and } \frac{\partial \psi_2(\cdot)}{\partial L} < 0$$

$$\psi_1(T_1^e, 0) = 0, \frac{\partial \psi_1(\cdot)}{\partial T_2^p} > 0 \text{ and } \frac{\partial \psi_1(\cdot)}{\partial T_1^e} < 0$$

The second order derivatives are such that the poaching function is concave with respect to poaching effort, convex with respect to anti-poaching effort and the marginal productivity of poaching effort decreases with anti-poaching enforcement.

$$\frac{\partial^2 \psi_i(\cdot)}{(\partial T_2^p)^2} \leq 0, \frac{\partial^2 \psi_2(\cdot)}{\partial L^2} \geq 0, \frac{\partial^2 \psi_1(\cdot)}{\partial (T_1^e)^2} \geq 0, \frac{\partial^2 \psi_2(\cdot)}{\partial T_2^p \partial L} = \frac{\partial^2 \psi_2(\cdot)}{\partial L \partial T_2^p} < 0 \text{ and } \frac{\partial^2 \psi_1(\cdot)}{\partial T_1^e \partial T_2^p} = \frac{\partial^2 \psi_1(\cdot)}{\partial T_2^p \partial T_1^e} < 0$$

It is assumed that there is no relationship between the stock of wildlife in the conservancy and the national park because the conservancy is enclosed such that wildlife cannot move across borders⁷. The conservancy only purchased live animals once when it was established to boost its wildlife stock and thereafter restocking ceased. The stock of wildlife on communal land is linked to the population of wild animals in the national park due to the absence of an effective fence. Thus, the wildlife stock on communal land replenishes itself

⁷ Of course, in exceptional cases, the conservancy can purchase live animals from the national park when restocking is required due to exogenous forces like severe drought or floods.

because of its relationship with the park (i.e. wildlife is ordinarily harvested when roaming on communal land and recovers when it returns to the national park).

Currently, the specification of property rights is such that wildlife falls in the hands of the state, both inside and outside the national park (Child, 1996; and Murombedzi, 1999). Therefore, both communities have user rights to wildlife. From this perspective, land tenure ceases to be an important variable in this analysis. The park agency is responsible for allocating hunting quota h_i to other players in the industry. Let h_1 and h_2 be the quota allocated to the conservancy and CAMPFIRE communities respectively. In practice, this could be implemented as $h_i = \bar{h}_i + \varepsilon_i$ where average quota is adjusted on the basis of overall impressions about the community's conservation effort, rather than the actual stock size, because the park agency usually lack vital information such as animal counts and trophy quality in the study area⁸.

The state has the right to grant appropriation authority (this includes both the right to use and right to income) to any individual or community (Murombedzi, 2003). In the case of the CAMPFIRE programme, the state gave the appropriation rights to the RDC instead of the local communities directly. Therefore, the RDC collects the revenues and makes the decisions about how the proceeds from wildlife conservation are allocated. The RDC generates wildlife income by selling hunting licenses to safari operators who, in turn, sell the licenses at a premium (s) to clients from overseas. The RDC's gross wildlife income is given by the following expression:

$$W = W(h_2, X_0) = (P^* - s)h_2 \dots\dots\dots (4)$$

The parameter (s) can be interpreted as a premium charged by the safari operator above the fee paid to the RDC and includes his time spent looking for clients, time spent with clients during the actual hunting sessions, his skills, guns, etc. P^* is the fixed price per unit of harvest paid by the trophy hunters, and is exogenous to the communities as there is a competitive environment in the wildlife sector, such that no single community can influence the trophy price. Moreover, the fact that Zimbabwe is only one of the many countries offering sport-hunting opportunities motivates the price-taking assumption (Fischer et al., 2011). A fraction of the income ($0 < \tau < 1$) goes into the hands of local communities, while the remainder ($1 - \tau$) is retained by the RDC. Hence the community receives

$$\tau W = \tau W(h_2, X_0) = \tau(P^* - s)h_2 \dots\dots\dots (5)$$

The CAMPFIRE community is involved in different production activities, for example, agricultural production, poaching, anti-poaching enforcement and selling hunting licenses. The property wildlife rights of the park manager are not effectively protected and enforced on communal land, and hence, the local people are not effectively prevented from harvesting wildlife. The harvesting of wildlife resources takes place legally through trophy hunting and illegally through poaching. The legal harvesting of wildlife is not carried out by the respective CAMPFIRE communities themselves, but the RDC sell hunting licenses h_2 to the safari operators who, in turn, sell them to overseas clients who eventually utilize the quota.

⁸ In practice, CAMPFIRE communities have generally complained that the quota does not change much and seems irresponsive to stock dynamics. This perception could be true as quotas for selective hunting do not change much (Muchapondwa, 2003). For simplicity, we assume the fixed quotas rule $h_i = \bar{h}_i$ which reflects the behaviour of an agency that is understaffed and does not dare take new initiatives (Fischer et al., 2011).

Both communities allocate a fixed amount of effort (\bar{T}_i) between the two activities, namely agricultural production (T_i^a) and wildlife activities (i.e. either anti-poaching enforcement or illegal harvesting). Assuming a binding time constraint, we have:

$$\bar{T}_i = T_i^a + T_i^j \dots\dots\dots (6)$$

where the superscripts $\{j = p, e\}$ represent poaching effort T_2^p by the CAMPFIRE communities and anti-poaching enforcement T_1^e exerted by the conservancy.

For a fixed size of agricultural land and hence neglecting the possible loss of wildlife habitat through agricultural expansion (Johannesen & Skonhofs, 2014), the agricultural yield function in the absence of wildlife damage depends on effort when all other variable inputs are assumed to be fixed. The agricultural technology is given by:

$$A_i = A_i(T_i^a) = A_i(\bar{T}_i - T_i^j) \dots\dots\dots (7)$$

The agricultural production function satisfies the usual concavity assumptions i.e. $A(0) = 0$, $A'(\cdot) > 0$ and $A''(\cdot) \leq 0$.

More wildlife means more nuisances, so that damages are proportional to the amount of wildlife (Carlo & Wetzsten, 1994; and Hueth et al., 1998) i.e.

$$D_i \propto X_i \Rightarrow D_i = \beta X_i \dots\dots\dots (8)$$

where $\beta \geq 0$ is a fixed constant and $D \in [0,1]$. Ideally, β captures the nuisance effect of the wildlife stock (see also Zivin et al., 2000). If the quantity of crops not damaged is $1 - D_i = 1 - \beta X_i$, then the net crop benefits are given by

$$Q_i = A_i(T_i^a) - A_i(T_i^a)\beta X_i = A_i(\bar{T}_i - T_i^j)[1 - \beta X_i] \dots\dots\dots (9)$$

3.1 The park agency's problem

We assume that the park agency gets most of its income from benign tourism and budget allocation from the state, but not from selling hunting licenses since trophy hunting is not permitted inside the national park. The park agency employs a small fraction of its anti-poaching effort L outside the national park so that there is a small probability of being caught $\theta_0(\cdot)$ if the community decides to harvest wildlife illegally. We assume further that the probability of detection is a function of the anti-poaching effort of the park agency and poaching effort. The probability of being detected when hunting illegally is assumed to be an increasing function of the time spent hunting illegally, as well as the level of law enforcement exerted by the park agency i.e. $\partial\theta_0(\cdot)/\partial T_2^p > 0$ and $\partial\theta_0(\cdot)/\partial L > 0$. In addition, we have $\theta_0(L,0) = \theta_0(0,T_2^p) = 0$. The marginal probability of detection increases with the level of anti-poaching effort $\partial\theta_0(\cdot)/\partial L T_2^p > 0$.

The park agency receives four types of benefits: i) budget from the state \bar{M} , ii) revenue from benign tourism $R(X_0)$, iii) the public goods value of wildlife $G(\cdot)$, and iv) proceeds from poaching fines $\theta_0(\cdot)c_0$ imposed on detected perpetrators. It is assumed that $G(0) = 0$, $G'(\cdot) > 0$, and $G''(\cdot) \leq 0$. The total cost of managing the park is given by v_0L where v_0 is the fixed cost per unit of anti-poaching effort. The park agency chooses hunting quotas to allocate to different communities and the level of anti-poaching effort to employ, which is split according to the land sizes inside and outside the park. The agency maximizes net benefits subject to stock dynamics of wild animals shared by the park agency and CAMPFIRE community, the stock of wildlife roaming the conservancy, the budget constraints and the participation constraints of the two communities where the discount rate is given by $\delta > 0$.

$$\underset{\{L, h_1, h_2\}}{\text{Max}} \pi_0(L, h_1, h_2) = \int_{t=0}^{\infty} [G(X_0, X_1) + R(X_0) + \bar{M} + \theta_0(L, T_2^p)c_0 - v_0L]e^{\delta t} dt \dots\dots\dots(10)$$

$$\begin{aligned} \text{St: } \dot{X}_0 &= F(X_0, L) - h_2 - \psi_2(L, T_2^p) \\ \dot{X}_1 &= F(X_1, T_1^e) - h_1 - \psi_1(T_1^e, T_3^p) \\ v_0L &\leq \bar{M} \text{ [Budget constraint - assumed to hold with equality]} \\ P^*h_1 &\geq \bar{U}_1 \text{ [Participation constraint for private game farms - assumed to hold with equality]} \\ (P^* - s)h_2 &\geq \bar{U}_2 \text{ [Participation constraint for local community - assumed to hold with equality]} \end{aligned}$$

As in Mukanjari et al. (2012) and Johannesen & Skonhofs (2014), the park agency bases its decision on inter-temporal consideration because they have the property rights to wildlife on both public and private land, and chooses optimal amount of effort towards anti-poaching activities, and optimal quota to give to CAMPFIRE communities and conservancy. However, before they calculate the quota, they need to know the wildlife stock in each community first. The current value Hamiltonian is given by:

$$\begin{aligned} H(\cdot) &= G(X_0, X_1) + R(X_0) + \bar{M} + \theta_0(L, T_2^p)c_0 - v_0L + \lambda[F(X_0, L) - h_2 - \psi_2(L, T_2^p)] \\ &+ \mu[F(X_1, T_1^e) - h_1 - \psi_1(T_1^e, T_2^p)] + \Lambda_0[\bar{M} - v_0L] + \Lambda_1[\bar{U}_1 - P^*h_1] + \Lambda_2[\bar{U}_2 - (P^* - s)h_2] \dots\dots\dots 10(a) \end{aligned}$$

with h_1, h_2 and L as the control variables, X_i as state variables, $\lambda > 0$ and $\mu > 0$ as shadow prices⁹ for the shared stock X_0 and the stock inside the conservancy X_1 respectively and Λ_i as Lagrange multipliers. The following expressions can be obtained from the first-order condition:

$$\frac{\partial \theta_0(L, T_2^p)}{\partial L} c_0 + \lambda \frac{\partial F(X_0, L)}{\partial L} = v_0(1 + \Lambda_0) + \lambda \frac{\partial \psi_2(\cdot)}{\partial L} \dots\dots\dots 10(b)$$

According to equation 10(b) above, the park agency employs anti-poaching effort until benefits of stopping crime and growing the shared stock X_0 equals the value of reduced poaching plus the marginal cost of employing anti-poaching enforcement. Equation 10(c) and 10(d) tells us that the park agency allocates hunting quotas until the shadow price of the stock equals the market value.

$$\mu = -\Lambda_1 P^* \dots\dots\dots 10(c)$$

$$\eta = -\Lambda_2 (P^* - s) \dots\dots\dots 10(d)$$

The portfolio conditions (equation 10(e) and 10(f) below) indicates that the sum of the wildlife gain and the net stock effect resulting from maintaining one unit of wildlife must be equal to the marginal benefit of harvesting and putting the proceeds into the bank.

$$\dot{\lambda} + \frac{\partial G(\cdot)}{\partial X_0} + \frac{\partial R(X_0)}{\partial X_0} + \lambda \frac{\partial F(\cdot)}{\partial X_0} = \delta \lambda \dots\dots\dots 10(e)$$

$$\dot{\mu} + \frac{\partial G(\cdot)}{\partial X_1} + \mu \frac{\partial F(\cdot)}{\partial X_1} = \delta \mu \dots\dots\dots 10(f)$$

On the assumption of the functional forms reported in the appendix, the market equilibrium levels of anti-poaching effort by the park agency and the respective stocks of wildlife roaming inside the national park and on communal land, and in the conservancy can be computed from the first order conditions given above. The steady-state offtake of wildlife

⁹ The shadow price measures the approximate decrease in the present value of net benefits resulting from a unit decrease in the wildlife stock.

can be solved for by substituting the optimal wildlife stock and anti-poaching effort into the harvesting function. For comparison purposes, all solutions to the maximization problems presented in this analysis are shown at the end of this section.

3.2 The conservancy community

The private game farms employ T_1^a in agricultural production and anti-poaching effort T_1^e in order to grow the wildlife stock. Benefits enjoyed by the private game farms come from agricultural production $A_1(\cdot)$, selling hunting licenses h_1 , revenues from tourism activities $R(\cdot)$ and proceeds from poaching fines $\theta_1(\cdot)c_1$ imposed on detected perpetrators on their land. Anti-poaching enforcement is costly with v_1 as the fixed cost per unit of anti-poaching effort. It is assumed that revenue from non-consumptive tourism $R(X_1)$ increases with the stock of wildlife; that is, $R(0) = 0$, $\partial R(\cdot)/\partial X_1 > 0$ and $\partial^2 R(\cdot)/\partial X_1^2 < 0$.

The decision to be made by the conservancy community is how much anti-poaching effort T_1^e to invest in, while taking the off-take as given, since this is determined by the park agency through quota allocation h_1 . Because the conservancy community has appropriation rights (legal rights to exploit wildlife), they have a long term view and therefore take the stock dynamics into consideration. For simplicity, we assume that the discount rate used by the park agency is the same as the discount rate used by the conservancy community and the social planner. Thus, the conservancy community's net benefits from agriculture and wildlife conservation are given by:

$$\begin{aligned} \underset{\{T_1^e\}}{\text{Max}} \pi_1(T_1^e) &= \int_{t=0}^{\infty} [P_a A_1(\bar{T}_1 - T_1^e) + P^* h_1 + R(X_1) + \theta_1(T_1^e)c_1 - v_1 T_1^e] e^{\delta t} dt \dots\dots\dots 11 \\ \text{St: } \dot{X}_1 &= F(X_1, T_1^e) - h_1 - \psi_1(T_1^e, T_3^P) \\ h_1 &\leq \bar{h}_1 \text{ [Harvesting can not exceed quota]} \\ \bar{T}_1 &= T_1^a + T_1^e \end{aligned}$$

The production activities inside the conservancy are constrained by stock dynamics, the hunting quota and labour effort. The current value Hamiltonian is given by:

$$H(\cdot) = P_a A_1(\bar{T}_1 - T_1^e) + P^* h_1 + R(X_1) + \theta_1(T_1^e)c_1 - v_1 T_1^e + \mu [F(X_1, T_1^e) - h_1 - \psi_1(T_1^e, T_3^P)] + \Omega_1 [\bar{h}_1 - h_1] \dots\dots\dots 11(a)$$

The first order condition with respect to anti-poaching effort is therefore given by:

$$\frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 + \mu \frac{\partial F(X_1, T_1^e)}{\partial T_1^e} = P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} + v_1 + \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e} \dots\dots\dots 11(b)$$

Equation 11(b) tells us that the conservancy community will employ T_1^e until the benefit of catching a poacher as a result of increasing effort by a margin and growing the stock of wildlife equals the value of losing agricultural harvest as a result of employing anti-poaching enforcement, the marginal cost of anti-poaching enforcement and the value of reduced poaching. In other words, they allocate time towards anti-poaching activities until the loss from agriculture and anti-poaching equals the value of the growth in stock plus marginal benefits from collecting fines. According to 11(c), the conservancy community would maintain the stock of wildlife at a level that equates the return from trophy hunting and tourism activities with the return from alternative assets.

$$\dot{\mu} + \frac{\partial R_1(\cdot)}{\partial X_1} + \mu \frac{\partial F(X_1, T_1^e)}{\partial X_1} = \delta \mu \dots\dots\dots 11(c)$$

On the assumption of the functional forms shown in the appendix, the market equilibrium levels of anti-poaching effort by the conservancy community can be computed from the first order conditions. The optimal wildlife stock is the same whether computed by the park agency or conservancy.

3.3 The CAMPFIRE community

We assume that the CAMPFIRE community takes both stock size and legal off-take h_2 as given. This is consistent with the behaviour we discovered in the survey, which suggest that community institutions are not strong enough to be proactive in conservation. The local community allocates its fixed endowment of labour effort \bar{T}_2 between two production activities, namely agriculture T_2^a and poaching T_2^p with v_2 as the fixed per unit cost of poaching effort. As a result, there is a probability of being caught denoted by $\theta_i(\cdot)$, if community members engage in illegal harvesting of wildlife resources. If caught, the community is levied a fixed fine $\theta_0(\cdot)c_0$ or $\theta_1(\cdot)c_1$, paid to the park agency or the conservancy community respectively.

As usual, the unit price of agricultural output P_a and illegal wildlife offtake ω are assumed to be fixed where $\omega = P^* - \varepsilon$ and ε is the discount associated with illegal sales. It is reasonable to assume that the price of the illegal offtake could be far less than the market price (*i.e.* $\omega \ll P^*$) because of institutional constraints associated with selling on the black market. Poachers sell their trophies at a lower price because they want to attract buyers and dispose of the trophies as quickly as possible to reduce the risk of being caught. The legal benefits from wildlife conservation $\tau(P^* - s)h_2$ are exogenous to the local community. We assume that τ is fixed overtime and it only gets decided on by the RDC at the beginning of the CAMPFIRE programme. In a way, this also removes the decision power of the RDC in deciding how much revenue to allocate to CAMPFIRE communities, where all elements are given and not at its discretion. The CAMPFIRE community is taxed twice, first by the Safari operator who charges a total commission of $\tau s h_2$ for the specialist services offered, and then a second tax amount of $(1 - \tau)P^* h_2$ by the RDC for general programme administration.

We assume that local people maximise short-run gains. Johannesen and Skonhott (2014) argue that this myopic behaviour is reasonable because, in most cases, the legal benefits from conservation going into the hands of CAMPFIRE communities are too small relative to the cost of living with wildlife. Therefore, it is rational for the CAMPFIRE community to harvest as much as possible today, because of perceived risk and uncertainty in the future *e.g.*, they do not know if they may be effectively prevented from harvesting tomorrow due to, say, improved law enforcement. Thus, the CAMPFIRE community maximizes current net benefits shown in equation (12) subject to the labour constraint.

$$\text{Max}_{\{T_2^p\}} \pi_2(T_2^p) = P_a A_2(\bar{T}_2 - T_2^p) + \tau(P^* - s)h_2 + \omega\psi_2(L, T_2^p) - v_2 T_2^p - \theta_0(L, T_2^p)c_0 \dots \dots \dots (12)$$

$$\bar{T}_2 = T_2^a + T_2^p \dots \dots \dots 12(a)$$

The first order conditions are given by

$$\omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} = P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + v_2 + \frac{\partial \theta_0(\cdot)}{\partial T_2^p} c_0 \dots \dots \dots 12(b)$$

The local communities employ T_2^p until the benefits from increasing a unit of poaching effort by a margin equates to the loss in agriculture, the cost of poaching effort and marginal loss due to paying fines. On the assumption of the functional forms indicated in the appendix, the

market equilibrium level of poaching effort by the local communities can be computed from the first order conditions.

If benefits from wildlife conservation increase, then the welfare of the local community as a whole also increases. This could be achieved when the poaching effort exerted by the CAMPFIRE community is reduced and the population of wildlife on communal land increases, such that the quota allocation given to the local community is also increased. Using proceeds from wildlife conservation, local communities around the GNP invest in public goods that benefit the society as whole, such as schools, clinics, electricity and grinding mill, rather than distributing the income to households. Investing in public goods could have a significant impact on community welfare.

3.4 The social planner's problem

The social planner chooses anti-poaching enforcement, poaching effort and hunting quotas in order to maximise the present value of net benefits from the activities of all the agents (e.g., agricultural production, trophy hunting, tourism activities, state budget, the public good value of the wildlife stock and proceeds from poaching fines) subject to stock dynamics, budget, participation and harvesting constraints. The existence or cultural value from the public goods might be different to what the park agency assumes. The social planner knows about the existence value ϕ that the local community places on the wildlife stock in their area and, hence, incorporates it in his valuation. The social planner is confronted with the following maximization problem:

$$\underset{\{L, T_1^e, T_2^p, h_1, h_2\}}{\text{Max}} \pi_3(.) = \int_{t=0}^{\infty} [G(X_0, X_1) + R(X_0) + \bar{M} + P_a A_1 (\bar{T}_1 - T_1^e) + P^* h_1 + R(X_1) + \theta_1 (T_1^e) c_1 + \dots] e^{\delta t} \quad (13)$$

$$\phi X_2 + P_a A_2 (\bar{T}_2 - T_2^p) + \tau (P^* - s) h_2 + \omega \psi_2 (L, T_2^p) - v_2 T_2^p - v_0 L - v_1 T_1^e$$

$$\dot{X}_0 = F(X_0, L) - h_2 - \psi_2 (L, T_2^p)$$

$$\dot{X}_1 = F(X_1) - h_1 - \psi_1 (T_1^e, T_2^p)$$

$$v_0 L \leq \bar{M} \text{ [Budget constraint - assumed to hold with equality]}$$

$$P^* h_1 \geq \bar{U}_1 \text{ [Participation constraint for private game farms - assumed to hold with equality]}$$

$$(P^* - s) h_2 \geq \bar{U}_2 \text{ [Participation constraint for local community - assumed to hold with equality]}$$

$$h_1 \leq \bar{h}_1 \text{ [Harvesting can not exceed quota]}$$

$$h_2 \leq \bar{h}_2 \text{ [Harvesting can not exceed quota]}$$

The current value Hamiltonian is, therefore, given by equation 13(a) where λ_1 and μ_3 are the shadow values (co-state variables) for the wildlife stock in the park, outside the park and in the conservancy.

$$\begin{aligned} H(.) = & G(X_0, X_1) + R(X_0) + \bar{M} + P_a A_1 (\bar{T}_1 - T_1^e) + P^* h_1 + R(X_1) + \theta_1 (T_1^e) c_1 + P_a A_2 (\bar{T}_2 - T_2^p) + \tau (P^* - s) h_2 \\ & + \omega \psi_2 (L, T_2^p) - v_2 T_2^p - v_0 L - v_1 T_1^e + \lambda [F(X_0, L) - h_2 - \psi_2 (L, T_2^p)] + \mu [F(X_1, T_1^e) - h_1 - \psi_1 (T_1^e, T_2^p)] \\ & + \phi X_0 + \Lambda_0 [\bar{M} - v_0 L] + \Lambda_1 [\bar{U}_1 - P^* h_1] + \Lambda_2 [\bar{U}_2 - (P^* - s) h_2] + \Omega_1 [\bar{h}_1 - h_1] + \Omega_2 [\bar{h}_2 - h_2], \dots \dots \dots 13(a) \end{aligned}$$

The first order conditions with respect to anti-poaching effort are given by:

$$\lambda \frac{\partial F(X_0, L)}{\partial L} = (\lambda - \omega) \frac{\partial \psi_2(\cdot)}{\partial L} + v_o(1 + \Lambda_0) \dots \dots \dots 13(b)$$

$$\frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 + \mu \frac{\partial F(\cdot)}{\partial T_1^e} = P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} + v_1 + \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e} \dots \dots \dots 13(c)$$

According to equation 13(b), the social planner employs anti-poaching effort until the benefits of growing the stock in and outside the park equals the value of reduced poaching, plus the cost of employing the anti-poaching effort. Equation 13(c) says that the social planner will allocate labour between agriculture and anti-poaching enforcement in the conservancy, until the benefit of catching a poacher as a result of increasing anti-poaching effort by a margin and growing the stock of wildlife equates the value of losing agricultural harvest as a result of employing anti-poaching enforcement, the marginal cost of anti-poaching enforcement and the value of reduced poaching.

The first order condition with respect to poaching effort is given by:

$$(\omega - \lambda) \frac{\partial \psi_2(\cdot)}{\partial T_2^P} = P_a \frac{\partial A_2(\cdot)}{\partial T_2^P} + v_2 \dots \dots \dots 13(d)$$

The social planner would allocate labour between agriculture and poaching until the benefits reduced poaching from increasing a unit of poaching effort by a margin (corrected for market distortions) equates to the loss in agriculture and the cost of poaching effort. Equation 13 (e) and 13(f) states that the social planner will allocate hunting licenses until the shadow price and market price are equated, again correcting for market distortions.

$$\mu = P^* (1 - \Lambda_1) - \Omega_1 \dots \dots \dots 13(e)$$

$$\lambda = (P^* - s)(\tau - \Lambda_2) - \Omega_2 \dots \dots \dots 13(f)$$

Equations 13(g) and 13(h) show the evolution of the co-state variables over time. The social planner would, therefore, maintain the wildlife stock at a level that equates the return from wildlife conservation with the return from alternative assets. The return from the stock of wildlife is in terms of the change in the marginal valuation of the stock and stock effects on revenue from wildlife tourism (in the case of wildlife stock in the conservancy) and natural growth of the wildlife stock.

$$\dot{\lambda} + \frac{\partial G(\cdot)}{\partial X_0} + \frac{\partial R(\cdot)}{\partial X_0} + \lambda \frac{\partial F(\cdot)}{\partial X_0} + \varphi = \delta \lambda \dots \dots \dots 13(g)$$

$$\dot{\mu} + \frac{\partial G(\cdot)}{\partial X_1} + \frac{\partial R(\cdot)}{\partial X_1} + \mu \frac{\partial F(\cdot)}{\partial X_1} = \delta \mu \dots \dots \dots 13(h)$$

The social planner's explicit solution can be computed from the first order conditions using the functional forms assumed and presented in the appendix. From the maximization problems discussed above, one can solve for the optimal anti-poaching effort by the park agency and conservancy community i.e. L^* and T_1^{e*} respectively, poaching effort exerted by the CAMPFIRE communities i.e. T_2^{P*} , the steady state wildlife stock i.e. X_0^* and X_1^* and the optimal quota allocation i.e. h_1^* and h_2^* from all the equations presented in section 3.1 through section 3.4. Table 2 shows the comparison between the market equilibrium and the social planner's solution. The real result from this analysis is the uncovering of the policy

instrument to improve outcomes in the CAMPFIRE communities and that was not imposed exogenously. We focus on policy because it is crucial on the conservation side by affecting the stock dynamics and is also crucial on the welfare side by affecting economic values.

Table 2: Comparison of the market solution and the social planner's solution

Market Solution	Sign	Social Planner
$L^* = \left[\frac{\lambda \gamma b_0}{v_o(1 + \Lambda_o) + \lambda b_0 - g_o c_0} \right]^{\frac{1}{1-\gamma}}$	< >	$L^* = \left[\frac{\gamma \lambda b_0}{v_o(1 + \Lambda_o) + \lambda b_0 - \omega b_0} \right]^{\frac{1}{1-\gamma}}$
$X_0^* = K_0 \frac{\lambda(r - \delta) + 2q}{2r\lambda}$	<	$\Rightarrow X_0^* = K_0 \frac{\lambda(r - \delta) + 2q + \varphi}{2r\lambda}$
$X_1^* = K_1 \frac{\mu(r - \delta) + q}{2r\mu}$	<	$\Rightarrow X_1^* = K_1 \frac{\mu(r - \delta) + 2q}{2r\mu}$
$h_1^* = F[X_1^*] - \psi_1(T_1^{e*}, T_2^{P*})$	<	$h_1^* = F[X_1^*] - \psi_1(T_1^{e*}, T_2^{P*})$
$h_2^* = F[X_0^*] - \psi_2(L^*, T_2^{P*})$	<	$h_2^* = F[X_0^*] - \psi_2(L^*, T_2^{P*})$
$T_1^{e*} = \left[\frac{\alpha \mu b_1}{P_a A_1 + v_1 + \mu b_1 - g_1 c_1} \right]^{\frac{1}{1-\alpha}}$	=	$T_1^{e*} = \left[\frac{\alpha \mu b_1}{P_a A_1 + v_1 + \mu b_1 - g_1 c_1} \right]^{\frac{1}{1-\alpha}}$
$T_2^{P*} = \left[\frac{\phi \alpha \omega}{P_a A_2 + v_2 + g_o c_0} \right]^{\frac{1}{1-\phi}}$	>	$T_2^{P*} = \left[\frac{\phi \alpha (\omega - \lambda)}{P_a A_2 + v_2} \right]^{\frac{1}{1-\phi}}$

Source: own calculations 2015

4. Results and discussion

In this section we start by commenting on the key differences in table 2 and then narrow them down to the key role of poaching and institutions in influencing biodiversity outcomes. We also consider some comparative statics and numerical illustrations of the theoretical model.

4.1 Comparative statics

Our results are consistent with theoretical expectations. The results above show that the stock of wildlife roaming in and outside the protected area, i.e., the shared stock X_0^* and the stock managed by the conservancy X_1^* could be less than what the social planner would prescribe. This also implies that the optimal harvest on communal land and in the conservancy is less than that of the social planner. The solution of anti-poaching enforcement by the park agency L^* is ambiguous. The market solution is greater than the social planner's prescription if $g_o c_0 > \omega b_0$ and vice versa. The fact that the market solution differs from the social planner's outcome suggest that anti-poaching effort exerted by the park agency is suboptimal. Duffy (1999) reported some inefficiency associated with anti-poaching enforcement in Zimbabwe. Anti-poaching effort exerted by the park agency decreases with the cost of employing that effort i.e. $\partial L^* / \partial v_o < 0$ while increasing anti-poaching enforcement increases the probability

of being caught i.e. $\partial L^* / \partial g_o > 0$. Given the latter result, it might be beneficial for the park agency to increase L in order to grow the shared wildlife stock X_0^* .

If the conservancy community value wildlife the same as the social planner, then the level of anti-poaching enforcement T_1^{e*} exerted by the conservancy achieves social optimality i.e. both the market and the social planners' solution are the same. This is the case when a market efficient outcome is equal to a social optimal level. With this level of anti-poaching enforcement, poaching activities are kept at their lowest level and, hence, the stock inside the conservancy will grow. We argue that the offtake inside the conservancy is efficient, since harvesting is determined by the quota set by the park agency, and poaching is contained through the employment of an efficient level of effort which increases the probability of being caught i.e. $\partial T_1^{e*} / \partial g_1 > 0$. Therefore, starting from a lower level of stock, if the anti-poaching effort exerted by the conservancy is both efficient and socially optimal, then this could drive the wildlife stock inside the conservancy towards optimality, provided that harvesting does not exceed the maximum sustainable yield.

The CAMPFIRE communities exert more poaching effort than what the social planner would recommend. The role of poaching is to reduce the stock of wildlife when it is roaming on communal land. The offtake on communal lands is suboptimal, since harvesting is not only determined by the quota set by the park agency, but also by communities through poaching. Again, starting from a lower level, the wildlife stock in the community could diverge from the social planner's recommendation due to resource overexploitation. The differences between the market and the social planner's solutions are driven by externalities. Given the fact that we are considering non-marketed goods, the market solution suffers from externalities while the social planner takes externalities into account. To capture the deviation between the market and social equilibria, a parameter ω is included in the model to take into account of the potential for the divergence to worsen under market equilibrium. Thus, as the price of the illegal harvest increases, the community increases its poaching effort (i.e. $\partial T_2^{p*} / \partial \omega > 0$) in order to increase net benefit. This behaviour could lead to overexploitation of wildlife resources on communal land as the community seeks to maximize net benefits.

Our results show a negative relationship between poaching effort and the price of agricultural output $\partial T_2^{p*} / \partial P_a < 0$, the discount associated with illegal sales $\partial T_2^{p*} / \partial \varepsilon < 0$ and probability of being caught $\partial T_2^{p*} / \partial g_o < 0$. From the analysis, it is evident that the CAMPFIRE communities suffer a double tax; initially, the safari operator charges a commission s for the services rendered, and then the community loses a fraction $1 - \tau$ which goes to the RDC. Effectively, the price faced by the local community becomes $\tau(P^* - s)$ while the conservancy community gets P^* . Consequently, anything that deviates from the social planner's solution is not optimal and, thus, must be corrected. The following policy interventions could potentially benefit the CAMPFIRE communities if they were to be implemented.

i. Reducing taxation on CAMPFIRE communities: From a policy stand point, local communities would benefit if they could operate with the same self-sufficiency as the conservancy community because both taxes could be avoided. The ways in which this could be achieved include hiring a manager or building internal capacity to match that in the conservancy community. The differences in the level of education between these two communities are revealing: the average number of years in school in the CAMPFIRE community is 7 compared to 15 in the conservancy.

ii. Reduce the price of illegal offtake: Likewise, a policy instrument that increases the risk premium ε could decrease the effective price of the illegal offtake and, hence, poaching

effort i.e. $\partial T_2^{p*} / \partial \varepsilon < 0$. Reducing the effective price of the illegal offtake discourages the community from poaching by eroding the incentives, since $\partial T_2^{p*} / \partial \omega > 0$. It is possible to integrate the risk premium into CPR institutions by carefully designing policy instruments that are adapted to local conditions.

iii. Appropriate institutional reforms: As reported earlier, the survey results for the CAMPFIRE community point to weak institutions which are not supportive of proactive conservation. This is dramatically opposite to the behaviour observed in the conservancy community. As a result, it motivates us to explore whether an institutional reform in the CAMPFIRE community is what could take its welfare and conservation outcomes closer to those of the seemingly successful conservancy community. Since the local community exerts more poaching effort in the market solution than what is socially optimal, we investigate the transition to social optimality by introducing an institutional variable which portrays a constraint on poaching behaviour. We argue that institutions affect biodiversity indirectly through constraining human behaviour (Ntuli and Muchapondwa, 2015). Thus, we introduce an institutional variable ρ , which enters the model through the poaching function $\psi(\cdot)$. For this purpose, we will consider a variable ρ measuring lack of cooperation, such that when ρ is zero, the community has sound institutions and cooperation is also high. When ρ is one, then institutions are very weak and there is no cooperation in the community. Accordingly, $\rho=0$ produces zero poaching, while $\rho=1$ produces maximum poaching. Assuming the following explicit form, $\psi(\cdot) = a[\rho T_2^P]^\phi - b_0 L, b_2 > 0$ and $\rho \in [0,1]$, the modified solution for poaching effort is thus given by:

$$T_2^{p*} = \left[\frac{\rho^\phi \phi a \omega}{P_a A_2 + v_2 + g_0 c_0} \right]^{\frac{1}{1-\phi}}$$

Most importantly, improvement in institutions might have significant impact on growth of the wildlife stock through its role in constraining behaviour i.e. $\partial T_2^{p*} / \partial \rho > 0$. Thus, constraining poaching effort might drive the stock shared by the park agency and CAMPFIRE communities towards the social planner's solution and avert tragedy of the commons. The institutional variable ρ is a function of several other variables, such as governance, monitoring & enforcement, community level trust and endogenous punishment (see Ntuli and Muchapondwa, 2015). As a matter of policy, we want ρ to be a number which is low and very close to zero.

One way to iron out all issues with the current CAMPFIRE setup is to give local communities autonomy and capacitate the wildlife management committees, so that they are able to effectively discharge their duties. This entails building local level institutions that will, in turn, set the community agenda on new social norms which are pro-conservation. For instance, an improvement in governance structures at community level, monitoring and enforcement, and community level trust might contribute towards the attainment of a healthy biodiversity outcome as well as contain poaching activities. This could also be achieved through capacity building (institutional capacity) or training and funding to equip CAMPFIRE communities with the much needed resources. Moreover, if the community is allowed to endogenize punishment, then poaching might subside to social optimally levels.

4.2 Numerical illustrations

The theoretical model will now be illustrated using functional form assumptions and data which fit well with the exploitation of the African elephant population by communities

around the Gonarezhou ecosystem. African elephants are threatened by local communities because they cause more damage on agricultural crops than other wild animals (Fischer et al, 2011). Each year, quite a significant proportion of elephants leaves the national park and visits the nearby communal areas during the agricultural season. Using MATLAB, we compute the optimal solutions from all the optimization problems presented above, and then proceed to show the stock dynamics as we vary anti-poaching effort, poaching effort and constrain the poaching effort while holding other variables constant. Model simulation was done using the following stock dynamic equation in discrete form.

$$X_i(t+1) = X_i(t) + F(X_i, \cdot) - h_i(X_i(t)) - \psi_i(\cdot, T_2^P) \text{ given } X_i(0) = X_i^{(0)} \text{ at time } t = 0, \dots, 14$$

Following Johannessen and Skonhøft (2000), we normalize the catch-ability coefficient η to one so that the Schaefer harvesting function becomes $h_i(t) = \sigma X_i(t)$. The harvesting effort now belongs to the interval $0 < \sigma < 1$ so that the off-take cannot exceed the available resources. The natural growth function is specified as shown in the annexes, and again we normalise the size of the stock by setting the carrying capacity equal to one i.e. $K = 1$. The size of the wildlife stock (measured in biomass level) is thus expressed as a fraction of the carrying capacity and must be in the interval $0 \leq X_i(t) \leq 1$. Furthermore, the intrinsic growth rate r is set equal to 0.3 (Caughley and Sinclair, 1994; and Johannessen and Skonhøft, 2000). In line with other studies, we also force both poaching and anti-poaching effort to lie between 0 and 1 i.e. $0 \leq L \leq 1, 0 \leq T_1^e \leq 1$ and $0 \leq T_2^p \leq 1$.

The model simulation results confirm the theoretical predictions in section 4.1. In equilibrium, the anti-poaching effort by the park agency is less than the level of effort recommended by the social planner, while anti-poaching effort exerted by the conservancy community is just the same as that prescribed by the social planner. The poaching effort employed by the CAMPFIRE community is twice as much as that required for social optimality. The equilibrium stocks under the market solution are less than the social planner's solution.

Table 3: Numerical illustration – optimal solutions

Market Equilibrium	Social Equilibrium
$L^* = 0.6957$	$L^* = 0.6231$
$X_0^* = 0.5321$	$X_0^* = 0.5877$
$X_1^* = 0.5622$	$X_1^* = 0.5901$
$T_1^{e*} = 0.5992$	$T_1^{e*} = 0.6012$
$T_2^{p*} = 0.5183$	$T_2^{p*} = 0.2640$

Source: model simulation results 2015

Figure 1 shows the changes in the next period stock (i.e. the shared stock) as we vary anti-poaching enforcement exerted by the park agency between 0 and 1 while holding other variables constant. The figure shows that size of the wildlife stock on communal land increases as the park agency increases anti-poaching effort up to a certain point, and later on stabilizes at a slightly lower level than the social planner's recommendations. The gap between the market solution and the social planner's prescription does not completely iron out due to resource limitations. The numerical illustrations show that anti-poaching enforcement might grow the stock on communal land up to a certain level of effort $L^* = 0.62$

that is socially optimal, beyond which the stock ceases to grow due to other factors beyond the park agency's control.

Figure 1: Market solution for the park agency versus the social planner

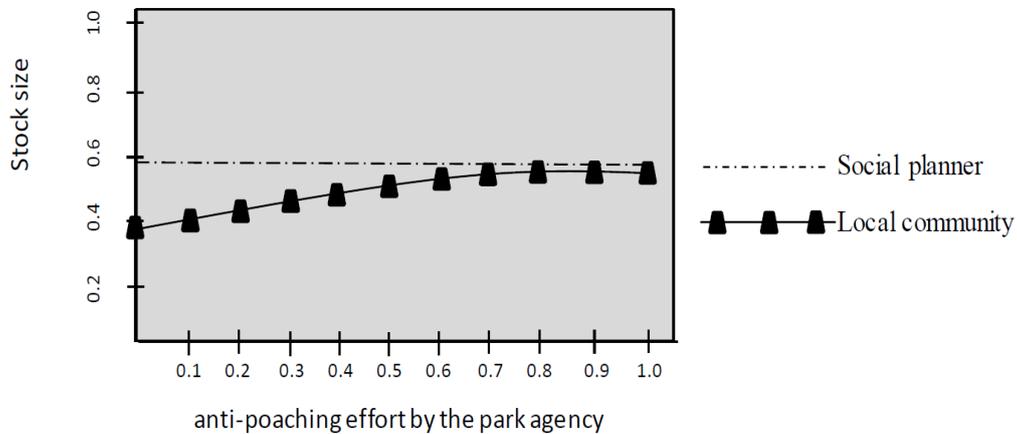


Figure 2 shows the changes in the next period stock inside the conservancy as we vary anti-poaching effort exerted by the conservancy community between 0 and 1 while holding other variables constant. The diagram shows that if anti-poaching effort by the conservancy community is optimal, then the stock size prescribed by the social planner and the market solution will eventually coincide with each other. This is the case when market solution is equal to social optimality. The convergence of the two solutions is very fast in the case of the conservancy community.

Figure 2: Market solution for the conservancy community versus the social planner

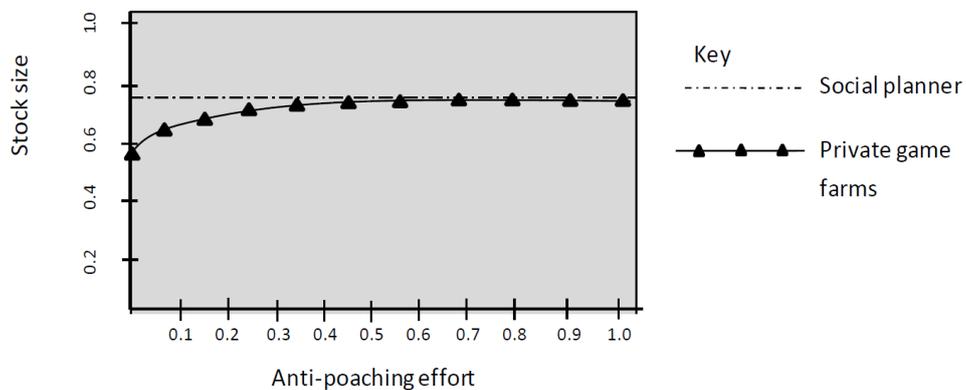


Figure 3 shows the changes in the next period stock (i.e. shared stock) as we vary the poaching effort exerted by the CAMPFIRE community between 0 and 1 while holding other variables constant. The figure shows that the stock size on communal land diverges from the social planner's solution if poaching continues unabated. Initially, the wildlife stock outside the park increases with very low levels of poaching but up to a certain point (about 0.26) then it starts to decrease tremendously. If local communities continue to increase the level of poaching effort beyond this point, then this could drive the resource system towards economic or physical extinction. Beyond a certain level of stock, again, the wildlife stock will not be able to regenerate itself without human intervention.

Figure 3: Market solution of CAMPFIRE community versus the social planner

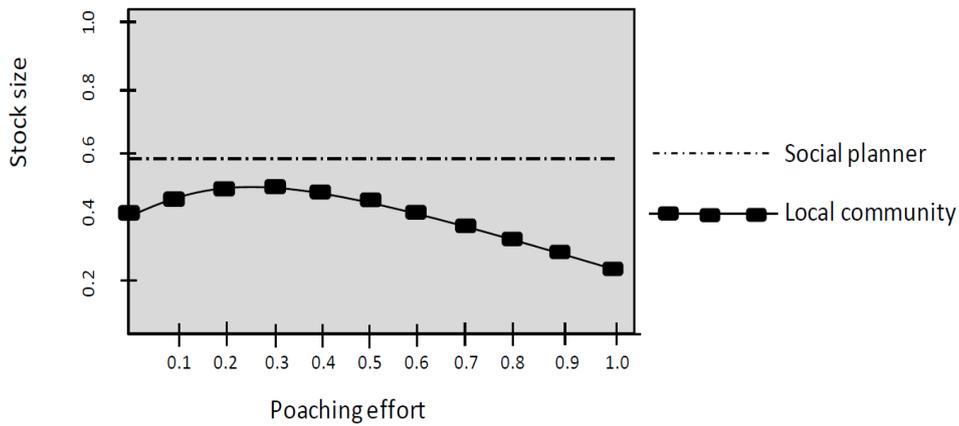
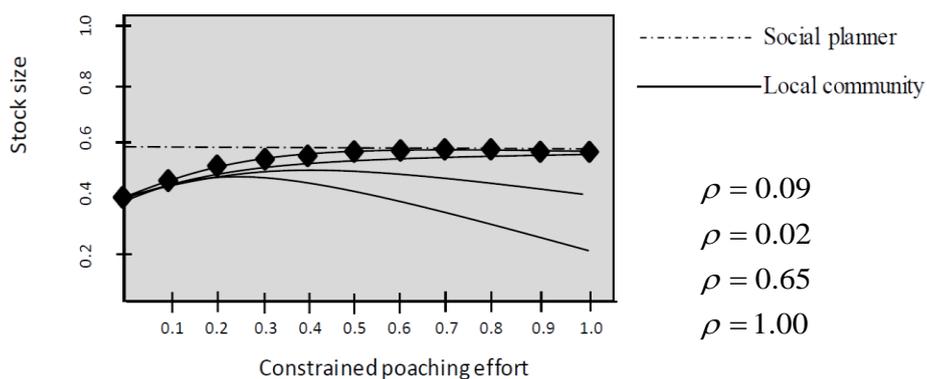


Figure 4 shows the changes in the next period stock of wildlife (i.e. shared stock) as we introduce a variable for institutions and vary constrained poaching effort exerted by the CAMPFIRE community between 0 and 1 while holding other variables constant. Starting from a lower level, the stock size in the local community's conservation area grows in a nonlinear fashion until the solution coincides with the prescriptions of the social planner, if the poaching effort is constrained. Ideally, we would want parameter ρ to be some number which is lower or very close to zero for faster convergence. The figure below shows that starting with $\rho = 1$ (i.e., with the situation in figure 4 above), an improvement in institutions, such that the parameter rho is forced towards zero (i.e. $\rho \rightarrow 0$), the shared stock mimics the dynamics of the wildlife stock inside the conservancy. The sensitivity analysis demonstrates how stronger institutions help to bridge the divide between the market and social planner's solution quicker than with weaker institutions. The graph below is drawn for the different values of rho i.e. $\rho = 1.00, 0.65, 0.02, 0.09$ and $\phi = 0.3$.

Figure 4: Market solution of local communities (with institutions) versus social planner



5. Conclusions and policy implications

Integrated Conservation and Development Projects are central for future rural development in Southern Africa. However, the impact of benefit-sharing schemes, such as the CAMPFIRE programme in Zimbabwe, is limited by possible dilemmas in the actual design of the scheme

or trade-offs inherent in linking development and conservation objectives. The objectives of this paper are to compare wildlife management and utilization under the CAMPFIRE communities and conservancy community, and to consider the possibility of wildlife tenure and institutional reforms that might replicate conservancies' successful outcomes on communal areas implementing CAMPFIRE. Therefore, unlike previous studies, this paper seeks to establish the conditions under which a CAMPFIRE community can be incentivized to behave like the conservancy community, which is more successful in revenue generation and stewardship practice.

To achieve the objectives above, we used a bio-economic model. We developed and compared the problems for benefit-sharing arrangements under CAMPFIRE and the conservancy communities operating adjacent to the Gonarezhou national park. Firstly, the paper showed that the conservancy community is superior to the pure benefit-sharing scheme in terms of employment of effort and the long-run wildlife stock. Secondly, the paper analyzed wildlife management and utilization under the assumption that the communities in question are given autonomy to the degree that they are able to invest in stronger CPR institutions.

Our results show that the level of anti-poaching enforcement by the park agency could be lower than the social planner's prescription. It might not be optimal for the park agency to provide anti-poaching enforcement inside the national game park and in communal areas. This result seems to support policy or institutional reforms that convey greater control of natural resources through devolution and decentralization of NRM functions, and decision-making to the community's grass roots level, since the community incurs lower cost of monitoring and enforcement. The social planner recommends higher levels of wildlife stock in the conservancy and on communal land i.e. shared stock.

If the conservancy community values wildlife the same as the social planner, then their level of anti-poaching enforcement achieves social optimality. This could drive the wildlife stock in the conservancy towards the social planner's solution, starting from a lower stock level. CAMPFIRE communities exert more poaching effort than what the social planner would recommend. As a result, the size of the shared stock might diverge over time from the social planner's prescription, starting from a lower level. Since both communities are carrying out similar activities, they should potentially be able to achieve similar results. The differences in observed outcomes between them could be a result of the differences in community institutions. Our results confirm that an improvement in community institutions might have significant impact on growth of the wildlife stock through its role of constraining behaviour. This result calls for policy instruments that will facilitate or promote the development of sound CPR institutions that are tailored to suit local conditions and endogenous to the community.

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7. Annexes

Table xx: Summary of definitions of symbols used in this paper

$G(.)$	Public goods value
X_0	Wildlife stock remaining inside the national game park
X_1	Wildlife stock in the conservancy
X_2	Wildlife stock in the community's conservation area
h_1	Hunting quota for private game farms
h_2	Hunting quota for private game farms
$\psi_i(.)$	Poaching function
$R(.)$	Revenue from tourism activities
L	Total antipoaching enforcement (by the park agency)
\bar{T}_i	Total production effort
T_i^a	Amount of effort towards agricultural production
T_i^e	Antipoaching enforcement (private game farms)
T_2^p	Poaching effort (peasant farmers)
θ_i	Probability of being caught
ρ	Effectiveness parameter/institutions (lack of cooperation)
π_i	Net benefits
λ_i	Shadow value of the wildlife stock inside the national park
μ_i	Shadow value of the wildlife stock inside the conservancy
η_i	Shadow value of the wildlife stock outside the national park
τ	Proportion of income going into the hands of the local community
v_i	Per unit cost of effort
c_i	Fine imposed on poachers
A_i	Agricultural technology
β	Nuisance parameter
P^*	Average fixed marginal valuation of the offtake or price
P_a	Price of agricultural produce
s	Premium charged by the Safari operator or private game farms for their service
ε	Risk premium charged by buyers
\bar{M}	Budget/income from the state

Functional forms

$$G(.) = qX_0 + qX_1 + qX_2 = q(X_0 + X_1 + X_2)$$

$$R(.) = qX_i$$

$$h = kmX_i$$

$$A_1(.) = AT_1^a = A_1[\bar{T}_1 - T_1^e]$$

$$A_2(.) = AT_2^a = A_2[\bar{T}_2 - T_2^p]$$

$$\psi_2(.) = a[T_2^p]^\phi - b_0L, b_0 > 0 \text{ and } 0 < \phi < 1$$

$$\psi_1(.) = a[T_2^p]^\phi - b_1T_1^e, b_1 > 0 \text{ and } 0 < \phi < 1$$

$$\theta_0(L, T_2^p) = g_0(L + T_2^p)$$

$$\theta_1(T_1^e) = g_1T_1^e$$

$$F(X_0, L) = rX_0 \left[1 - \frac{X_0}{K_0} \right] + b_0L' \text{ [growth inside the national game park]}$$

$$F(X_1, T_1^e) = rX_1 \left[1 - \frac{X_1}{K_1} \right] + b_1(T_1^e)^\alpha \text{ [growth inside the conservancy]}$$

The Park Agency

The first order conditions (maximum principle) are given by

$$\begin{aligned}\frac{\partial H(\cdot)}{\partial L} = 0 &\Rightarrow \frac{\partial \theta_0(L, T_2^P)}{\partial L} c_0 - v_o + \lambda \frac{\partial F(X_0, L)}{\partial L} - \lambda \frac{\partial \psi_2(\cdot)}{\partial L} - \Lambda_0 v_0 = 0 \\ &\Rightarrow \frac{\partial \theta_0(L, T_2^P)}{\partial L} c_0 + \lambda \frac{\partial F(X_0, L)}{\partial L} = v_o(1 + \Lambda_0) + \lambda \frac{\partial \psi_2(\cdot)}{\partial L} \dots\dots(b)\end{aligned}$$

$$\frac{\partial H}{\partial h_1} = -\mu - \Lambda_1 P^* = 0 \Rightarrow \mu = -\Lambda_1 P^* \dots\dots(c)$$

$$\frac{\partial H}{\partial h_2} = -\lambda - \Lambda_2(P^* - s) = 0 \Rightarrow \lambda = -\Lambda_2(P^* - s) \dots\dots(d)$$

$$\dot{\lambda} = \delta \lambda - \frac{\partial H(\cdot)}{\partial X_0} = \delta \lambda - \frac{\partial G(\cdot)}{\partial X_0} - \frac{\partial R(\cdot)}{\partial X_0} - \lambda \frac{\partial F(\cdot)}{\partial X_0} \dots\dots(e)$$

$$\dot{\mu} = \delta \mu - \frac{\partial H(\cdot)}{\partial X_1} = \delta \mu - \frac{\partial G(\cdot)}{\partial X_1} - \mu \frac{\partial F(\cdot)}{\partial X_1} \dots\dots(f)$$

Solving for X_0^*

$$\begin{aligned}\Rightarrow \dot{\lambda} &= \delta \lambda - \frac{\partial G(\cdot)}{\partial X_0} - \frac{\partial R(\cdot)}{\partial X_0} - \lambda \frac{\partial F(\cdot)}{\partial X_0} \\ \Rightarrow \dot{\lambda} &= \delta \lambda - q - q - r\lambda \left[1 - \frac{2X_0}{K_0} \right]\end{aligned}$$

In equilibrium

$$r\lambda \left[1 - \frac{2X_0}{K_0} \right] = \delta \lambda - 2q$$

$$X_0^* = K_0 \frac{\lambda(r - \delta) + 2q}{2r\lambda}$$

Solving for L^*

$$\begin{aligned}\Rightarrow \frac{\partial \theta_0(L, T_2^P)}{\partial L} c_0 + \lambda \frac{\partial F(X_0, L)}{\partial L} &= v_o(1 + \Lambda_0) + \lambda \frac{\partial \psi_2(\cdot)}{\partial L} \\ \Rightarrow g_0 c_0 + \lambda b_0 \gamma L^{\gamma-1} &= v_o(1 + \Lambda_0) + \lambda b_0 \\ \Rightarrow \lambda \gamma b_0 L^{\gamma-1} &= v_o(1 + \Lambda_0) + \lambda b_0 - g_0 c_0 \\ \Rightarrow L^{\gamma-1} &= \frac{v_o(1 + \Lambda_0) + \lambda b_0 - g_0 c_0}{\lambda \gamma b_0}\end{aligned}$$

$$\Rightarrow L^* = \left[\frac{v_o(1 + \Lambda_0) + \lambda b_0 - g_0 c_0}{\lambda \gamma b_0} \right]^{\frac{1}{\gamma-1}}$$

$$\Rightarrow L^* = \left[\frac{\lambda \gamma b_0}{v_o(1 + \Lambda_0) + \lambda b_0 - g_0 c_0} \right]^{\frac{1}{1-\gamma}}$$

Solving for X_1^*

$$\begin{aligned}\Rightarrow \dot{\mu} &= \delta \mu - \frac{\partial G(\cdot)}{\partial X_1} - \mu \frac{\partial F(\cdot)}{\partial X_1} \\ \Rightarrow \dot{\mu} &= \delta \mu - q + \mu r \left[1 - \frac{2X_1}{K_1} \right]\end{aligned}$$

In equilibrium

$$\mu r \left[1 - \frac{2X_1}{K_1} \right] = \delta \mu + q$$

$$X_1^* = K_1 \frac{\mu(r - \delta) + q}{2r\mu}$$

$$F(X_1, T_1^e) - h_1 - \psi_1(T_1^e, T_2^P) = 0$$

$$\Rightarrow h_1 = F(X_1^*, T_1^e) - \psi_1(T_1^e, T_2^P)$$

$$\Rightarrow h_1^* = rX_1^* \left[1 - \frac{X_1^*}{K_1} \right] + b_1(T_1^{e*})^\alpha - \psi_1(T_1^e, T_2^P)$$

$$F(X_2, L) - h_2 - \psi_2(L, T_2^P) = 0$$

$$\Rightarrow h_2 = F(X_2^*, L^*) - \psi_2(L^*, T_2^P)$$

$$\Rightarrow h_2^* = rX_1^* \left[1 - \frac{X_1^*}{K_1} \right] + b_0(L^*)^\gamma - (a[T_2^P]^\phi - b_0 L^*)$$

$$\Rightarrow h_2^* = rX_1^* \left[1 - \frac{X_1^*}{K_1} \right] + b_0(L^*)^\gamma - b_0 L^* - a[T_2^{P*}]^\phi$$

Private game farming community

The first order conditions are given by:

$$\begin{aligned}\frac{\partial H}{\partial T_1^e} = 0 &\Rightarrow -P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} + \frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 - v_1 + \mu \frac{\partial F(X_1, T_1^e)}{\partial T_1^e} - \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e} = 0 \\ &\Rightarrow \frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 + \mu \frac{\partial F(X_1, T_1^e)}{\partial T_1^e} = P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} + v_1 + \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e} \\ \dot{\mu} = \delta \mu - \frac{\partial H(\cdot)}{\partial X_1} &= \delta \mu - \frac{\partial R_1(\cdot)}{\partial X_1} - \mu \frac{\partial F(X_1, T_1^e)}{\partial X_1}\end{aligned}$$

Solving for T_1^{e*}

$$\begin{aligned}\frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 + \mu \frac{\partial F(X_1, T_1^e)}{\partial T_1^e} &= P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} + v_1 + \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e} \\ \Rightarrow g_1 c_1 - P_a A_1 - v_1 + \alpha \mu b_1 (T_1^e)^{\alpha-1} - \mu b_1 &= 0 \\ \Rightarrow \alpha \mu b_1 (T_1^e)^{\alpha-1} &= P_a A_1 + v_1 - g_1 c_1 + \mu b_1 \\ \Rightarrow (T_1^e)^{\alpha-1} &= \frac{P_a A_1 + v_1 + \mu b_1 - g_1 c_1}{\alpha \mu b_1} \\ \Rightarrow T_1^e &= \left[\frac{P_a A_1 + v_1 + \mu b_1 - g_1 c_1}{\alpha \mu b_1} \right]^{\frac{1}{\alpha-1}} \\ \Rightarrow T_1^{e*} &= \left[\frac{\alpha \mu b_1}{P_a A_1 + v_1 + \mu b_1 - g_1 c_1} \right]^{\frac{1}{1-\alpha}}\end{aligned}$$

The local community

The first order conditions are given by:

$$\begin{aligned}\frac{\partial \pi_2}{\partial T_2^p} = 0 &\Rightarrow -P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + \omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} - v_2 - \frac{\partial \theta_0(\cdot)}{\partial T_2^p} c_0 = 0 \\ &\Rightarrow \omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} = P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + v_2 + \frac{\partial \theta_0(\cdot)}{\partial T_2^p} c_0\end{aligned}$$

Solving for T_2^{p*}

$$\begin{aligned}\Rightarrow \omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} &= P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + v_2 + \frac{\partial \theta_0(\cdot)}{\partial T_2^p} c_0 \\ \Rightarrow \phi \alpha \omega [T_2^p]^{\phi-1} &= P_a A_2 + v_2 + g_0 c_0 \\ \Rightarrow [T_2^p]^{\phi-1} &= \frac{P_a A_2 + v_2 + g_0 c_0}{\phi \alpha \omega} \\ \Rightarrow T_2^{p*} &= \left[\frac{P_a A_2 + v_2 + g_0 c_0}{\phi \alpha \omega} \right]^{\frac{1}{\phi-1}} \\ \Rightarrow T_2^{p*} &= \left[\frac{\phi \alpha \omega}{P_a A_2 + v_2 + g_0 c_0} \right]^{\frac{1}{1-\phi}}\end{aligned}$$

Introducing the institutional variable

$$\begin{aligned}\Rightarrow \omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} &= P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + v_2 + \frac{\partial \theta_0(\cdot)}{\partial T_2^p} c_0 \\ \Rightarrow \phi \rho^\phi \alpha \omega [T_2^p]^{\phi-1} &= P_a A_2 + v_2 + g_0 c_0 \\ \Rightarrow [T_2^p]^{\phi-1} &= \frac{P_a A_2 + v_2 + g_0 c_0}{\rho^\phi \phi \alpha \omega} \\ \Rightarrow T_2^{p*} &= \left[\frac{P_a A_2 + v_2 + g_0 c_0}{\rho^\phi \phi \alpha \omega} \right]^{\frac{1}{\phi-1}} \\ \Rightarrow T_2^{p*} &= \left[\frac{P_a A_2 + v_2 + g_0 c_0}{\rho^\phi \phi \alpha \omega} \right]^{\frac{1}{\phi-1}} \\ \Rightarrow T_2^{p*} &= \left[\frac{\rho^\phi \phi \alpha \omega}{P_a A_2 + v_2 + g_0 c_0} \right]^{\frac{1}{1-\phi}} \\ \Rightarrow T_2^{p*} &= \left[\frac{\rho^\phi \phi \alpha \omega}{P_a A_2 + v_2 + g_0 c_0} \right]^{\frac{1}{1-\phi}}\end{aligned}$$

The social planner

First order conditions

$$\begin{aligned}\frac{\partial H(\cdot)}{\partial L} = 0 &\Rightarrow \omega \frac{\partial \psi_2(\cdot)}{\partial L} + \lambda \frac{\partial F(X_0, L)}{\partial L} - \lambda \frac{\partial \psi_2(\cdot)}{\partial L} - v_o - \Lambda_0 v_0 = 0 \\ &\Rightarrow \lambda \frac{\partial F(X_0, L)}{\partial L} = (\lambda - \omega) \frac{\partial \psi_2(\cdot)}{\partial L} + v_o(1 + \Lambda_0) \dots \dots \dots (13b)\end{aligned}$$

$$\frac{\partial H}{\partial h_1} = P^* - \mu - \Lambda_1 P^* - \Omega_1 = 0 \Rightarrow P^*(1 - \Lambda_1) - \mu - \Omega_1 = 0 \Rightarrow \mu = P^*(1 - \Lambda_1) - \Omega_1 \dots \dots \dots (13c)$$

$$\frac{\partial H}{\partial h_2} = \tau(P^* - s) - \lambda - \Lambda_2(P^* - s) - \Omega_2 = 0 \Rightarrow (P^* - s)(\tau - \Lambda_2) - \lambda - \Omega_2 = 0 \Rightarrow \lambda = (P^* - s)(\tau - \Lambda_2) - \Omega_2 \dots \dots \dots (13d)$$

$$\frac{\partial H}{\partial T_1^e} = \frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 - P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} - v_1 + \mu \frac{\partial F(\cdot)}{\partial T_1^e} - \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e} = 0 \dots \dots \dots (13e)$$

$$\frac{\partial H}{\partial T_2^p} = -P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + \omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} - v_2 - \lambda \frac{\partial \psi_2(\cdot)}{\partial T_2^p} = 0 \dots \dots \dots 13(f)$$

$$\dot{\lambda} = \delta \lambda - \frac{\partial H(\cdot)}{\partial X_0} = \delta \lambda - \frac{\partial G(\cdot)}{\partial X_0} - \frac{\partial R(\cdot)}{\partial X_0} - \lambda \frac{\partial F(\cdot)}{\partial X_0} - \varphi \dots \dots \dots 13(g)$$

$$\dot{\mu} = -\frac{\partial H(\cdot)}{\partial X_1} = \delta \mu - \frac{\partial G(\cdot)}{\partial X_1} - \frac{\partial R(\cdot)}{\partial X_1} - \mu \frac{\partial F(\cdot)}{\partial X_1} \dots \dots \dots 13(h)$$

Solving for L^*

$$\Rightarrow \lambda \frac{\partial F(X_0, L)}{\partial L} = (\lambda - \omega) \frac{\partial \psi_2(\cdot)}{\partial L} + v_o(1 + \Lambda_0)$$

$$\Rightarrow \gamma \lambda b_0 L^{\gamma-1} = (\lambda - \omega) b_0 + v_o(1 + \Lambda_0)$$

$$\Rightarrow \gamma \lambda b_0 L^{\gamma-1} = (\lambda - \omega) b_0 + v_o(1 + \Lambda_0)$$

$$\Rightarrow L^{\gamma-1} = \frac{(\lambda - \omega) b_0 + v_o(1 + \Lambda_0)}{\gamma \lambda b_0}$$

$$\Rightarrow L^* = \left[\frac{(\lambda - \omega) b_0 + v_o(1 + \Lambda_0)}{\gamma \lambda b_0} \right]^{\frac{1}{\gamma-1}}$$

$$\Rightarrow L^* = \left[\frac{\gamma \lambda b_0}{v_o(1 + \Lambda_0) + (\lambda - \omega) b_0} \right]^{\frac{1}{1-\gamma}}$$

Solving for X_0^*

$$\Rightarrow \dot{\lambda} = \delta \lambda - \frac{\partial G(\cdot)}{\partial X_0} - \frac{\partial R(\cdot)}{\partial X_0} - \lambda \frac{\partial F(\cdot)}{\partial X_0} - \varphi$$

$$\Rightarrow \dot{\lambda} = \delta \lambda - 2q - \varphi - r\lambda \left[1 - \frac{2X_0}{K_0} \right]$$

In equilibrium

$$\Rightarrow r\lambda \left[1 - \frac{2X_0}{K_0} \right] = \delta \lambda - 2q - \varphi$$

$$\Rightarrow 1 - \frac{2X_0}{K_0} = \frac{\delta \lambda - 2q - \varphi}{r\lambda}$$

$$\Rightarrow \frac{2X_0}{K_0} = 1 - \frac{\delta \lambda - 2q - \varphi}{r\lambda}$$

$$\Rightarrow X_0^* = K_0 \frac{\lambda(r - \delta) + 2q + \varphi}{2r\lambda}$$

Solving for X_1^*

$$\Rightarrow \dot{\mu} = \delta\mu - \frac{\partial G(\cdot)}{\partial X_1} - \frac{\partial R(\cdot)}{\partial X_1} - \mu \frac{\partial F(\cdot)}{\partial X_1}$$

$$\Rightarrow \dot{\mu} = \delta\mu - q - q - r\mu \left[1 - \frac{2X_1}{K_1} \right]$$

In equilibrium

$$\Rightarrow r\mu \left[1 - \frac{2X_1}{K_1} \right] = \delta\mu - 2q$$

$$\Rightarrow 1 - \frac{2X_1}{K_1} = \frac{\delta\mu - 2q}{r\mu}$$

$$\Rightarrow \frac{2X_1}{K_1} = 1 - \frac{\delta\mu - 2q}{r\mu}$$

$$\Rightarrow X_1^* = K_1 \frac{\mu(r - \delta) + 2q}{2r\mu}$$

$$\Rightarrow X_1^* = K_1 \frac{\mu(r - \delta) + 2q}{2r\mu}$$

Solving for T_1^{e*}

$$\frac{\partial H}{\partial T_1^e} = \frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 - P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} - v_1 + \mu \frac{\partial F(\cdot)}{\partial T_1^e} - \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e}$$

$$\Rightarrow \frac{\partial \theta_1(\cdot)}{\partial T_1^e} c_1 - P_a \frac{\partial A_1(\cdot)}{\partial T_1^e} - v_1 + \mu \frac{\partial F(\cdot)}{\partial T_1^e} - \mu \frac{\partial \psi_1(\cdot)}{\partial T_1^e} = 0$$

$$\Rightarrow g_1 c_1 - P_a A_1 - v_1 + \alpha \mu b_1 (T_1^e)^{\alpha-1} - \mu b_1 = 0$$

$$\Rightarrow \alpha \mu b_1 (T_1^e)^{\alpha-1} = P_a A_1 + v_1 - g_1 c_1 + \mu b_1$$

$$\Rightarrow (T_1^e)^{\alpha-1} = \frac{P_a A_1 + v_1 + \mu b_1 - g_1 c_1}{\alpha \mu b_1}$$

$$\Rightarrow T_1^e = \left[\frac{P_a A_1 + v_1 + \mu b_1 - g_1 c_1}{\alpha \mu b_1} \right]^{\frac{1}{\alpha-1}}$$

$$\Rightarrow T_1^{e*} = \left[\frac{\alpha \mu b_1}{P_a A_1 + v_1 + \mu b_1 - g_1 c_1} \right]^{\frac{1}{1-\alpha}}$$

Solving for T_2^{p*}

$$\frac{\partial H}{\partial T_2^p} = -P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + \omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} - v_2 - \lambda \frac{\partial \psi_2(\cdot)}{\partial T_2^p}$$

$$\Rightarrow -P_a \frac{\partial A_2(\cdot)}{\partial T_2^p} + \omega \frac{\partial \psi_2(\cdot)}{\partial T_2^p} - v_2 - \lambda \frac{\partial \psi_2(\cdot)}{\partial T_2^p} = 0$$

$$\Rightarrow -P_a A_2 + \phi \omega a [T_2^p]^{\phi-1} - v_2 - \phi \lambda a [T_2^p]^{\phi-1} = 0$$

$$\Rightarrow \phi \omega a [T_2^p]^{\phi-1} - \phi \lambda a [T_2^p]^{\phi-1} = P_a A_2 + v_2$$

$$\Rightarrow \phi a [T_2^p]^{\phi-1} (\omega - \lambda) = P_a A_2 + v_2$$

$$\Rightarrow [T_2^p]^{\phi-1} = \frac{P_a A_2 + v_2}{\phi a (\omega - \lambda)}$$

$$\Rightarrow T_2^p = \left[\frac{P_a A_2 + v_2}{\phi a (\omega - \lambda)} \right]^{\frac{1}{\phi-1}}$$

$$\Rightarrow T_2^{p*} = \left[\frac{\phi a (\omega - \lambda)}{P_a A_2 + v_2} \right]^{\frac{1}{1-\phi}}$$

Numerical illustration of stock dynamics

$$X_i(t+1) - X_i(t) = F(X_i, L)$$

In the national game park

$$X_0(t+1) = X_0(t) + F(X_0, L) \text{ given } X_0^{(0)} \text{ and } t = 0$$

In the conservancy

$$X_1(t+1) - X_1(t) = F(X_1, T_1^e) - h_1 - \psi_1(T_1^e, T_2^P) \text{ given } X_1^{(0)} \text{ and } t = 0$$

Outside the national game park

$$X_2(t+2) - X_2(t) = F(X_i, L) - h_i - \psi_1(L, T_2^P) \text{ given } X_2^{(0)} \text{ and } t = 0$$

Outside the national game park (with constrained poaching)

$$X_2(t+1) - X_2(t) = F(X_i, L) - h_i - \psi_1(L, \rho T_2^P) \text{ given } X_2^{(0)} \text{ and } t = 0$$