

## *A Bioeconomic Analysis of Bushmeat Hunting*

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## SUMMARY

Unsustainable bushmeat hunting is a major threat to mammal species particularly in West/Central Africa. We develop a multispecies dynamic simulation model of hunter behaviour, parameterised using data from the Ashanti region, Ghana. The model distinguishes between two hunting techniques, snaring and gun hunting. We analyse the impact of key economic parameters on offtakes. Economic incentives determine the effort devoted to hunting, the choice of hunting technique, and the species that are consumed domestically or traded in markets. These factors, together with the growth rates and catchabilities of hunted species, determine the ecological impact of hunting. Results suggest that increased bushmeat prices are likely to lead to a switch from snaring, which is cheaper but less efficient, to gun hunting, with a consequent impact on vulnerable species. Increases in agricultural prices have an ambiguous effect on hunter behaviour, depending on the balance between incentives to invest in agriculture and increased consumption as incomes improve. Penalties are more effective if they target bushmeat sales, rather than the act of hunting. This model is a step forward because it explicitly considers bushmeat as a component of the household economy. This has important implications for developing policies to conserve species hunted for bushmeat.

Key words: Ashanti, Ghana, snaring, gun hunting, agriculture, household economy

## ***Introduction***

Bushmeat hunting threatens the survival of many forest mammal species, particularly in West/Central Africa (Bakarr *et al.* 2001, Robinson & Bennett 2000). It is of current concern for a range of reasons including rising demand from an urbanising population as incomes improve, human population growth and expansion into previously remote forest areas, the spread of more efficient technologies such as guns, and populations of particular species reaching critically low levels (Milner-Gulland *et al.* 2003). However hunting is apparently sustainable in some areas, either because vulnerable species have already been extirpated (Cowlshaw *et al.* in press) or because hunting pressure remains low (Hill & Padwe 2000). Bushmeat hunting is not only important in a conservation context, but is also a major component of people's livelihoods (de Merode *et al.* 2004). It is argued both that this is of concern, given that livelihoods are tied to a rapidly depleting resource (Bennett 2002, Fa *et al.* 2003), and that bushmeat hunting could contribute to development if managed for sustainability and transparently integrated into the general economy (Brown 2003).

Many bushmeat hunters also farm (Mendelson *et al.* 2003; Ntiamoa-Baidu 1998). Farmers may trap bushmeat around their fields for both home consumption and local sale. Others hunt commercially with guns and sell the majority of their produce in urban markets (Ntiamoa-Baidu 1998). Hence the amount of time devoted to hunting and the gear used is a decision taken in the context of the household's other income-generating activities. The role of bushmeat hunting within the household economy is a crucial issue which has received little quantitative attention beyond a few empirical studies (e.g. de Merode *et al.* 2004). However, the success of policy recommendations for the management of bushmeat hunting is dependent on the effects control measures have on the hunting-farming decision. These measures may

include altering bushmeat prices, penalties for hunting protected species, or raising agricultural prices.

Here we examine the role of bushmeat hunting within the household economy, when households can invest their limited productive time in hunting or agriculture, and hunting involves two technologies; snares or guns. We follow the conceptual framework outlined in Damania *et al.* (2003). First we explore analytical solutions to a simple model of household behaviour, and then parameterise the model using data from the Ashanti region, Ghana.

### ***The Model***

We focus on farm households engaging in production and consumption. There are two production activities: farming and bushmeat hunting. We assume that all agricultural output and a fraction of the bushmeat is sold in markets at given prices. The remainder of the bushmeat is consumed at home. Although we assume no home consumption of agricultural produce, the results generalise to the case in which a proportion of this produce is consumed at home. Income from bushmeat and crop sales is used to purchase food and other commodities. We distinguish between two widely-used hunting techniques - hunting with snares and guns. The simulations presented in Section 3 suggest that this distinction is of both biological importance and economic significance (see also Rowcliffe *et al* 2003).

There are  $i = 1, 2, \dots, I$  potentially hunted species, which may be captured by snares or guns.

$H_i^s$  is the total number of individuals of species  $i$  caught in snares,  $H_i^G$  the total number of individuals of species  $i$  killed with guns. A fraction  $\gamma_i \in [0, 1]$  of the offtake is consumed by the household and the remaining  $(1 - \gamma_i)$  is sold. There are  $N$  households with utility represented by a Cobb Douglas function:

$$U = \alpha_F \ln(F) + \alpha_h \ln \sum_{i=1}^I \gamma_i (H_i^G + H_i^S) \quad (1)$$

where  $\alpha_F + \alpha_h = 1$ ;  $F$  is a composite consumption good. By equation (1) household utility depends on consumption of the composite good and bushmeat. It is maximised subject to the budget constraint:

$$p_q Q + \sum_{i \in H} (1 - \gamma_i)(p_i H_i^G - \delta_i t_i^G) + \sum_{i \in S} (1 - \gamma_i)(p_i H_i^S - \delta_i t_i^S) = p_f F + \sum_{i \in I} \gamma_i \delta_i \theta (H_i^G + H_i^S + K) + C_G \sum_{i \in I} H_i^G + C_S \sum_{i \in I} H_i^S \quad (2a)$$

where superscript  $S$  denotes species hunted with snares, superscript  $G$  denotes species hunted with guns.  $Q$  is agricultural output,  $p_r$  ( $r=q,f,i$ ) are prices of good  $r$ , net of transport costs,  $\delta_i$  is an indicator variable taking the value 1 if the species is protected and there is a penalty for hunting and zero otherwise. We allow for the possibility that the expected penalty on sold bushmeat may differ from that on domestically consumed bushmeat, because bushmeat sold on open markets is more likely to be detected than that consumed at home.  $\theta$  is the probability of detecting a protected species at the hunting stage and  $0 \leq \mu \leq 1 - \theta$  is the probability of detecting the protected species when it is sold, where  $\theta + \mu \leq 1$ .  $K$  is the fine.  $t_i^j = (\theta + \mu)(H_i^j + K)$  is the expected penalty when protected species are sold.  $C_j$  ( $j= S, G$ ) is the hunting cost parameter, assumed linear based on the survey data used in the simulations.

Following Barrett and Arcese (1998), agricultural output depends on labour inputs with elasticity  $\beta$ .

$$Q = L_q^\beta \quad (2b)$$

where  $L_q$  is labour time devoted to agriculture.

The gun hunting production function is defined by:

$$H_i^G \equiv \frac{N_i}{A} g_i^\rho L_G^{b_i} \quad (2c)$$

where  $N_i$  is the biomass of species  $i$ ,  $A$  is the hunting area,  $g_i$  is group size of species  $i$ ,  $L_G$  is labour time devoted to gun hunting,  $\rho$  and  $b_i$  are parameters. Equation (2c) is taken from Rowcliffe *et al* (2003), and implies that the probability of an encounter with a species depends upon the density of the species  $N_i/A$ , the group or herd size ( $g_i$ ) and labour inputs ( $L_G$ ).

Snare captures are defined by:

$$H_i^s = (1 - e^{-2Dv_iN_i})L_s \quad (2d)$$

Equation (2d) is also taken from Rowcliffe *et al* (2003), and implies that the probability of capturing an animal in a trap depends upon the day range of the animal ( $v_i$ ), the number of animals ( $N_i$ ) and the distance at which the trap is triggered ( $D_i$ ). For a given density of animals the number coming into contact with a trap follows a Poisson distribution with mean  $2DN_i$ .

Thus (2c,d) define the off-take.

Finally (2e) describes the time allocation constraint, which requires that all available time be allocated between hunting and agriculture.

$$L = L_G + L_s + L_q \quad (2e)$$

The utility maximisation problem is based on the notion that households have no property rights in the wildlife that they hunt and therefore have little incentive to take account of the future biological consequences of current decisions. Hence they are assumed to solve a static optimisation problem, taking the time path of variables, such as wildlife stocks, as given.

Equation 1 is maximised with respect to  $\gamma$  and the labour supply variables  $(L_H, L_s, L_q)$ , subject to the constraints (2a) – (2e). To illustrate the properties of the model, we reduce the dimensions of the problem and consider the simpler case of two species. This restriction does not alter the qualitative properties of the equilibrium. The first-order-conditions are given in Appendix 1. By these conditions, households allocate the harvest of each species between consumption and sale, up to the point where the marginal utility from consumption is equal to the foregone net payoffs from the sale of the harvest. Labour is allocated to (say) gun hunting to equalise the net marginal payoffs from gun hunting to the marginal payoffs from agriculture. Hence, the opportunity cost of hunting (by either technique) is defined by the marginal returns to labour allocated to agriculture.

Despite the simple functions adopted, there are no analytical solutions available for the endogenous variables. Hence to assess the properties of the equilibrium, we derive the general comparative static properties of the first-order conditions (see Appendix 1). The impact of changes in the exogenous variables are in general indeterminate, typically because of conflicting income and substitution effects.

There are, however, identifiable situations where the effects can be unambiguously signed. Consider the effect of a rise in the price of (say) species 1. In this case the proportion of species 1 sold always rises (or falls). Moreover, higher bushmeat prices increase the payoffs from hunting relative to agriculture, so more labour time is devoted to hunting. If as a result, the harvest of other less valuable species increases sufficiently, then households substitute and consume the lower valued product (species 2) and sell a greater proportion of the higher valued product (species 1).

Turning next to the labour allocation decisions. Higher bushmeat prices always lead to a shift in labour supply from agriculture to hunting. However, the distribution of labour between snaring and gun hunting is ambiguous. If (say) gun hunting is relatively more efficient at capturing the higher valued species than snaring, there will be an increase in gun hunting and vice-versa. These results are summarised in the following remark. See Appendix 1 for proofs.

***Result 1:*** *An increase in the price of species  $i$  will: (a) lead to a greater proportion of species  $i$  being sold if other lower priced species can be caught with sufficient ease (b) induce an increase in the use of whichever technology is relatively more efficient in capturing species  $i$ .*

The effect of an increase in the payoffs from agriculture on all the endogenous variables is ambiguous (Appendix 1). Intuitively, an increase in the price of crops raises income and the demand for all goods, including bushmeat. There is therefore a (consumption driven) incentive to increase the amount of labour time devoted to hunting. However, since the relative payoffs from agriculture are now higher, labour tends to shift to agriculture. It follows that the effects on labour allocation decisions and hence hunting levels are ambiguous. For similar reasons, the impact on household consumption levels is also ambiguous.

***Result 2:*** *An increase in the price of agriculture has an ambiguous impact on the proportion of bushmeat consumed and the amount of labour time allocated to each hunting technique.*

Turning next to the effect of penalties on harvest decisions. The qualitative impact of raising the expected fine on *sold* bushmeat is clearly identical in its effects to a reduction in the net price of bushmeat. Hence the conclusions from Result 1 apply. Raising the expected fine for hunting per se ( $\theta$ ) increases the expected costs of harvesting, which lowers the total amount of labour devoted to hunting. The impact on the distribution of hunting effort between snaring and gun hunting is ambiguous and depends on the interaction between the hunting technology

parameters, the intensity of demand for domestically consumed bushmeat and the relative payoffs from sold bushmeat. Similarly, the impact on the proportion of the harvest consumed is also ambiguous.

***Result 3:*** *An increase in the expected fine for hunting lowers hunting effort, but has an ambiguous impact on the amount of labour time allocated to each hunting technique and the proportion of the harvest of each species consumed.*

### ***Description of the simulation study***

The ambiguity of the comparative static results suggests the need for empirical work. Hence we carried out a simulation of bushmeat hunting in the Ashanti region, Ghana. This is a mixed savannah-forest area with widespread agricultural activity as well as some protected areas of natural vegetation. Bushmeat hunting is common and supplies both local village markets and urban markets (Ntiamo-Baidu 1998). Data were obtained from detailed interviews conducted in July 2002 with 85 households in 3 villages, including 17 hunting households. Key informant estimates and the household survey both suggested that hunters made up 2-4% of the population, coinciding with the results of previous studies (Hofmann *et al.*, 1999, Ntiamo-Baidu 1998).

Households were asked about their annual revenues from all livelihood activities. 89% of the households farmed, but hunting households were particularly dependent on farming; 73% of the hunting households' non-hunting income was derived from farming compared to 46% in the sample as a whole. Hunters answered detailed questions about the costs of hunting, including fixed and variable costs of the gear employed and travel costs to market. They also gave information on frequency and length of hunting trips, revenues obtained from sales and agricultural revenues. The hunters partitioned their catch into species eaten at home, given away and sold, and species most frequently caught by each gear type.

For tractability we focus on five species frequently traded in the urban bushmeat market in Kumasi (making up 68% of open season trade over the period 1987-2002, Crookes *et al.*, submitted). These species are also mentioned as important by hunters in the village surveys, and as being caught by both guns and snares. They are grasscutter (*Thryonomys swinderianus*), giant rat (*Cricetomys spp.*), bushbuck (*Tragelaphus scriptus*), black duiker (*Cephalophus niger*) and brush-tailed porcupine (*Atherurus Africanus*). We also include two potentially vulnerable species which are only hunted with guns, and are also mentioned by hunters in the village surveys: the African civet cat (*Viverra civeta*) and the Mona monkey (*Ceropithecus mona*). The exact choice of species used in the simulations is less important than obtaining a representative spread of life histories, gear selectivity and protected status.

The discrete time logistic function (Begon *et al.* 1996) was used to describe the biological growth of each species. Thus the net population level of each species is given by:

$$N_{it} = \frac{e^{r_i} N_{it-1} \Phi_i}{K_i + (e^{r_i} - 1) N_{it-1}} - H_{it}^G - H_{it}^S \quad (4)$$

where  $N_{it-1}$  is the population level in period  $t-1$ .  $\Phi_i$  is the carrying capacity and  $r_i$  is the intrinsic growth rate of species  $i$ . These equations were parameterised using allometric relationships in Rowcliffe *et al.* (2003) and information from the literature (see Appendix 2).

There were no biological data available from the study site.

To assess the impact of bushmeat hunting we combine the model of hunter household behaviour with the biological growth equations to determine the time path of wildlife stocks under alternative scenarios. In the absence of explicit closed form solutions, the model is solved numerically. Thus, the solution to equations (1) - (2e) defines the household's labour

supply and consumption decisions for given wildlife stocks as defined in the allometric equations. The level of hunting emerges from the optimising decisions and in turn affects wildlife stocks (equation 4), and hunting and consumption decisions the following year. Model parameters are altered to determine the sensitivity of different species to changes in economic circumstances. Appendix 2 provides full details of the parameter values, sources of information and estimation methods used to derive certain parameters.

### ***Simulation results***

The benchmark simulation is based on parameter values relating to the current situation in Ashanti. We assume that there is no penalty for harvesting in the benchmark case. The steady state equilibrium values are given in Table 1. All species are above 50% of carrying capacity, varying from 55% (civet cat) to 93% (Mona monkey). This suggests that none of the species is over-exploited. Moreover the bulk of hunting effort is devoted to snaring, reflecting the relative costs of the techniques. The survey data indicate that the marginal cost of gun hunting (mainly cartridges) is considerably higher than the marginal cost of snaring (mainly wire). When returns from hunting are low, there is a preference for using less expensive snares to harvest bushmeat. Table 1 also summarises the proportion of each harvested species consumed. As expected, a relatively higher proportion of the lower priced species (giant rats, civet cats and porcupines) are consumed at home rather than being sold.

If the price of all bushmeat is increased by 20%, there is a noticeable reduction in the population of all species, accompanied by an increase in hunting with both snares and guns (Table 1). Moreover, civet cats and mona monkeys are hunted to extinction as a consequence of the increase in gun use. With higher prices there is a stronger incentive to sell a greater proportion of the harvest.

The harvest of some species (e.g. grasscutters and giant rats) increases under higher prices, while that of others declines (e.g. bushbucks and black duikers). This is a consequence of the interaction between the equilibrium harvest function (which is increasing in wildlife stocks) and the logistic concave biological growth curve (equation 4). Figure 1 illustrates a possible equilibrium for a single species. A price increase induces an upward movement of the harvest function. If at the new equilibrium the harvest curve intersects the growth curve to the right of the maximum sustainable yield (MSY) point, the harvest will increase and vice-versa. This explains why for sufficiently small price increases, the harvest of some species rises, and of others declines. The simulations reveal that the harvest of grasscutters rises by a substantial amount (60%) but giant rats by a more modest 18%.

With a 30% and a 50% rise in the price of all species, population levels decline even further. With a 50% price increase the bushbuck and grasscutter populations approach extinction. In this scenario, there is a more extreme switch from snaring to hunting by guns. The population decline is sharp, with equilibrium populations varying from 2.8% of carrying capacity (grasscutters) to 27% of carrying capacity (porcupines). As a consequence the harvest of all species is lower than in the benchmark case. The simulations therefore reveal that when prices rise sufficiently, adopting the more productive and expensive hunting technique becomes profitable. This switch in technique results in a noticeable decline in wildlife populations. The over-harvesting stimulated by higher prices results in an overall decrease in welfare levels. This is a consequence of the excessive harvesting and depleted resource stocks which typify open access regimes with high prices (Clark 1990).

Since civet cats and Mona monkeys are more vulnerable to extinction than other species it is useful to assess the impact of a penalty imposed on either the harvest or sale of these species. For the simulations we assume that bushmeat prices are 30% higher than in the benchmark case. The harvest of civets and mona monkeys is deemed illegal, and detection results in confiscation of the carcass and a fine of 100,000 cedis. Because we are assuming that hunters cannot select their targets, they still kill the protected species if they use guns, and hence are at risk of a penalty if it is imposed on hunting per se. If the penalty is imposed at the point of sale however, they can avoid it by consuming the protected species at home. Hence a penalty imposed at the point of sale has negligible effect on hunter offtakes or welfare, and the two protected species are still extirpated. It is only when a substantial penalty is incurred for hunting the protected species that hunter behaviour changes significantly, towards the benchmark situation of high wildlife stocks, negligible gun hunting and a high proportion of offtake consumed at home (Table 2a).

We also examine the case in which penalties are imposed across the board for either hunting or sale of bushmeat species. A 20% chance of obtaining a penalty for hunting any bushmeat species has little effect on the outcome, whereas a 20% chance of a penalty on the sale of bushmeat leads to almost complete recovery of wildlife stocks, and offtake being almost exclusively consumed at home. Only very highly priced species are still worth selling (Table 2b). Hence the results suggest that imposing penalties on the sale of bushmeat has a much more profound effect on hunter behaviour, sustainability and welfare than penalties imposed on hunting. This is because the sale of bushmeat brings a benefit through the household budget, while hunting for home consumption affects utility only (equations 1 and 2a).

Since labour allocated to agriculture defines the opportunity cost of hunting, it is useful to assess whether rising agricultural incomes can be used to curb hunting levels. We examine this possibility for a scenario in which there is a 10% probability of detection and a 100,000 cedis fine for both sold and consumed meat of the two vulnerable species. Agricultural prices are increased by 25%, 50% or 75% (Table 3). The results indicate that total labour time allocated to hunting declines with increased agricultural prices. However, with each consecutive price rise, there is an increase in gun harvesting and a reduction in snaring. Hence, most wildlife populations decline and the two vulnerable species go extinct. The “technique switching effect” induced by rising agricultural prices thus negates the beneficial impact of the reduction in labour time devoted to hunting. Intuitively, higher agricultural prices raise the opportunity cost of hunting and this therefore makes it more profitable to use the more efficient and expensive hunting technique. This suggests that policies aimed at lowering hunting effort by increasing the payoffs to alternative activities may be less effective in protected endangered species than direct regulations.

### ***Conclusions***

Although the importance of bushmeat hunting as a component of livelihoods is widely recognised (e.g. LWAG 2003, Brown 2003), the implications of this have not been explored analytically. The effects of changing the relative profitability of different hunting and non-hunting activities on wildlife populations are not necessarily intuitively obvious. In this paper we have developed a simple modelling approach to the household economy with the aim of providing a firm theoretical foundation for discussions of policy options for managing the bushmeat trade.

The general model shows that increases in agricultural prices are ambiguous in their effects on bushmeat hunting because they have the dual effect of increasing the proportion of labour devoted to agriculture rather than hunting, and also increasing the consumption of bushmeat because incomes have risen. Hence the actual allocation of effort between hunting and agriculture is not clear. This is important because a common suggestion for reducing bushmeat hunting is to invest in agricultural extension (Milner-Gulland *et al.* 2003), which our model suggests may have the unexpected and undesirable side effect of promoting consumption-driven increases in hunting pressure. Even more worrying, our simulations suggest that even when labour devoted to hunting is reduced because of higher agricultural prices, it is likely to become more focussed on the more expensive and efficient technology. In our case study, raising agricultural prices actually worsens the conservation status of vulnerable species which are selectively hunted by guns rather than snares.

The general model shows that increases in overall bushmeat prices increase both hunting rates and bushmeat consumption due to improved incomes. The income effect on consumption was demonstrated empirically by Auzel & Wilkie (2000) for a study site in the Republic of Congo. They showed that the presence of a logging camp increased household bushmeat consumption from 39% of meals in unaffected villages to 49% of meals in villages servicing the logging camp. This was caused by an increase in hunting income caused by the high demand for bushmeat from consumers in the logging camp; logging workers had disposable incomes, and hence 76% of their meals contained bushmeat.

The simulation model shows that increases in bushmeat prices also change the technology used for hunting away from the cheaper and less efficient technology (in this case from snares to guns). This has an impact on the species killed, again potentially leading to declines in the

more vulnerable species. Whether offtake levels go up or down as hunting effort increases depends on the initial population size (Figure 1). The simulations also show that changes in bushmeat prices lead to substantial changes in the proportion of different species consumed at home rather than being sold on the market. Hence one finding from our simulations is that there is no need to invoke differential pricing of bushmeat species to explain observed changes in species composition in the market; an overall increase in all prices can also lead to compositional changes. Changes in species composition can reflect changes in species availability, and hence depletion of more vulnerable species (Rowcliffe *et al.*, 2003). Here we show that they can also reflect changes in gear technology and/or the balance of consumption versus sale of offtake by hunters.

In our simulations, the proportion of grasscutters on sale in the market increased dramatically. This is in line with empirical observations; a market in Kumasi was monitored during a rise in all bushmeat prices, and a substantial increase in the proportion of grasscutters on sale was observed, with all other species remaining relatively stable (Crookes *et al.*, submitted). Despite this qualitative empirical match, it is not possible to use the Kumasi market data to validate our model more fully, because there is no information available about changes in the proportion of offtake consumed at home, or about the effects of rising prices on the number of new hunters entering the system.

The general model suggests that although penalties reduce hunter effort, they have an ambiguous effect on the distribution of effort between technologies and on consumption versus sale of offtake. In the simulations, we examined the effects of detection while hunting and at the point of sale separately. This has policy relevance because it has been proposed that restrictions on protected species should be strongly enforced, while allowing legal hunting on

more resilient species to continue. This is suggested as a way to enable participants in the bushmeat trade to receive much the same welfare benefits as previously, but reducing pressure on vulnerable species (Milner-Gulland *et al.* 2003).

We started by using the currently legislated fine for hunting protected species in Ghana, 10,000 cedis (US\$1.14), but unsurprisingly this fine had no effect. A fine rate of 100,000 cedis on the two vulnerable species only had an effect if detection probabilities at the point of sale were high. Since hunters are unable to select between gun-hunted species, the effect is to cause a switch away from gun-hunting, which leads to an increase in the population size of all species, not just the protected species. Hence overall welfare levels were also reduced. The simulations suggest, therefore, that targetted law enforcement, based on the most vulnerable species, is likely to have wider-ranging effects that might have been anticipated, if it is reducing hunters' abilities to use efficient technology because of the non-selective nature of hunting. The results also suggest that the current fine level is insufficient to have any effect on hunter behaviour or offtake rates; this is as observed in empirical studies; for example Ntiamoa-Baidu (1998) found protected species on sale during the closed season.

In this study we have developed a simple general model of the household economy as a way of putting bushmeat hunting into the wider context of individual decision-making. This is a first step towards a theoretical understanding how conservation and development policies might affect hunter behaviour, and hence both the conservation status of species and welfare of participants in the bushmeat trade. It highlights the importance of considering linkages between agriculture and hunting when developing conservation policies. This work now needs to be integrated with detailed empirical studies of the bushmeat trade, to produce a more rounded understanding of the factors underlying the "bushmeat crisis".

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**Table 1. Equilibrium values for the simulation model with no penalties imposed for hunting. Price rises: all prices increase by a percentage over the benchmark case.**

Price rise		Benchmark	Benchmark	Benchmark	+20%	+20%	+20%
Species	Carrying Capacity (CC, 100 km <sup>2</sup> )	Numbers (% of CC)	Fraction consumed at home	Offtake	Numbers (% of CC)	Fraction Consumed at home	Offtake
Grasscutter	1800	1437 (79%)	0.2	173	868 (48%)	0	275
Giant Rat	22800	19300 (85%)	0.68	1811	14900 (65%)	0.57	2123
Bushbuck	670	448 (67%)	0	38	175 (26%)	0	34
Black Duiker	4300	3375 (78%)	0	56	219 (5%)	0	37
Porcupine	400	280 (72%)	0.39	415	191 (47%)	0.16	421
Mona Monkey	570	531 (93%)	0	220	0	0	0
Civet cat	200	110 (55%)	0.27	8	0	0	0
Gun Hunting hrs p.a.		45			147		
Snaring hrs p.a.		4964			12360		
Welfare Level		2723			2700		

Price rise	+30%	+30%	+30%	+50%	+50%	+50%
Species	Numbers (% CC)	Fraction Consumed at home	Offtake	Numbers (% K)	Fraction Consumed at home	Offtake
Grasscutter	566 (31%)	0	172	51 (2.8%)	0	66
Giant Rat	10520 (46%)	0.39	3005	2750 (12%)	0.08	2651
Bushbuck	110 (16%)	0	21	19 (3%)	0	8
Black Duiker	1953 (45%)	0	32	803 (19%)	0	17
Porcupine	191 (47%)	0.09	536	109 (27%)	0	518
Mona Monkey	0	0	0	0	0	0
Civet cat	0	0	0	0	0	0
Gun Hunting hrs p.a.	972			12400		
Snaring hrs p.a.	11530			14		
Welfare Level	2718			2175		

**Table 2a. Equilibrium values for the simulation model with penalties imposed for hunting certain species (civet cats & Mona monkeys) and a 30% increase in bushmeat prices. Detection probabilities are given as % for hunting and for sale.**

Detection probabilities	Benchmark (no penalty)	0% - hunting 20% - sale	0% - hunting 20%- sale	0% - hunting 20% -sale.	15% - hunting 20% - sale	15% - hunting 20% - sale	15% - hunting 20% - sale
Species	Numbers	Numbers (% CC)	Fraction consumed at home	Offtake	Numbers (% CC)	Fraction consumed at home	Offtake
Grasscutter	566 (31%)	594 (33%)	0	108	1480 (82%)	0.42	96
Giant Rat	10520 (46%)	11220 (47%)	0.392	2500	19900 (87%)	0.48	1048
Bushbuck	110 (16%)	130 (19%)	0	13	458 (68%)	0.02	12
Black Duiker	1953 (45%)	2088 (48%)	0	20	3531 (82%)	0	15
Porcupine	191 (47%)	193 (48%)	0.17	420	284 (71%)	0.28	261
Mona Monkey	0	0	0	0	543 (95%)	0	140
Civet cat	0	0	0	0	120 (60%)	0.35	3
Gun Hunting hrs p.a.	972	960			18		
Snaring hrs p.a.	11530	11498			4965		
Welfare Level	2718	2710			2640		

**Table 2b. Equilibrium values for the simulation model with penalties imposed either for hunting all species or for selling all species, and a 30% increase in bushmeat prices. Detection probabilities are given as % for hunting and for sale.**

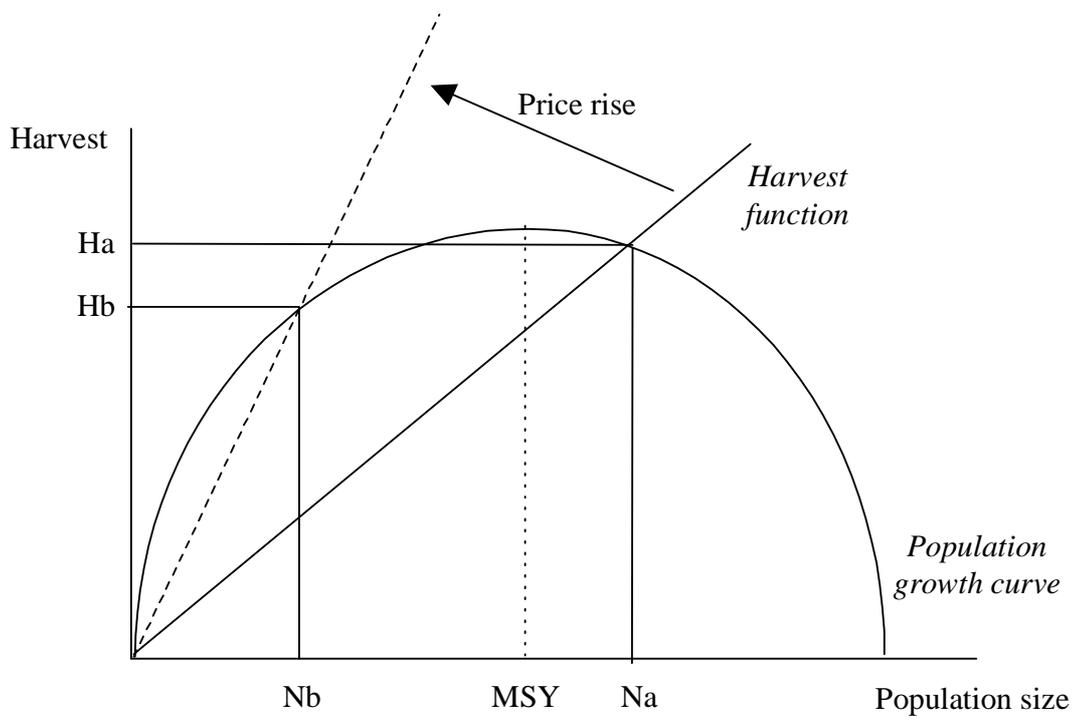
Detection probabilities	Benchmark (no penalty)	20% - hunting 0% - sale	20% - hunting 0%- sale	20% - hunting 0% -sale.	0% - hunting 20% - sale	0% - hunting 20%- sale	0% - hunting 20% -sale.
Species	Numbers	Numbers (% CC)	Fraction consumed at home	Offtake	Numbers (% CC)	Fraction consumed at home	Offtake
Grasscutter	566 (31%)	575 (32%)	0	168	1748 (97%)	0.82	25
Giant Rat	10520 (46%)	9980 (44%)	0.36	3100	22150 (97%)	1	840
Bushbuck	110 (16%)	111 (16%)	0	21	503 (75%)	0.65	9
Black Duiker	1953 (45%)	1966 (45%)	0	29	4126 (95%)	0.99	6
Porcupine	191 (47%)	195 (48%)	0.08	100	380 (93%)	0.61	230
Mona Monkey	0	0	0	0	570 (100%)	0.	0
Civet cat	0	0	0	0	200 (100%)	0	0
Gun Hunting hrs p.a.	972	938			0		
Snaring hrs p.a.	11530	10590			12500		
Welfare Level	2718	2685			2600		

**Table 3 Equilibrium Values with Higher Crop Prices.**

<b>Crop price rise</b>	<b>25%</b>	<b>25%</b>	<b>50%</b>	<b>50%</b>	<b>75%</b>	<b>75%</b>
<b>Species</b>	<b>Numbers (% CC)</b>	<b>Fraction consumed at home</b>	<b>Numbers (% CC)</b>	<b>Fraction consumed at home</b>	<b>Numbers (% CC)</b>	<b>Fraction consumed at home</b>
Grasscutter	350 (19%)	0	360 (20%)	0	381 (21%)	0
Giant Rat	7612 (33%)	0.36	7016 (31%)	0.33	6800 (29%)	0.39
Bushbuck	98 (15%)	0	111 (16%)	0	109 (15.8%)	0
Black Duiker	1638 (38%)	0	1488 (34%)	0	1565 (36%)	0
Porcupine	172 (43%)	0.09	166 (41%)	0.2	165 (41%)	0.3
Mona Monkey	0	0	0	0	0	0
Civet cat	0	0	0	0.	0	0
Gun Hunting hrs p.a.	2905		5795		5988	
Snaring hrs p.a.	9680		5632		5300	
Welfare Level	2859		2856		2864	

## Figure Legend

Figure 1. The equilibrium size of an exploited biological stock and the corresponding harvest rate are determined by the point where the harvest function intersects the biological growth curve (e.g. points  $N_a$  = equilibrium population size;  $H_a$  = equilibrium harvest rate). A price rise has the effect of rotating the harvest function to the left (dashed line). Whether this causes harvests to increase or decrease depends on whether the equilibrium moves from one side to the other of the Maximum Sustainable Yield (MSY) point. In the case of the price rise shown, harvest rate is reduced (point  $H_b$ ). Even though we are unable to solve explicitly for the harvest function, it is recognised that it is unlikely to be linear, as shown here. Hence there are likely to be multiple equilibria - not all of which will be stable. For a useful discussion of these issues see May 1975.



## Appendix 1

First order conditions for the analytical model are:

$$\frac{\alpha_h}{\gamma_1} - \lambda[P_1(k_1L_G^{b_1} + V_1L_s) + \delta_1\theta(k_1L_G^{b_1} + V_1L_s)] = 0 \quad (A1a)$$

$$\frac{\alpha_h}{\gamma_2} - \lambda[P_2(k_2L_G^{b_2} + V_2L_s) + \delta_2\theta(k_2L_G^{b_2} + V_2L_s)] = 0 \quad (A1b)$$

$$\frac{\alpha_h k_1 b_1 L_G^{b_1-1}}{k_1 L_G^{b_1} + V_1 L_s} + \frac{\alpha_h k_2 b_2 L_G^{b_2-1}}{k_2 L_G^{b_2} + V_2 L_s} + \lambda[\Omega_G - C_H(k_1 b_1 L_G^{b_1-1} + k_2 b_2 L_G^{b_2-1})] = 0 \quad (A1c)$$

$$\frac{\alpha_h V_1}{k_1 L_G^{b_1} + V_1 L_s} + \frac{\alpha_h V_2}{k_2 L_G^{b_2} + V_2 L_s} + \lambda[\Omega_s - C_s(V_1 + V_2)] = 0 \quad (A1d)$$

where  $\Omega_G = -\beta p_q(L - L_G - L_s)^{\beta-1} + b_1(1 - \gamma_1)P_1 k_1 L_G^{b_1-1} + b_2(1 - \gamma_2)P_2 k_2 L_G^{b_2-1} - \delta_1 \theta \gamma_1 k_1 b_1 L_G^{b_1-1} - \delta_2 \theta \gamma_2 k_2 b_2 L_G^{b_2-1}$

$\Omega_s = [-\beta p_q(L - L_G - L_s)^{\beta-1} + (1 - \gamma_1)P_1 V_1 + (1 - \gamma_2)P_2 V_2 - \delta_1 \theta \gamma_1 V_1 - \delta_2 \theta \gamma_2 V_2]$

$P_i = p_i - t_i$  is the net expected price of a species,  $\lambda$  is the Langrange multiplier,  $V_i =$

$2v_i N_i D$ ,  $k_i = \frac{N_i}{A} g_i^\rho$  and subscripts 1 and 2 denote species 1 and 2.

By equations (A1a) and (A1b) households allocate the harvest of each species between consumption and sale, up to the point where the utility from consumption is equal to the foregone net payoffs from the sale of the harvest. Equations (A1c) and (A1d) describe the labour allocation decisions.

The proof of the results is as follows:

### Result 1

Totally differentiating the system of equations (3a) – (3d) yields:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{12} & a_{22} & a_{23} & a_{24} \\ a_{13} & a_{23} & a_{33} & a_{34} \\ a_{14} & a_{24} & a_{34} & a_{44} \end{bmatrix} \begin{bmatrix} d\gamma_1 \\ d\gamma_2 \\ dL_G \\ dL_s \end{bmatrix} = - \begin{bmatrix} U_{\gamma_1 p_1} \\ 0 \\ U_{L_G p_1} \\ U_{L_s p_1} \end{bmatrix} dp_1$$

where:  $a_{12} = 0$ ;  $a_{i3} = \lambda b_i L_G^{b_i-1} k_i (-P_i - \delta_i \theta) < 0$  for  $i = 1, 2$ ,

$a_{i4} = \lambda(1 - e^{v_i})(-P_i - \delta_i \theta) < 0$  for  $i = 1, 2$

$$a_{34} = -\frac{\alpha_h(1-e^{v_1})k_1b_1L_G^{b_1-1}}{((1-e^{v_1})L_s+k_1L_G^{b_1})^2} - \frac{\alpha_h(1-e^{v_2})k_2b_2L_G^{b_2-1}}{((1-e^{v_2})L_s+k_2L_G^{b_2})^2}$$

$$+\lambda(\beta(\beta-1)p_q(L-L_G-L_s)^{\beta-2}) < 0$$

$$U_{\gamma_1 p_1} = -\lambda(k_1L_G^{b_1} + (1-e^{v_1})L_s) < 0; U_{L_G p_1} = \lambda(b_1k_1L_G^{b_1-1}(1-\gamma_1)) > 0;$$

$$U_{L_s p_1} = \lambda((1-\gamma_1)(1-e^{v_1})) > 0$$

Let  $\Delta$  be the determinant of the system. By the second-order-conditions  $\Delta > 0$ ,  $a_{ii} < 0$  ( $i = 1, 2, 3, 4$ ) and  $|a_{ii}| > |a_{ij}|$  for  $i = 1, 2, 3, 4$  and  $i \neq j$ .

Using Cramer's Rule:

$$\frac{d\gamma_1}{dp_1} = \frac{-(AU_{L_s p_1} + BU_{L_G p_1} + CU_{\gamma_1 p_1})}{\Delta} > (<) 0;$$

$$\text{where } A = a_{13}(a_{23}a_{24} - a_{22}a_{34}) + a_{14}(a_{22}a_{33} - a_{23}^2)$$

$$B = a_{13}(a_{22}a_{44} - a_{24}^2) + a_{14}(a_{24}a_{23} - a_{22}a_{34})$$

$$C = \begin{vmatrix} a_{22} & a_{23} & a_{24} \\ a_{23} & a_{33} & a_{34} \\ a_{24} & a_{34} & a_{44} \end{vmatrix} < 0 \text{ by the second order conditions.}$$

It follows that if  $a_{2i} > \frac{a_{22}a_{34}}{a_{2j}}$  for  $i, j = 3, 4; i \neq j$  0 then since

$$|a_{ii}| > |a_{ij}| \text{ for } i = 1, 2, 3, 4 \text{ and } i \neq j, A < 0 \text{ and } B < 0 \text{ so that } \frac{d\gamma_1}{dp_1} < 0.$$

Following an identical procedure:

$$\frac{dL_g}{dp_1} = \frac{(A1U_{L_G p_1} + B1U_{\gamma_1 p_1} + C1U_{L_s p_1})}{\Delta} > (<) 0$$

$$\text{where } A1 = -a_{11}a_{22}a_{33} + a_{11}a_{23}^2 + a_{22}a_{13}^2 > 0$$

$$B1 = a_{13}(a_{22}a_{44} - a_{24}^2) + a_{14}(a_{24}a_{23} - a_{22}a_{34})$$

$$C1 = a_{11}(a_{22}a_{34} - a_{23}a_{24}) - a_{14}a_{13}a_{22}$$

As  $v_l \rightarrow 0$  then  $a_{14} \rightarrow 0$  and  $U_{L_s p_1} \rightarrow 0$ . Thus  $\frac{dL_g}{dp_1} > 0$ .

Similarly:

$$\frac{dL_s}{dp_1} = \frac{(A2U_{L_G p_1} + B2U_{\gamma_1 p_1} + C2U_{L_s p_1})}{\Delta} > (<) 0$$

$$\text{where } A2 = a_{11}(a_{22}a_{34} - a_{23}a_{24}) - a_{14}a_{13}a_{22}$$

$$B2 = a_{13}(a_{23}a_{24} - a_{22}a_{34}) + a_{14}(a_{22}a_{33} - a_{22}a_{14})$$

$$C2 = -a_{11}a_{22}a_{33} + a_{11}a_{23}^2 + a_{22}a_{13}^2 > 0$$

As  $k_l \rightarrow 0$  then  $a_{13} \rightarrow 0$  and  $U_{L_G p_1} \rightarrow 0$  and then  $\frac{dL_s}{dp_1} > 0$

## Result 2

Totally differentiating the system of equations (3a) – (3d) yields:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{12} & a_{22} & a_{23} & a_{24} \\ a_{13} & a_{23} & a_{33} & a_{34} \\ a_{14} & a_{24} & a_{34} & a_{44} \end{bmatrix} \begin{bmatrix} d\gamma_1 \\ d\gamma_2 \\ dL_G \\ dL_s \end{bmatrix} = - \begin{bmatrix} U_{\gamma_1\theta} \\ U_{\gamma_2\theta} \\ U_{L_G\theta} \\ U_{L_s\theta} \end{bmatrix} d\theta$$

where:  $U_{\gamma_i\theta} = -\delta_i(k_i L_G^{b_i} + (1-e^{v_i})L_s) < 0$  ( $i = 1, 2$ );

$$U_{L_G\theta} = \lambda \sum_{i=1}^2 (-\delta_i b_i k_i L_G^{b_i-1} (1-\gamma_i)) - \sum_{i=1}^2 (\delta_i \gamma_i b_i k_i L_G^{b_i-1}) < 0;$$

$$U_{L_s\theta} = \lambda \sum_{i=1}^2 (-\delta_i (1-e^{v_i}) (1-\gamma_i)) - \sum_{i=1}^2 \delta_i (1-e^{v_i}) < 0$$

Using Cramer's rule:  $\frac{d\gamma_1}{d\theta} < (>) 0$ , since  $\begin{vmatrix} U_{\gamma_1\theta} & a_{12} & a_{13} & a_{14} \\ U_{\gamma_2\theta} & a_{22} & a_{23} & a_{24} \\ U_{L_G\theta} & a_{23} & a_{33} & a_{34} \\ U_{L_s\theta} & a_{24} & a_{34} & a_{44} \end{vmatrix} > (<) 0$

$$\frac{dL_g}{d\theta} > (<) 0 \text{ since } \begin{vmatrix} a_{11} & a_{12} & U_{\gamma_1\theta} & a_{14} \\ a_{12} & a_{22} & U_{\gamma_2\theta} & a_{24} \\ a_{13} & a_{23} & U_{L_G\theta} & a_{34} \\ a_{14} & a_{24} & U_{L_s\theta} & a_{44} \end{vmatrix} > (<) 0$$

$$\frac{dL_s}{d\theta} > (<) 0 \text{ since } \begin{vmatrix} a_{11} & a_{12} & a_{13} & U_{\gamma_1\theta} \\ a_{12} & a_{22} & a_{23} & U_{\gamma_2\theta} \\ a_{13} & a_{23} & a_{33} & U_{L_G\theta} \\ a_{14} & a_{24} & a_{34} & U_{L_s\theta} \end{vmatrix} > (<) 0$$

## Result 3

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{12} & a_{22} & a_{23} & a_{24} \\ a_{13} & a_{23} & a_{33} & a_{34} \\ a_{14} & a_{24} & a_{34} & a_{44} \end{bmatrix} \begin{bmatrix} d\gamma_1 \\ d\gamma_2 \\ dL_G \\ dL_s \end{bmatrix} = - \begin{bmatrix} 0 \\ 0 \\ U_{L_G p_q} \\ U_{L_s p_q} \end{bmatrix} dp_q$$

where  $U_{L_G p_q} = -\lambda\beta(L-L_G-L_s)^{\beta-1} < 0$ ;  $U_{L_s p_q} = -\lambda\beta(L-L_G-L_s)^{\beta-1} < 0$

$$\frac{d\gamma_1}{dp_q} = \frac{(AU_{L_s p_q} + BU_{L_G p_q})}{\Delta} > (<) 0$$

$$A = a_{22}(a_{14}a_{33} - a_{13}a_{34}) + a_{23}(a_{13}a_{24} - a_{14}a_{23}) > (<) 0$$

$$B = a_{22}(a_{13}a_{44} - a_{14}a_{34}) + a_{24}a_{14}a_{23} - a_{13}a_{24}^2 > (<) 0$$

$$\frac{dL_G}{dp_q} = \frac{(A1U_{L_G p_q} + B1U_{L_S p_q})}{\Delta} > (<) 0$$

$$\text{where } A1 = -a_{11}a_{22}a_{44} + a_{14}^2a_{22} + a_{11}a_{24}^2 > 0$$

$$B1 = -a_{11}a_{23}a_{24} + a_{14}a_{22}a_{13} + a_{11}a_{22}a_{34} > (<) 0$$

$$\frac{dL_S}{dp_q} = \frac{(A2U_{L_G p_q} + B2U_{L_S p_q})}{\Delta} > (<) 0$$

$$\text{where } A2 = -a_{11}a_{22}a_{34} + a_{11}a_{24}a_{23} + a_{14}a_{22}a_{13} > (<) 0$$

$$\text{where } B2 = -a_{11}a_{22}a_{33} + a_{11}a_{23}a_{23} + a_{13}^2a_{22} < 0$$

## Appendix 2

### Data used in the simulations

Variable	Value	Source
(L) total labour time (hours)	12600	Survey data (based on 6 people per household x 6hrs. per day x 350 days)
(K) Fine (cedis)	100000	Assumed value
(C <sub>G</sub> ) cost of gun hunt/individual caught (cedis)	6240	Computed from survey data
(C <sub>S</sub> ) cost of snaring /individual caught (cedis)	2820	Computed from survey data
(A) hunting area (km <sup>2</sup> )	100	Assumed value
( $\rho$ ) parameter on group size (elasticity)	0.434	Rowcliffe <i>et al</i> 2003
(D) trap trigger distance (cm)	10	Rowcliffe <i>et al</i> 2003
( $\beta$ ) coefficient agricultural production function	0.8	Barrett & Arcese 1998
( $\alpha_h$ ) coefficient utility function	0.15	Barrett Arcese 1998
<hr/>		
( $p_i$ ) Market prices (cedis per individual)		Crookes <i>et al.</i> (in prep)
Grasscutter	16654	
Giant rat	2797	
Bushbuck	68729	
Black duiker	41577	
Porcupine	10819	
Mona monkey	8835	
African civet	17930	
<hr/>		
( $v_i$ ) Day ranges (km)		Calculated from allometric equations in Rowcliffe <i>et al</i> 2003
Grasscutter	0.277	<i>Rodentia</i> estimate
Giant rat	0.31	
Bushbuck	1.6	
Black duiker	2.17	
Porcupine	0.4	
<hr/>		
( $g_i$ ) Group sizes (number of individuals)		
Grasscutter	1	OIA (2000)
Giant rat	1	OIA (2000)
Bushbuck	4	OIA (2000)
Black duiker	2	<i>Mammals of Africa</i> www.wildafrica.com
Porcupine	2	OIA (2000)
Mona monkey	12	Glenn (2003) & www.bbc.co.uk/wildfacts
African civet	1	<i>Mammals of Africa</i> www.wildafrica.com
<hr/>		
( $r_i$ ) Intrinsic growth rates		Calculated from allometric

Grasscutter	0.58
Giant rat	0.7
Bushbuck	0.46
Black duiker	0.49
Porcupine	0.6
Mona monkey	0.793
African civet	0.18

### Estimates of $b_i$

There are no data available on the coefficient of labour ( $b_i$ ) in the gun hunting production function. However, we have survey data on the time devoted to gun hunting  $L_G$ , group size ( $g_i$ ), and the parameter on group size  $\rho$ . There is no information on biological stocks in the Kumasi region. One solution is to assume that wildlife populations are in a steady state, which is some proportion  $x_i \in [0,1]$  of the

carrying capacity of each species. This implies that  $H_i^G \equiv \frac{x_i \Phi_i}{A} g_i^\rho L_G^{b_i} = N_{it} - N_{it-1}$ ,

where subscript  $t$  denotes time and the growth of each species is defined by equation (4) in the text. Thus for different values of  $x_i$ , this equation can be solved for  $b_i$ . To guard against exaggerating the threat from gun hunting we set a high value for  $x_i$ , which exceeds the current wildlife population levels in the survey region. Accordingly we assume that the steady state population is at  $x=90\%$  of the carrying capacity. This yields the following values:

Species	Value of $b_i$
Grasscutter	0.38
Giant rat	0.4
Bushbuck	0.3
Black duiker	0.32
Porcupine	0.3
Mona monkey	0.4
African civet	0.35