The Australian Journal of Agricultural and Resource Economics, 48:4, pp. 613–627

Wildlife trade and endangered species protection*

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Markets for endangered species potentially generate incentives for both legal supply and poaching. To deter poaching, governments can spend on enforcement or increase legal harvesting to reduce the return from poaching. A leader–follower commitment game is developed to examine these choices in the presence of illegal harvesting and the resulting impacts on species stocks. In addition, current trade restrictions imposed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora are examined. With Cournot conjectures among poachers, the model details the subgame perfect equilibrium interactions between poaching levels, enforcement and legal harvesting.

1. Introduction and background

While habitat destruction and transformation has been considered the leading factor in endangering species, several high-profile extinctions have been the direct result of over-harvesting, and many other currently endangered species are subject to harvesting for international trade. CITES, the Convention on International Trade in Endangered Species of Wild Fauna and Flora, was enacted in March 1973 in an attempt to ensure that species do not become extinct as a result of such harvesting. Under the Convention, species listed in Appendix I (such as the giant panda, tiger, and Australian dugong) are subject to complete bans on international trade, while those in Appendix II (including the bottle-nosed dolphin, whale shark, and black

* This research was supported in part by the Social Sciences and Humanities Research Council of Canada (SSHRC) Doctoral Fellowship number 752-97-1609. The author is grateful for the comments of John Mullen, two anonymous referees, Ida Ferrara, Charles Plourde, Sam Bucovetsky, Elie Appelbaum and Jim Brox, and seminar participants at Wilfrid Laurier University, the University of Manitoba, Washington College, Lakehead University, the University of Saskatchewan and the 1999 Canadian Economics Association meetings (Toronto). Any errors remain the responsibility of the author.

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spider monkey) tend to have less severe restrictions on trade, including quotas on harvests and customs requirements.

While the actual hunting or gathering of species may be relatively simple and subject to open-access, the poaching of endangered species for sale in foreign markets is potentially limited to those with the resources and connections to transport and sell plants or animals internationally without being easily caught (likely more so for trade in live animals). This implies that previous models of wildlife management, predominantly characterised by either perfect competition or a single user (monopoly), do not always accurately portray the realities of wildlife poaching. Imperfect competition among poachers, where individual poachers have some impact on prices, would be a more appropriate modelling choice for many species markets.

The use of game theory allows the interaction between poachers to be explicitly modelled in order to better describe how these agents will respond to the actions of their competitor poachers and to the harvesting and enforcement decisions of the government. Specifically, quantity (or Cournot) competition among poachers is employed in the present paper, where each poacher independently selects their own harvest and that harvest interacts with the legally sanctioned harvest and the harvests of other poachers through the price of the good, and can also be affected by enforcement through the expected punishment of being caught. Hence, the present paper examines two distinct policy options available to concerned governments of countries with harvested endangered species. The first is to use physical or monetary resources for protected areas, guards, special customs officers, and the like, in order to increase the probability of catching illegal harvesters, thereby increasing the expected fine/punishment for poaching. The second deterrence method is to sanction the provision of species to the market, driving down the price and, therefore, the return to poaching.

Modelling the choice of the legal harvest of the government simultaneously with the harvest choice of poachers would result in a market characterised by perfect competition (unless the legal costs and benefits are substantially different from those of poachers). The government would be a single producer among many, each without the capacity to significantly affect the price. Therefore, deterrence through higher legal harvests would not be possible, as the price received by poachers would not change. If the government were, instead, able to commit to particular harvest and enforcement levels prior to the decisions of poachers, the government could have an impact on those decisions and be in a position to actively limit (some) poaching with its wildlife management policy. For this purpose, the government choice of harvest (or domestic legal quota if direct control is not possible) and enforcement is here considered as the first move in a two-stage non-cooperative game with poachers.[1] Again, while certain species markets may be better suited to a competitive open-access characterisation (such as many commonly consumed fish species), many endangered species or their parts cannot simply be taken across a nearby border and sold to an end-user, but must be transported over long distances to countries with strict import regulations; and, accordingly, their markets can more appropriately be modelled with a limited number of harvesters (or limited entry). Australia, for example, is a major (legal) net exporter of crocodile skins and importer of wild orchids (World Resources Institute 2000), as well as having burgeoning illegal markets for macaws, palm cockatoos and other birds.

Open-access with illegal activity has received much more attention in the published resource management literature, beginning with Anderson and Lee (1986) and Milliman (1986), and more recently, Bulte and van Kooten (1999), Burton (1999), Alexander (2000) and Kremer and Morcom (2000). Limited entry with illegal activity has also been previously analysed by Sutinen and Andersen (1985) and Crabbé and Long (1993). Both of these papers abstract from pricing dynamics and focus on harvest decisions. In the present paper, the goal is to simultaneously determine the levels of enforcement, legal harvesting and poaching when poachers have some degree of market power. Poachers act according to Cournot conjectures (so there is no strategic collaboration), and choose their illegal harvests after the government has set the legal harvest quantity or quota. In the context of the proposed framework, the impact of the CITES policies on welfare, poaching, enforcement and endangered species stocks is explicitly evaluated. For example, particular trade bans, such as the 1989 elephant ban, can be examined.[2]

The remainder of the present paper describes the subgame perfect Nash equilibria of the two-stage game. Backward induction, beginning with poaching and working back to the government choices, is used to solve the

[1] The international oil market can be thought of in the same way, with the Organisation of Petroleum Exporting Countries cartel setting its own oil production for a period and other small producing countries then choosing their own production levels. The key difference here is that both the first and second movers select species from the same stock.

[2] African range states have shown mixed results after the ban, although many have observed overall increases in elephant populations despite population pressures, civil wars, habitat destruction and local killing in response to crop-raiding. Some nations, including Cameroon, Malawi and Tanzania, have experienced lower estimated poaching after the ban, while others, such as Kenya and Zimbabwe, have higher post-ban poaching estimates, despite the fact that enforcement in terms of monetary expenditures have decreased in all five of these nations (1989 estimates from Barbier *et al*. (1990); 1995 (non-speculative) estimates from Said *et al*. (1995)).

game. In the second stage, detailed in section 2, the individual poachers choose their harvest levels given the legal harvest and enforcement level set by the government. In sections 3 and 4, the government chooses the legal harvest and enforcement level under a pure profit objective (section 3) and a profit-and-stock objective (section 4), accounting for how individual and total poaching are affected by its decisions.

2. Individual and total poaching choice

Limited entry is modelled through a fixed and finite number of risk-neutral poachers, n, with identical costs. If we let h_j^P be the harvest of poacher j, using the superscript P to differentiate poaching from the legal harvest, and s be the stock, the cost of harvesting (which is stock-dependent) will be $c(s)h_j^P$, with $c_s < 0$ and $c_{ss} \leq 0$. Poachers are assumed to contribute nothing to the protection of habitat to maintain the species stock. The harvest of all poachers other than poacher j, denoted can h_{-j}^P, can be written as:

$$h_{-j}^P = \sum_{i \neq j}^{n} h_i^P. \tag{1}$$

As in the above mentioned studies, the market for legal and illegal products is the same: there is a single demand curve for the product in question, independently of the method by which it is provided. A representative poacher maximises expected individual profits, given the legal harvest, h^L, and the government enforcement level, e, as determined by the first stage (and, therefore, constant for the purpose of poaching choice), and the harvests of all other poachers, h_{-j}^P. The expected individual profits, or the difference between poaching revenues and the costs related to harvesting and (expected) punishment, are:

$$E(\pi_j^P) = p(h_j^P + h_{-j}^P + h^L)h_j^P - c(s)h_j^P - \alpha(e)\gamma(h_j^P), \tag{2}$$

where s is the final stock level, which is equal to its initial value less the sum of the total harvest of poachers and the legal harvest, or $s = \bar{s} - (h_j^P + h_{-j}^P + h^L)$; $p(h) \equiv p(h^P + h^L)$ is the demand function with $p_h < 0$ and $p_{hh} \geq 0$; γ is the punishment function (exogenous and convex); and $\alpha(e)$ is the enforcement technology, with $\alpha' > 0$ and $\alpha'' \leq 0$; that is, the probability of catching a poacher is increasing in the government-chosen level of enforcement with non-increasing returns.

The profit-maximising condition, which yields the reaction function, $h_j^P(h_{-j}^P, h^L)$, of poacher j, is:

$$p_h h_j^P + p - c + c_s h_j^P - \alpha\gamma' = 0. \tag{3}$$

Hence, poachers harvest until the benefit from harvesting one additional unit (the price received from output) equals the sum of the marginal cost of harvesting that unit, the increase in the expected fine and the profit lost through the resulting decrease in the price of output. Assuming a symmetric Cournot equilibrium among poachers (as in Crabbé and Long 1993), the reaction function for total poaching is:

$$p_h(h)\frac{h^P}{n} + p(h) - c(s) + c_s(s)\frac{h^P}{n} - \alpha(e)\gamma'\left(\frac{h^P}{n}\right) = 0 \tag{4}$$

where the total harvests by all poachers is:

$$h^P \equiv h_j^P + h_{-j}^P = nh_j^P \tag{5}$$

by symmetry. The reaction function for total poaching, equation (4), shows how total poaching is affected by the first-stage government choice variables: the legal harvest (h^L) and enforcement level (e). The particular reactions to these variables are provided below. Rearranging equation (4), total poaching harvest can be written as

$$h^P = n\left[\frac{c + \alpha\gamma' - p}{p_h + c_s}\right], \tag{6}$$

or that each poacher receives a price for each harvested unit (p) greater than the sum of the cost and expected punishment from the last unit ($c + \alpha\gamma'$), as the denominator is negative. For poaching to not occur, the price associated with the optimising legal harvest would then have to be lower than the sum of the expected cost and punishment associated with the first unit poached. This could occur if: (i) legal harvesting has a significant cost advantage so that the legal harvest is large and the market price consequently low; or (ii) enforcement is sufficiently high or effective so that the expected punishment is high relative to the price.

Returning to the poaching choice and the poaching reaction function, we can observe (by total differentiation of equation (6)) that the reaction of total poaching to legal harvest levels, *ceteris paribus*, is:

$$R^L \equiv \frac{dh^P}{dh^L} = \frac{-\frac{h^P}{n}p_{hh} - p_h - c_s + c_{ss}\frac{h^P}{n}}{\frac{h^P}{n}p_{hh} + p_h + \frac{p_h}{n} + c_s + \frac{c_s}{n} - c_{ss}\frac{h^P}{n} - \frac{\alpha\gamma''}{n}} < 0, \tag{7}$$

which is strictly negative.[3] Higher legal harvests influence poaching in several ways; the most important being the price effects through the demand function and cost effects through the stock-dependency of the poaching cost functions. Furthermore, we know that total poaching decreases by less than one unit when legal harvesting increases by one unit, or[4]

$$0 < | R^L | < 1. \tag{8}$$

This follows from two elements: that individual firms can collectively exercise some (possibly small but positive) degree of market power, and that enforcement is effective, as

$$R^e \equiv \frac{dh^P}{de} = \frac{\alpha'\gamma'}{\frac{h^P}{n} p_{hh} + p_h + \frac{p_h}{n} + c_s + \frac{c_s}{n} - c_{ss}\frac{h^P}{n} - \frac{\alpha\gamma''}{n}} < 0. \tag{9}$$

A decrease in legal offtake would then provide a price incentive to expand poaching output; but, at the same time, enforcement imposes a cost on poaching additional units. With a convex punishment function, the marginal expected punishment may be quite high. Enforcement effects partially offset price effects and, as a result, poaching will increase, but not by the full change in the legal harvest. For a given number of poachers and initial stock, the reaction function for total poaching is downward sloping in both enforcement and legal harvest, so enforcement and legal harvests are poaching deterrents. In selecting the legal harvest (h^L) and enforcement level (e) to maximise its objective, the government must take into account these reactions of total poaching. Accordingly, we move to the first stage of the game, incorporating the reaction function for total poaching (equation (4)) into the government objective; whether this be to maximise the returns from the legal harvest (the following section) or from both the legal harvest and the stock level (section 4).

[3] The second order condition for poaching (divided by n) is $p_{hh}(h^P)/n + p_h/n + c_s/n - c_{ss}h^P/n - \alpha\gamma''/n < 0$, so that (when combined with $p_h < 0$ and $c_s < 0$) the denominator is negative. In addition, the numerator is positive since the slope of marginal revenue is less (or equal to) than the slope of the demand curve (which implies: $-p_{hh}h^P - p_h \geq 0$) and $c_{ss} > 0$.

[4] In this case, the numerator is a subset of the denominator. The additional terms in the denominator all have the same reinforcing sign (negative), making the denominator a larger negative number. This implies that the entire R^L must be a fraction; hence, the absolute value is less than one.

3. Stock-independent resource management

For the purposes of this section, we assume that the government maximises the legal net return from the management of the stock; that is, the revenues from legal harvesting sales and expected fines, less the costs of habitat protection and harvesting. This may be the case when control over harvesting is made by a resource manager concerned only with the direct return from the stock, and serves as a benchmark for the following section, where welfare also depends on stock management.[5] To allow for differences in the cost structures between the (identical) poachers and the legal harvesters, let the legal harvest cost function be $d(s)h^L$. In addition to production costs, we assume that there is an opportunity cost of land, so that higher stock levels require additional habitat and take land from alternative uses. The cost of habitat protection ($l(s)$, inclusive of opportunity costs of land) required to sustain a particular stock level is assumed to be increasing in the stock at an increasing rate ($l_s > 0$ and $l_{ss} \geq 0$). Land costs serve to decrease conservation incentives, whether the resource manager is concerned with the stock level or not.

We consider the government to have either direct control over harvesting or indirect control over the distribution of individual quotas, which sum to the total legal harvest, h^L; the latter being consistent with Appendix II of CITES. With quotas, distributive effects are ignored, so that the government may freely distribute or charge a fee for the quotas; and the legal harvesting sector becomes passive in the sense that legal harvest choices of individual firms are given by the distribution of quotas. Enforcement capital, e, is purchased on a competitive international market at a parametric price, $r = 1$. The total expected return from the stock is then the difference between the revenues from the legal harvest and fines applied to caught poachers and the costs of harvesting, enforcement and land protection:

$$E(\pi^L) = p(h)h^L - d(s)h^L - l(s) + n\alpha(e)\gamma\left(\frac{h^P}{n}\right) - e. \tag{10}$$

Maximisation of equation (10) with respect to h^L, with R^L from equation (7) taken into account, yields the (interior) legal take of species, given by:

$$p + p_h h^L R^L + d_s h^L R^L + l_s = d + d_s h^L + p_h h^L + l_s R^L - \alpha\gamma' R^L. \tag{11}$$

[5] Other government objectives, including achieving a particular stock level by selling licensing fees and balancing their budget, are distinct possibilities, but are outside the scope of the present paper.

Optimal enforcement expenditure is found by maximising equation (10) with respect to e, with R^e from equation (9) taken into account, which yields:

$$p_h h^L R^e + d_s h^L R^e + n\alpha'\gamma = 1 - \alpha\gamma' R^e - l_s R^e. \qquad (12)$$

These two conditions, equations (11) and (12), can be interpreted in a relatively straightforward manner. The marginal benefit of harvesting, or the left-hand-side of equation (11), is comprised of the direct additional revenues from selling the last unit at the market price (p) and the indirect additional revenues derived from: (i) the decrease in total harvesting costs as a result of stock effects ($d_s h^L$) and (ii) the increase in the price (p_h) (each generated by the negative relationship between legal harvesting and the level of total poaching (that is, through R^L); and (iii) the reduction in the habitat protection cost (l_s), as a higher harvest implies a lower remaining stock to conserve. The marginal cost of harvesting, the right-hand-side of equation (11), is composed of the direct additional cost of harvesting the last unit (d), the indirect costs of the lost revenues on all units sold at a lower price because of a higher harvest ($p_h h^L$), the effects on total harvesting costs from harvesting more ($d_s h^L$), the additional habitat protection costs (l_s) and the expected loss in punishment revenues ($\alpha\gamma' R^L$) from the consequent reductions in poaching (again, through R^L). Similarly, the left-hand-side of equation (12) is the marginal benefit of enforcement, which consists of a higher price of (and revenue from) the harvested good ($p_h h^L$), a lower unit harvesting cost (d_s, from lower poaching through R^e), and a higher probability of catching poachers and, therefore, higher expected fines ($n\alpha'\gamma$). The right-hand-side of equation (12) is the marginal cost of enforcement, which consists of the expenditure itself, the expected lost fine revenue ($\alpha\gamma'$), and the higher habitat protection required (l_s) from less poaching (again through R^e).

From equation (11), the legal harvest may be zero and only poaching may occur when, among other factors, habitat protection is particularly expensive or legal harvesting costs are prohibitively high, poaching is significantly more efficient, or poaching levels are high (so that the price is low relative to costs, as is potentially the case when the number of poachers, n, is large).

To illustrate the relationship between legal and poaching harvests, consider the example provided in figures 1–3.[6] Figure 1 shows the legal harvest and total poaching under different numbers of poachers in the market. As

[6] The example provided is for illustrative purposes only. See Appendix for details. All of the conclusions and inferences that follow are general and, therefore, not restricted to the example in question. Partial output and enforcement levels are permitted for simplicity.

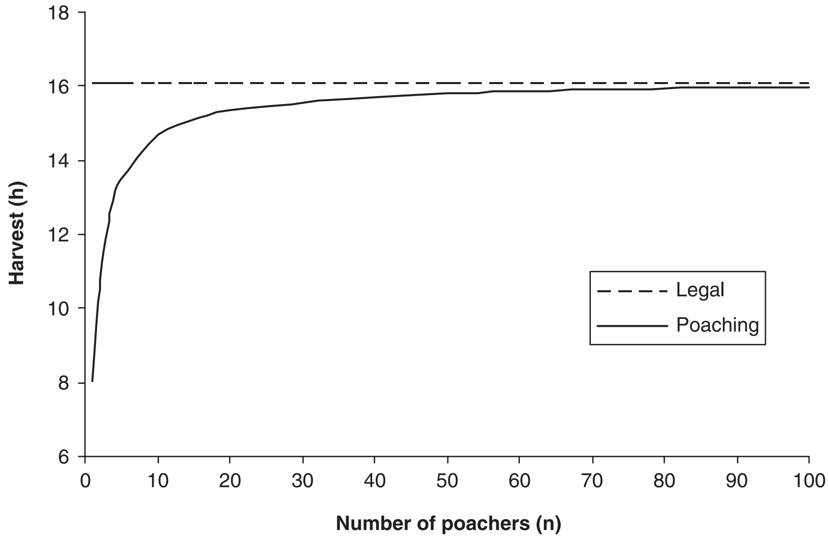

Figure 1 Legal and poaching harvests with pure-return objective and identical costs (identical harvesting costs but positive government habitat protection costs).

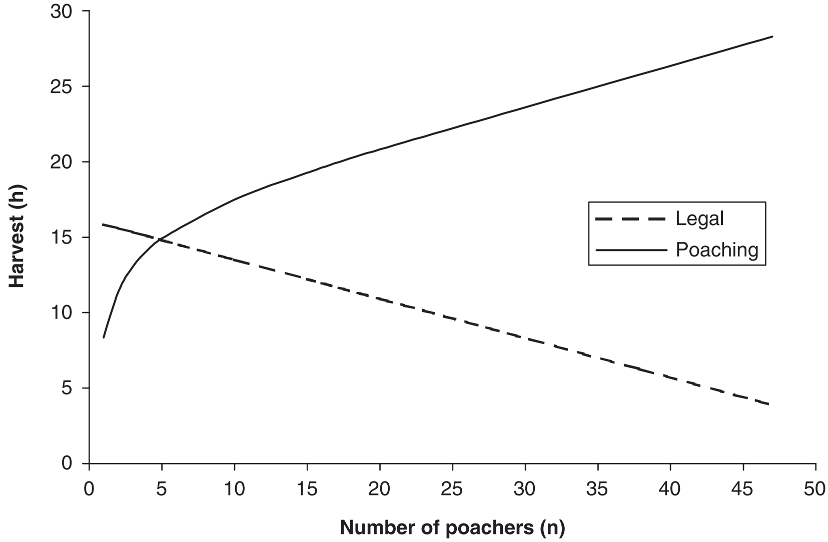

Figure 2 Legal and poaching harvests with pure-return objective and a cost advantage to poachers.

the number of poachers increases, there is little change in the legal harvest, but poaching increases; asymptotically converging to the legal harvest (so that the total of legal and poaching harvests is strictly increasing in the number of poachers). At low numbers of poachers (n), individual poachers utilise their (non-collusive) market power to trade-off units poached for higher product prices. However, as competition increases among poachers, this trade-off disappears and the reaction of total poaching to legal harvesting approaches negative one (that is, if poaching was perfectly competitive, a decrease in legal harvesting by one unit would increase poaching by the same amount, according to equation (7)), and enforcement becomes less effective, from equation (9).[7] Nonetheless, the first move of the government in selecting a particular legal harvest level prior to poachers selecting their own harvests ensures a legal harvest that is higher than total poaching for any finite number of poachers. Figure 2 shows the same situation, but with poachers having a cost advantage over legal harvesters: such as when harvesting costs are the same, but the government incurs significant habitat protection costs. Here, the lower harvesting costs may allow poachers to overcome the first-mover advantage of legal harvesters and earn higher profits, as poaching levels can exceed legal harvests.

Bans on legal harvesting can be implemented under agreements such as CITES, or can be unilaterally enforced by importing or exporting countries. In the context of the model, suppose initially that the relationship between the probability of catching poachers and illegal harvests remains the same after the implementations of a ban. A ban on legal harvesting will limit h^L to zero, promoting poaching through the (higher) price of output. However, to ascertain the overall impact on poaching, we must examine the impact on enforcement as well. Under a ban, poachers collectively harvest h^P to satisfy equation (4), as previously. The relationship between h^P and e (that is, R^e) remains negative and unchanged from equation (8), and the government simply maximises the net expected return earned from enforcement less habitat protection costs, or:

$$E(\pi^L) = n\alpha(e)\gamma\left(\frac{h^P}{n}\right) - e - l(s). \tag{13}$$

Therefore, enforcement is chosen according to:

$$n\alpha'\gamma = 1 - \alpha\gamma' R^e - l_s R^e, \tag{14}$$

which differs from its counterpart, equation (12), in that it excludes the benefits of a higher price of the harvested good (p) and lower land protection

[7] Enforcement becomes less effective here because the small individual poacher's harvest under competition reduces the expected punishment more than proportionally because of the convexity of the punishment function. If the expected punishment was linear in the poaching level, there would be no change in the effectiveness of enforcement.

costs (l_s). Therefore, for the same poaching harvest, enforcement has a smaller marginal benefit and unchanged marginal cost and, therefore, would decrease after a ban. However, the increased poaching associated with the reduction in legal harvesting increases the marginal benefit of enforcement and decreases its marginal cost, pushing enforcement upwards. These two opposite effects generate two possibilities. If the reaction of total poaching choice to the legal harvest (R^L) is relatively large, both poaching and enforcement could increase as a result of a trade ban. Conversely, when enforcement is highly effective and legal harvest changes have small effects on poaching choice (R^e is low, such as when the number of poachers is small), enforcement increases and the poaching harvest decreases. Both cases, however, would result in higher stock levels than before the ban. In each case, total poaching, in general, is less than the sum of legal and illegal harvesting that result in the absence of a ban, and, as such, trade bans can be said to be more conservative than when permitting legal harvesting.

Once a ban is instituted, however, illegal products cannot enter countries in the guise of legal goods, and a ban may, therefore, have the effect of increasing the probability of catching poachers, even if enforcement and poaching levels do not change, say from $\alpha(e)$ to $\theta(e)$, where $\theta(x) > \alpha(x)$ and $\theta'(x) > \alpha'(x)$ for all $x > 0$. In other words, the enhancement of the enforcement technology may serve to rotate the probability function upwards. In this case, a ban would have the additional positive effect of increasing enforcement effectiveness, as the reaction of total poaching to enforcement becomes:

$$\hat{R}^e = \frac{\theta'\gamma'}{\frac{h^P}{n}p_{hh} + p_h + \frac{p_h}{n} + c_s + \frac{c_s}{n} - c_{ss}\frac{h^P}{n} - \frac{\theta\gamma''}{n}} < R^e < 0. \tag{15}$$

At the same time, the marginal cost of enforcement increases (because of fewer fines and higher habitat protection costs), and this implies less enforcement effort. Hence, two conflicting effects on total poaching ensue: a lower enforcement level (e), but more effective enforcement (a higher R^e). Therefore, it is possible that total poaching falls, even with lower enforcement, as long as the change in the probability of catching poachers is sufficiently large.

4. Domestic and external conservation benefits

When a government takes into account that private individuals may hold non-use values or species may provide indirect benefits not captured in trade markets (above land use costs), the lower harvest levels associated

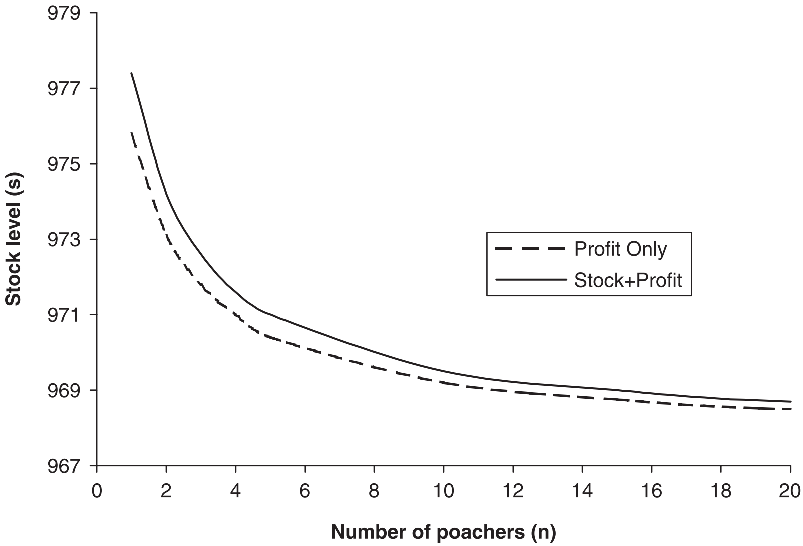

Figure 3 Stock levels under pure profit and stock-and-return objectives.

with trade restrictions may make them preferred over the free market.[8] In such a case, the poaching reaction function is unchanged from equation (4), but the government maximises a joint objective, such as:

$$U(E(\pi^L), s), \tag{16}$$

which is assumed, for simplicity, to be additively separable and quasilinear in expected profits or, equivalently, that the marginal utility of profits is unaffected by the stock level. The social value function can then be written as:

$$U = \xi E(\pi^L) + v(s), \tag{17}$$

where ξ is the constant, positive weight placed on expected profits, and $v' > 0$ and $v'' \leq 0$, or there is positive but diminishing marginal utility from the stock level. Given that poachers react to their harvest and enforcement level according to equation (7) and (9), respectively, the legal harvest is chosen according to:

$$p + p_h h^L[1 + R^L] - d + d_s h^L[1 + R^L] + l_s[1 + R^L] + \alpha\gamma' R^L - \frac{v'}{\xi}[1 + R^L] = 0 \tag{18}$$

[8] The market here, except for enforcement, is unregulated in the sense that no taxes or other measures can be employed to correct the market failure.

and enforcement according to:

$$p_h h^L R^e + d_s h^L R^e + l_s R^e + n\alpha'\gamma + \alpha\gamma' R^e - 1 - \frac{v'}{\xi} R^e = 0. \tag{19}$$

Compared to the profit-maximising choices of the previous section, the variation here is generated by: (i) the additional marginal cost of harvesting in equation (18) in the amount of the utility lost from increased harvesting and the resulting stock decrease, v'/ξ, net of the effects of the resulting reduction in poaching (that is, through R^L); and (ii) the utility gain from enforcement in equation (19), generated by reduced poaching (that is, through R^e). The presence of the stock in the objective function, therefore, serves to decrease legal harvesting and increase enforcement. While the former increases poaching, the latter tends to decrease it. The overall effect depends on these relative changes, so that poaching increases if enforcement is particularly ineffective (implying that the change in the marginal cost with a ban is small). Any increase in the level of total poaching does not exceed the reduction in legal harvesting, and the stock level is higher relative to that under pure profit maximisation, as illustrated in figure 3. Even with identical costs, this implies that poaching may well exceed the legal harvest, depending on the number of poachers (n), as the government reduces its own harvest to ensure a higher stock level despite the resulting higher poaching harvest.

With a trade ban, optimal enforcement is such that:

$$\alpha'\gamma + \alpha\gamma' R^e + l_s R^e - 1 - \frac{v'}{\xi} R^e = 0, \tag{20}$$

which differs again from the profit-maximising case in that there is an additional benefit derived from the larger stock as poaching falls. This would imply that enforcement would be higher than with a ban and no existence values. Lower poaching would result as well.

Alternatively, and potentially more importantly, we may consider a situation in which existence values for a species are not held by local individuals but by those in other countries, as in the case when domestic individuals have more urgent concerns than the survival of a particular neighbouring species (higher demand for environmental amenities is often associated with increasing incomes). Under CITES, decisions regarding species are made during the biannual Convention of Parties, in which the majority of members represent countries other than those containing the species themselves. A perusal of reservations towards species' listings (objections to a particular classification or trade restriction) shows that most reservations are made by host countries. The question then arises as to whether a ban on harvesting is superior to the mismanagement of the profit-maximising resource manager: a ban has the benefit of a higher stock level, but the profits from legal harvesting are absent. With no consideration for profits a ban would prevail, but the decisions of CITES are based on both profits and stock levels. A ban is only preferable in this scenario when marginal existence values (v') are high, equilibrium fines per unit are high and enforcement is quite effective, so that poaching does not substantially increase with a ban, reducing the stock so much that lost profits are not offset.

5. Conclusions

The present paper attempts to formalise the interaction between poaching, enforcement and legal harvesting. In doing so, the limited entry, illegal activity literature is extended by endogenising all three of these variables. In situations where poaching is not perfectly competitive, commitment to legal harvests and enforcement levels in anticipation of poaching can serve to reduce poaching; and in cases of either highly effective and efficient enforcement or of a significant legal harvesting cost advantage, possibly eliminate poaching altogether. High opportunity costs for land, however, would significantly reduce the likelihood of this occurring, so that partial deterrence of poaching by legal harvests would likely result. Depending on the nature of the demand for the product derived from the species, the costs of harvesting and the effectiveness of enforcement, the model described here illustrates that legal harvesting may, in fact, be more effective at reducing poaching levels than higher enforcement expenditures. This is certainly not always the case, but a precommitment to legal harvesting does reduce poaching in general.

The reaction function for total poaching is downward sloping in both the legal harvest and enforcement. With respect to legal harvesting, the slope of the reaction function is greater than negative one, so that decreases in legal harvests are only partially offset by increases in poaching. Optimal legal harvests may be zero when habitat protection costs are high, poaching has a significant cost advantage, or the number of poachers is high. In general, however, a combination of legal harvest and enforcement expenditure yields higher returns than enforcement alone.

In order to regulate trade in endangered species, CITES has typically employed trade bans and harvest quotas. When a government (or resource manager) simply maximises the rents received from legal harvests, a trade ban (or zero legal harvest) unambiguously reduces profits. If the reaction function of poaching is steep (poaching is quite sensitive to the legal harvest), both poaching and enforcement increase as a result of a ban. If, instead, enforcement is highly effective and legal harvests do not have large impacts on total poaching (such as when the number of poachers is small), a ban can result in higher enforcement and lower poaching. In any case, the positive effectiveness of enforcement expenditures on poaching levels leads to higher species stock levels with bans, as the increase in poaching does not completely offset the reduced legal harvest. This higher stock level makes a ban more appealing when a government is concerned with the stock level as well as the returns from legal activity than under a profit-maximising objective.

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Appendix

A numerical example was used to create figures 1–3. The choice of parameter values was arbitrary and was meant to illustrate the theoretical results. To this end, a linear inverse demand curve of the form $P = A - b(h^L + h^P)$, a stock-dependent cost function, $c(s) = k(s_0 - s)/s_0$, a concave probability function, $\alpha = a(e)^{1/2}$, and an exponential punishment function, $\gamma = g(h^P/n)^2$, were used, with A, b, a, k and g being specified parameters. Individual and total poaching harvests were found as a function of the government choice variables and, consequently, the legal harvest was found to maximise the legal objective subject to the individual and total poaching reaction functions. For the figures, the fixed number of poachers was varied to demonstrate the various potential outcomes under different degrees of poaching competition.