Can the restrictive harvest period policy conserve mopane worms in Southern Africa? A bio-economic modelling approach

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Abstract

Imbrasia Belina also known as the mopane worm, like other edible insects and caterpillars, is a vital source of protein to Southern African countries. The worms live and graze on mopane trees, which occupy agricultural land. With increasing commercialization of the worm, the management of the worm, which was hitherto organized as a common property resource, has degraded to a near open access. In this paper, a simple bio-economic modeling approach has been taken to show that, for some optimal land allocation, the restrictive period harvest season policy that is advocated by community leaders may not lead to sustainable harvesting of the worm.

Keywords: Land Use; Agricultural Policy; Bio-economic Model; Dynamic Analysis; Mopane Worm

JEL Classification: Q15, 18, 57; C61

1 Introduction

Edible insects and caterpillars constitute one of the cheapest sources of animal protein in most African countries (Chavunduka, 1975; Wilson, 1989; Banjo et al., 2006; Defoliart, 1995). Most of these insects and caterpillars contain more protein, fat, and carbohydrates than equal amounts of beef or fish, and a higher energy value than soybeans, maize, beef, fish, lentils, or other beans (FAO, 2004; Illgner and Nel, 2000; Banjo et al., 2006). In some African countries, children are fed with flour made from dried caterpillars to curb malnutrition, while pregnant and nursing women as well as people who are anaemic are encouraged to eat caterpillars that are high in protein, calcium, and iron (FAO, 2004; Moruakgomo, 1996 cited in Illgner and Nel, 2000). Owing to the nutritional properties of the caterpillars, a South African entomologist, Rob Toms (see Toms et al., 2003), recommended that people who are HIV-positive eat the caterpillars to boost their nutritional levels.

One of the most dietary and economically important caterpillars in Southern Africa is the Imbrasia Belina, the scientific name for what is colloquially called the 'mopane worm', found particularly

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in Zimbabwe, Botswana, Namibia, South Africa and Zambia. The worm grazes primarily on the leaves of Colophospermum mopane or mopane trees (Chavunduka, 1975) that occupy land that could be farmed if the forest is cleared. It has been estimated that the processed mopane worm (dried and ready for consumption) contains 60.70% crude protein, 16.70% crude fat, and 10.72% minerals, on a dry matter basis (Headings and Rahnema, 2002). Furthermore, the worm contains high levels of lysine, tryptopan and methionine (Dreyer, 1968, cited in Illgner and Nel, 2000) and three times the protein content of beef by unit weight and has the advantage that it can be stored for many months (Menzel, and D'Aluisio, 1998, cited in Illgner and Nel, 2000). Befittingly, it is listed in the 'Big Twelve African Insects' by entomologists (Toms et al., 2003), which highlights its importance in the region. Table 1 provides a summary of the nutritional qualities of the mopane worm compared to other common foods. As can be seen from the table, the worm has higher protein, fat, carbohydrate and calcium content than beef, biltong and chicken.

With minimal barriers to entry into both the collection and trade of the worm, coupled with increasing incidence of poverty in Southern African countries where the worms are found, there is a general increasing trend of overexploitation and a decline in selective harvesting (Hobane, 1995). Consequently, there have been reports of disappearance of the worms from parts of Botswana and South Africa (Illgner and Nel, 2000). Moreover, the institutional capacities to govern forest resources, which are mostly communally owned[1] in most African countries, are very weak. With the poor heavily dependent on the collection and marketing of the worm, policies towards sustainable management will contribute to alleviation of poverty and increase food security especially among the rural poor. The only existing policy instrument, which is informally employed by some traditional leaders, is embargos on harvesting the worm during certain periods (Toms and Thagwana, 2005). This, on its own, has proved insufficient as overexploitation continues to be of major concern, prompting the need to look into alternative policies.

In this paper, we present a two stage bio-economic model to explore the effectiveness of the aforementioned policy instrument (i.e. embargos on harvesting during certain times). First, the social planner's land allocation problem is modeled (where a proportion of the community land is optimally allocated to some agricultural activity (which could be cultivation of crops and/or livestock rearing), which is a private activity, and the rest to the cultivation of the mopane trees that host the worm). Second, given the optimal land allocation obtained from the first stage, an expression for a possible Pigouvian tax that guarantees sustainable instantaneous (restrictive) harvesting is derived. Furthermore, we explore the comparative static analyses of increased social discount rate and increased number of exploiters on the tax. The result, which is unambiguous, shows that some optimal tax must accompany the instantaneous or restrictive harvest policy if the number of resource exploiters is very large. The tax rate is negatively related to the benefit discount rate but positively related to the number of harvesters. To the best of our knowledge, no bio-economic model has been developed to understand the implications of this existing management regime (i.e. instantaneous/restricted harvest period policy).

The rest of the paper is organized as follows. In section 2 a brief description of the life cycle and the method of harvesting and processing of the worm is presented. Section 3 introduces the social planner's problem from which optimal land allocation decision is derived. Section 4 has the model for instantaneous competitive harvest management regime, taking the optimal land allocation derived in section 3 as given. In section 5 we derive the expression for optimal tax and explore

[1]In Zimbabwe, for example, mopane trees are found around homesteads, in communal grazing areas, on large-scale commercial farms and on state farms, while in Botswana much of the mopane trees are located in tribal areas where customary law allows anyone to harvest (Stack et al., 2003).

the conditions under which the optimal tax could be zero. In addition we undertake comparative static analyses for some policy relevant variables. The conclusions and policy recommendations are presented in section 6.

2 The life cycle, harvesting and marketing of the mopane worm

The mopane worm is actually the caterpillar of the mopane moth. The adult moths lay single clusters of 50 to 200 eggs over a two month period and the larval stage lasts approximately 6 weeks during which time the caterpillars undergo a 4000 fold increase in body mass.[2] The worm completes five larval stages in their life cycle before pupation. During the first three stages, the caterpillars strictly aggregate in numbers between 20 to 200 and forage together. Then the caterpillars disperse immediately to become solitary (Tom et al., 2003). At the end of the larval stage the fifth instar caterpillars burrow into the soil, where they undergo a period of diapause. Although the mature larvae are prefered to the younger ones, harvesting is indiscriminate of age and size. Thus, the population of the worms that are not harvested in one period determine the intensity of the outbreak in the next period. Those caterpillars that survive the harvesting burrow underground to pupate and after some six to seven months reach the adult stage which is crucial as this is the stage at which they mate and lay eggs marking the beginning of an outbreak of the worms. In general the species is bivoltine with the first generation emerging from pupation in November to January and the second in March to May; only in more arid areas is it univoltine (Toms et al., 2003).[3]

Traditionally, mopane worms of all sizes are collected, prepared and consumed by rural communities within the range of the mopane woodlands. The bulk of the harvesting and processing of the worms is principally done by women and children. A survey in Botswana indicated that 95% of harvesters are poor, rural women and of these, 73% live within 50 kilometers of the harvesting areas (Illgner and Nel, 2000). The most common and basic method of collection is to manually pick the worms from both the ground and the trees. After the larvae are collected the undigested material in the gut is removed by either squeezing them between the thumb and fingers or by using a bottle as a roller to squeeze out the contents. While younger larvae have relatively large amounts of the gut content, fully-grown larvae have less of it and their bodies are filled with a yellow nutritive material that is liked by consumers. After removing the gut content the larvae are then charcoal roasted or boiled and then dried to enable it to be preserved (Kozanayi and Frost, 2002).

Owing to economic misfortunes faced by rural communities, the mopane worms have become a vital trading commodity in Southern Africa. Unemployed males close to urban areas are becoming increasingly involved in the collection of the worms and, in most cases, are contracted by local traders (Kozanayi and Frost, 2002). The women are generally engaged in the sale (including barter) of the commodity in small volumes while men tend to be engaged mainly in the more lucrative long-distance and large-volume trade which could sometimes be of cross-border nature (Kozanayi and Frost, 2002). The dried larvae are sold with the measures (containers) ranging from a litre tin to a 90-kilogram bag.

Moreover, increasing levels of poverty in urban areas has created demand for low cost protein such as the mopane worm for relish (Stack et al., 2003). Over the years supermarkets have become the main retail outlets for pre-packed and labeled mopane worms supplied by wholesale food

[2] Source: http://www.mopane.org/biology.htm
[3] See Ghazoul et al. (2006) for comprehensive literature on the life cycle of the worm.

packaging companies such as Quality Foods and Jasbro in Zimbabwe (Kozanayi and Frost, 2002). Research indicates that in South Africa, about 16000 tonnes of mopane worms were traded on the commercial market in 1982, some of which were traded as animal feed (Dreyer and Wehmeyer, 1982, cited in Illgner and Nel, 2000). A sizeable amount of trade occurs at bus termini, roadside markets, and beer halls where the worms are sold as snacks.

3 The mopane worm model: the social planner's problem

In this section, the social planner's or the decision maker's land allocation and the mopane resource management problem is presented. Suppose a single rational decision maker manages the land for the agricultural activity and the mopane trees. Thus, the social planner will choose an optimal size of land to be allocated to mopane forest and for agricultural activities that maximizes overall benefit. This is tantamount to the domestication of the worm, a possible policy that some researchers have advocated and for which there have been some projects to test its feasibility (Ghazoul, 2006). Suppose the stock evolution equation for the biomass of worm is

$$\frac{dx}{dt} = x = \gamma x \left(1 - \frac{x}{\beta a l}\right) - h \tag{1}$$

where x is the stock/biomass of the worm; h is harvest (biomass in kilograms) of the worm. Note that since all sizes of the worm are harvested the biomass model is preferred to an age-structured model; l is the size (proportion) of the arable land area devoted to mopane forestry, (assuming the total land area is normalized to one); $a > 0$ is the forage productivity of the land; $\beta > 0$ converts the size of the forage to carrying capacity of the worm; and γ is the intrinsic growth rate of the worm. It is estimated that, on average, the ratio of biomass feed intake to worm production is 3:1 (Toms et al., 2003). Since there is very little scientific evidence on the impact of the worm on the mopane tree, we assume for simplicity that this relationship is symbiotic. This is because although the tree is a host plant for the worm, the worm also produces droppings that may accelerate the growth of the plant. Furthermore, although some foresters tend to consider caterpillars as pests, the trees usually respond to the defoliation by the worm by producing a second crop of leaves, which limits the long-term damage to host plants (Reeler et al., 1991 cited in Vantomme et al., 2004). Moreover, since there is no existing information on the migratory pattern of the worm, it is assumed for simplicity that there is no cross-country migration.

The objective of the social planner is to maximize the net benefits from both agricultural production and the sale of mopane worms, while taking into consideration the effects the harvesting of the worms has on its stock dynamics. Normalizing the price of the agricultural product to one, the social planner's economic problem can be set out as follows:

$$\underset{\{h,l\}}{Max} \int_0^\infty \left[ph - c(x)h + q(1-l)\right] e^{-\delta t} dt \tag{2}$$

Subject to equation (1), with $x \geq 0, h \geq 0, l \geq 0$ and $x(0) = x_0$. where p is the competitive market price per kilogram of the worm; $c(x) = \frac{c}{\sigma x}$is the cost per unit harvest of the worm (c is cost per unit effort and $\sigma$is the catchability coefficient of the worm, which is normalized to one) ; $q(\cdot)$is a well-behaved agricultural production function (i.e.$q_{(1-l)} > 0$ and $q^2_{(1-l)} \leq 0$, and $(1-l)$,by implication, is the size (proportion) of total land area devoted to agriculture. The current value Hamiltonian associated with this problem is equation (3).

$$H(h,l,\lambda,x) = ph - c(x)h + q(1-l) + \lambda\left(\gamma x\left(1-\frac{x}{\beta\alpha l}\right) - h\right) \tag{3}$$

The Pontryagin maximum principle is

$$\frac{\partial H}{\partial h} = p - c(x) - \lambda\begin{pmatrix} > \\ = \\ < \end{pmatrix} 0, \Longrightarrow \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0, \Longrightarrow \begin{pmatrix} h = h_{\max} & if & x > x^{**} \\ h = h^{*} & if & x = x^{**} \\ h = h_{\min} & if & x < x^{**} \end{pmatrix} \tag{4}$$

where $x^{**}$is the optimum stock, and

$$\frac{\partial H}{\partial l} = q_1 + \frac{\lambda\gamma x^2}{\beta\alpha l^2} = 0 \Longrightarrow \lambda\frac{\gamma}{\beta\alpha}\left(\frac{x}{l}\right)^2 = -q_l \tag{5}$$

From equation (4), the maximum principle indicates that in an intertemporal equilibrium, the marginal profit from harvesting the mopane (i.e.$(p - c(x))$) should reflect or equate the scarcity value of the stock of mopane (i.e.λ). Note that, if $p - c(x) < \lambda$, then the level of stock is less than what is optimally desired (i.e.$x < x^{**}$), hence it is more valuable to preserve the worm. Therefore harvest will be at its minimum (i.e.$h = h_{\min}$). On the other hand if $p - c(x) > \lambda$, the worm is less valuable to preserve and harvest will be at its possible maximum. Furthermore, from equation (5), the value of the loss in agricultural productivity as a result of converting a unit of land to mopane forest, $q_1$should be equal to the value of the marginal benefit from increased stock of mopane as a result of increasing the carrying capacity by one unit of land (i.e.$\lambda\frac{\gamma}{\beta\alpha}\left(\frac{x}{l}\right)^2$). The costate equation is

$$\dot{\lambda} - \delta\lambda = -\frac{\partial H}{\partial x} = c_x h - \lambda g_x \tag{6}$$

where $g_x = \gamma\left(1 - \frac{2x}{\beta al}\right)$. Thus, in a dynamic equilibrium, the returns from harvesting the resource today on the margin (i.e.$\delta\lambda$) should be offset by the capital gains from postponing that additional harvest (i.e.$\dot{\lambda}$) plus the stock effect, $(\lambda g_x - c_x h)$. Since we are interested in sustainable harvesting of the worm, which is a renewable resource, we explore the steady state conditions. In steady state, $\dot{\lambda} = \dot{x} = 0$. From the costate and the stock dynamic equations, the optimum shadow value of the stock of mopane is

$$\lambda^* = \frac{c_x h}{(g_x - \delta)}. \tag{7}$$

Solving for the optimal values of l (and,x, h, λ) from equations (4) through to (7) and using $h^* = g(x^{**}, l)$, we obtain $l^* = l(p, c, \delta, a, \gamma)$ [4].Thus, in this first stage the social planner decides on the optimal land allocation to mopane trees, and consequently, the agricultural activity. Note that if the worms are harvested under open access, the worms will have no capitalised value (i.e.$\lambda = 0$), hence with the current rate of exploitation in many communities, the stock is likely to become extinct.

[4]By assuming a logistic biomass growth function of the worm, we have a unique solution of the proportion of the land allocated to cultivating the worms.

4 Instantaneous competitive harvest model

This section analyzes the stock and harvest dynamics under instantaneous competitive harvest management regime, in accordance with the prevailing management policy. An instantaneous or restrictive competitive harvest management regime is defined as a regime in which the harvest of the worm is limited to an instantaneous harvesting period (i.e. harvest reduces escapement but does not affect the growth of the biomass), a situation which mimics the fact that some traditional leaders allow harvesting only during certain periods (Toms and Thagwana, 2005). As in the previous case, we assume that harvesters are price takers. Thus, it is assumed that the social planner (the community leader) allocates an optimal size (or proportion) of arable land to mopane trees (as per the preceding section). Given this land allocation, he imposes an instantaneous harvest policy.

Drawing from the escapement model of Reed (1979) and Clark (1990), we specify the stock dynamics of the instantaneous harvest or limited harvesting season as

$$\dot{x} = \Lambda(z) - M \tag{8}$$

where $\Lambda(z) = \gamma z \left(1 - \frac{z}{\beta \alpha l^*}\right)$, $z = x - M$ is escapement (i.e. the biomass of worm that escapes capture at each point in time), $M = \sum_{i=l}^{n} h_i = h_i + M_{-i}$ is the total harvest of the worm, and n is the total number of harvesters.[5] Note that since the social planner predetermines land allocation at l^*,each harvester i will have the following optimization program.

$$\underset{\{h_i\}}{Max} \int_0^\infty [ph_i - \varsigma(x, h_i + M_{-i})] e^{-\delta t} dt \tag{9}$$

where $\varsigma(x, M) = \varsigma(x, h_i + M_{-i}) = \int_{x-M}^{x} \varsigma(z) dz = \int_{x-M}^{x} \left(\frac{c}{z}\right) dz = c \ln\left(\frac{x}{x-M}\right)$. Equation (9) is maximized subject to equation (8). The Hamiltonian associated with this problem for the i^{th} harvester is

$$H^I = ph_i - \varsigma(x, h_i + M_{-i}) + \mu_i (\Lambda(z) - M) \tag{10}$$

Assuming symmetric harvests of the worm so that $M = nh_i$, the maximum principle and the costate equations are defined by equations (11) and (12) respectively

$$\frac{\partial H^I}{\partial h_i} = 0 \Longrightarrow p - n\varsigma_M + \mu_i (n\Lambda_z z_M - n) = 0 \Longrightarrow p - n\varsigma_M = \mu_i n (1 - \Lambda_z z_M) \tag{11}$$

$$\dot{\mu}_i - \delta\mu_i = -\frac{\partial H^I}{\partial x} \Longrightarrow \dot{\mu}_i - \delta\mu_i = \varsigma_x - \mu_i \Lambda_z \tag{12}$$

The interpretation of the maximum principle remains the same; in an intertemporal equilibrium, the marginal profit obtained from harvesting the worm (i.e.$p - n\varsigma_M$), must reflect the scarcity value of the stock of the worm (i.e.$\mu_i n (1 - \Lambda_z z_M)$). Clearly, the terms for the marginal profit and the shadow value are different from what is in equation (4). A clear indication is that the instantaneous equilibrium harvests derived from the two maximum principles will not be the same. Furthermore,

[5] Note that the discrete time representation of the model is $x_{t+1} = z_t \left(1 + \gamma - \frac{\gamma z_t}{\beta \alpha l^*}\right)$.This implies that the biomass in the next period is the escapement plus the growth of the escaped biomass. By letting $x_{t+1} - x_t \approx \dot{x}$, in continues time, this equation is rewritten as equation (8).

from the costate equation (i.e. equation 12), the capital returns on investment of proceeds from harvesting an additional unit of the worm (i.e.$\delta\mu_i$) should be equal to capital gains (i.e.$\dot{\mu}_i$) plus some stock effect given by $(\varsigma_x - \mu_i\Lambda_z)$ .It is also clear that this dynamic equilibrium condition is different from that of equation (6), implying that harvest levels under the restrictive harvest policy will be suboptimal.

Thus the foregoing analysis indicates that an instantaneous harvest policy may lead to suboptimal outcomes. It is therefore imperative that alternative policies need to be considered to complement the existing one (i.e. the limited harvest season policy). In this paper we propose a hybrid instrument that combines a pigovian tax and the instantaneous harvest policy. This is discussed further in the following section.

5 The economic policy instrument (tax)

In this section we derive an expression for the optimal tax and then explore the condition under which the optimal tax may not be necessary (i.e. the tax is zero). We then derive comparative static analysis for some relevant policy variables. Consequently, some relevant propositions have been derived.

Proposition 1 *The optimal tax is defined by the expression*

$$t^* = \frac{n\varsigma_x(\Lambda_z + 1)}{(\Lambda_z - \delta)} - \frac{c_x h}{g_x - \delta} + (n\varsigma_M - c(x))$$

Proof. By substracting $c(x) + \lambda$ from both sides of equation (11) and rearranging the terms, the maximum principle could be written as

$$p - c(x) - \lambda = \omega_i\Lambda_z + (n\varsigma_M - c(x)) + (\omega_i - \lambda), where\ \omega_i = n\mu_i \tag{13}$$

Comparing equations (4) and (13) and following Akpalu and Parks (2007), we derive the expression in equation (14) for the tax rate. ■

$$t = \omega_i\Lambda_z + (n\varsigma_M - c(x)) + (\omega_i - \lambda) \tag{14}$$

Furthermore, in steady state, $\dot{\mu}_i n = \dot{\omega}_i = \dot{\lambda} = 0$,which implies that $\omega_i = \frac{n\varsigma_x}{(\Lambda_z-\delta)}$. Also from equation (7) we know that $\lambda = \frac{c_x h}{(g_x-\delta)}$. Substituting these values into the tax expression gives $t^* = \frac{n\varsigma_x(\Lambda_z+1)}{(\Lambda_z-\delta)} - \frac{c_x h}{(g_x-\delta)} + (n\varsigma_M - c(x))$.

This tax corrects for undervaluation of the scarcity value of the mopane stock under the instantaneous harvest, differences in harvest costs and some stock externality.

5.1 *The existence of zero optimal tax*

It may not be necessary to impose any tax on harvest (i.e.$t^* = 0$) if the stock level in the absence of the tax coincides with what is optimally desired (i.e. if an instantaneous harvest policy leads to optimal resource stocks and harvest levels), which is indeed a *rare* condition. From the tax expression if the (optimal) harvest is defined in terms of effort and stock, it is straightforward to see that there exists replicate dynamics between the level of stock and e.g. effort, all other things, including the number of resource harvesters, being equal. In this section we tabulate such equilibrium relationships assuming some specific functional forms and for different number of the resource users. Note that no tax implies

$$t^* = \frac{n\varsigma_x(\Lambda_z+1)}{(\Lambda_z-\delta)} - \frac{c_x h}{(g_x-\delta)} - (c(x) - n\varsigma_M) = 0 \tag{15}$$

Using the following parameter values, which are assumed for convenience, $\gamma = 0.001, \delta = 0.03, c = 0.1, \alpha = 0.02, \beta = 0.001$; assuming that half of the land is optimally allocated to cultivating the mopane trees (i.e.$l^* = l(\bullet) = 0.5$); Table 2 presents simple simulated results of the relationship between harvest, the number of harvesters and the optimum level of stock. In general, if the number of harvesters increases, the optimum level of stock must increase to guarantee a given level of per unit harvest. It is also clear from the table that the levels of stock that may accommodate the given level of harvest may never be realized if the number of resource users is very large. Consequently, the tax should be imposed if, all other things being equal, the number of harvesters is sufficiently large.

5.2 *Characterising the Optimal Tax*

Proposition 2 *The optimal tax must increase if the number of the harvesters of the worm increases, all other things being equal.*

Proof. The proof of this proposition requires taking comparative statics of the optimal tax with respect to the number of harvesters and characterizing the results to show that the derivative is positive. From equation (14), we have the following ■

$$\frac{\partial t^*}{\partial n} = \frac{n\varsigma_x\Lambda_{zn}(\delta+1)}{(\Lambda_z-\delta)^2} + \frac{\varsigma_x(\Lambda_z+1)}{(\Lambda_z-\delta)} + \varsigma_M + n\varsigma_{Mn} > 0 \tag{16}$$

Note that $-\varsigma_x\Lambda_{zn} > 0, n\varsigma_{Mn} > 0$,and $\frac{\varsigma_x(\Lambda_z+1)}{\Lambda_z-\delta} > 0$.Therefore $\frac{\partial t^*}{\partial n} > 0$ if it can be shown that $\varsigma_x(\Lambda_z+1) > -\varsigma_M(\Lambda_z-\delta)$.Since $\delta > 0$,we will have $\frac{\partial t^*}{\partial n} > 0$ if $\varsigma_x > -\varsigma_M$.But we know from the specific function forms that $\varsigma_x = c\left(\frac{1}{x} - \frac{1}{x-M}\right)$ and $\varsigma_H = \frac{c}{x-M}$. It follows that $\varsigma_x > -\varsigma_M \Longrightarrow \frac{c}{x} > 0$, which is a given. Thus, as the number of the worm exploiters increases, the tax rate must increase to ensure sustainable harvesting of the worm.

Proposition 3 *The optimal tax t^* must decrease if the benefit discount rate increases, all other things being equal.*

Proof. The proof of this proposition, like that of the second proposition, is straightforward. It requires taking the first derivative of the optimal tax with respect to the discount rate and characterizing the results to show that the derivative is negative. Thus, from equation (14) we have the following

$$\frac{\partial t^*}{\partial \delta} = \frac{n\varsigma_x(\Lambda_z+1)}{(\Lambda_z-\delta)^2} - \frac{c_x h}{(g_x-\delta)^2} \tag{17}$$

From equation (17), since $(g_x-\delta)^2 < (\Lambda_Z-\delta)^2 \forall x_i > 0$, it follows that $\frac{\partial t^*}{\partial \delta} < 0$ if $n\varsigma_x(\Lambda_z+1) > c_x h$. Using the specific functional forms of the cost functions, $\left(i.e c_x = -\frac{c}{x^2} \text{ and } \varsigma_x = -\frac{c}{x}\left(\frac{M}{x-M}\right), \text{and } M = nh\right)$, we have $\frac{\partial t^*}{\partial \delta} < 0$ if $x - nh < n^2 x$,which is true, since $n \geq 1$. ■

Increasing discount rates implies increased returns on investment of proceeds from the worm. Consequently, as the discount increases more worms must be harvested to earn higher returns on investment of the proceeds therefore the tax rate will have to decrease.

6 Conclusions

Inadequate forest resource management policies in Southern Africa, like in other regions of Africa, are the main reason for unsustainable exploitation of mopane worms. It has already been noted that overexploitation has led to the disappearance of the worms from parts of Botswana and South Africa (Illgner and Nel, 2000). Clearly, in view of the important role of the worms in poverty alleviation and food security in the region, adequate and timely policy interventions are needed to address the problem. It is therefore not surprising that some community leaders have placed embargos on harvesting during certain periods.

Using a simple bio-economic modeling approach, this paper has investigated whether, for some predetermined optimal land allocation, limiting the harvesting season to an instantaneous harvest as currently advocated, will result in sustainable harvesting of the worms. Our results have shown that some optimal tax that corrects for undervaluation of the scarcity value of the mopane stock under the instantaneous harvest, differences in harvest cost and some stock externality must accompany the instantaneous harvest policy. Furthermore, the optimal tax is negatively related to the benefit discount rate but positively related to the number of harvesters.

It is important to note that due to lack of evidence on the counterfactual, our model is restrictive in some ways. Firstly, we assume a symbiotic relationship between the mopane worm and the mopane tree, which may not be the case in some instances. Secondly, as for some biological organisms, it is assumed that the growth function of the worm is logistic and concave, although some ecological systems have thresholds. Nevertheless our simple model provides a benchmark upon which some reasonable extensions could be made.

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Table 1. Nutritional quality of dried mopane worms compared to other foods (g/100g of sample)

Sample	Protein	Fat	Carbohydrate (Including fiber)	Calcium
Mopane worm	56.8	16.4	13.8	0.458
Beef (cooked)	22.6	8.0	0	0.016
Biltong	55.4	1.5	0	0.016
Chicken (raw)	20.5	6.5	0	0.010

Source: Sekhwela, 1989.

Table 2. The equilibrium relationships between harvest and stock for different numbers of harvesters

$tax(t^*)$	n	h^*	x^*	l^*
0	**10**	10	**150**	0.5
0	**20**	10	**250**	0.5
0	**1,000**	10	**10,050**	0.5