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Summary

The paper treats the economy of controlling an African pest rodent, the multimammate rat, causing major damage in maize production. An ecological population model is presented and used as a basis for the economic analyses carried out at the village level using data from Tanzania. The control problem is specified as timing and duration strategies where the dosage of the poison is kept fixed per month whenever poison is used (consistent with recent practice in Tanzania). The most economically profitable control period seems to be just before the planting season. The damage at planting accounts for such a large portion of the total losses due to rodents, that minimising the population during that short period is enough to reduce yield losses. Controlling for a longer period will reduce rodent populations at a time when they do not damage the crop anyhow, and due to the very high reproductive capacity of the rodents, the population will increase fast as soon as control operations are stopped, repressing any long term effects. Two months of control just before planting season, January and February, or eventually in November and February, seem to be the best overall strategy. These economically most rewarding strategies differ significantly from today's practice of symptomatic treatment when heavy rodent damage is noticed. The paper demonstrates that shifting from such practices to more mechanistic control strategies; that is, emphasising the calendar instead of the pest abundance, can substantially improve the economic conditions for the maize producing farmers in the present case of multimammate rats. The best practices compared to today's symptomatic treatment will typically double the net economic benefit.

Abstract

The paper treats the economy of controlling an African pest rodent, the multimammate rat, causing major damage in maize production. An ecological population model is presented and used as a basis for the economic analyses carried out at the village level using data from Tanzania. This model incorporates both density-dependent and density-independent (stochastic) factors. Rodents are controlled by applying poison, and the economic benefits depend on the income from maize production minus the costs for maize production, fertiliser and poison. We analyse how the net present value of maize production is affected by various rodent control strategies, by varying the duration and timing of rodenticide application. Our numerical results suggest that, in association with fertiliser, it is economically beneficial to control the rodent population. In general the most rewarding duration of controlling the rodent population is 3-4 months every year, and especially at the end of the dry season/beginning of rainy season. The paper demonstrates that changing from today's practice of symptomatic treatment when heavy rodent damage is noticed to a practice where the calendar is emphasised, may substantially improve the economic conditions for the maize producing farmers. This main conclusion is quite robust and not much affected by changing prices and costs of the maize production.

Keywords: bio-economics, pest control, multimammate rat, crop production

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1. Introduction

Rodents represent major pest problems worldwide, both in the countryside and in the cities. They do, for instance, cause serious damage to crops (such as cereals, root crops, cotton and sugarcane) both before and after harvest. They also damage installations and are reservoirs or vectors for serious infectious diseases (Fiedler 1988).

In Africa more than seventy rodent species have been reported to be pest species (Fiedler 1988). Some of these exhibit irregular population dynamics with occasional explosions, typically occurring over extensive areas (Fiedler 1988a, Leirs *et al.* 1996). Within eastern Africa, multimammate rats (*Mastomys natalensis*) are among the most important pest rodents (Fiedler 1988). Damage during outbreaks is profound and significantly worsens the already unfavourable food situation on the African continent. The average rodent damage by the multimammate rat to maize in Tanzania has been estimated to be between 5 and 15% yield loss, and for Tanzania this amounts to an average of approximately 412.500 tonnes per year (FAO statistics 1998, Makundi *et al.* 1999). This corresponds to what would be sufficient to feed more than 2 million people for an entire year (at about 0.55 kg/day/person) or represents an estimated value of almost 60 million US\$ (September 1999 village market price in Tanzania, being around 14.5 US\$ per 100kg bag of maize). Eruptions of the multimammate rat population represent direct disasters for the subsistence farmers involved, but may also have national and even international political consequences. Panic-stricken authorities may initiate control operations – however, often too late and typically with quite poor results. There is thus a clear need to predict and, if possible, prevent such outbreaks of rodent populations (Mwanjabe 1990, Leirs 1999).

The control of pest rodents does, however, have both an ecological and an economic component interacting dynamically with each other so as to render intuitive reasoning difficult. In this paper we consider both the ecological and the economic components of rodent damage and control. This we do through the analysis of a bio-economic model – a model falling within the concept of ecologically-based-rodent-management (EBRM) (see, e.g., Singleton *et al.* 1999). We specifically evaluate the relations between control timing, control duration, and damage reduction. Our model is quite general; hence, our analysis may illustrate pest control involving rodents living in highly seasonally varying environments. The model consists of a well-established stage-structured ecological model (see Leirs *et al.* 1997a;

Leirs 1999; Stenseth *et al.* 2001) and is integrated with an economic model incorporating the damages by the rodents and the cost of controlling them.

The links between the ecological and the economic components are represented by the control measures affecting the mortality of the rodents as well as the rodents' damages on the maize crop. There is also a link through rainfall, having both a seasonal and stochastic component, which affects both the rodent population ecology and the crop yield. The timing of the rodents' breeding season is strongly related to the annual distribution of rainfall (Leirs *et al.* 1993). In addition, rodent survival and maturation are affected by precipitation in the preceding few months, as well as density-dependent factors (Leirs *et al.* 1997a). Thus, rainfall influences the crop yield in two ways; positively as a factor of production since more rain (within limits) implies higher yield, and negatively through a higher net growth of the rodent population following rain.

Control strategies are evaluated in terms of present-value net profit, integrating the benefit from crop harvesting, decreasing in the number of rodents, and the control costs, increasing in the amount of damage control. Two temporal scales are included in the model as the relevant time scale for rodent maturation and survival is one month while crop harvesting and the economic benefits from harvesting typically happen once a year. The double time scale results in a quite complicated ecology-economy interaction and makes the present bio-economic model rather unique as a very detailed and well-understood ecological background is combined with detailed economic considerations. Our model represents an original contribution to the more general literature on the economics of pest control as well as provides important policy implications for managing and controlling agricultural production in an environment with pest populations, cf. the overview in Carlson and Wetzenstein (1993). Only very few papers in the literature focuses on vertebrate pest control problems with particular emphasis on small mammals. Hone (1994) summarises a number of simple static pest control models, and presents some estimates of rodent damages as well as damages related to other mammals. See also Barnett (1988). Saunders and Robards (1983) provide detailed estimates of what the damage and economic losses were during a mouse outbreak in Australia and the costs of the control operations. However, in all these papers there is no dynamic link between the economic considerations and the rodent population ecology such as to say when a control strategy becomes economic efficient. This is also the case for Tisdell (1982) who provides a detailed study of the damages and control costs of feral pigs in an

Australian context. The cost and benefit of feral pig, causing damages on Californian rangeland, is also studied in a recent paper by Zivin *et al.* (2000). This problem is analysed within an optimal control framework as they use a lumped ecological model and quite simple cost and damage functions. Our analysis reported in this paper is to some extent inspired by this study, as our model is built around a control and a damage function interacting through the ecology. However, contrary to Zivin *et al.* (2000), we work with a stage-structured ecological model within a stochastic framework (rainfall) with more realistic, and complex, cost and benefit functions and a double time-scale. Because of this complexity, the model is not formulated within an optimal programming framework. Instead we single out some reasonable main strategies and compare these outcomes through simulations. As in all models, however, real life situations are simplified: the possibility of replanting is for example not considered.

In order to fix ideas, we consider a small village consisting of a number of individual farmers, and that the management problem is at the level of an agricultural officer who implements the rodent control strategy for a wide area. The model may thus be seen as a planning model where the agricultural officer serves as the social planner. This social planner will, presumably, have a relatively long planning horizon and a fairly low discount rate (Dasgupta and Mäler 1995). In a follow up paper we will analyse what happens at the farm level when having a shorter time horizon, and where each farmer typically does not obtain the full benefit of removing pest from his farm; that is, externalities are present. Throughout the present paper, the ecological model is at the scale of one hectare. However, this does not mean that we literally assume that the village agricultural area is of the size of just one hectare. The area may be fairly large, justifying the assumption of no dispersal into the field when controlling the rats (as we indeed assume, see below). One hectare is also the scale used for the agricultural benefit, as well as the costs of rodent control.

The paper is organised as follows. In the next section we briefly present the ecological model. In Section 3 the cost and damage functions of pest control are outlined. Section 4 presents the various control strategies while the results of the numerical analyses are shown in Section 5.

2. The ecological model under pest control

2.1. The studied model system and some simplifying assumptions

As a basis for the ecological model we have used population data from Morogoro, Tanzania (see Leirs *et al.* 1997a, Leirs 1999, Stenseth *et al.* 2001). The rainy season in Morogoro is bimodal, with a first, but unreliable, peak between October and December and a second peak starting in February-March and continuing until May (Mwanjabe & Leirs 1997). After the onset of heavy rains in February-March, fields are ploughed and prepared for planting. Hence, planting of maize seeds typically takes place in March, although the exact timing depends on rainfall. Planting is more or less synchronous in a large area within a period of a few weeks.

Rodent damage typically occurs immediately after planting and until the maize seedlings have reached the three-leave stage (about 2-3 weeks after planting). When heavy rodent damage to the seedlings becomes obvious (about ten days after the original planting), farmers may decide to replant. Nevertheless, we have simplified the setting for our model by assuming that planting always (and only) occurs in March and that damage caused by rodents is not remedied by replanting.

Harvesting occurs in July-August. If rainfall in October-December is very abundant, which rarely happens, then planting is possible in that season as well. However, farmers generally do not trust this first part of the rainy season since it is very unreliable. Hence, even though planting may be possible, they are afraid that rainfall will not be sufficient during the rest of the growing season. Thus, planting in that season does happen only in some years and even then, only a part of the farmers decide to participate. Here we ignore such a second crop.

2.2. The population model

As noted in the introduction, we consider two, partly overlapping, time scales; one for the ecological population dynamics processes, and another for the economic processes. The economic yearly time scale relates to the fact that crop-harvesting normally takes place once a year, whereas the ecological time scale is monthly. Since pest control actions may take place several times a year, the control costs will also be given with a time step of one month.

However, these costs are accounted for once a year, and as a result collapse into the yearly time scale. We refer to the month by the index n (0, 1, ..., 11, 12, 13, ..., 23, 24, 25, ...) and the year by the index t (0, 1, 2, ...). Each month equal to 8, 20, 32, ... (i.e., August each year), corresponds to harvesting time and is defined so as to determine the beginning of a new production period, or 'cropping year'.

The ecology is based on the model presented by Leirs *et al.* (1997a) and further explored by Leirs (1999) and Stenseth *et al.* (2001). Reproduction and survival parameters are governed both by density-dependent processes and rainfall, the latter being treated as a density independent and time-dependent stochastic factor. The scale of the model is at one hectare, while the agricultural area considered may be quite large; hence, we ignore, as is typical within population dynamics modelling, dispersal. Our model further describes only the female part of the population; the demographic parameter estimates are more reliable for females than for males. Moreover, it is, after all, the female part of the population that is instrumental in generating the population dynamics through reproduction, which is typically being limited by the number of breeding females. The ecological model is a stage-structured model (see, e.g., Getz & Haight 1989 for a general overview) with four stages, and where the vector $\mathbf{N}_n = (N_{j0,n}, N_{j1,n}, N_{sa,n}, N_{a,n})$ describes the rodent population per ha at the beginning of month n . $N_{j0,n}$ is the number of juveniles in the nest, $N_{j1,n}$ is the number of juveniles which are weaned but not yet in the trappable population, $N_{sa,n}$ is the number of sub-adult (non-reproducing) individuals, and $N_{a,n}$ is the number of adult (reproducing) individuals. The total abundance at the beginning of month n is then given as $N_n = N_{j0,n} + N_{j1,n} + N_{sa,n} + N_{a,n}$.

The population dynamics is, in matrix form, represented by $\mathbf{N}_{n+1} = \mathbf{M}\mathbf{N}_n$, and where \mathbf{M} is defined as (cf. Stenseth *et al.*, 2001)

$$(1) \quad \mathbf{M} = \begin{bmatrix} 0 & 0 & 0 & B(V_n, N_n^{(e)}) \\ s_{0n} & 0 & 0 & 0 \\ 0 & s_{0w} & (1-m_n) \cdot s_1(V_n, N_n^{(e)}) \cdot (1-\psi(V_n, N_n^{(e)})) & 0 \\ 0 & 0 & (1-m_n) \cdot s_1(V_n, N_n^{(e)}) \cdot \psi(V_n, N_n^{(e)}) & (1-m_n) \cdot s_2(V_n, N_n^{(e)}) \end{bmatrix}$$

when B is the reproductive rate per adult female over one time step (being one month); s_{0n} is the monthly survival of juveniles still in the nest, and s_{0w} is the survival of juveniles during the first month after weaning, both assumed to be fixed irrespective of the environmental conditions; s_1 is the survival of sub-adults, s_2 is the survival of adults, and ψ is the maturation rate of sub-adults to adults (i.e., the probability that a subadult will mature to become a reproducing adult over the intervening month, given that it stays alive). The density relevant for defining the density-dependent structure of the demographic rates is given by $N_n^{(e)} = N_{sa,n} + N_{a,n}$ (juveniles are not yet recruited into the population and their number therefore does not affect the demographic rates). The parameter m_n , represents the reduction in natural

survival (i.e., the death rate, due to pest control action during month n). Consequently, by definition, when $m_n > 0$ the population is being affected by the application of poison. The effect of the control is assumed to be the same for sub-adult and adult; hence, the same m_n . The control is assumed to have no effect on the juveniles as they just are born and still in the nest (or maybe just out of the nest) and will not eat the poison. There are therefore no control effects operating through the survival rate of juveniles, s_0 . Rainfall affects the demographic rates through the cumulative rainfall during the preceding three months $V_n = (P_{n-1} + P_{n-2} + P_{n-3})$ where P_{n-1} represents the amount of rainfall during the month $n-1$, etc. (Leirs *et al.* 1997a). The three-months time lag is used since rainfall has an indirect effect through vegetation (hence, the symbol V_n). The effects of density and precipitation are non-linear; below a certain rainfall or density threshold, the demographic parameters have one value, above the threshold, they have another value. The parameters of the ecological model are given in the Appendix, Table A1. Notice that rodent demography is not directly affected by crop production, the link is indirectly through rainfall. Moreover, crop production as such has little effects on the rodents: they damage planted seeds (i.e., before crop production has started) and then the ripening seeds at harvest time, but at that moment, the amount of available seeds are is much larger than what can be consumed by the rodents, even in poor harvest years. During the crop growing period, the rodents do not damage the crop but live from alternative food in and around the fields (Makundi *et al.* 1999).

Stenseth *et al.* (2001) have explored how this ecological model behaves when a simple and fixed control-induced mortality is introduced. They show that not only the magnitude of m_n is important, but also over which period the control is applied; a permanently applied control (i.e., control every month), may reduce the population considerably (and even drive the population to extinction), while there is little effect when control is applied at high densities only, even when there is large increase in mortality. Whether a permanently applied control is economic rewarding, however, was not studied as no economics were included in these considerations of Stenseth *et al.* (2001).

2.3. The control induced mortality: linking pest control measures to population dynamics

Our analysis is restricted to control measures affecting survival, and where the effect on the control-induced reduction m_n of natural survival is assumed to result from the application of poison. Generally there is a two-stage effect on survival. Let X_n be the amount of control

measures (i.e., some poison) applied per ha in month n . Its efficiency typically decreases with increasing precipitation during the month as the baits or the active ingredients degrade under humid conditions. In the present analysis, however, we assume that precipitation has a negligible effect during the current month. In addition, we make the reasonable assumption for the Tanzania multimammate rat system that after one month no effect of the poison persists in the environment in a form being available to the rats (Buckle 1994). Consequently, in what follows, the amount of effective control in month n coincides with the actual control measure the same month (and given by X_n). In the numerical analysis, consistent with current practices in the rural areas in Tanzania (Mwanjabe & Leirs 1997), we further assume that X_n is fixed either at zero or at some fixed non-zero level. The present control problem is therefore not analysing how much poison to use and of what type; keeping the dosage of the poison per application fixed, we investigate in which month to apply the control measure (the timing), and for how long time (the duration).

The demographic effect of the pest control, the control or kill function (Carlson and Wetzstein 1993), is generally represented by a function where the death rate increases with the management intensity; that is,

$$(2) \quad m_n = m(X_n, N_n).$$

The reduction in natural survival, being in the domain $[0,1]$, is therefore given as $\partial m / \partial X_n \geq 0$ with $m(0, N_n) = 0$. $\partial m / \partial N_n \leq 0$ should also hold, but since the control measure operates through increased mortality rate, and not directly on the number of individuals killed, this effect can be quite complex. In the proceeding analysis, we have therefore chosen a pragmatic approach and neglected any influence through the size of the rodent population. For the given dosage X_n , we assume that the combined effect of natural mortality and the rodenticide-induced mortality is constant and always 0.90. This is actually consistent with the field experience of rodent control officers in Tanzania; the used poisons are effective in killing rodents and at the used quantities they should be more than sufficient to kill all rats in the field. Usually, however, about 10% of the rodents in a field survive the rodenticide application because they do not eat the bait, either accidentally or because they avoid it (Mwanjabe, personal communication). Hence, $(1-m_n) \cdot s_i(V_n, N_n^{(e)}) = 0.10$ is fixed every month when rodenticides are applied, and $s_i(V_n, N_n^{(e)})$ in other months (see below and Table A1 in the Appendix for further details).

3. Benefit and cost functions

The economics of rodent control consist of two basic components; the cost of controlling the rodents, and the benefits of doing so being realised through reduced crop damages. We first formulate the yield function in the absence of rodents. The crop is maize, and the yield depends on the quality of the agricultural land, labour input, fertiliser use, and rainfall (Ruthenberg 1980). Empirical evidence from small-holder maize farming in Tanzania indicates that fertiliser and rainfall are substitutes as well as complements, while all other production factors are more or less fixed, or remain at a fixed proportion to the yield (see, e.g., McDonagh *et al.* 1999 and Figure A1 in the Appendix). Assuming one crop per year and that fertiliser use and rainfall are the limiting production factors, the yield in kg per ha agricultural land in absence of rats is

$$(3) Y_t = Y(F_t, A_t)$$

where F_t is the amount of nitrogen fertiliser applied and A_t is the amount of rainfall accumulated throughout the maize growing season (i.e., precipitation during the five months prior harvesting, typically in August). $Y(F_t, A_t)$ is generally increasing in both A_t and F_t up to some threshold level, but at a decreasing rate; i.e., $\partial Y / \partial F_t > 0$ and $\partial^2 Y / \partial^2 F_t \leq 0$, and $\partial Y / \partial A_t > 0$ and $\partial^2 Y / \partial^2 A_t \leq 0$. In addition, no rain means a small and negligible harvest, hence, $Y(F_t, 0) = 0$. Figure A1 in the Appendix gives the yield function used in the numerical simulations. Notice that the empirical evidence on fertiliser use is limited and that we lack data of fertilising beyond 140 kg per ha.

Damages caused by the rats are composed of two components, one relating to the damage taking place during planting, expressed as a fraction of the yield, and another one relating to the damage through direct consumption of grain during harvesting, measured as absolute yield loss. Between planting and harvesting there is essentially no damage caused by the multimammate rat (Makundi *et al.* 1999). The fraction of maize planted in month n that is damaged is directly related to the abundance of rats; that is,

$$(4) D_n^p = D^p(N_n)$$

with $\partial D^p / \partial N_n > 0$. The specific functional form $D_n^p = a + b \cdot N_n / (c + N_n)$ is used in the numerical simulations where a represents the background death rate of young maize plants (i.e., germination failure or damages not directly related to the rat population), b is the maximum damage level, and c is the rat density for which damage is $b/2$. The Appendix (Table A2) gives the parameter values.

Assuming no further rodent damage, the annual maize yield will then be $Y(F_t, A_t) \cdot (1 - D_n^p)$. However, there will be a further reduction during the harvesting period. The harvesting damage, measured in absolute loss (kg per ha), is also directly related to the rodent abundance

$$(5) D_n^h = D^h(N_n),$$

with $\partial D^h / \partial N_n > 0$ and $D^h(0) = 0$. The function is specified linear $D_n^h = d \cdot N_n$ where the value of d is based on information about the daily food consumption of rats (again, see the Appendix for more details). Consequently, the actual maize production in year t is

$$(6) NY_t = \max[0, Y(F_t, A_t) \cdot (1 - D^p(N_{n-\tau})) - D^h(N_n)]$$

where the time lag τ , the length of the maize growing season (typically five months), is introduced to scale the two types of damages occurring in different months.

Gross agricultural profit per ha and year (i.e., the profit without accounting for the cost of rodent-control) is given as

$$(7) R_t = p \cdot NY_t - q \cdot F_t - K,$$

where p represents the ‘net’ market price of the crop; that is, the market price of the maize corrected for cost factors being in fixed proportions to the yield, q the fertiliser price and K the fixed costs. All costs and prices are assumed to be constant over time. In the following we assume labour use, the basic production factor in addition to water and fertiliser, to be fixed per ha, and, hence, not related to the yield per ha. The opportunity cost of labour, if any, is therefore embedded in K (see Appendix for details). With these assumptions, p therefore basically reflects the price of maize.

The control cost at time n (i.e., month) is given as

$$(8) C_n = C(X_n)$$

with $\partial C/X_n > 0$ and $C(0) = 0$. The specific functional form used in the simulations is assumed to be linear, $C_n = w \cdot X_n$ where the unit cost w essentially reflects the purchasing cost of the poison. However, the unit cost may contain the opportunity costs of labour linked to the spreading of the poison as well. If so, however, we are not explicitly considering any trade-off between labour uses in crop production and pest control. As already mentioned, consistent with recent practise in Tanzania, we assume that X_n is fixed either at zero or at some non-zero level, and if applied, typically a treatment will be carried out with 2 kg of poisoned bait per ha. Hence, in the proceeding analysis C_n is fixed at some non-zero value per month whenever poison is applied, and zero otherwise.

Having defined the control and damage cost functions, the current net profit in year t reads

$$(9) \pi_t = p \cdot NY_t - q \cdot F_t - K - \sum C_n$$

where the summation of the control cost is taken over the year (that is, $n = 8$ to 19 cover the year $t = 1$, etc). Equation (9) implies that the effect of discounting within the year is neglected. The current net profit function also neglects, if any, negative poison effects on crop production. Environmental costs caused by the poison are neither taken into account.

4. The management problem and the control strategies

While the crop profit without damages and control costs one year is invariant of the current crop profit without damages and control costs previous year, this is obviously not so for the current net crop profit. Through damages and control costs, the net crop profit one year is contingent upon the ecological state of the system previous years. Hence, the net benefit in various years is linked together through the size of the rodent population. The management problem is therefore dynamic, and the problem is to find a control strategy X_n , being either zero or at some fixed non-zero level in a specified sequence of months over the year, reducing

the survival rate m_n that balances the control costs and crop damages in a way that makes the present-value net profit per ha

$$(10) \quad PV = \sum_1^{T+1} \frac{\pi_t}{(1+\delta)^t}$$

as large as possible over the planning horizon T years, while δ is the rate of discount. As mentioned, we consider the management problem as a planning problem at the village level where the agricultural officer acts as the social planner. The planning horizon will then be expected to be relatively long while the rate of discount δ should reflect the social one. In the basic scenarios, we use $T=10$ years and 7% rate of discount, $\delta=0.07$.

It should be remembered that the rodent control considered in this paper refers to an environmental situation where both the crop yield and the rodent population growth are subject to large fluctuations since rainfall is largely stochastic. The ecology-economy interaction is also fairly complicated, basically due to the double and partly overlapping time scale. Moreover, in addition to X_n , the use of fertiliser F_t may also be considered as a control variable, making the problem even more complicated. For these reasons, rather than trying to formulate an optimising model within an optimal programming (or control) framework and finding one control strategy among all possible that maximises present-value net profit, we single out some reasonable main strategies and compare these outcomes.

As indicated above, today's practice in Tanzania consists mainly of symptomatic treatment when heavy rodent damage is noticed. In some cases, depending on the visible presence of many rats or issued outbreak warnings, farmers may choose to organise a prophylactic treatment at planting time. Such practices will be included in our analysis, but we also analyse strategies where the control is applied for various consecutive months. All strategies include a fixed use of fertiliser for which we have data, and $F_t=40$ kg/ha will be used in the basic simulations (cf. the Appendix). However, the consequences of more fertiliser use and no fertilising at all, will also be studied. The effects of changing economic conditions will be studied as well. As baseline values we use $p=100$ Tsh/kg maize, $q=220$ Tsh/kg fertiliser, $w=6500$ Tsh/kg poison, and $K=10.000$ Tsh/ha as the fixed cost (for more details, see Table A2 in the Appendix).

Altogether we consider the following control strategies X_n , being either zero or at a fixed non-zero level, related to the calendar:

1. Control for a given number of consecutive months, including no control and control every month;
2. Control only for certain predetermined months (e.g., only every February or both February and March).

In addition, we have combined the above strategies with various conditions related to the state of the system (such as conditioning the application of poison on rodent density or precipitation).

Since rainfall patterns are a major component of the model's variability, simulations have been run with a large number of different rainfall series¹. We use monthly rainfall values (Meteorological Station, Morogoro, Tanzania) that were drawn from rainfall data obtained for that particular month in the period 1971-1997; that is, for each month of the run, and independently from the values for the other months, we choose a value at random from the 27 years for which we had values for that month. For each control strategy, and set of model parameters, the model was run 100 times, each time with a different random seed, resulting in 100 different rainfall series. The model simulations always started in December with an average number of animals comparable to what is observed in the field in that month (no juveniles, 133 sub-adult females and no adult females). In order to reduce the effect of initial conditions, each model run ran for 248 months before pest control and economic evaluation started; it then continued for a number of years, reflecting the given planning horizon, T . Accordingly, the evaluation of the profitability of each control strategy is done by calculating the median present-value net profit (PV) of equation (10) for the 100 runs, together with the variability, given by the 95%-range values.

5. Results

5.1 Preamble

¹ The model was implemented numerically using *Stella Research, version 5.1.1* (High Performance Systems, Inc., Hanover, NH, USA).

To see the basic logic of the numerical simulations, Figure 1 provides four examples based on two rainfall series and two different control strategies; control applied once a year in February (just before planting), and no control at all. The two panels A and B are for different (random) rainfall series, chosen from different runs of the model; the examples are representative for the general pattern. As can be seen, under the rainfall pattern in Panel A, the rat abundance is subject to large fluctuations both with and without control. However, the actual yearly harvest NY_t is quite modest accompanied by small values for the current net profit π_t when applying no control, whereas under the February control the yield as well as the current net profit are higher. The same broad picture is also provided in Panel B.

Figure 1 about here

For the given fertiliser use and the baseline values for prices and costs, these results clearly indicate that pest control is economic rewarding as the average yield and current profit, and hence, also the PV (not shown), are higher when control is carried out. Of course, care must be taken as Figure 1 exhibits only two runs for each strategy. We now turn to the full-scale simulations where the results present the median PV, together with the variance, for 100 simulations within each strategy are shown.

5.2 Duration and timing of the control

Figure 2 summarises the results where we have simulated the application of pest control for different numbers of consecutive months. The duration of the control (i.e., number of consecutive months) is indicated along the horizontal axis where we altogether have included 5 months as the rat population goes extinct beyond 4 months (see below). No control at all is included as well, indicated by the number 0 along the axis. For each number of months applying control, except no control at all (0), there are 12 possible months to start controlling. Hence, we have generally twelve medians and 95% range plots within each possible duration of control as indicated by JFM...ND (January, February, Mars..., November, December). Panel A represents the median present-value net profit (PV) with bold points, and the 95% range with thin vertical lines. The PV without rats at all are also shown, displayed as Maximum PV and with its 95% range variation as the shaded area. Panel B gives the number of rodents at the end of the planning horizon, also as median and 95%-range values.

Figure 2 about here

From panel A in Figure 2, three main features should be noticed:

- (1) The median present-value is low without control (0 months), but increases in general for strategies with up to 4 consecutive months of control, beyond which the present-value net profit (PV) start decreasing. Hence, the patterns only up to 5 consecutive months are displayed. A rewarding strategy is therefore clearly to control the rats for some months, but not for too long.
- (2) It is more profitable to control during certain months than during others. If poison is applied one or two months every year, it seems most rewarding to start controlling in January/February, whereas if poison is applied for 3-5 months, it is most rewarding to start controlling in August-December/January.
- 3) There are small differences between the most economic rewarding strategies.

For the given fertiliser use, prices and costs, the most rewarding strategy is to apply poison during 4 consecutive months starting in November, but many of the other strategies shown in Figure 2 do not result in a significantly lower PV. Strategies having significantly lower median PV include controlling for 1 month, and from 8 up to 12 months (the last ones not shown in the figure), while increasing the duration of control above 5 months all the time reduces the PV (not shown). Some of the strategies for 5 and more consecutive months may give higher PV than strategies applied for, say, 2 and 3 months (see also below). Strategies having significantly lower PV also include applying control for 2-3 months during the cropping season (i.e., starting in March). The timing of the control period seems therefore to be more important than its duration, especially for control periods of 3 months or less. Hence, poisoning will be most rewarding just before the growing season as to reduce the number of rodents before planting of maize. Generally, the variability of the PV increases up to 3 months duration of the control. After that it decreases again slightly and stays more or less constant for 5 months and longer duration of control (not reported in the figure). Thus, the economic outcome of control during 3 months or more is more uncertain than with shorter periods.

Panel B in Figure 2, presenting the rodent population at the end of the planning horizon, shows that some of the strategies applying rodent control 1-2 months each year do not affect population development very much. However, if the duration of control is more than 3

months, the rodent population reduces slowly towards extinction, and faster for longer duration of the control. The population goes extinct at the end of the planning horizon after 4 consecutive months. Hence, these graphs clearly indicate that control for more than 4 months is not economic meaningful as more control means more control costs, but no further reduction in number of rats, and hence, no further reduction in crop damages. It is important to notice that the patterns in panel A and B are not concurrent, showing that the relation between numbers of rodents and economic benefit is not a trivial one. Notice also the high population variability.

5.3 Other control strategies

For all results presented so far we have applied rodent control during consecutive months and always during these months. However, the economic benefit of using pest control might be higher if we split the control months into two (or more) periods each year separated by at least one month. We tested this for two control periods each year with a total of 2 (1 + 1), 4 (2 + 2), 6 (3 + 3) and 8 (4 + 4) months. For these simulations, the present-value profit (PV) were generally highest when rodent control was used during 3 months separated by at least 1 month. Hence, we also tried all possible combinations of 3 (1+2), but also 4 (1+3) months separated with at least 1 month. The 20 most rewarding strategies of duration and timing of rodent control are presented in Table 1. As can be seen, combinations of 3-4 months control in the period before the start of the cropping season are still the most rewarding, together with a 2 months control in February and November. There are, however, no significant present-value net profit differences between the 20 strategies shown in the table; all strategies fall within the range of 57% and 68% of the PV of the hypothetical case of no rodents at all (line one in Table 1, see also Figure 2). Still, compared to no control at all (the bottom line) there are clear differences.

Table 1 about here

We also investigated whether an upper or lower threshold value on precipitation or rodent density before applying poison could affect the sequence of the most economically rewarding strategies. The only way a threshold value improved some of the PV estimates, was if we applied control for 4 months or more with a very low threshold value on rodent density (threshold value = 5 animals/ha for 4 months, 10 animals/ha for 5 months or more). Such a

low population density is, however, hardly possible to estimate reliably; hence, this is not a very applicable strategy.

The economic consequences of symptomatic treatment was also studied. As already indicated, today's practice in Tanzania represents an ad-hoc approach, and typically poison control is applied when observed damage is high during planting season, or just before harvest. This practice was simulated by introducing density dependent control in March and July. Various threshold values were tried, and the median PV values fell within the interval 280.000 - 305.000 Tsh when observing 100-200 rats per ha. Hence, these values are less than half of the most promising control practices reported in Figure 2 and Table 1. Under the present baseline values of prices and costs, these strategies were even worse than the option of no control at all.

5.4 Variations in the maize price, costs and fertiliser use

The above results were calculated for a fertilising intensity of $F_t = 40$ kg/ha. We have also analysed what happens under two other fertilising scenarios; no fertiliser use at all, and 140 kg/ha (see Figure A1). Since rodent demography is not directly dependent on crop production (cf. section 2.2), the rodent population dynamics is not affected by fertiliser use. Hence, for each control strategy, the simulated rodent densities are identical for each of these three fertiliser applications. Because of this one-way link between fertiliser and the bio-economy, the economic effect of shifting the yield function through variations in fertiliser use is straightforward, and hence, more fertiliser use will be economic rewarding as long as the value of the increased yield more than out-weights the additional cost of the fertiliser. For the baseline value of the crop price and fertiliser cost, it turns out that the profitability increases when more fertiliser is used. Consequently, all the PV's in Figure 2A shift up more or less uniformly when the fertiliser use is increased from 40 kg/ha to 140 kg/ha while they shift down in the same manner when there is no fertilising at all. As Figure 3 demonstrates, the ranking of the most economic rewarding control strategies is therefore only modestly affected. However, unprofitable strategies may become profitable when increasing the fertiliser use, and profitable strategies may turn out to be unprofitable when not fertilising at all.

Figure 3 about here

We have also studied what happens under different price and cost assumptions. A permanent negative shift in the producer price of maize, p , will generally make shorter duration of the control relatively more profitable. The intuitive basis for this result is straightforward as lower marginal income must be compensated by lower marginal cost (i.e., reduced duration of the control). On the other hand, the effect on the timing is quite modest. Table 2 demonstrates the results where the most economically rewarding strategies under each of the 12 consecutive months treatment are shown under different price and cost assumptions. Hence, compared to the base-line simulations where 4 and 5 consecutive months together with 1 month gave highest PV (see also Figure 2, except that duration above 5 and more months are omitted), 1 month, 2 months and no control at all are the best duration when the maize price is halved.

Table 2 about here

The economic conditions for the farmers may also be less favourable due to more expensive poison. A positive permanent shift in the price of the poison, w , also lead towards in the direction of shorter duration of the control being relatively more profitable. Hence, instead of 4 months, 5 months and 1 month duration per year being the most economic rewarding strategies under the base-line assumptions, we find that doubling the poison price makes duration of 1 month, 2 months and no control the most economic rewarding strategies. Thus, more expensive poison means that more rats and a higher level of crop damage will be accepted in the optimal strategy. Doubling the fertiliser price, q , shifts down the profitability, but does not change the profitability ranking.

The economic consequences of symptomatic treatment was also studied under shifting price and cost assumptions. All the time, the best practices compared to today's practises of introducing density dependent control in March and July were typically doubled. Finally, we also studied the effects of reducing the planning horizon and making the problem more myopic by setting $T=5$ years. Generally, there are small changes taking place (not reported here).

6. Discussion

Throughout this paper we have considered a rodent pest problem where the management is in the hand of a social planner and where the agricultural area can be quite large. The control problem is specified as timing and duration strategies where the dosage of the poison is kept fixed per month whenever poison is used (consistent with recent practice in Tanzania). The most economically profitable control period seems to be just before the planting season. The damage at planting accounts for such a large portion of the total losses due to rodents, that minimising the population during that short period is enough to reduce yield losses.

Controlling for a longer period will reduce rodent populations at a time when they do not damage the crop anyhow, and due to the very high reproductive capacity of the rodents, the population will increase fast as soon as control operations are stopped, repressing any long term effects. The simulations, however, only indicate small profitability differences among various combinations of control months towards the start of the planting season. Although we have not valued environmental costs of the use of poison (see, e.g., Carson 1962) and negative impacts, if any, upon crop production are neglected, the small differences between the best strategies strongly suggests to opt for a strategy amongst these that use the least poison.

Hence, taking environmental economic considerations into account, two months of control just before planting season, January and February, or eventually in November and February, seem to be the best overall strategy.

These economically most rewarding strategies differ significantly from today's practice of symptomatic treatment when heavy rodent damage is noticed. The economic threshold concept and the idea of adjusting the timing of pesticide use to pest density is an old one (Carlson and Wetzstein 1993), but works poorly here because of the high reproductive rate of the rats and the short period after sowing during which most of the damage is done. Hence, the present paper demonstrates that shifting from such practices to more mechanistic control strategies; that is, emphasising the calendar instead of the pest abundance, can substantially improve the economic conditions for the maize producing farmers in the present case of multimammate rats. The best practices compared to today's symptomatic treatment will typically double the net economic benefit. The question of how to choose between an economic threshold model and a mechanistic control model is of general interest and should be examined further, but following our analysis it seems to be population growth characteristics of the pest rather than its taxonomic status that should drive that choice (see also Regev *et al.* 1976).

The economic viability of different control strategies is strongly related to the fertiliser use in the crop production, but the ranking of the most rewarding control strategies is only modestly affected. It is also important to notice that if no fertiliser is used, the economic reward of controlling the rodent population is small. Hence, if rodent control should make economic sense, it must be combined with fertilisation, simply because the yield without fertiliser will be too small to pay for control. The opposite seems also to be true as fertilisation has only modest economic effect unless it is combined with rodent control. Moreover, we find that permanent changes in prices and costs give effects that are more or less in line with intuition. A less valuable crop and higher poison cost make shorter duration of the control and hence, living with more rats and nuisance, relatively more profitable. On the other hand, the optimal timing (i.e., in which months to apply poison) is only modestly affected by changing prices and costs. Consequently, it seems that the optimal timing is more closely related to the ecology and the abundance of rats than prices and costs, while the economy plays a more important role when it comes to the optimal duration of the control. One reason for this may be that the damage effect is far more important during some parts of the year, e.g., just before planting.

Throughout our simulations, we interpreted the pest control problem as taking place at the village level where an agricultural officer serves as the social planner. While it mostly will remain the individual farmer's decision to apply control on his fields, the agricultural officer indeed plays an important role. His advise will be very influential not only to farmers, but also in ensuring timely access to rodenticides; in village shops, shelf-life of these poisons is limited so usually only limited quantities are available locally. The social planning horizon is also relevant because in case of an outbreak coming through, the government will be required to organise costly emergency measures (Makundi et al. 1999). When making the problem more myopic through reduced planning horizon, however, we find that the results are only modestly influenced. For the more myopic African farmer, when neglecting externalities due to various control practices within the management area, the above findings therefore also basically hold. However, when interpreting the results at the farm level, it should also be noticed that subsistence farmers frequently face credit restrictions, and typically, for such farmers, there is cash only for seed (see, e.g., Dasgupta and Mäler (1995) for a general discussion). The implication is that some poison control strategies may be beneficial for farmers using no fertiliser while other strategies may be beneficial for farmers having cash for fertiliser and poison, the 'capital-intensive' farmers.

Models are only an approximation of how we conceive reality, and they are only as good as the assumptions on which they are based. Regarding our population model, the basic building block of the present analysis, two major assumptions do not hold in reality. The first one is that the model uses discrete time steps of one month; however, a lot can happen in a rodent population in one month. . Secondly, our model does not yet include immigration processes but it is obvious that these can play an important role, particularly when the densities after rodent control have become much lower than in the surrounding fields. In such cases, a population may even be capable of recovering from a rodenticide application in the course of a few weeks (see, e.g., Leirs *et al.* 1997b), thus reducing the efficacy of control actions considerably. Regarding the agricultural activities, our model does not yet include the common practice of replanting after rodent damage, sometimes in combination with rodenticide application, and thus partially remedying damage. Prices and costs are also kept fixed throughout the planning horizon, and the maize price is assumed to be the same in years with poor and good harvest. For all these reasons, the results should be interpreted very cautiously and the model is not yet ready to be confronted with farmers and taken into practice. However, the main finding of the above analysis, emphasise the calendar instead of the pest abundance when controlling the rats, will probably hold under more realistic assumptions and is clearly an application rule that is quite easy to implement.

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Appendix

The Ecology

Table A1 summarises the demographic parameters in the ecological model.

Table A1 about here

The specification of the demographic effect of the pest control equation (2) is problematic since it should include the effect of the rat abundance. Moreover, not discussed in the main text, it should also include the combined effects of natural and poison-induced mortality and the immediate effect of the latter on the former (through density-dependent mechanisms). Such information for a more detailed and realistic description of the control function is not yet available. We are collecting more detailed information about the control function, but for now, we have used the very specific function assuming that the total mortality under application of rodenticides is always 0.90.

The Economics

Figure A1 gives the maize yield function (depending on rainfall and fertiliser use). The empirical evidence on fertiliser use is restricted, and data of fertiliser use beyond 140 kg per ha are lacking.

Figure A1 about here

The parameters of the crop damage function during the planting season $D_n^p = a + bN_n / (c + N_n)$ are given in Table A2. The establishment of this function, based on a very detailed set of field data from Morogoro, Tanzania, is presented elsewhere (Mulungu *et al.* 2002). The crop damage function during the period just before harvesting $D_n^h = dN_n$ is based on the theoretical consideration that a small rodent on average has a daily food intake of approximately 10% of its body weight (Petrusewicz 1970). Since *Mastomys natalensis* rats weigh on average are 45 g during the pre-harvesting period (Leirs 1985), since rodent damage to ripening maize cobs starts approximately 1 month before harvest and assuming that rats climbing the stalks spill or damage about the same amount as what they actually eat, the parameter d was set to be $d = 30 \text{ days} \cdot 4.5 \text{ g/day} \cdot 2 = 270 \text{ g}$. The length of the maize growing season τ is 5 months from planting to harvesting, as common in Morogoro, Tanzania, with the locally used maize varieties. When applying crop damage function at planting or harvesting time, we always doubled the calculated rodent population size N_n since the model only represented the female part of the population.

The price of the maize crop production, p , the per unit fertiliser price, q , and the per unit poison price, w , refer all to 1999 market prices in Morogoro. The price for the poison is based on a bromadiolone bait poison. The fixed cost K includes the costs for field preparation, seed material and maintenance and is estimated to be 10.000 Tsh per ha for a subsistence farmer, carrying out virtually all work with own family labour power for which we have included no opportunity cost. The parameter values used in the baseline simulations are given in Table A2.

Table A2 about here

Figure legends

Figure 1. Four examples of model runs. Panel A and B for different (random) rainfall series. Two different control strategies; no control and control applied once a year in February.

Figure 2. Results when control applied for different number of months and various timing. The duration of the control in number of consecutive months along the horizontal axis (up to 5 months). For each number of months applying rodent control (except 0) there are 12 possible months when to start controlling. The first set of values along the vertical axis are for starting control in January, the second for starting in February, and so on until the last starting in December. Panel A; the median PV (with a planning horizon of 10 years from the beginning of control) with bold points, and the 95% range with vertical lines. The shaded area with maximum PV shows the median (95% range) in a hypothetical situation without rodents. Panel B; the number of animals per ha at the end of the planning horizon. Note, however, that for 4 months of pest control the rodent population do not always go completely extinct, but is not visible at the scale of the figure (<1 animal/ha).

Figure 3. The interaction effect of fertiliser and consecutive duration of control up to 5 months. The control strategies represented are the ones with timing giving the highest PV within each duration of control (cf. Figure 2).

Figure A1. Maize yield functions, dependent on the amount of nitrogen-fertiliser applied and rainfall during the growing season (adopted from McDonagh *et al.* 1999).

Table 1

Ranking of the 20 most economic rewarding control strategies given by timing and length (total number of months of the control). The hypothetical case of no rodents (upper line) and the case of no control (lower line) included as well. PV (in Tsh) is presented by the median and the lower (0.025) and upper (0.975) percentile for the 100 simulations performed for each strategy. c = consecutive months

Rank	Timing	Length	PV		
			Median	Lower	Upper
No rodents			1 017 164	903 556	1 145 799
1	Jan, Feb - Nov	3	681 744	543 466	810 470
2	Feb - Nov	2	666 459	556 871	812 710
3	Feb - Oct, Nov	3	666 234	555 562	816 033
4	Jan - Oct, Nov	3	654 459	525 340	806 269
5	Feb - Nov, Dec	3	648 464	529 765	803 311
6	Jan, Feb - Oct, Nov	4	637 847	518 648	772 004
7	Sep - Nov, Dec	3	625 949	449 078	795 851
8	Nov, Dec, Jan, Feb	4 (c)	622 630	478 324	741 145
9	Jan, Feb - Oct	3	621 457	496 610	788 839
10	Aug, Sep - Nov, Dec	4	616 728	497 419	755 186
11	Sep, Oct, Nov, Dec	4 (c)	614 712	476 300	752 397
12	Aug, Sep, Oct, Nov	4 (c)	611 053	483 100	749 886
13	Oct, Nov, Dec, Jan	4 (c)	606 667	485 560	746 475
14	Jul, Aug - Oct, Nov	4	605 362	478 341	740 140
15	Sep, Oct - Dec, Ja	4	603 483	489 075	746 489
16	Feb, Mar - Nov, Dec	4	600 332	465 492	727 482
17	Feb, Mar - Oct, Nov	4	594 932	483 280	732 855
18	Jan, Feb - Sep, Oct	4	590 364	488 483	746 194
19	Jul, Aug - Nov, Dec	4	588 382	455 086	724 599
20	Dec, Jan, Feb, Mar	4 (c)	574 708	441 271	703 753
		0	282 360	190 534	377 130

Table 2

Ranking of the most economic rewarding control strategies (median PV) by means of consecutive duration in total number of months of control. Various price and cost assumptions (Tsh per kg). Baseline values: w =6500, q =220, p =100.

		Price poison (w)		Price fertiliser (q)	
		6500	6500	13000	13000
Net price maize (p)		220	440	220	440
		100	4	4	1
		5	5	2	2
		1	1	0	0
		2	2	4	4
		3	3	3	3
		6	6	5	5
		7	7	6	6
		8	8	7	7
		0	0	8	8
		9	9	9	9
		10	10	10	10
		11	11	11	11
		12	12	12	12
	50	1	1	0	0
		2	2	1	1
		0	0	2	2
		4	4	3	3
		3	3	4	4
		5	5	5	5
		6	6	6	6
		7	7	7	7
		8	8	8	8
		9	9	9	9
		10	10	10	10
		11	11	11	11
		12	12	12	12

Table A1

Monthly demographic parameter values for each of the combined rainfall-density regimes in the population dynamics model. The values for s_{0n} and s_{0w} are arbitrarily set, the other values were obtained from demographic analysis (from Leirs *et al.* 1997a).

<i>Regime definition</i>							
Rainfall in the past 3 months (mm)	V_n	<200	<200	200-300	200-300	>300	>300
Density per ha	$N_n^{(e)}$	>150	<150	>150	<150	>150	<150
<i>Demographic rates</i>							
Net reproductive rate	$B(V_n, N_n^{(e)})$	1.29	5.32	0.30	6.64	4.69	5.82
Juvenile survival in the nest	s_{0n}	1.0	1.0	1.0	1.0	1.0	1.0
Juvenile survival after weaning	s_{0w}	0.5	0.5	0.5	0.5	0.5	0.5
Subadult survival	$S_1(V_n, N_n^{(e)})$	0.629	0.513	0.682	0.617	0.678	0.595
Subadult maturation	$\psi(V_n, N_n^{(e)})$	0.000	0.062	0.683	0.524	0.155	1.000
Adult survival	$S_2(V_n, N_n^{(e)})$	0.583	0.650	0.513	0.602	0.505	0.858

Table A2

Baseline values prices and costs (1999-prices Morogoro, Tanzania), damage function and other parameters

Description	Parameter	Default value
<i>Economic parameters</i>		
Net price maize	p	100 Tsh/kg
Price fertiliser	q	220 Tsh/kg
Price poison	w	6500 Tsh/kg
Fixed costs per ha maize field	K	10 000 Tsh/ha
Planning horizon	T	10 Yrs
Discount rate	δ	0.07
<i>Damage at planting</i>		
Background death rate of seedlings	a	0.0827
Maximum proportion of seedlings damaged	b	0.8339
Rodent population size at half of maximum damage	c	36.068
<i>Damage before harvesting</i>		
Amount damaged by 1 multimammate rat during 30 days	d	0.270 kg
<i>Other</i>		
Fertiliser per ha	F	40 kg
Amount of poison used per ha	X	2 kg

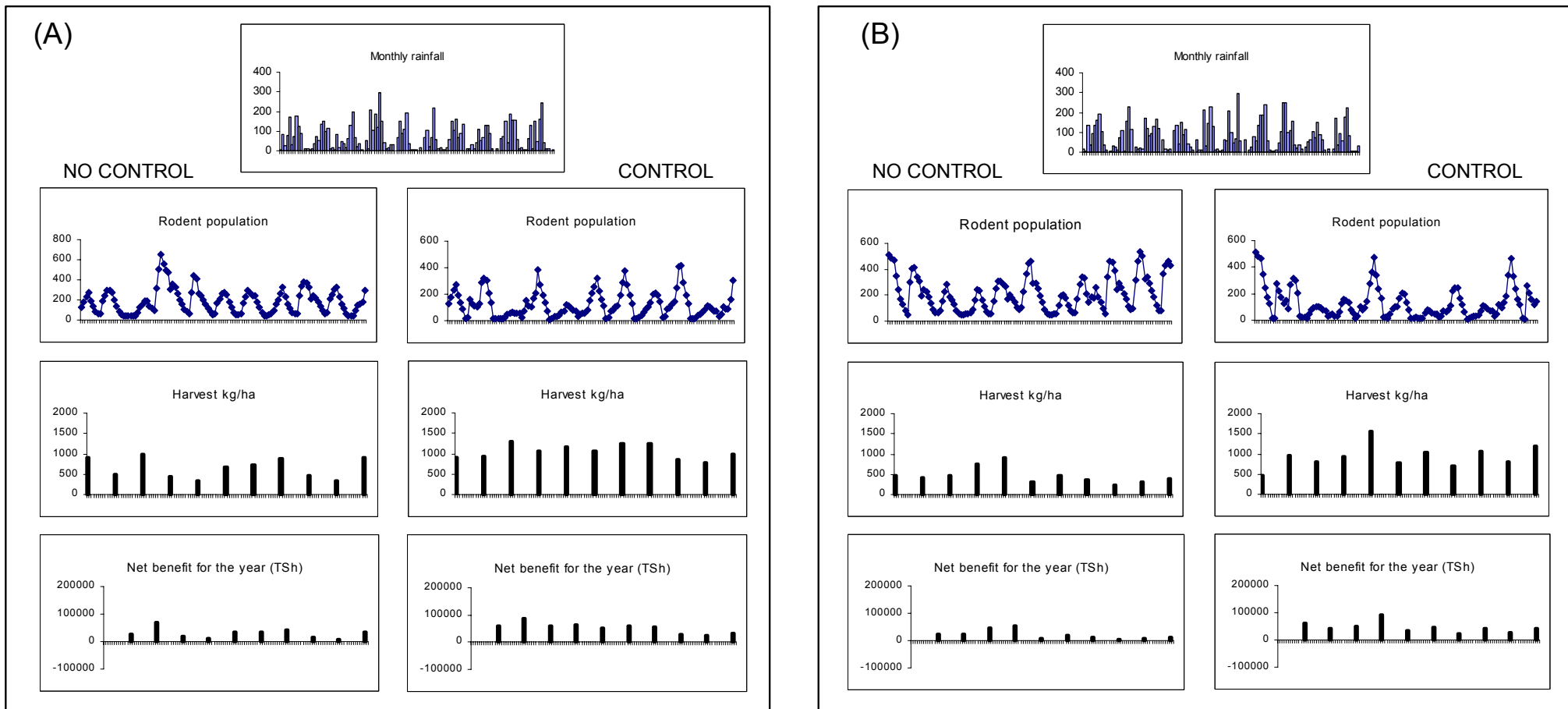


Figure 1. Skonhoft et al.

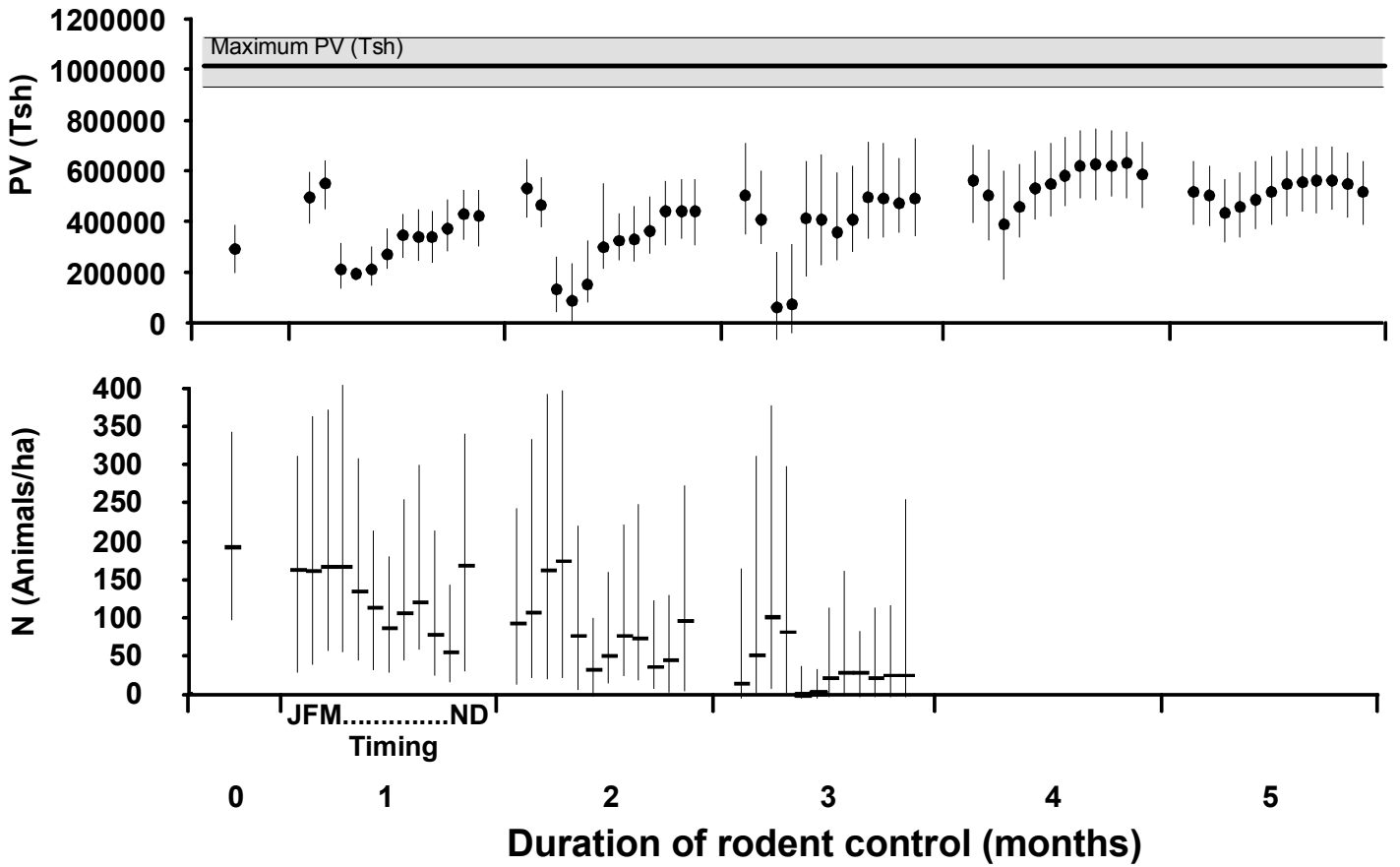


Figure 2. Skonhoft et al.

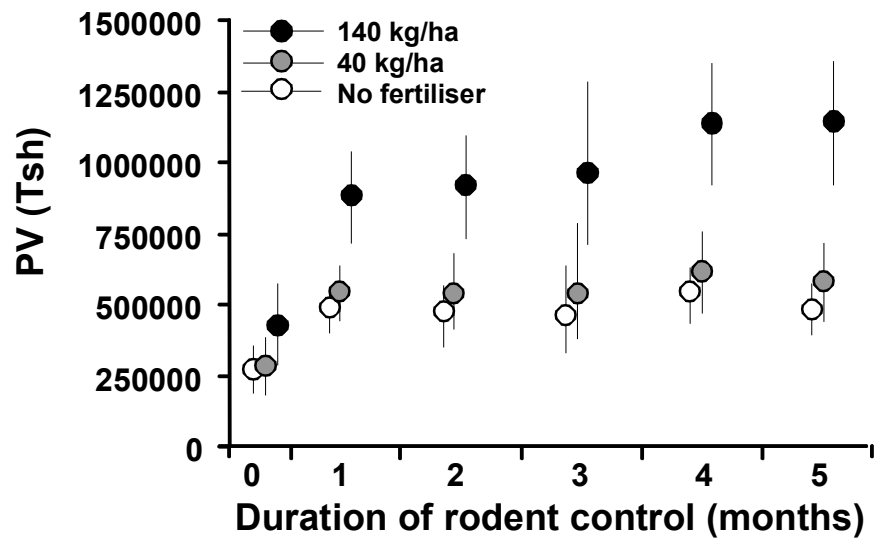


Figure 3. Skonhoft et al.

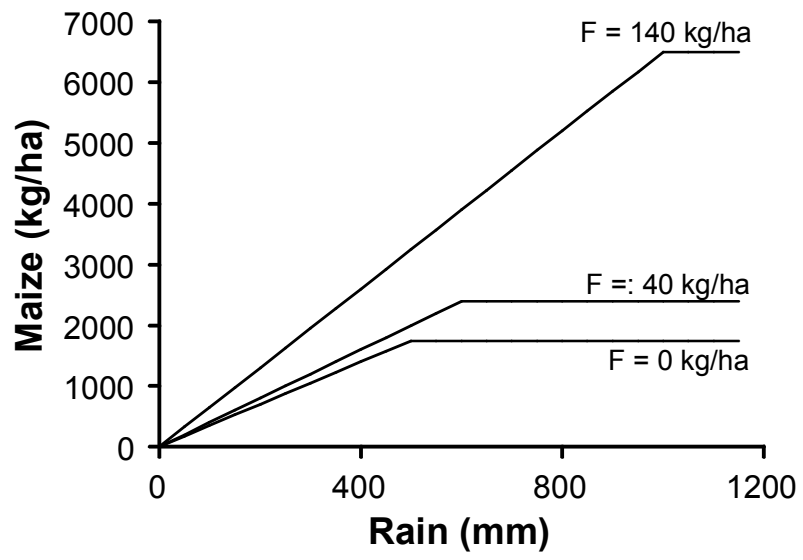


Figure A1. Skonhøft et al.