Integrated pest management and allocation of control efforts for vector-borne diseases

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ABSTRACT: Applications of various control methods were evaluated to determine how to integrate methods so as to minimize the number of human cases of vector-borne diseases. These diseases can be controlled by lowering the number of vector-human contacts (e.g., by pesticide applications or use of repellents), or by lowering the proportion of vectors infected with pathogens (e.g., by lowering or vaccinating reservoir host populations). Control methods should be combined in such a way as to most efficiently lower the probability of human encounter with an infected vector. Simulations using a simple probabilistic model of pathogen transmission suggest that the most efficient way to integrate different control methods is to combine methods that have the same effect (e.g., combine treatments that lower the vector population; or combine treatments that lower pathogen prevalence in vectors). Combining techniques that have different effects (e.g., a technique that lowers vector populations with a technique that lowers pathogen prevalence in vectors) will be less efficient than combining two techniques that both lower vector populations or combining two techniques that both lower pathogen prevalence, costs being the same. Costs of alternative control methods generally differ, so the efficiency of various combinations at lowering human contact with infected vectors should be estimated at available funding levels. Data should be collected from initial trials to improve the effects of subsequent interventions on the number of human cases. ***Journal of Vector Ecology* 26(1): 32-38. 2001.**

Keyword Index: IPM, vector-borne diseases, pest management, ticks, mosquitoes

INTRODUCTION

Contemporary Integrated Pest Management (IPM) has developed primarily according to an agricultural model (Apple & Smith 1976, Metcalf & Luckmann 1982). The benefit of an intervention is assessed as the value of the crops that are saved from destruction by insects because of the intervention. This benefit is compared to the cost of the intervention to derive an "economic injury level," a pest population level at which costs of control equal benefits (Headley 1972). For disease vectors, there is no analogous measure of the benefit of an intervention, because it is inherently difficult to put a dollar value on preventing cases of human disease. Therefore, the economic injury level may not be an appropriate concept in vector management.

IPM for vector-borne diseases might be best viewed as an allocation problem, more amenable to cost-efficiency analyses than to cost/benefit analyses (Phillips et al. 1993). Specifically, given a certain level of funding, managers optimize resource allocation so as to minimize the number of human cases of disease (Mills & Drummond 1987, Ginsberg 1993a, Mills 1994). Crucial to any such analysis is predictive information about the relative efficacies of alternative control techniques. The relative effectiveness of various control methods can be estimated using data from field trials and from mathematical models of disease transmission cycles. Phillips et al. (1993) provide guidelines for assessing the effectiveness of a control measure based on its effect on the vectorial capacity of the vector species.

An enormous amount of literature exists on the efficacy of various interventions for specific vectors, but few general rules have been derived about how to integrate different management methods for vector-borne diseases. In general, what types of techniques should be integrated to have the greatest effect on the number of human cases of vector-borne disease? In this paper I compare management techniques that lower vector-human encounters with those that lower pathogen prevalence in vectors, and examine ways to integrate these techniques so as to minimize human disease incidence.

METHODS

Management methods were analyzed using a simple model of the probability of human exposure to pathogens via arthropod vectors. For the purpose of this analysis the many methods available to manage vector-borne diseases are classified as either vector-oriented or pathogen-oriented approaches. Vector-oriented methods lower the number of vectors (e.g., broadcast pesticide applications, water management for mosquitoes) or lower the number of vector-human contacts (e.g., repellents, window screens, avoidance of infested sites). Most currently-used methods of vector control fit under this category. However, several recent innovations have targeted control at the pathogen within the vector. For example, vaccination of wild reservoirs (white-footed mice) has been proposed as a management approach for Lyme disease. Similarly, the use of permethrin-treated cotton balls (Mather et al. 1987) targets ticks on the mouse reservoir of the spirochete , and can lower infection rate in ticks, even when it fails to lower tick numbers (Ginsberg 1992). Thus, pathogen-oriented methods lower the prevalence of pathogens in vectors, and include control or vaccination of efficient reservoir species, host-targeted pesticides, fostering populations of non-reservoir hosts, etc.

The effect of management on disease transmission can be analyzed by examining its effect on the probability of human exposure to the pathogen (P_1), which is the probability of at least one contact with an infected vector (Ginsberg 1993b).

$$P_1 = 1 - (1 - k_v)^n$$

where k_v = the proportion of vectors infected with the pathogen, and n = the number of vector-human contacts (e.g., mosquito bites). The analysis assumes that a single infective contact (e.g., bite by an infected mosquito) is sufficient for transmission of the pathogen.

This probabilistic approach to the likelihood of human encounter with an infected vector is related to the probabilistic portion of the Reed-Frost epidemic model (Frost 1976), and gives a more realistic assessment of this encounter probability than the linear relation between infected vectors and human exposure utilized in older models (Fine 1981). Probabilistic estimators of the likelihood of encounter between infected vectors and humans based on the binomial distribution (as in this paper) or on the Poisson distribution (which gives similar results) are now commonly utilized in models of the transmission dynamics of vector-borne diseases such as malaria (Dietz et al. 1974) and Lyme disease (Porco 1991).

Given that the purpose of IPM for vector-borne diseases is to integrate techniques to have the greatest possible impact on human disease incidence, available money should be allocated so as to minimize P_1 . Thus, rather than comparing predicted costs to predicted benefits as in agricultural IPM, this analysis compares different combinations of management techniques in terms of their effects on the probability of human exposure to pathogens. The probability of exposure was calculated with various combinations of control techniques to evaluate whether it is best to integrate techniques that lower n with techniques that lower k_v, or better to integrate different techniques that lower the same one of these factors. For example, if a mosquito management program lowers the density of nuisance mosquitoes, and additional money is allocated to suppress an outbreak of arboviral encephalitis, would it be more efficient to supplement the mosquito control program with a program to manage or vaccinate reservoirs or enzootic vectors of the virus (so as to lower the proportion of human-biting mosquitoes infected) or would it be more efficient to spend extra money on additional efforts to lower the number of mosquitoes biting humans?

To assess the effect on human disease of integrating various control techniques, P_1 was calculated starting from various initial conditions of vector abundance and prevalence of infection with pathogens. P_1 was then calculated when n was reduced from the initial point to zero, when k_v was reduced to zero, and when efforts were split so as to reduce both n and $k_{v.}$

RESULTS AND DISCUSSION

If costs are equivalent for the two approaches (it costs the same amount to lower the number of mosquito bites by 10% as it does to lower the proportion of mosquitoes infected by 10%), and if there is no additional marginal cost (it costs the same to lower n or k_v an additional 10% regardless of how much the initial control method lowered them), then the efficiency of integrating different approaches is illustrated in Figure 1. The horizontal axis in Figure 1 is the proportion of control effort allocated to lowering

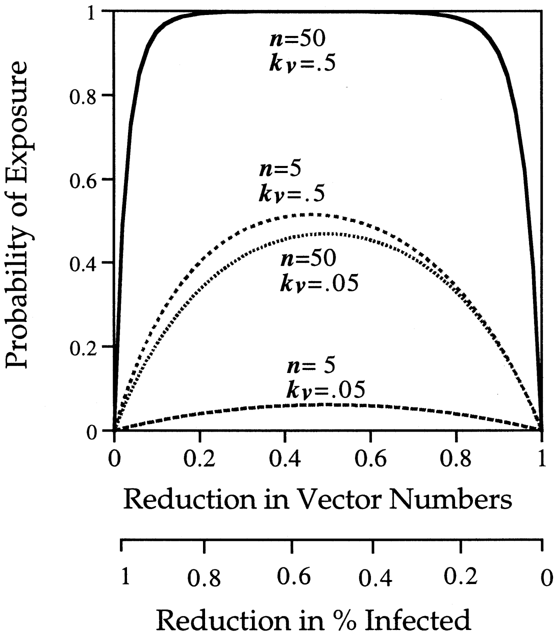

Figure 1. Influence of integrating management techniques on probability of exposure. Proportional allocation of efforts to techniques that lower vector numbers (***n***), or prevalence of pathogen in vectors ($\boldsymbol{k}_v$), where proportional reduction in ***n*** + proportional reduction in $\boldsymbol{k}_v$ = 1.0.

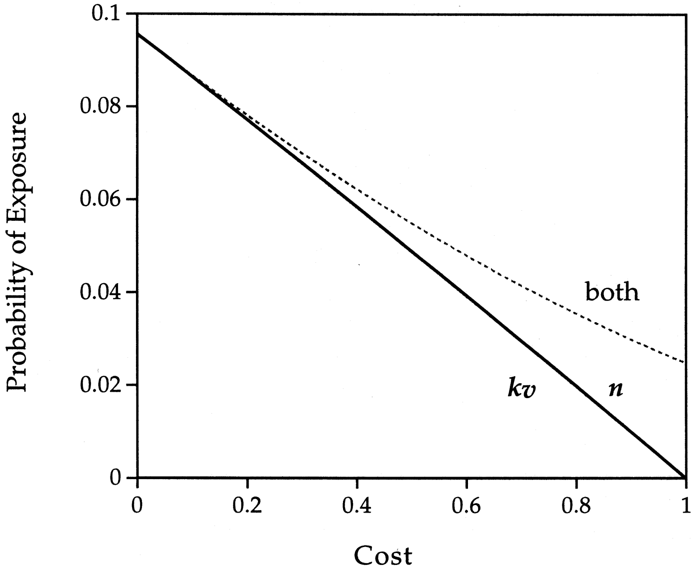

Figure 2. Effect on probability of exposure of lowering ***n*** to zero, lowering $\boldsymbol{k}_v$ to zero, or dividing resources equally between techniques that lower ***n*** and those that lower $\boldsymbol{k}_v$ (initial ***n*** = 10, $\boldsymbol{k}_v$ = 0.01).

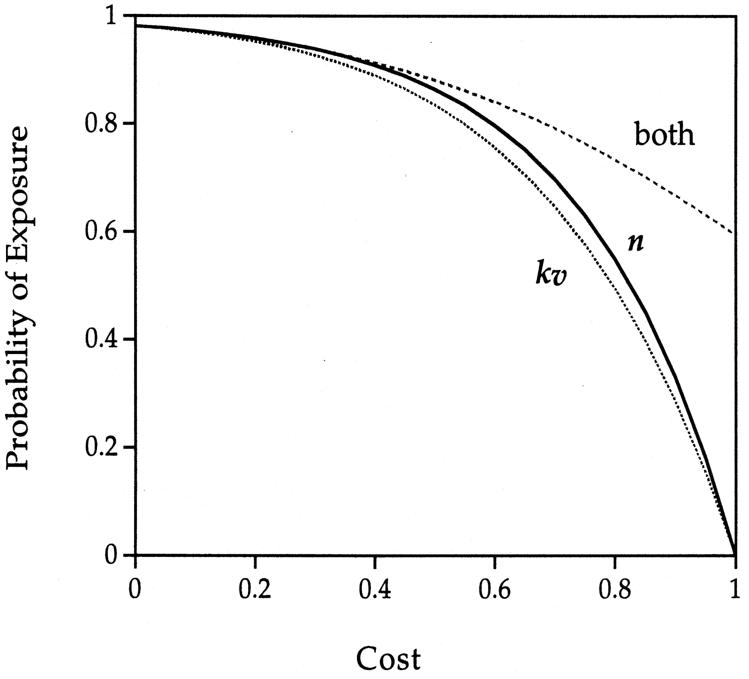

Figure 3. Effect on probability of exposure of lowering ***n*** to zero, lowering $\boldsymbol{k}_v$ to zero, or dividing resources equally between techniques that lower ***n*** and those that lower $\boldsymbol{k}_v$ (initial ***n*** = 10, $\boldsymbol{k}_v$ = 0.33).

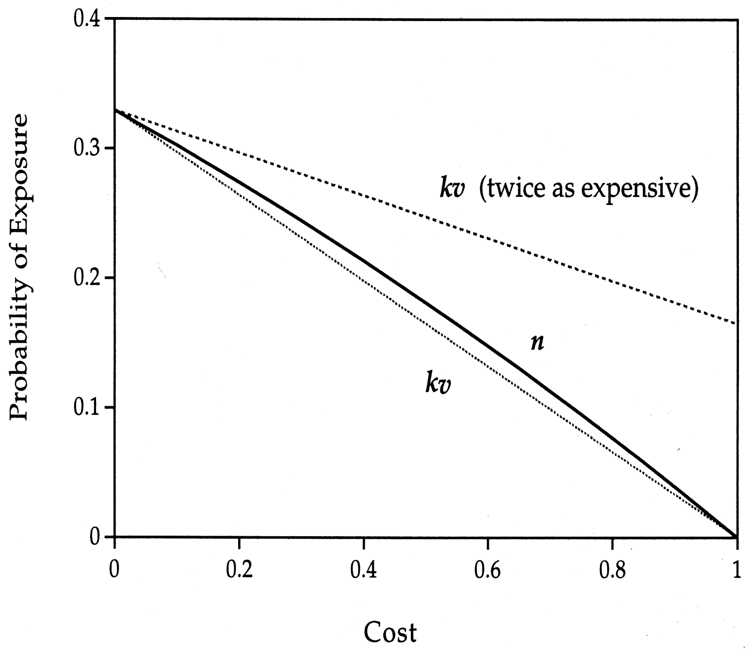

Figure 4. Effect of cost on utility of technique for lowering probability of exposure. Curves plotted for cost of reducing ***n*** equal to cost of reducing $\boldsymbol{k}_v$, and for cost of reducing $\boldsymbol{k}_v$ when it is twice as expensive as reducing ***n*** an equivalent amount. Initially, ***n*** = 1, and $\boldsymbol{k}_v$ = 0.33.

n, as opposed to lowering k_v. At x=0, n has not been lowered at all, and k_v has been lowered to zero. At x=0.5, both n and k_v have been lowered by half. At x=1.0, n has been lowered to zero, but k_v has not been lowered at all. At different points along the x-axis, n and k_v have been lowered to various extents such that the proportion to which n plus the proportion to which k_v have been lowered equals one. This is not meant to imply that there is an inverse relationship between n and k_v. Indeed, some control methods have the effect of lowering both. Figure 1 was set up this way specifically to illustrate the effect of splitting resources into lowering both n and k_v, as opposed to putting most or all of those resources into lowering either n or k_v alone.

When either n or k_v is lowered to zero, the probability of human exposure to the pathogen is, of course, zero. At intermediate points, however, the probability of exposure is greater. Thus, combining techniques that lower the same factor gets you closer to either end of the x-axis, where P_1 is low. In contrast, combining techniques that lower n with techniques that lower k_v gets you closer to the middle of the x-axis, where P_1 is highest. Therefore, to lower human exposure to the pathogen, it is more efficient (costs being equal) to integrate different techniques that do the same thing (e.g., several techniques to lower n, or several techniques to lower k_v), than to integrate techniques that do different things. In the case of the mosquito control program, putting the additional money into further lowering the number of mosquito bites would have a greater effect on human disease incidence than putting the additional money into lowering pathogen prevalence in mosquitoes, costs being the same. Note, however, that the curves in Figure 1 are asymmetric, so under certain specialized circumstances (when x is near 0.5) this general rule might not apply.

An example of the application of this principle is shown in Figure 2. Here, the relationship between the probability of exposure and the cost of control is plotted for initial conditions of n =10 (e.g., an average person gets 10 mosquito bites) and k_v =0.01 (1% of the mosquitoes are infected). This might apply to an outbreak of mosquito-borne arbovirus with a moderate mosquito population (an average of 10 bites per person during a hike in the woods) and an infection rate in mosquitoes of one percent. Under these initial conditions, lowering n has the same effect as lowering k_v on the probability of exposure. However, if efforts are divided equally between treatments that lower n and treatments that lower k_v ("both" in Figure 2), then the probability of exposure is higher; the treatment is less effective at lowering disease incidence in humans, costs being the same for all treatments. Another example is illustrated in Figure 3, where the results are plotted for initial conditions of n=10 and k_v=0.33. This might apply to Lyme disease in a wooded area, where humans are exposed to a substantial number of tick bites (10 for the period under consideration), and the infection rate in ticks is high (33%, which matches nymphal infection with Lyme spirochetes at selected sites in New York state; Falco & Fish 1988, Ginsberg 1992). In this case, lowering k_v has a slightly greater effect than lowering n, but as in the previous case, splitting efforts between n and k_v has less effect on P_1 than placing all resources into lowering one alone.

Of course, costs generally are not the same for different techniques. An example of the potential impact of cost on the efficiency of control is given in Figure 4, where the change in the probability of exposure is plotted as a function of cost for a disease with initial values of n=1 and k_v=0.33 (this would fit the case of Lyme borreliosis on some residential lawns). Under these initial conditions, when costs of control efforts are equal for lowering n or k_v, then it is slightly more efficient to lower k_v. However, if it is twice as expensive to lower k_v (i.e., it costs twice as much to lower infection rate in vectors by 10% than to lower the number of vector bites by 10%), then money should be spent on lowering n, because that approach would prevent more cases of human disease.

Potential complicating factors

Several factors complicate the selection of management methods for vector-borne diseases. For example, after initial lowering of the number of vector-human contacts, additional attempts to lower vector numbers or vector-human contacts may become increasingly expensive. Therefore, in order to integrate techniques efficiently, data are needed on the marginal costs of additional declines in vector-human contacts compared to declines in vector infection rates. Furthermore, some techniques simultaneously lower vector numbers and infection rates in vectors (Deblinger & Rimmer 1991, Ginsberg 1992), or have other effects on vector populations that influence transmission dynamics (Phillips et al. 1993). In addition, when different techniques are combined their effects might not be additive. For example, use of insecticides might lower the efficacy of biological control agents. Predictions of the ultimate effects of such management methods on human disease incidence require analyses specifically tailored to each case. Finally, because some vector-borne diseases are endemic over long time periods, techniques that are not cost-effective over one season might have cumulative effects that result in increased relative effectiveness over several years. For example, techniques that decrease vector feeding on reservoir hosts might have little influence on disease transmission during the first year of treatment (because infected vectors are already active), but might reduce the proportion of vectors infected in subsequent years. An implication of this diverse suite of complicating factors is that general rules derived from simple models are useful only to the extent that the model's assumptions are satisfied. Again, actual outbreaks of vector-borne disease require individually-tailored analyses.

Applicability

To apply this analysis to an IPM program for an actual vector-borne disease, it is necessary to know how effectively each available control technique reduces the number of vector bites and the pathogen prevalence in host-seeking vectors. Furthermore, the complicating factors mentioned above (effects of changes in marginal costs, incompatibilities between control methods, multiple effects of individual methods) should be quantified and included in the analysis. The expected decline in the probability of exposure can then be estimated for given expenditures on any technique or combination of techniques. Environmental considerations can be explicitly included in the pest management process by developing alternative programs that are environmentally benign, and that have the same effects on the probability of exposure as do environmentally damaging approaches (Ginsberg 1994). Once data on efficacy of control methods are available, costs of effective and environmentally acceptable IPM programs can be estimated.

Unfortunately, data with the degree of accuracy necessary for such analyses are often lacking, and even if available they might not be applicable to sites other than the study plots. Research results are most useful as guidelines: they can be used to develop preliminary IPM programs, but the programs must be monitored to provide information to improve performance in subsequent years. This is equivalent to an "adaptive management" approach (Holling 1978), where data collected during initial management trials are used to incrementally improve management efficacy in successive years.

Sophisticated models that can be used to plan efficient management strategies are available for several vector-borne diseases. However, many vector management programs are devised primarily to mitigate nuisance problems, especially in areas where vector-borne diseases occur only intermittently. When disease problems arise in these areas, decisions must often be made with little information. General analyses (as in this paper) and compilations of empirical research can be used to develop rules of thumb for efficient management of vector-borne diseases in such situations.

One such rule of thumb, suggested by the analysis in this paper, is that integrating two control techniques that have the same effect is likely to be more effective than combining techniques that have different effects. Another rule of thumb, suggested by Figures 1-3 and by Ginsberg (1993b) is that the effectiveness of a control technique depends on initial conditions of vector abundance and infection rate with pathogens. However, both of these general rules depend on simple models, and idiosyncracies in such factors as marginal effectiveness, costs, and multiple or incompatible effects of control methods can alter the results of this analysis. Therefore, the most important take-home message is that management programs for vector-borne diseases should consider locally-suitable control methods and specific circumstances of a disease outbreak to predict which combination of methods (or single method) would most likely have the greatest effect on the number of human cases of disease. During application, appropriate data should be collected to improve the efficacy of management in subsequent outbreaks. Thus, rules of thumb for vector-borne disease management do not so much provide guidelines on how to manage an outbreak, but rather provide guidelines on how to analyze the outbreak to provide the most effective possible management program.

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