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Prevention programs are often assumed to be the most cost-effective method for managing invasive plants. However, there is very little information available about economic and biological factors that determine the forage benefits resulting from prevention programs. We developed an easy to use economic model to assess potential savings in livestock forage that might result from implementing prevention programs. The model can be used to determine potential loss in forage production caused by invasive plants and to estimate potential income savings by preventing invasive plant infestations. The model compares a prediction of populations with and without a prevention program using a logistic growth function. Animal unit month (AUM) price and interest rates are the primary economic input variables. The primary biological input variables are amount of invasive plant utilization, size of the initial infestation, and the spread rate with and without prevention. Our model suggests that as the AUM price increases and/or the interest rate decreases, the total savings increases for each AUM that was protected through a prevention program. The model also shows savings per AUM increases as the size of the initial infestation decreases, suggesting that prevention should focus on eliminating seed sources and seed production early in the program. Using our model inputs, the savings per AUM was about $9.20 for each percent reduction in spread rate over 100 yr.

Key words: Economics, invasive plants, prevention.

Invasive species are the second-most important threat to biodiversity after habitat destruction (Pimm and Glipin 1989; Randall 1996; Wittenberg and Cock 2001). In addition, Wilcove et al. (1998) estimated invasive species have contributed to the placement of 35 to 46% of the plants and animals on the US federal endangered species list. With over 500 introduced plant species that have become weed pests, total costs of introduced plants to the U. S. economy in 2005 were estimated to be $27 billion annually (Pimental et al. 2005). The biological and economic impacts of invasive plant infestations, such as cheatgrass (*Bromus tectorum* L.), yellow starthistle (*Centaurea solstitialis* L.), and leafy spurge (*Euphorbia esula* L.), are well documented (Sheley and Petroff 1999). What seems to be more difficult is obtaining information to assist managers in determining the value of preventing infestations. Traditionally, invasive plant management has focused on controlling invasive plants on already-infested rangelands, with less emphasis placed on preventing invasions. Often, an invasion is recognized only after it has entered an explosive phase (Asher and Spurrier 1998). Unfortunately, by this stage eradication is not an option (Mack et al. 2000), it becomes excessively expensive to control the increase of the invader (Huenneke 1996), and restoration of native vegetation in these areas is rarely successful (Vitousek et al. 1997). Such scenarios lead to a reactive crisis-response approach to managing invasive plants (Hobbs and Humphries 1995; Jenkins 2002).

Prevention is increasingly an essential component of a successful invasive plant management program aimed at protecting areas that are relatively weed-free (DiTomaso 2000; Sheley et al. 1996). A proactive approach focused on systematic prevention and early intervention would be more cost-effective and successful than the more common reactive approach (Peterson and Vieglasis 2001; Simberloff 2003; Zavaleta 2000). The major components of invasive plant prevention include reducing introductions of the invasive plant to uninfested areas (often through dispersal vector management) (Davies and Sheley 2007), early detection and eradication of satellite patches found away from the main infestation, and increasing the biotic resistance of desirable plant and soil communities to invasion (Davies and Johnson 2011; Sheley et al. 1999).

Prevention programs are often assumed to be the most cost-effective method for managing invasive plants, but there is very little information about biological and/or economic factors that determine the benefits resulting from prevention programs. Finnoff et al. (2007) reported that managers associate more uncertainty with prevention programs. Managers

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were unsure if their dollars spent for prevention were actually effective and tended to limit the use of prevention programs for this reason. If it could be demonstrated that by implementing a prevention program resources are saved in the long term, managers may be more willing to adopt such programs. It is difficult for a manager to justify the cost of a prevention program without an understanding of potential long term benefits.

In order for managers to better understand the impacts of prevention programs, we developed a forage-based model for managers to begin to understand the potential benefits based on several important factors. Our goal was to provide land managers and livestock producers a tool they can parameterize with their own data to make some assessments about the potential value of their prevention program. It was developed to help determine the potential loss to forage production and thus lost income caused by invasive plants. Although invasive plants influence rangeland value by affecting its ability to provide many goods and services, forage for livestock is a critical benefit for livestock production and the economic sustainability of ranches throughout the western United States. The model incorporates the percent of an area currently infested, estimated spread rate, reduction of spread rate resulting from prevention program, utilization potential of invading plants by livestock, economic value in animal unit months (AUMs), time value of money, and time to estimate the savings value (AUMs in this example) from invasive plant prevention. The model compares the savings in AUMs from a spread rate with and without a prevention program and allows users to vary the parameters to fit their situation. In this manuscript, we describe the model, explore the relative influence of various factors used in the model on savings, and discuss the implications of the results for prevention programs that are based on protecting forage production.

Model Description

This model allows the user to choose the current infestation level, weed invasion rates (with and without prevention program), the degree livestock consume the invasive plants, the value of an AUM, an interest rate for the future value of money, and the time over which the prevention program would be effective. The model uses these components to determine an estimate of savings in dollars per AUM as a result of implementing a prevention program. The standard unit of measure (AUM) is the amount of forage required by one mature cow for one month, typically 362 to 453 kg of air-dried forage. Livestock producers purchase land and determine stocking rates based upon AUM production. Therefore, understanding prevention in terms of savings per AUM allows a quantifiable mechanism to assess the potential value of prevention programs. The primary component in the model is a prediction of invasive populations with and without a prevention program using a logistic growth function (Higgins and Richardson 1996). Hengeveld (1989) suggested that this simple demographic function may be adequate for forecasting when the growth rate is known or the rate of invasion is primarily determined by the population's reproductive rate. The basis of this model is a logistic function that comprises the law of population growth. This law is defined by the following equation:

$$P(t) = K \cdot P_0 \cdot e^{Rt} / \left[K + P_0\left(e^{Rt} - 1\right)\right] \qquad [1]$$

where $P(t)$ is the population (P) at time (t) is a function of the carrying capacity of the system (K). In this equation, P_0 is the percentage of land infested by an invasive species at time zero, e is the exponential function and R is the rate at which the population is increasing based on an annual percentage increase, such as 12.5%. In our use of the equation K, P_0 and R are all set by the user. The carrying capacity is defined as the maximum abundance of plants the environment can sustain. In this model, carrying capacity (K) is set to 100 and used as a percent, similar to that of Jayasuriya et al. (2011). When the carrying capacity (K) is set to 100 the equation calculates the percentage infestation at any time, which is subtracted from 100 to calculate the percentage of uninfested area.

Livestock generally consume a portion of invasive weeds and utilization levels are widely variable depending upon plant species and class of livestock (Launchbaugh and Walker 2006). Our model allows the user to set the percent of the invasive plant(s) utilized (u), which is then multiplied by infested area to estimate the total percent of an AUM that includes invasive plants. The total percent of an AUM consisting of invasive plants is added to the total percent of an AUM consisting of desired plants. This provides the percentage of the original AUM that remains present at time (t). In order to convert AUMs remaining to dollars, the time value of money formula must be considered, which is:

$$PV = FV / [(1+i)^n] \qquad [2]$$

where PV is the present value, FV is the future value, i is the interest rate and n is the number of periods

(Hovey 2005). However, we used a derivative of this formula for the present value of an annuity to allow incorporation of the price of an AUM. The present value of an annuity with fixed payments is

$$PV(A) = A/i \cdot \{1 - 1/[(1+i)^n]\} \qquad [3]$$

This formula is used to calculate the present value of purchasing a single AUM at a price and time in number of years (n) set by the user. In this equation, A is the price of the AUM. This provides an estimate of the value of the AUM without prevention over time. To calculate the additional value of the AUM added in a given year as a result of implementing prevention practices, $PV(A)$ at period n–1 is subtracted from $PV(A)$ at period n. The additional value of the AUM is multiplied by the percentage of the original AUM that remains present at time (t) to determine the additional value of the remaining AUM portion after invasion. This additional value is added to the sum of prior additional AUM values to calculate the total value. To calculate the lost value of AUMs because of invasion, the value of an AUM after infestation is subtracted from the original value of the AUM. The results of running this equation provide the loss at time (t) for a given invasive plant spread rate.

One goal of prevention programs is to slow the spread rate of invasive species. The basis for this model relies on comparing the AUM value lost over 100 yr without a prevention program with the AUM value lost when invasion is slowed or prevented by management. This difference is described as "savings per AUM." The carrying capacity can be input as any unit, but was defined as 100 in the pre-prevention portion of the model. In order to calculate the savings per AUM as a result of a prevention program, the entire process is recalculated at a reduced spread rate determined by the effectiveness of the prevention efforts. The final calculation of "savings per AUM" is obtained by subtracting the loss per AUM based on the reduced spread rate from the loss calculated at the natural spread rate.

Assumptions. We set several parameters to create a base model. For the base model, it was assumed the initial invasive plant infestation was equivalent to 5% of the entire carrying capacity, the annual spread rate was assumed to be 12.5%, interest rate was set at 4%, and the livestock utilization rate of the invasive plants was 40%. We assessed the value of an AUM at \$20. The evaluation of each model parameter's effect on saving was conducted by comparing their changes to that of the base model. All of these parameters can be re-set by the user. One biological assumption in the model is the capability of a site to produce a maximum amount of biomass and this maximum amount can be attained by either invasive weeds or desired species. In this case, the removal of portions of one group results in a corresponding increase in the other group, suggesting 100% niche overlap (Carpinelli et al. 2004; Sheley et al. 2009).

Assessing model parameters. To assess the model parameters, we used numbers that represent the range of real values based upon the literature and actual prevention programs (Goodwin et al. 2012, Launchbaugh and Walker 2006, Sheley and Petroff 1999). To assess the value of prevention, the spread rate was reduced from 12.5% (base model) to 10, 7.55, and 2.5%. These reductions in spread rate represent increasing degrees of effectiveness of a prevention program. For all other parameters, the spread rate of the post-management portion of the model was set at 5%. The effect of the price of an AUM on savings per AUM was assessed at prices of \$10, \$20, and \$30. The effect of invasive plant population size (P_0) on savings was evaluated at 5, 3, and 1% of the entire plant community on the day the prevention program was implemented. This relates to a prevention program that aggressively controls existing infestations to keep them from spreading to nearby areas. Since livestock consume invasive plants, the effect of their utilization level on savings as a result of prevention was evaluated at 20, 40, and 60% use. We also tested for an interaction by simultaneously reducing the spread rate and the invasive plant population below that of the base models (i.e. spread rate = 2.5%; initial population = 3%).

Results and Discussion

Base model. In our base model where a prevention program reduces the spread rate from 12.5% to 5% indicates there is minimal savings during the first decade of implementation (Figure 1a). After 50 yr, the prevention program saved about \$60 per AUM. This means for each area producing one AUM, a manager can spend \$60 throughout the time period of 50 yr or \$75 today to achieve a 7.5% reduction in invasive plant spread over the following 100 yr to breakeven. If the costs of prevention are distributed across the years, the amount a manager can afford to spend and still breakeven also increases.

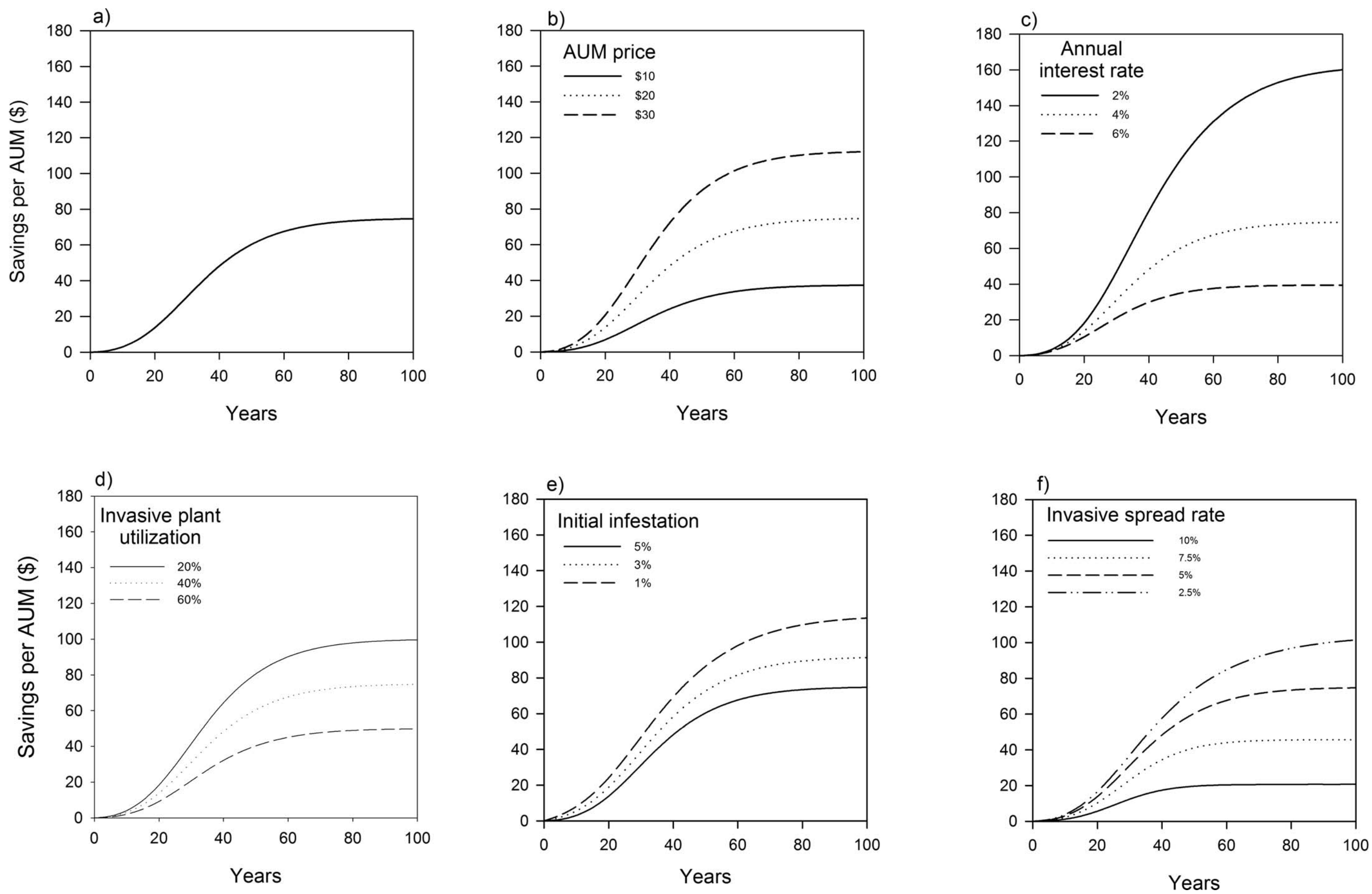

Figure 1. (a) Saving in AUM's using the base model to which other scenarios are compared. Base model assumptions were: initial infestation was 5% of the entire carrying capacity, an invasive plant spread rate of 12.5%, and the amount of weedy plants livestock would consume was 40%. The interest rate was set at 4% and the price of an AUM was set at $20. (b–f) Models showing the influence of altering the AUM price, interest rate, invasive plant utilization levels, invasive plant population size and invasive plant spread rate from that used in the base model, respectively.

Economic parameters. *AUM price*. The price of an AUM is predictably related to the savings rate and total savings based on this model (Figure 1b). As the price of an AUM increases, the time to breakeven is shortened. When the model was run with different AUM prices of $10, $20, and $30, the total savings over 100 yr were about $38, $75, and $112 per AUM, respectively. For each dollar increase in AUM price, the total savings per AUM increased by about $3.80 after 100 yr of prevention.

Interest rate. The savings per AUM was highly dependent upon the interest rate associated with the present value of money (Figure 1c). The present value of money is the current worth of a future sum of money; therefore if the interest rates for money remain low, applying money to prevent infestations of invasive weeds now will yield the most savings over 100 yr. The lowest interest rate (2%) yielded the most rapid savings rate and the highest total savings over 100 yr. At this interest rate, the total savings at year 100 was about $160 per AUM, whereas the total savings at 6% interest rate was only $39 at that time. At 6%, the savings rate nears an asymptote at 45 yr.

Biological parameters. *Utilization level*. Invasive plants vary in their palatability and livestock have preferences for certain invasive weeds depending on animal type (Heitschmidt and Stuth 1991). In addition, invasive plant nutritive value varies with plant phenology, which influences their use by livestock (Olson and Wallender 2001). We found an inverse relationship between the invasive plant utilization level and savings per AUM under a prevention program (Figure 1d). In this model, 20% utilization resulted in the most rapid savings rate and yielded a total savings of about $100 per AUM. If livestock consumed 60% of the invasive plants, the total savings was only about $50 per AUM after 100 yr of prevention that reduced the spread rate by 5%. The more the invasive plants are consumed by livestock, the less a prevention program saves because the potential losses are lower.

Initial invasive plant population. Prevention programs are more effective if they focus on controlling "satellite" infestations while they are small (Moody and Mack 1988). Ecologically, it is reasonable that at the onset of a prevention program reducing the infestation size will provide the best chance of delaying spread. Consequently, the total value of savings in AUM was higher where the initial percent infestation level was smaller (Figure 1e). If the initial infestation was reduced on the first day of the prevention program to 3% rather than 5% of the entire area, the total savings per AUM increased by about $17 after 100 yr of prevention. If the initial infestation was reduced to 1%, the total savings per AUM was about $113 assuming a spread rate of 5% per year. Thus, it is both ecologically and economically valuable to implement a prevention program early in the invasion process and to lower the size of the area invaded early in the program.

Spread rate. A comprehensive invasive plant prevention program has many aspects, ranging from minimizing dispersal through vector management to controlling "satellite" populations, but the primary focus is to reduce their rate of spread (Davies and Sheley 2007). Estimates for spread rates for major invasive plants tend to range from 8 to 24% depending on species and environmental conditions, with an average of about 12.5% (Duncan and Clark 2005). In our assessment, there was a nearly linear relationship between the reduction in spread rate and the total value saved per AUM (Figure 1f). If the spread rate was reduced from 12.5 to 10, 7.5, 5, or 2.5%, the total savings per AUM was $21, $46, $75, or $101, respectively. This equates to a savings per AUM of about $ 9.20 for each percent reduction in spread rate over 100 yr as a result of implementing a prevention program. Thus, lowering the spread rate slows the rate of AUM loss and increases savings.

Interaction of initial population size and spread rate. One important question is if reducing the initial population size and reducing the spread rate simultaneously interacts to reduce losses associated with invasion more than either alone? A small initial population size and a slow spread rate yielded more savings per AUM than a larger and more rapidly spreading population. The total savings per AUM increased from $75 to $91 by reducing the initial population to 3% and a total savings per AUM increased from $75 to $100 by reducing the spread rate from 5 to 2.5%. Simultaneously reducing the spread rate and the initial infestation increased the savings per AUM to $112. Although the total savings was greater than reducing either factor alone, it was $4 per AUM less than the savings of their added effects relative to the base model. Reducing the initial population size combined with reducing the spread rate does not provide a synergistic improvement in savings per AUM. In fact, addressing these two factors simultaneously may be slightly antagonistic on savings. This negative interaction occurs because reducing one factor lowers the overall invasion potential. A lower invasion potential reduces the potential loss, which in turn lowers the total savings per AUM of the second factor.

Prevention programs can potentially save enough forage (AUMs) to justify their implementation. In our example model, land managers can spend about $0.75 per AUM in today's dollars each year to reduce the spread rate from 12.5 to 5% if the program is implemented for 100 yr. Expenditures less than $0.75 per AUM in today's dollars each year, represents actual savings. Because this suggests that less than $0.01 can be spent per AUM per year in order to breakeven, the amount that can be spent on prevention is extremely limited based solely on forage production.

Multiple economic and biologic factors determine the efficacy of invasive plant prevention programs and the ultimate amount of savings associated with protecting forage for livestock. Economically, as the AUM price increases and the interest rate decreases, the total savings per AUM increases. Biologically, the less livestock consume of the invasive plants, the more the potential loss, which results in greater potential savings. Our example model also shows that savings per AUM increases as size of initial infestation decreases, suggesting early detection and/or rapidly controlling new infestations is central to saving forage. Using our inputs, the savings per AUM was about $9.20 for each percent reduction in spread rate over 100 yr. Reducing the initial size of the infestation and the spread rate will likely provide the highest savings in AUMs. This model provides a relatively simple estimate in savings as a result of initiating a prevention program to keep invasive plants from spreading. Estimating losses from invasive plants is a complex issue and the model does not include a number of factors that may exist in real situations. However, the model is designed to be conservative in potential savings and is a tool that managers can use to help better understand impacts of implementing a prevention program.

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