Staff Papers Series

Staff Paper P90-71 November 1990

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A Bioeconomic Model of Weed Management in Corn

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Staff papers are published without formal review within the Department of Agricultural and Applied Economics.

Abstract

WEEDSIM is a bioeconomic simulation model that supports weed control decisions in corn. Weed control treatments are evaluated based upon the expected net present value of crop yield that is protected from loss in the current year and the following one. The control decision affects both current season crop yield and the state of the dynamic seed bank for each weed species. Germination equations link the seed bank to expected weed densities, which in turn reduce crop yield and the associated net revenue. Currently under development are soybean rotations, whole-farm constraints on the number of days suitable for field work, and stochastic simulation of weather and available field working days.

The model improves upon previous weed management decision models by incorporating fuller information on weed population dynamics. As such, it offers a better tool for agricultural extension recommendations. Among its potential research uses are 1) estimation of the value to a farm manager of weed population information, 2) estimation of *ex ante* returns to agronomic research, and 3) analysis of the farm-level impact of public policies designed to restrict agricultural chemical use. An application illustrates the impact of atrazine usage restrictions.

WEEDSIM:

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Social Costs of Weeds and Chemical Weed Control

Weeds cause serious crop losses by competing for light, water, space and nutrients. A study by the Weed Science Society of America found the average annual value of U.S. crop losses due to weeds to be $7.5 billion during 1975-79 (Chandler et al.). Corn (*Zea mays* L.) and soybeans (*Glycine max* (L.) Merr.) account for over half of these losses.

Chemical herbicides are the preferred means of weed control in the United States. Most of the herbicides used in this country are applied to corn and soybeans. In 1988, herbicides were used on 96% of U.S. corn and soybean acreage, and accounted for 81% of all herbicides applied to U.S. crops that year (Osteen and Szmedra). A drawback of herbicide use is the potential health hazard posed by leaching into groundwater. A 1988 survey found atrazine, the leading herbicide used in corn, in 31% of Minnesota wells sampled (Klaseus et al.).

The threat to health has led policy makers to consider how consumers can be protected from groundwater contamination by herbicides without seriously compromising the incomes of American farmers. Several economic models have examined the effects of herbicide bans, taxes and marketable use permits (e.g., Giannessi, et al., Osteen and Kuchler). These have begun from the assumption that farmers use an amount of herbicide that maximizes profits. However, bioeconomic models by King et al., Taylor and Burt, and others suggest that farmers often do not consider the dynamics of weed populations in attempting to maximize profits. Instead, many overuse herbicides by applying them without regard to the weed density threshold at which weed control becomes economic.

Role of a Bioeconomic Model

By taking into account the yield-reducing consequences of future weed infestations caused by weeds allowed to reach maturity and set seed, dynamic bioeconomic models recommend that weeds be controlled at lower population densities than would be recommended in a one-season model. This implies heavier weed control in early periods than would be called for by a static model. However, heavy initial weed control reduces the stock of viable weed seeds in the soil, making weed control unnecessary in some subsequent periods. Hence, in addition to increasing long-run profits, herbicide use tends to be reduced relative to conventional practice, which favors prophylactic chemical weed control as a matter of course.

While existing bioeconomic models have reached important conclusions, they have focused on simple weed-crop systems, typically a single weed in a single crop with a single available weed control treatment (e.g., Auld et al., Cousens et al. 1986, Doyle et al., Murdoch, Pandey, Pannell). To become useful applied decision tools, such models must be extended to the range of weeds and weed control methods that farmers confront. In particular, a model designed to support farmer decisions must account for the fact that weeds grow in mixed populations which change in response to weed control treatments. Such a model must also recognize that many farmers want to avoid the risk that if weeds are not controlled at the earliest opportunity, rain may keep them from their fields until weeds have already begun to damage the crop.

Apart from serving as an applied decision aid, a bioeconomic weed management model can serve an important research purpose. It can offer weed scientists and economists a coherent framework for organizing and directing current and future research. Simulation experiments can highlight areas of agronomic research offering the highest economic returns. The need for such a framework is highlighted in a recently accepted proposal to the U.S. Department of Agriculture for a regional research project (Anonymous).

Structure of WEEDSIM

WEEDSIM is a dynamic, multispecies bioeconomic model for weed management in corn. It is structured for use in any decision setting where data on the necessary technical parameters are available. Initially, it is being oriented toward conditions in Minnesota. The model is still under development. The current version does not yet incorporate planned whole-farm constraints on physical resources and field time. While it has been verified, the model has not yet been validated.

The model incorporates a set of biological systems modules into an economic decision-making framework. The objective function in the current version of WEEDSIM is the maximization of the present value of expected net revenue over a given planning horizon. The general structure of the model is illustrated in the flow chart in Figure 1.

The biological part of the model is driven by four kinds of functions. These simulate: 1) weeds germinating from the soil seed bank, 2) weeds killed by control treatments, 3) crop losses resulting from competition with surviving weeds, and 4) seed bank dynamics resulting from seed loss (due to germination and seed death) and seed rain by weeds that reach maturity. Functional forms have been chosen based upon theoretical consistency, statistical "fit" and availability of the necessary data. Coefficients for the germination, seed bank and yield loss functions have been estimated statistically from agronomic research data. The weed control efficacy step function is based on efficacy ratings in Gunsolus et al.

In order to distinguish weeds by species, control treatment, time of season, and year, the following notation is adopted: **S** refers to weed seed density per square meter, **W** to weed density per square meter, $\mathbf{W}^e$ to density of weed seedlings emerged from the soil, $\mathbf{W}^h$ to weed density at crop harvest, **Y** to crop yield, and $\mathbf{Y}_{wf}$ weed-free crop yield. The numeric subscripts **0**, **1** and **2** signify the period of the crop season, with **0** prior to crop planting, **1** between crop planting and POST-emergent weed control, and **2** just prior to crop harvest. Additional subscripts associated with these variables are **i**, weed species, **j**, weed control treatment, and **t**, year.

The model is driven by the economic cost of crop yield loss due to weed competition. The rectangular hyperbolic functional form proposed by Cousens is used to model crop yield response to weed pressure. This is given in equation (1), where the coefficient $\mathbf{I}_i \epsilon [0,100]$ is the percent yield loss due to weed species **i** as density approaches zero, and $\mathbf{A} \epsilon [0,100]$ is the maximum percentage yield loss possible as weed density approaches infinity.

$$Y_j = Y_{wf}\left\{1 - \frac{\sum_i I_i W_{ij}}{100\,(1 + \sum_i I_i W_{ij}/A)}\right\} \qquad \textbf{(1)}$$

The principle behind this form is that the marginal crop yield loss diminishes as weed density increases. This can be seen by differentiating equation (1) with respect to the density of any given weed species **n** under treatment **j**. Equation (2) presents the result, in simplified form:

$$\frac{\partial Y_j}{\partial W_{nj}} = I_n \left[\frac{-Y_{wf} A^2}{100\,(A + \sum_i I_i W_{ij})^2} \right] \tag{2}$$

Since $\mathbf{Y_{wf}}$ and $\mathbf{W_{ij}}$ are non-negative, yield declines monotonically with increases in weed density.

Three simple, linear equations track weed density during a given crop season. In each, the coefficient α_i denotes the proportion of weed seedlings of species **i** germinating, and the coefficient κ_{ij} denotes the proportion of weeds of species **i** killed by weed treatment **j**. Equation (3) describes the weed seed bank after crop planting, which has been reduced by the proportion α_{0i} of seeds which germinated before crop planting. These weed seedlings are assumed to be killed by the planting operation.

$$S_{1it-1} = (1 - \alpha_{0i})\, S_{0it-1} \tag{3}$$

Equation (4) describes weed density at crop planting. Since pre-emergent herbicides kill a proportion κ_{1ij} of germinating weed seedlings before they emerge from the soil, $\mathbf{W^e}_{ij}$ gives the number of weed seedlings surviving any pre-emergent weed control.

$$W_{ijt}^{e} = (1-\kappa_{1ij})\,\alpha_{1i}S_{1it-1} \tag{4}$$

Weed density at crop harvest is given by equation (5) as the sum of those emerged weeds that survived any post-emergent weed control **($1-\kappa_{2ij}$)** and late-germinating weed seedlings.

$$W_{ijt}^{h} = (1-\kappa_{2ij})\,W_{ijt}^{e} + \alpha_{2i}S_{2ijt-1} \tag{5}$$

The soil weed seed bank is the state variable that relates crop yield and weed density in one season to control decisions in the previous season. In equation (6), the weed seed bank for species **i** in period **t** is given as that proportion of the weed seeds from year **t-1** that failed to germinate (α) or die (β) during the three sub-periods of year **t** plus the product of new weed seeds (γ) shed per plant and the number of weeds at harvest in year **t**.

$$S_{it} = (1-\sum_{s=0}^{2}\alpha_{si}-\beta_{i})\,S_{it-1} + \gamma_{i}W_{ijt}^{h} \tag{6}$$

The weed control decision rule in period **t** is to pick the combination of pre-emergent (PRE) and post-emergent (POST) weed treatments, $\mathbf{h}_{jt}$, that maximizes the present value of expected net revenue ($\mathbf{E[R_t]}$) over the current as well as the next season, as shown in equation (7):

$$\max_{h_{jt}} \left\{ E[R_t] + \frac{E[R_{t+1}]}{(1+r)} \right\} \tag{7}$$

subject to :

$$p\left(\Delta Y_{jt} + \frac{\Delta Y_{j't+1}}{(1+r)}\right) \geq c_j h_{jt} + \frac{c_{j'} h_{j't+1}}{(1+r)} \tag{8}$$

where equation (8) states the weed control threshold constraint that the value of additional yield obtained by weed control must exceed the accompanying cost. In equations (7) and (8), **r** denotes the discount rate, and **j'** denotes treatment chosen in year t+1. The expected yield increment is defined as

$$\Delta Y_{jt} \equiv E[Y_{jt}] - E[Y_{0t}] \tag{9}$$

where $\mathbf{Y_{0t}}$ denotes yield in the absence of weed control. Finally, expected revenue is defined as

$$E[R_t] = pE[Y_t] - c_j h_{jt} - C_{0t} \tag{10}$$

Crop price (**p**) and the cost ($\mathbf{c_j}$) of weed control treatment $\mathbf{h_{jt}}$ are assumed constant, while other variable and allocated fixed costs, $\mathbf{C_{0t}}$, may vary.

This decision rule leads to lower weed densities and higher expected net revenue than one based on yields in the current year alone. Only in the final year of a simulation can this fail to be the case, since the next year is of no consequence. Hence, the model switches to a myopic, one-year decision rule for the final year. The decision rule is an optimal control over a two-year time horizon.

In principle, of course, it would be desirable to have an optimal control for the entire planning horizon, in the manner of the single-weed models of Pandey, and Taylor and Burt. However, dimensionality becomes a problem for multiple weed species, since the seed bank state variable of each must be tracked, and these are not easily made discrete while preserving the biological character of their growth. The decision rule proposed here is a compromise, using more information than a strictly myopic single-year rule, but less than a true optimal control.

An Application: Impact of Restrictions on Atrazine

An application of the model illustrates the economic impact of three scenarios governing atrazine use: 1) the current limit of 3 lbs/acre annually (the U.S. Environmental Protection Agency label restriction for 1990), 2) a return to no limitations, and 3) a total ban on atrazine use. This application covers continuous corn production in the presence of mixed green and yellow foxtails (*Setaria* spp.), common lambsquarters (*Chenopodium album* L.), and redroot pigweed (*Amaranthus retroflexus* L.).

Most of the parameters, given in Table 1, were estimated from agronomic data on field trials carried out in Morris, Minnesota, during 1985-86 (Forcella, Forcella and

Lindstrom). The yield loss parameters are much smaller than those estimated with other data from Minnesota and Wisconsin. Weed seed mortality in the seed bank (β) was assumed to be 25% annually for each species. Weed treatment options included for PRE- and POST-emergent control, along with associated costs, are given in Table 2. Weed control efficacy ratings were obtained from Gunsolus et al. Other parameters were set as follows: $\mathbf{p}$ = \$2.50, $\mathbf{Y_{wf}}$ = 160 bu/acre, $\mathbf{C_{0t}}$ = \$150, $\mathbf{r}$ = 4%, $\mathbf{A}$ = 90%.

The model was run for each of 11 initial seed bank densities. These were set equal for the three weed species at 100-seed intervals from 0 to 1000 seeds per square meter. The simulation period was five years. The results indicate that over a five-year period a total ban on atrazine could reduce the present value of net revenue per acre[1] by 3.2% relative to the no restrictions case. This is the case when the initial seed bank is high, at 1000 seeds/m^2, causing a difference of \$7.97 in the annualized present value of net revenue, as shown in Figure 2. The same initial seed bank causes a reduction of \$5.27 or 2.3% in present value of net revenue per acre due to the 3 lbs/acre restriction on atrazine use. Even at low initial seed bank levels, the total ban imposes significant costs relative to the unrestricted case, beginning at \$6.58 per acre when the seed

[1] Defined as returns to operator labor, management and land.

bank is as low as 100 seeds/m^2. The moderate restriction of 3 lbs/acre begins to reduce net revenue noticeably only after the initial seed bank reaches 200 seeds/m^2.

Atrazine is both less costly and more effective against a broad spectrum of weed species than the other weed control treatments in the model. Table 3 shows that when no restrictions are placed on atrazine use, it is the only herbicide recommended. Under the current 3 lbs/acre limitation, which effectively forces a choice between pre- and post-emergent atrazine use, continuous atrazine remains the recommendation for post-emergent weed control. The effect of the restriction is to reduce pre-emergent herbicide use (accepting the concomitant corn yield losses), and to switch herbicides from atrazine to dicamba and cyanazine. Under a total ban on atrazine, WEEDSIM recommends 2,4-D for post-emergent broadleaf weed control, with cyanazine for pre-emergent grass weed control.

Restricting atrazine use has a twofold economic impact: First, treatment costs are higher. Second, the value of crop yield losses due to weed competition is greater in almost all cases, as shown in figures 3, 4 and 5. This is because the higher treatment cost of an atrazine substitute delivering the same weed control efficacy implies a higher threshold for weed control (equation 8). Hence, more crop yield is lost to weed competition. Indeed, the value of yield losses is probably underestimated due to the low yield loss parameters used.

Because not all the model parameters have been validated yet, these results should be interpreted with caution. This illustration simply serves to show that the popularity of atrazine has an economic basis. If atrazine use is restricted, the social benefits realized by reducing groundwater contamination will be obtained at the expense of increasing producers' costs while lowering their crop yields.

Future Developments Planned

Three further developments are underway. The first involves moving the model from its present per-acre basis to a whole-farm basis. When the entire farm is the decision unit, timeliness of operations becomes crucial. Timeliness depends upon the suitability of weather conditions for field access by agricultural machinery. From a modeling standpoint, this entails changing from three time steps per season to a weekly, or even daily, time step. It also requires introducing land, labor, and equipment endowments. Delays in crop planting will be associated with a penalty in the attainable weed-free crop yield. The feasible timing window of opportunity for post-emergence weed control will also be limited according to crop and weed development. The expected result is a switch away from post-weed emergence to pre-weed emergence control methods.

The second planned development is to incorporate a soybean crop rotation with the corn in the model. Agronomic research suggests that rotation of a broadleaf crop with a grass crop substantially reduces weed population densities (Forcella and Lindstrom).

The third development involves making the model stochastic. Weather is a crucial exogenous factor influencing weed treatment efficacy, field time availability, weed-free yield, weed emergence, and seed bank evolution. By modeling these as correlated random variables, and running the model in Monte Carlo fashion, it will be possible to simulate probability distributions of outcomes. This, in turn, makes it possible to evaluate the role of risk in weed management.

Uses of the Model

In its final form, different versions of WEEDSIM can be used for extension and for research purposes. An extension version will be designed exclusively for current year weed treatment recommendations (using the two-year decision rule). While an economic recommendations model would undoubtedly be preferable to existing herbicide selection models based on efficacy alone (e.g., Kidder et al.), a key requirement of WEEDSIM is knowledge of weed seed numbers in the soil or numbers of weeds emerged, by species.

A research version of the model, capable of running stochastic simulation experiments, will be used to evaluate the value of the extension model by 1) evaluating weed control strategies by farmers using different levels of information about the weed population, and 2) estimating the value to the farm manager of gathering (or buying) weed population information. The research model will further be used to evaluate alternative weed control decision rules, as well as to analyze the farm-level impacts of alternative public policies restricting herbicide use (such as the atrazine limitations illustrated above).

A final, particularly important use of the research model will be to identify high-payoff areas of agronomic research by running sensitivity analyses on different coefficients and equations in the model. Many of the values presented as coefficients in this paper can be thought of as the outcomes of complex biological functions. As research advances, the model can provide an economic shell for such biological sub-models.

Table 1: WEEDSIM parameter estimates used.

Equation	Foxtail	Lambs-quarters	Redroot Pigweed
Yield loss (I_i)	0.1	0.1	0.2
Seeds/plant (γ_i)	26	87	80*
Emergence			
Pre-plant (α_{0i})	0.000	0.049	0.000
Crop planting (α_{1i})	0.071	0.034	0.063*
Post-treatment (α_{2i})	0.003*	0.002	0.000
Total emerged	0.074	0.081	0.063

Note: Numbers marked with an asterisk are synthetic values. All others were estimated statistically.

Table 2: Weed control treatments included and associated costs per acre.

PRE-emergence treatment	cost/Ac*	POST-emergence treatment	cost/Ac*
No control	$ 0.00	No control	$ 0.00
Alachlor 4E	18.25	Atrazine 4E & oil	6.23
Atrazine 4F	9.45	Bromoxynil 2E	9.05
Cyanazine 4F	16.56	Cyanazine 4F	11.11
Dicamba 4S	8.55	Dicamba 4S	8.55
Eradicane 6.7E	17.40	2,4-D Amine 4S	4.44

* Cost/acre includes active ingredient cost plus $3.00 for application.

Table 3: Treatments recommended under three levels of atrazine restriction as initial weed seedbank density increases (5-year simulations).

Initial seedbank	No ban PRE	No ban POST	3 lbs/acre PRE	3 lbs/acre POST	Total ban PRE	Total ban POST
0	NC(5)*	NC(5)	NC(5)	NC(5)	NC(5)	NC(5)
100	NC(5)	Atr(5)	NC(5)	Atr(5)	NC(2) Cya(2) Ala(1)	24D(4) NC(1)
200	NC(5)	Atr(5)	NC(5)	Atr(5)	Cya(2) Ala(1) Dic(1) NC(1)	24D(5)
300	NC(3) Atr(2)	Atr(5)	NC(5)	Atr(5)	Cya(4) NC(1)	24D(5)
400	Atr(3) NC(2)	Atr(5)	NC(4)	Atr(5)	Cya(4) NC(1)	24D(5)
500	Atr(3) NC(2)	Atr(5)	NC(3) Atr(1) Cya(1)	Atr(4) 24D(1)	Cya(4) NC(1)	24D(5)
600	Atr(4) NC(1)	Atr(5)	NC(3) Atr(1) Cya(1)	Atr(4) 24D(1)	Cya(4) Dic(1)	24D(4) NC(1)
700	Atr(4) NC(1)	Atr(5)	Dic(2) NC(2) Cya(1)	Atr(5)	Cya(5)	24D(5)
800	Atr(4) NC(1)	Atr(5)	Dic(2) Cya(2) NC(1)	Atr(5)	Cya(5)	24D(5)
900	Atr(4) NC(1)	Atr(5)	Dic(2) Cya(2) NC(1)	Atr(5)	Cya(5)	24D(5)
1000	Atr(4) NC(1)	Atr(5)	Dic(2) Cya(2) NC(1)	Atr(5)	Cya(5)	24D(5)

* Number of years recommended (out of 5) in parentheses.

Abbreviations: NC, No Control; Atr, Atrazine; Ala, Alachlor; Cya, Cyanazine; Dic, Dicamba; 24D, 2,4-D.

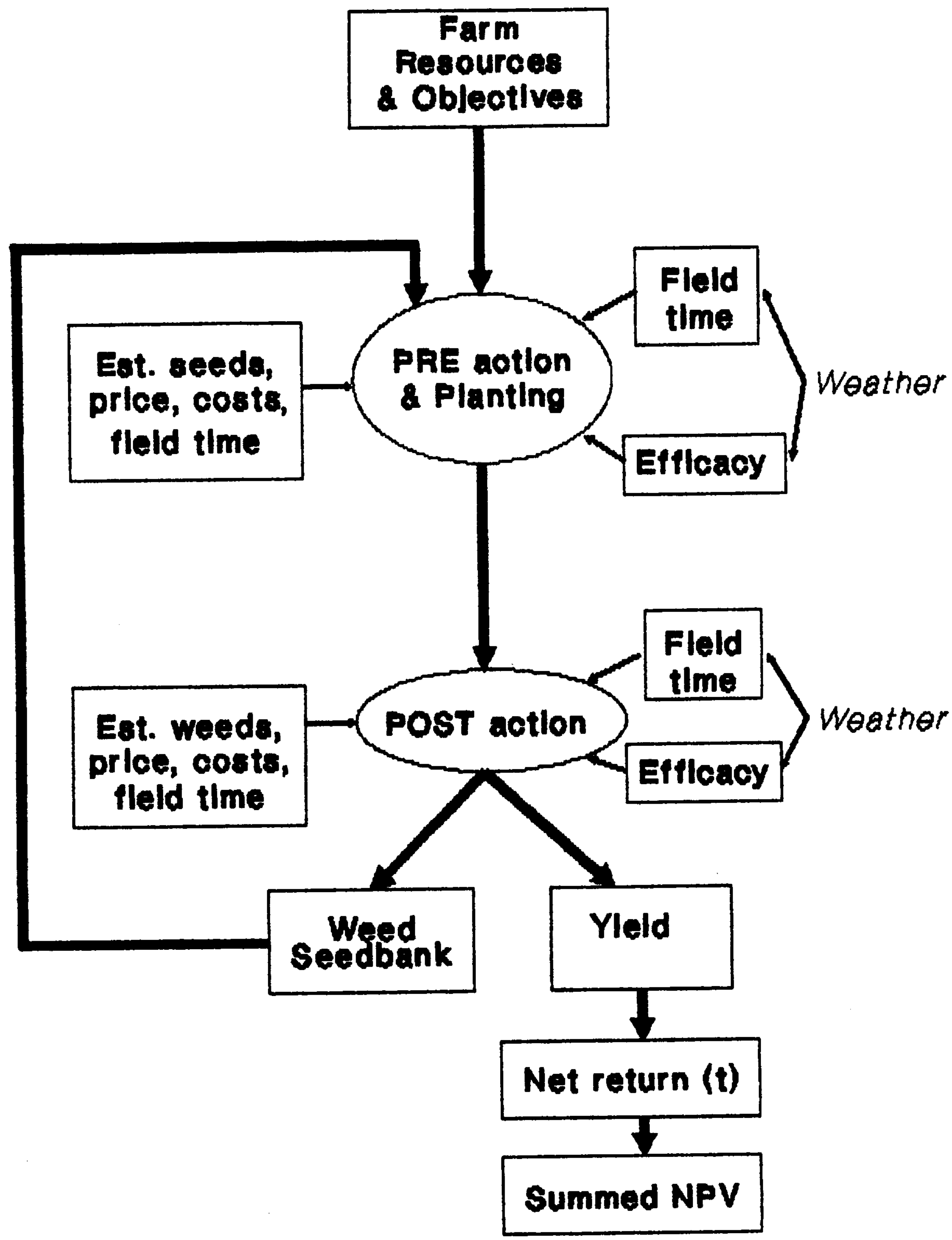

Fig. 1: Flow Chart of the Model.

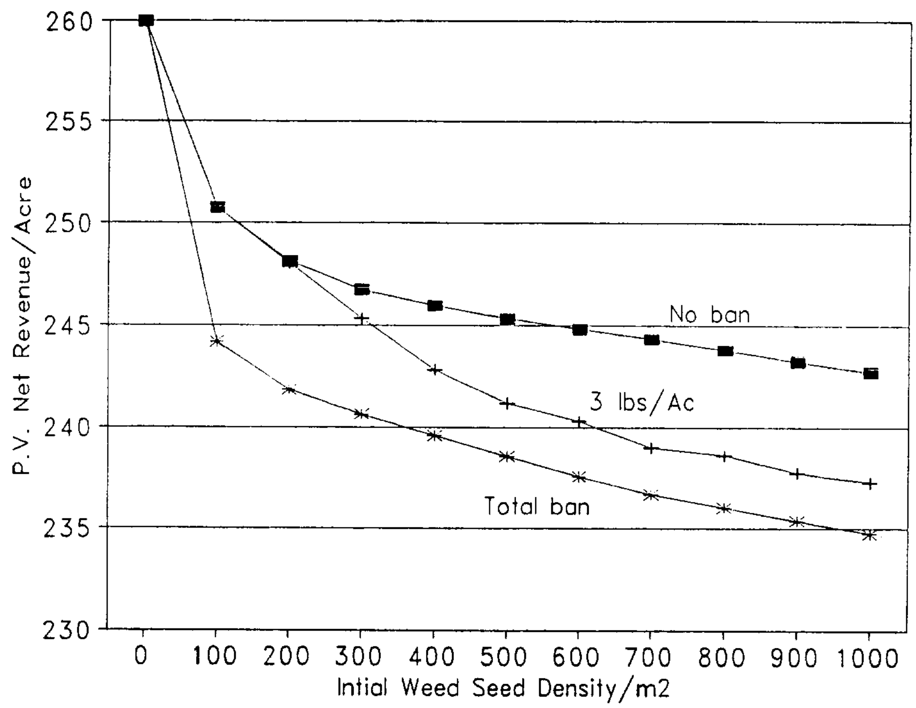

Figure 2: Annualized net revenue per acre under three levels of atrazine restriction (5-year simulations).

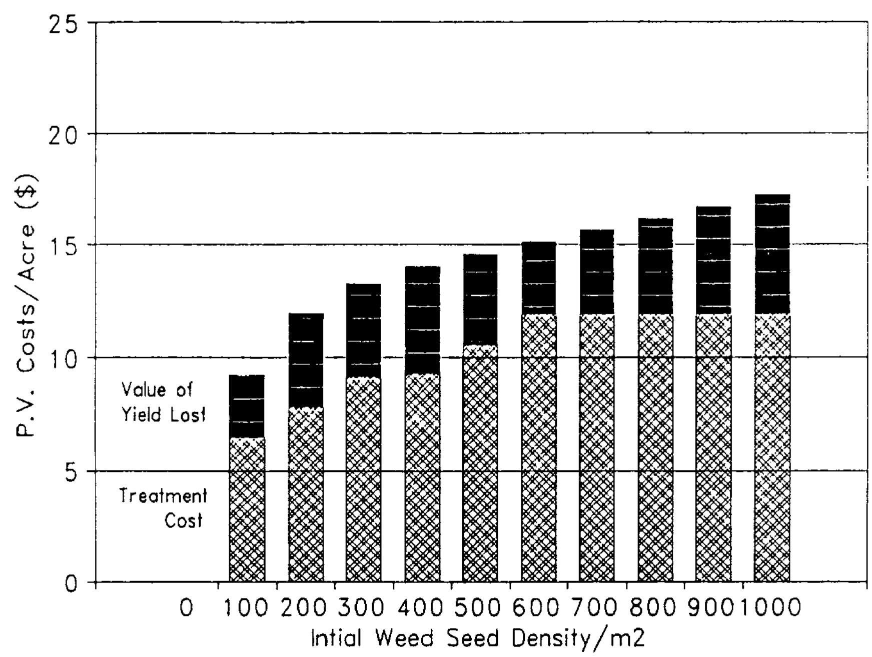

Figure 3: Annualized cost of recommended weed treatment with no atrazine restriction, by initial seedbank level.

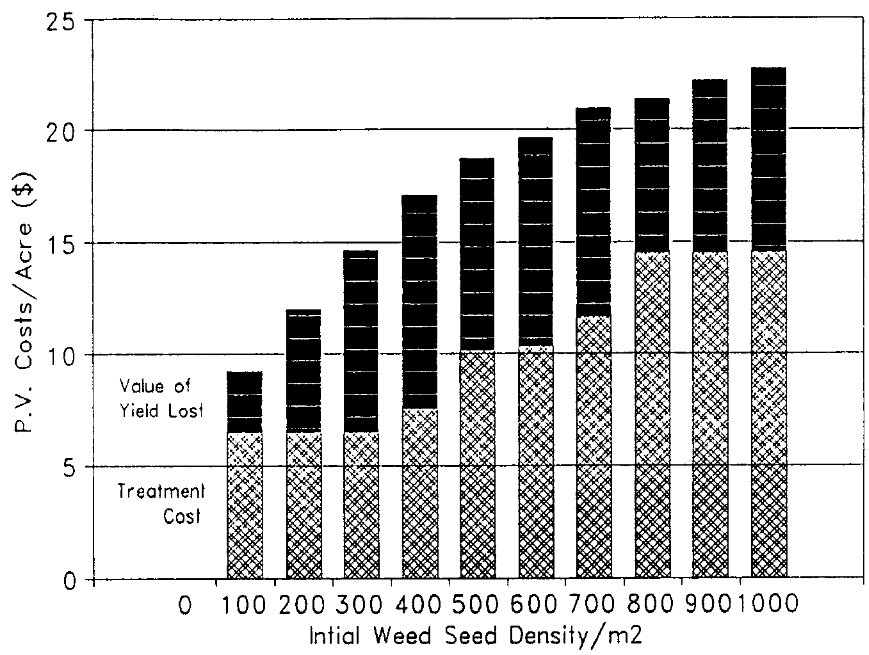

Figure 4: Annualized cost of recommended weed treatment under a 3 lbs/acre restriction on atrazine use, by initial seedbank level.

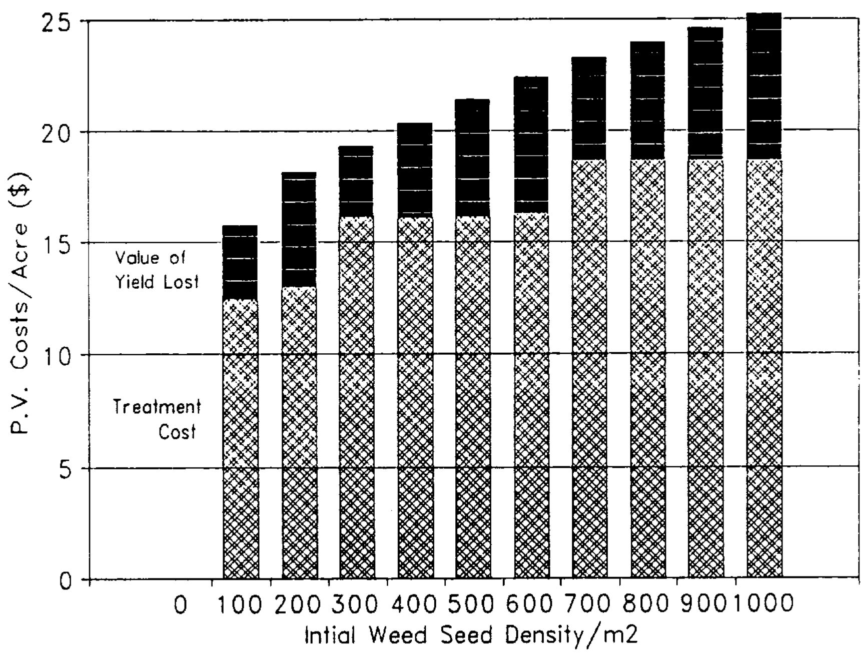

Figure 5: Annualized cost of recommended weed treatment under a total ban on atrazine use, by initial seedbank level.

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