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CAN INCREASING RETURNS OCCUR IN PEST MANAGEMENT?

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Abstract

This paper analyses the role of damage control inputs in production. Damage control inputs differ from conventional inputs in that they act indirectly or conditionally on output. Their productivity depends on the presence of a damage agent. Examples of damage control inputs include crime and fire protection, flood control and irrigation, disease prevention in people, plants and animals, and national defense. Agricultural economists, other agricultural researchers and foresters have also studied damage control inputs in pest management models. The indirect action of damage control inputs means that the marginal productivity of this class of inputs depends on their effectiveness in controlling the damage agent, the level of damage agent and the degree of production loss caused by a given level of damage agent. Our analysis shows that increasing returns to the damage control input, in terms of its effect on production, can occur even when the control and damage functions are concave.

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Introduction

Inputs which mitigate damage act conditionally or indirectly on output. If the factor which causes the damage is not present, then the application of the damage control input has no effect on the quality or quantity of production.[1] As Lichtenberg and Zilberman (1986), Babcock et al (1992), Carrasco-Tauber and Moffitt (1992) and Blackwell and Pagoulatos (1992) have argued, inputs which are used to prevent damage pose unique problems for model builders. Damage control inputs are used in a wide range of circumstances. Examples include investments in surveillance and crime protection in banks and stores, the use of pesticides in agriculture and forestry, fire prevention, disease prevention in people and animals, water and air purification systems and investments in irrigation and flood control infrastructure. Even national defense is an example of a damage control input.

Conventional inputs, X, are shown in Figure 1 as having a direct effect on the volume or quality of production. The marginal physical product of X depends on its direct relationship with output, Y, as summarized in the production function F(X). This type of direct effect is examined in detail in production economics texts. One of the hallmarks of the analysis is the requirement for eventually decreasing returns to ensure the existence of a finite optimal level of input use. Damage control inputs act through the mechanism illustrated in the lower portion of Figure 1. The damage control input, T, through the control function, C(T), reduces the incidence of the damage agent, Z. The level of Z, acting through the damage function, D(Z), influences production. The marginal physical product of T depends on the structure of both the damage and control functions.

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1 Some damage control inputs may even reduce output. For example a herbicide applied to a crop may have adverse effects on the crop itself.

Marginal productivity estimates for damage control inputs like pesticides at the aggregate (Headley) and at the farm level (Campbell) suggest that pesticides have been under applied. The Lichtenberg and Zilberman (LZ) model, which incorporates a damage abatement function and a potential yield function, explains part of the reason for these overuse findings. Blackwell and Pagoulatos include state variables omitted from the LZ specification through a process modeled production function. Their incorporation of natural abatement suggests that the marginal productivity of pesticides may be over estimated. Carrasco-Tauber and Moffitt have shown that aggregate pesticide productivity estimates depend on the functional form chosen for the damage function. Similarly, Cousens, Pannell and Swinton have shown that the functional specification of pesticide involvement in production influences the pest threshold at which pesticide is applied. The impact of alternative functional forms for the control or kill function has been examined in farm level threshold studies but has been ignored completely in aggregate studies of pesticide productivity. Generally, the damage and control functions have been implicitly collapsed into a single algebraic function. Interaction between the control and damage functions has not been studied systematically.

The purpose of this study is to explore the relationship between the damage and control functions and to indicate the possibility of increasing returns in the use of damage control inputs. Although a number of functional specifications for C(T) and D(Z) have been used in the literature, the available models impose a structure on the underlying biological and physical data that guarantees eventually decreasing returns. The analysis below shows that minor departures from the traditional models, even departures that maintain weak concavity in the control and damage functions, can lead to increasing returns in the damage control input, T, up to the point that the damage agent, Z, is eradicated. Under these circumstances, eradication can be a strategy which dominates over a wide range of price and cost conditions. Much of the empirical literature in this area has focused on pest management problems in agriculture and forestry. Our results offer a possible explanation of the high productivity estimates for pesticides which have been reported in this literature and raise concerns about the effectiveness of taxation schemes designed to reduce the use of pesticides.

Derivation of the Control and Damage Functions

The control function characterizes the proportion of the damage agent which is removed for a given level of treatment, T. That is

$$0 \leq C(T) = \frac{Z_0 - Z(T)}{Z_0} \leq 1 \qquad (1)$$

where Z_0 is the level of damage agent present in the absence of treatment and Z(T) is the level of damage agent at treatment level T. The Z(T) function, in general, could take on various shapes (see Figure 2). T could reduce Z at a constant rate, giving the linear function (a), it could act with decreasing marginal effect, (b), or with increasing marginal effect (c). Z(T) would cross the horizontal axis if eradication of the damage agent occurs. Inflection points in $Z(\cdot)$ are also possible. As a result, even if the marginal effect of the treatment on the damage agent is non-positive, $Z_T \leq 0$, Z_{TT} is of indeterminate sign, in general, and therefore

$$C_{TT} = - \frac{1}{Z_0} Z_{TT} \qquad (2)$$

is also of indeterminate sign.

Similarly, the damage function is defined as

$$0 \leq D(Z) = \frac{y_0 - y(Z)}{y_0} \leq 1 \qquad (3)$$

where y_0 is the level of production that would be forthcoming if no damage agent were present and y(Z) is the actual level of output obtained. Since y(Z) may exhibit various curvature properties even when $y_Z \leq 0$, the sign of y_{ZZ} and hence of D_{ZZ} is indeterminate.

The Structure of Damage Control Models

Given a control and damage function defined in terms of a proportionate loss, realized output, y, can be written as

$$y = y_0 \, (1 - D(Z)) \tag{4}$$

where

$$Z = Z_0 \, (1 - C(T)) \tag{5}$$

The total product curve is therefore

$$y = y_0 \, (1 - D \, (Z_0 - Z_0 \, C(T))) \, . \tag{6}$$

Actual yield depends on the pest free yield, initial pest density and the level of control agent along with parameters of the damage function and control function. Conventional inputs affect y_0 directly which in turn has a non-negative relationship with actual yield,

$$\frac{\partial y}{\partial y_0} = (1 - D(Z)) \geq 0 \, . \tag{7}$$

In contrast, actual yield will be lower with an increase in the initial pest population,

$$\frac{\partial y}{\partial Z_0} = -y_0 \, D_Z \, (1 - C(T)) \leq 0 \tag{8}$$

Both pest free yield and initial pest density act to shift the total product curves presented later in Figures 3 and 4.

The impact of the damage control input on actual yield is not as straight forward. The marginal physical product of T, the damage control input, is

$$y_T = y_0 \, Z_0 \, D_Z \, C_T \tag{9}$$

which by construction is non-negative. The marginal productivity of the damage control input thus depends on pest free yield, y_0, untreated pest density, Z_0, the marginal effect of pest level on yield, D_Z, and the marginal effect of the damage control input on the damage agent, C_T. The level of damage control input which maximizes profit equates $y_0 \, Z_0 \, D_Z \, C_T$ and the ratio of the price of the damage control input and the price of output. Whether this stationary value for T maximizes profits depends on the second derivative being non-positive. The sign of the second derivative,

$$y_{TT} = y_0 Z_0 \{D_Z C_{TT} - Z_0 D_{ZZ} C^2{}_T\} \qquad (10)$$

is indeterminate, even if C_{TT} and D_{ZZ} are negative. The slope and curvatures properties of the control and damage functions interact in ways that cannot, in general, guarantee a non-positive value. Even for the case of commonly assumed weakly concave damage and control functions, that is $C_{TT} \leq 0$ and $D_{ZZ} \leq 0$, if the slope of the control function (C_T) at high levels of control is large relative to the slope of the damage function, D_Z, at low levels of incidence of the damage agent, $D_Z C_{TT} - Z_0 D_{ZZ} C_T^2$ can be positive. Note that for a linear control function, $C_{TT} = 0$ and as long as $D_{ZZ} < 0$, then y_{TT} is positive, indicating increasing returns to damage control. The implications of this outcome are discussed below.

Functional Forms

Table 1 summarizes some of the properties of control and damage functions that have been studied by agricultural economists as well as the damage function popularized by Cousens and a square root function which we employ below. With the exception of the square root model, all of these functions are asymptotic. This means that eradication of the damage agent and complete loss of production cannot occur. Also, as high but not complete levels of control are achieved, that is as $x \rightarrow \infty$, $f'(x) \rightarrow 0$ and $f''(x) \rightarrow 0$. For a control function, this means that the first and second derivatives vanish as more and more damage control linput is applied. This will tend to make Y_T and Y_{TT} converge on zero, mitigating against increasing returns. When the functions in Table 1 are used as damage functions, their behaviour as $x \rightarrow 0$ is more important. As the table indicates, several of the functional forms in common use do not have first or second derivatives which disappear as $x \rightarrow 0$.

Two Examples

Exponential Functions

If both the damage and control functions are exponential so that

$$C(T) = 1 - e^{-cT} \tag{11}$$

and

$$D(Z) = 1 - e^{-dZ} \tag{12}$$

then

$$C_T = c\, e^{-cT} \geq 0$$

$$C_{TT} = -c^2 e^{-cT} \leq 0$$

$$D_Z = d\, e^{-dZ} \geq 0$$

$$D_{ZZ} = -d^2\, e^{-dZ} \leq 0$$

This situation is illustrated in Figure 3.

As T increases without limit and as Z approaches zero, C_T approaches zero from above, C_{TT} approaches zero from below, D_Z approaches d and D_{ZZ} approaches $-d^2$.

Under these circumstances, output is

$$y = y_0 e^{-dZ_0 e^{-cT}} \tag{13}$$

so that $y \to y_0$ as $T \to \infty$.

Recall that $Z(T) = Z_0(1 - C(T))$. The marginal product of T is

$$y_T = h'(T)\, y_0 e^{h(T)} = h'(T)\, y \tag{14}$$

where $h(T) = -d\, Z_0\, e^{-cT}$. It follows that

$$y_{TT} = y\{h''(T) + (h''(T))^2\} \tag{15}$$

so that the sign of $h''(T) + (h'(T))^2$ determines whether increasing returns to the use of T are present.

For $y_{TT} \leq 0$ to hold as $T \rightarrow \infty$, it must be true that

$$-h''(T) \geq (h\partial(T))^2$$

or

$$dc^2 Z_0 e^{-cT} \geq c^2 d^2 z^2{}_0 e^{-2cT}$$

Simplification gives

$$1 \geq Z_0 \, e^{-cT}$$

which clearly holds as $T \rightarrow \infty$. Therefore, by construction, a model of damage control which uses exponential damage and control functions imposes eventually diminishing marginal returns.

Eradication in the Control Function

An arguably small change in the structure of the model, however, can reverse this result even when $C_{TT} \leq 0$ and $D_{ZZ} \leq 0$. Suppose we retain the exponential damage function used in the previous example (12) but use the following control function,

$$C(T) = \begin{cases} c\sqrt{T} & \text{if } c\sqrt{T} \leq 1 \\ 1 & \text{if } c\sqrt{T} > 1 \end{cases} \qquad (16)$$

which is illustrated in Figure 4. The control function is quasi-concave but it allows for the possibility that complete control of the damage agent can be achieved for some finite application of the damage control input, T_e. An example of such a control function in agriculture is the control of weeds through herbicides.

This modification of the model gives a total product curve up to the point of pest eradication associated with application of T_e which can be written as

$$y = y_0 e^{-dZ_0 + dZ_0 c\sqrt{T}} = y_0 e^{g(T)} \qquad (17)$$

Therefore

$$y_T = g'(T)\, y \tag{18}$$

and

$$y_{TT} = y\, \{g''(T) + \{g'(T)\}^2\} \tag{19}$$

Because

$$g'(T) = \tfrac{1}{2}\, dcZ_0 T^{-\frac{1}{2}} > 0$$

and

$$g''(T) = -\tfrac{1}{4}\, dcZ_0 T^{-3/2} < 0$$

the sign of y_{TT} is determined by the relative magnitudes of $g'(T)$ and $g''(T)$. The result $y_{TT} \leq 0$ requires that

$$-g''(T) \geq \{g'(T)\}^2$$

As $T \rightarrow Te$

$$\tfrac{1}{4}\, dcZ_0 T^{-3/2} \geq \tfrac{1}{4}\, d^2c^2Z^2_0 T^{-1}$$

which simplifies to

$$T_e \leq \left(\frac{1}{dcZ_0}\right)^2$$

If this weak inequality does not hold, then increasing returns to T occur as $T \rightarrow Te$ as illustrated in Figure 5.

Note, that a damage function which allows for complete loss of production together with an exponential control function does not lead to increasing returns. If

$$d(Z) = \begin{cases} d\sqrt{Z} & \text{if } d\sqrt{Z} \leq 1 \\ 1 & \text{if } d\sqrt{Z} > 1 \end{cases}$$

and

$$C(T) = 1 - e^{-cT}$$

then

$$y_T = \frac{c}{2}\, y_0\, d\sqrt{Z_0}\, e^{\frac{-cT}{2}}$$

and

$$y_{TT} = -\frac{c}{2}^2 \; y_0 \, d\sqrt{Z_0} \, e^{\frac{-cT}{2}}$$

which approaches zero from below as $T \rightarrow \infty$

Under the scenario of increasing returns to the application of the damage control input as obtained with the assumption of eradication in the control of function, a profit maximizing firm (Figure 6) facing a fixed cost for damage control of V_0 and a variable cost of V_1 will opt for complete control. The response of optimal damage control to variations in prices and costs would be non-continuous. For example, a reduction in the price of output could initially have no effect on the level of the damage control input until some critical level is reached. Then control efforts jump to a lower level or even to zero. Proposals to influence use of pesticides through taxes could founder on this result. Depending on the structure of the underlying biological relationship embodied in the control and damage functions, a policy to reduce pesticide use by imposing a tax could have substantially different effects on the levels of use of different products.

Conclusions and Discussion

Functional forms that have been used in the pest control literature have invariably assumed that both the control and damage functions are asymptotic. This rules out the possibility of complete control or complete damage. Decision rules based on these models show a continuous response to variations in prices and costs and indicate that less than complete control is optimal. This result may be an artifact of the structure of the models that have been estimated and not an adequate reflection of the underlying biological relationships.

The possibility of increasing returns arising from the nature of the control function may vary across damage control problems. For example, complete control of a damage agent is more likely in weed control in field crops or disease control in confinement livestock production than in insect control in orchards, given the mobility of the damage agent. This suggests that researchers and model builders should exercise caution in using particular functional specifications in new circumstances.

Our results have important implications for experimental design and data interpretation in pest and disease management studies. A small variation in functional form, a variation which maintains quasi-concavity in the control function, can have a profound impact on the economic analysis. Pest control experiments often produce data points as in Figure 7. The ability of researchers to discriminate among classes of functional forms using these data is limited. Furthermore, it is the slope and curvature of the damage function at low levels of infestation and of the control function at high levels of T that matter. Experimental design should emphasize the slope and curvature of the damage function at low values of Z and the slope and curvature of the control function at high values of T in order to make efficient use of research inputs. The truncation of the control and damage functions also requires modification to standard regression techniques.

Several authors have suggested models to explain the apparently cautious pesticide use by farmers (see Robison and Barry, Ch. 8). These models are animated by risk aversion. Our results, which do not appeal to risk-based arguments, offer an alternative or supplementary explanation of the observed behaviour of farm firms. Damage control inputs have been largely ignored in the economics of production. The indirect action of these inputs creates a possibility of increasing returns which has not been acknowledged. The wide range of examples identified in the introduction suggests that the neglect of the mechanism of action of these types of inputs may have been a serious impediment to our understanding of a broad category of human behaviour.

References

Babcock, B.A., E. Lichtenberg and D. Zilberman. (1992) "Impact of Damage Control and Quality of Output: Estimating Pest Control Effectiveness." American Journal of Agricultural Economics 74:163-172.

Blackwell, M. and A. Pagoulatos (1992) "The Econometrics of Damage Control." American Journal of Agricultural Economics, 74(4):1040-1044.

Campbell, H.F. (1976) "Estimating the Marginal Productivity of Agricultural Pesticides: The Case of Tree Fruit Farms in the Okanagan Valley." Canadian Journal of Agricultural Economics. 24:23-30.

Carrasco-Tauber, C. and L.J. Moffitt. (1992) "Damage Control Econometrics: Functional Specification and Pesticide Productivity." American Journal of Agricultural Economics 74:158-162.

Cousens, R. (1985) "An Empirical Model Relating Crop Yield Loss to Weed and Crop Density and a Statistical Comparison with Other Models." Journal of Agricultural Science, 105:513-521.

Headley, J.C. (1968) "Estimating the Productivity of Agricultural Pesticides." American Journal of Agricultural Economics 50:13-23.

Lichtenberg, E. and D. Zilberman. (1986) "The Econometrics of Damage Control: Why Specification Matters." American Journal of Agricultural Economics 68:261-73.

Pannell, D.J. (1990) "Responses to Risk in Weed Control Decisions Under Expected Profit Maximization." Journal of Agricultural Economics, 41:391-404.

Robison, L. and P. Barry (1987). The Competitive Firm's Response to Risk. MacMillan, New York.

Swinton, S.M. (1991) "Responses to Risk in Weed Control Decisions Under Expected Profit Maximization: Comment." Journal of Agricultural Economics, 42:404-406.

Table 1: Alternative Control or Damage Functions

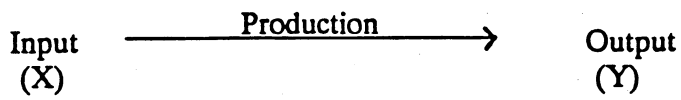
Function				$f'(x)$		$f''(x)$	
	$f(x)$	$f'(x)$	$f''(x)$	$x \to 0$	$x \to \infty$	$x \to 0$	$x \to \infty$
Pareto	$1-\left(\frac{K}{x}\right)^{\gamma}$	$\frac{\gamma}{K}\left(\frac{K}{x}\right)^{\gamma+1}$	$\frac{-\gamma(\gamma+1)}{K^2}\left(\frac{K}{x}\right)^{\gamma+2}$	$+\infty$	$0+$	$-\infty$	$0-$
Exponential	$1-e^{-\gamma x}$	$\gamma e^{-\gamma x}$	$-\gamma^2 e^{-\gamma x}$	γ	$0+$	$-\gamma^2$	$0-$
Logistic	$\frac{1}{1+e^{\gamma_1-\gamma_2 x}}$	$\frac{\gamma_2 e^{\gamma_1-\gamma_2 x}}{(1+e^{\gamma_1-\gamma_2 x})^2}$	$\frac{2\gamma_2^2\, e^{2\gamma_1-2\gamma_2 x}}{(1+\, e^{\gamma_1-\gamma_2 x})^3} - \frac{\gamma_2^2\, e^{\gamma_1-\gamma_2 x}}{(1+\, e^{\gamma_1-\gamma_2 x})^2}$	$\frac{\gamma_2\, e^{\gamma_2}}{1+\, e^{\gamma_2})^2}$	0	$\frac{2\gamma_2^2\, e^{2\gamma_1}}{(1+e^{\gamma_1})^3} - \frac{\gamma_2^2\, e^{\gamma_1}}{(1+e^{\gamma_1})^2}$	0
Weibull	$1 - e^{-x^{\gamma}}$	$\gamma x^{\gamma-1}\, e^{-x^{\gamma}}$ *or* $\frac{\gamma e^{\gamma \ln(x) - x^{\gamma}}}{x}$	$f'(x)\, (\frac{\gamma-1}{x} - \gamma x^{\gamma-1})$ *or* $f'(x)\, \frac{(\gamma-1)}{\gamma} - (f'(x))^2$	0	0	0	0

Rectangular Hyperbola (Cousens)	$\frac{\gamma_1 x}{1 + \frac{\gamma_1 x}{\gamma_2}}$	$\frac{\gamma_1 \gamma_2^2}{(\gamma_1 x + \gamma_2)^2}$	$\frac{-2\gamma_1^2 \gamma_2^2}{(\gamma_1 x + \gamma_2)^2}$	γ_1	0	$-\frac{2\gamma_1^2}{\gamma_2}$	0
Square Root	$\gamma\sqrt{x}$	$\frac{\gamma}{2}(x)^{-1/2}$	$-\frac{1}{4}\gamma(x)^{-3/2}$	∞	0	$-\infty$	0

Figure 1

Direct and Indirect Inputs in Production

Conventional Inputs



Damage Control Inputs

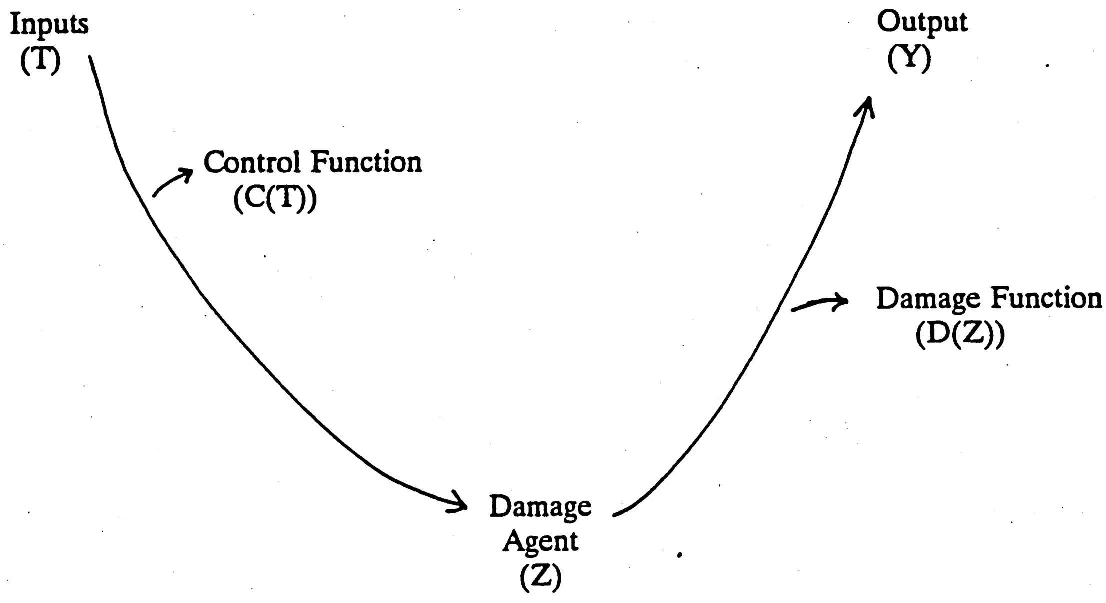


Figure 2

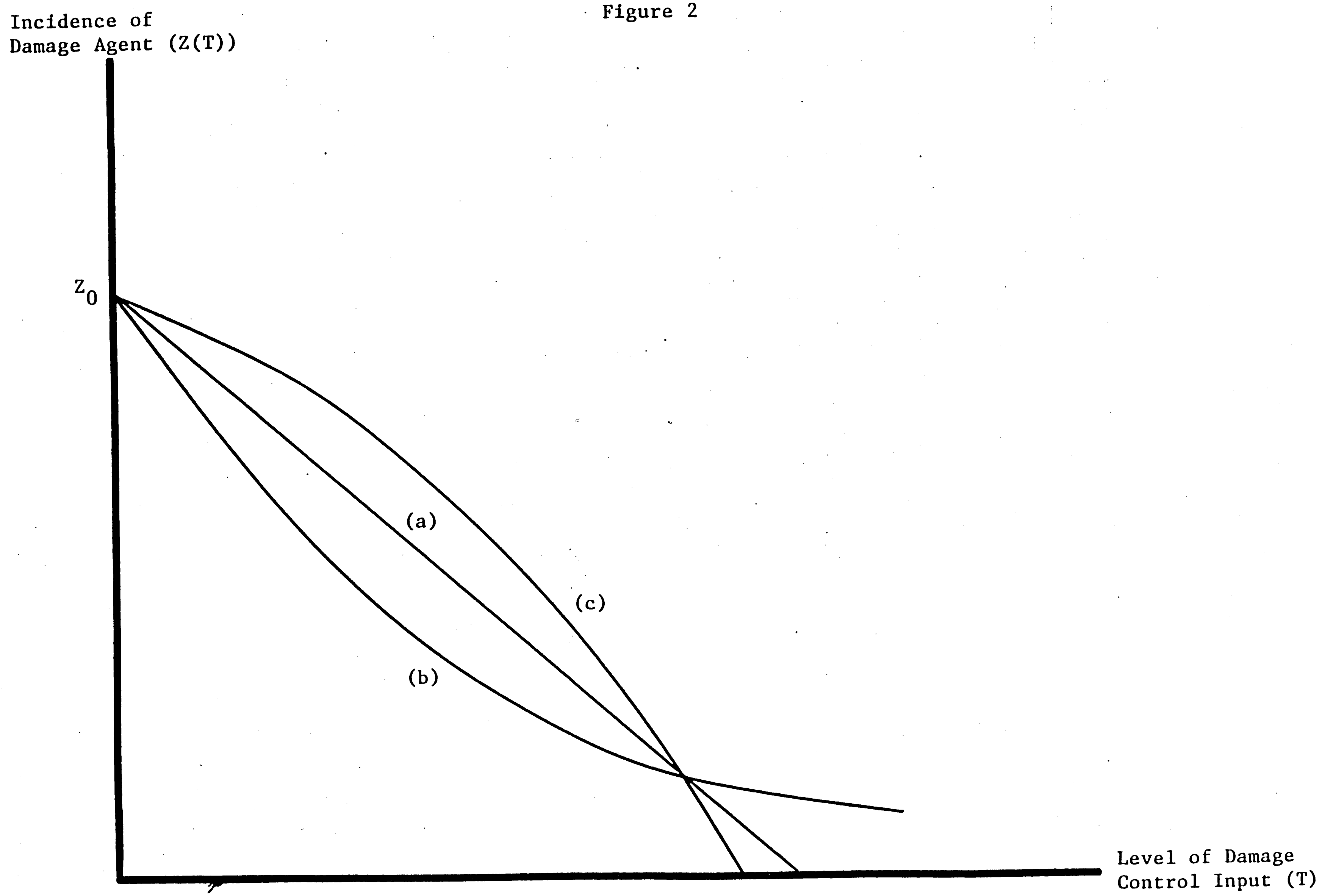
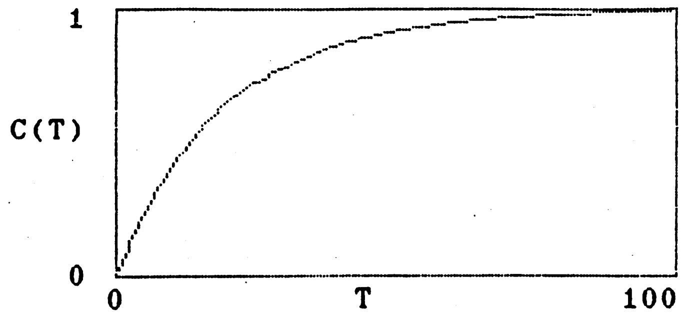

Incidence of
Damage Agent (Z(T))
Z_0
(a)
(b)
(c)
Level of Damage
Control Input (T)

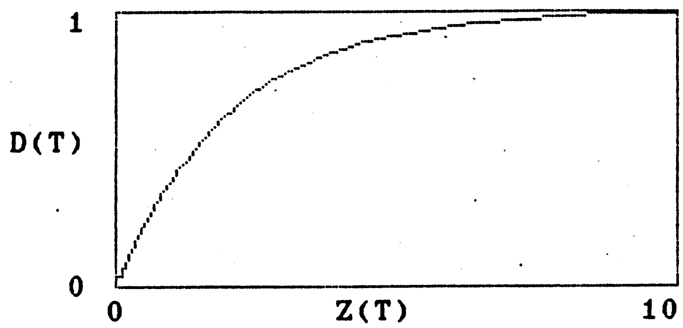
Figure 3

Exponential Damage and Control Functions

Control Function



Damage Function



Total Product Curve

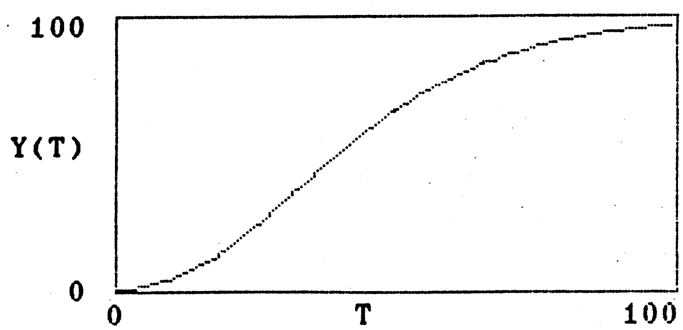


Figure 4

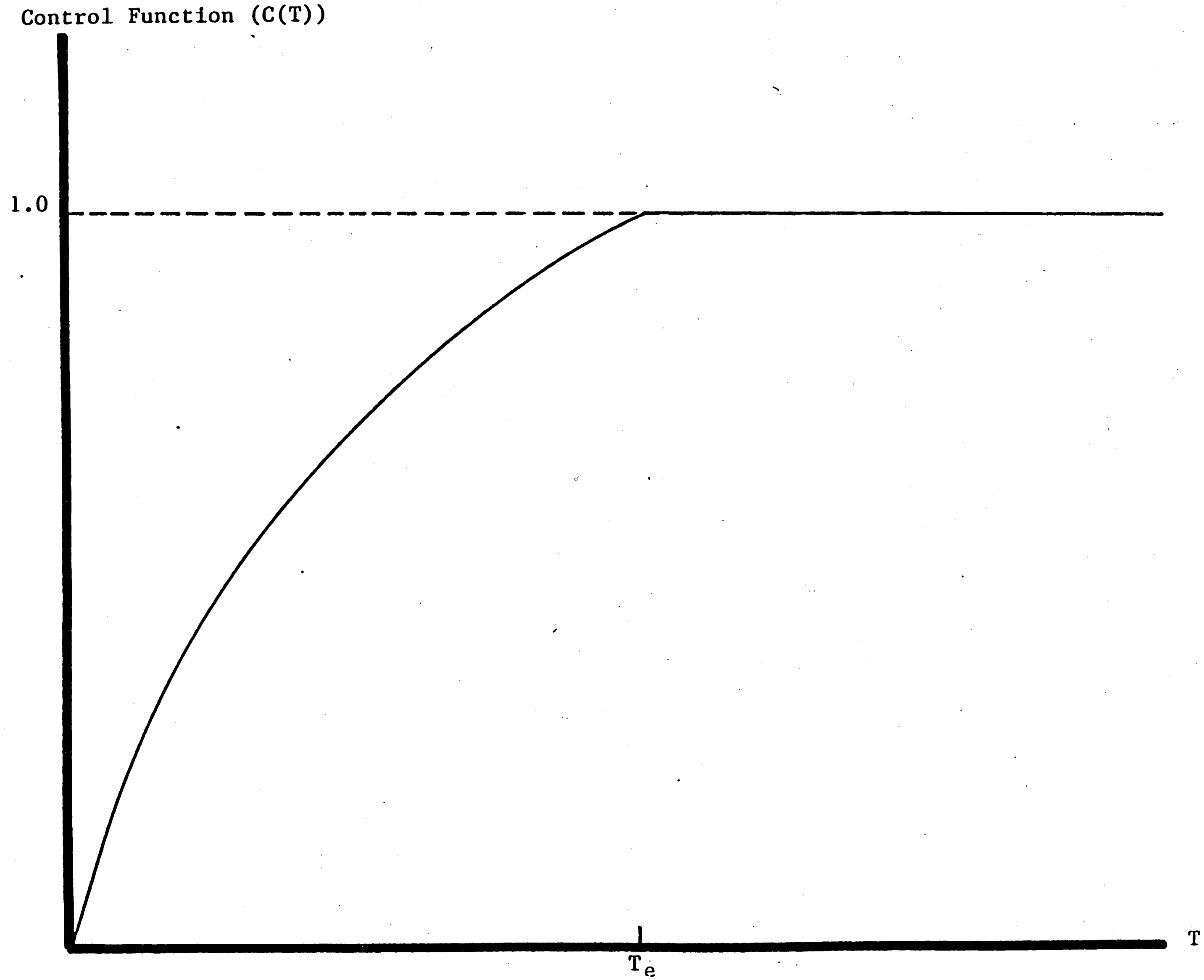


Figure 5
Exponential Damage Function and Square Root Control Function

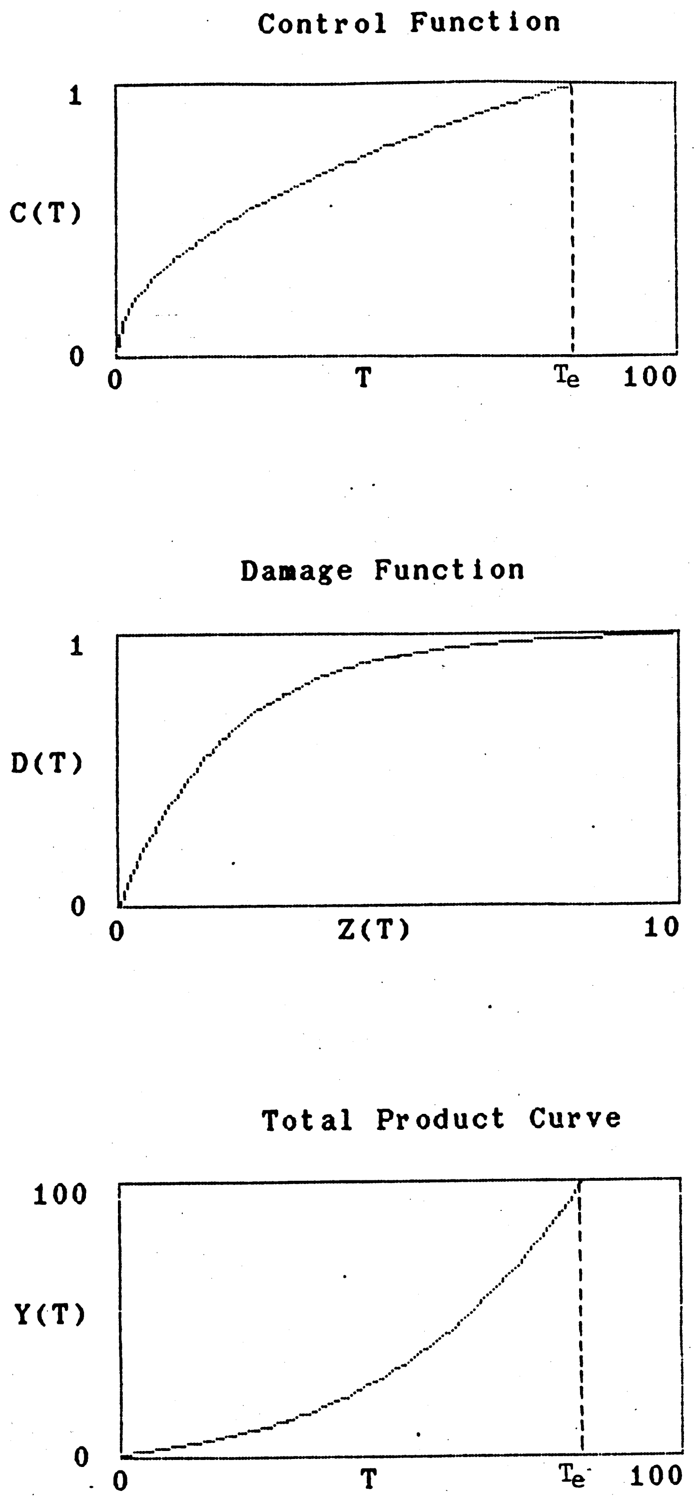


Figure 6

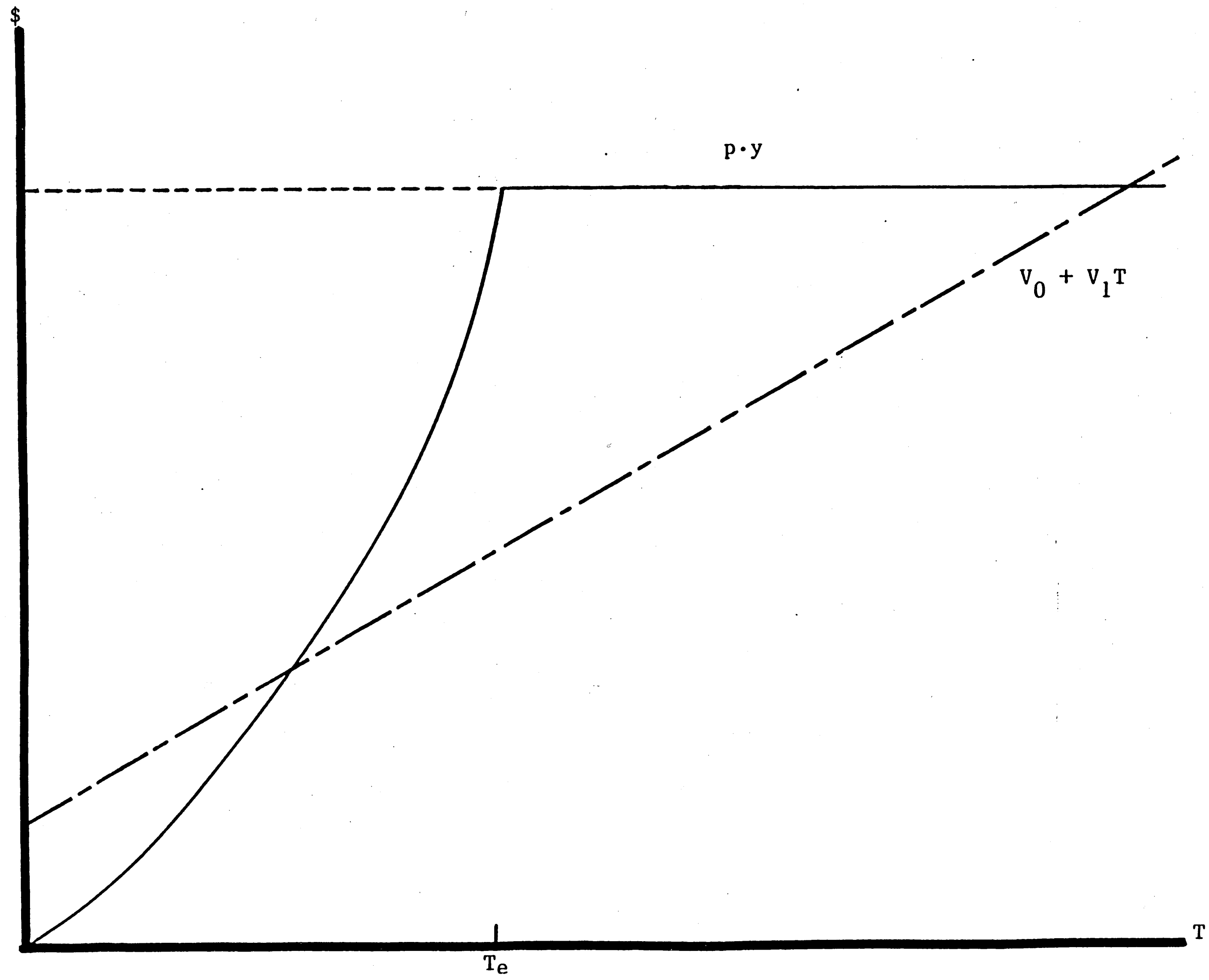


Figure 7