E C O N O M I C S   B U L L E T I N

Optimal soil management and environmental policy

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Abstract

This paper studies the effects of environmental policy on the farmer's soil optimal management. We consider a dynamic economic model of soil erosion where the intensity use of inputs allows the farmer to control soil losses. Inputs use induces a pollution which is accentuated by the soil fragility. We show, at the steady state, that environmental tax induces a more conservative farmer behavior for soil, but in some cases it can exacerbate pollution. These effects can be moderated when farmer introduces abatement activity.

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1 Introduction

Soil erosion is a critical issue for agriculture in developed countries as well as in developing countries. Some empirical studies (for instance Papendick, *et al.*, 1985 or Troeh *et al.*, 1991) show that crop yields decrease with soil depth in the long run. With a fixed amount of agricultural land, this diminution of agriculture yields is generally compensated by an increasing use of fertilizers, which involves pollution of surface and ground water. Hence, any environmental policy that aims at reducing pollution emissions may be required to take into account the effect of soil erosion. This paper focuses on these two features by considering an optimal farm management model and by examining the relationships between crop productivity, input use, pollution flows and the soil characteristics[1]. It thus describes the optimal farmer's behavior and discusses about the effects of an unit tax as environmental policy.

The problem of soil degradation is inherently a dynamic one, involving both temporal and intertemporal trade-offs, as in standard resource management models. However, the main difference with other renewable resources lies in the intrinsic dynamics of soil. Natural regeneration of soil is considered as fixed and insignificant with respect to the time horizon of human's life and soil erosion is a natural degradation process which is drastically amplified by intensified agriculture activity. Conversely, the rate of soil loss, characteristics of the soil profile, climate and crop grown decide how much soil erosion lowers the productivity of land (see McConnell, 1983, Saliba, 1985, Barbier, 1990, Grepperud, 1997 or Goetz, 1998 for further details on soil dynamics).

However, soil erosion is not only a problem of resource degradation, it also causes negative externalities like sedimentation or water pollution. Water pollution (surface and ground water) is a quite complex process since it involves both point and non-point source pollutions. The difference between them is not so apparent since all pollutants are emitted at a discrete point and are gradually dispersed to varying degrees as they are spread through the environment. From a policy point of view, the crucial distinction between point and diffuse sources relies on their ease of identification and susceptibility to monitoring. Except Loehman and Randhir (1999) and Hediger (2003), there is no paper which integrates optimal soil conservation and pollution externality. But neither of them studies explicitly the effects of the environmental policy on the asymptotic soil management. Here, we fill into this gap by developing a model of intertemporal efficiency of soil management with a point pollution and an environmental tax.

[1]The soil characteristics includes the depth, the texture, the fertility as well as other quality indicators of soil. This generic term works as the farmer's capital stock.

The remainder of the paper is organized as follows. The model is laid out in section 2. In section 3, the optimal conditions are derived and the dynamics of the model is analyzed. The environmental policy effects on soil management are examined in section 4. This section also considers the case of abatement expenditures which aims at reducing direct emissions. Finally, Section 5, summarizes the main findings.

2 The model

The model setup is provided by the standard approach of Goetz *et al.* (2000) and Hediger (2003). Let u_t be an index of inputs (the cultivation intensity), z_t, the overall soil depth and y_t, the physical yield of crop per hectare at date t. The agricultural production function is given by:

$$y_t = f(u_t, z_t), \tag{1}$$

where f is defined in such a way that $f(0,z) = f(u,0) = 0$, $f_u > 0$, $f_z > 0$, $f_{uu} < 0$, $f_{zz} < 0$, $f_{uz} = f_{zu} > 0$ and $[f_{uu}f_{zz} - (f_{uz})^2] > 0$. Dynamics of the soil depth z_t is described by the following state equation:

$$\dot{z}_t = g - h\left(u_t, z_t\right),\ z_0 > 0 \text{ given}, \tag{2}$$

where g is the pedogenesis rate, arbitrarily taken as constant due to the length of geological cycles and $h(u,z)$, the erosion function, which characterizes the magnitude of soil losses. Function h is such that $h_u > 0$, $h_z < 0$, $h_{uu} > 0$, $h_{zz} > 0$, $h_{zz}h_{uu} - (h_{zu})^2 > 0$ and $h_{uz} = h_{zu} < 0$. [2] We assume that the asymptotic Inada conditions hold for f and h.

In addition to soil erosion, the agricultural activity generates surface and ground water pollution. In territory where activity is intensive, this has resulted in phosphorus accumulation in surface runoff and soil erosion can accelerate the eutrophication of surface water. According to Hediger (2003), pollution flow e_t is defined by:

$$e_t = \gamma h(u_t, z_t) + \eta(u_t), \tag{3}$$

where $\gamma > 0$ is the (constant) soil pollutant content, or the soil fixation rate and $\eta(u_t)$, the rate of surface runoff, such that $\eta' > 0$ and $\eta'' > 0$.

The farmer is assumed to be price taker. Its net income at date t writes:

$$\pi_t = p_t f(u_t, z_t) - cu_t - \tau e_t, \tag{4}$$

where p_t is the output price, set equal to 1 without any loss of generality, c, the (constant) marginal cost of input use and τ, the (constant) unit taxation of any positive emission.

[2] Comments and geological meanings of these properties can be found in Troeh *et al.* (1991).

3 Farmer's program and dynamic analysis

The farmer's decision problem consists in choosing the input level that maximizes the sum of the instantaneous profit flows (4), discounted at a rate equal to the interest rate $r > 0$, subject to (2) and (3). Denoting by λ_t the co-state variable, *i.e.* the shadow cost of soil, the static and dynamic optimal necessary conditions write[3]:

$$f_u = c + \lambda h_u + \tau[\eta'(u) + \gamma h_u], \tag{5}$$

$$\dot{\lambda} = (r + h_z)\lambda - f_z + \tau\gamma h_z. \tag{6}$$

From (5), along any optimal trajectory, the marginal agricultural income must be equal to the marginal cost of cultivation which is threefold: (a) the marginal cost c of using u units of input, (b) the marginal cost of cultivation in terms of soil erosion, λh_u, (c) the marginal cost of cultivation in terms of pollution taxation, $\tau[\eta'(u) + \gamma h_u]$. In (6), $(r + h_z)$ reads as the marginal return rate of soil and it is assumed to be positive[4]. Then, $(r + h_z)\lambda$ is the marginal return of holding a unit of non-cultivated soil. The other term $(f_z - \tau\gamma h_z)$ is the marginal gain of using a unit of soil as input, *i.e.* the marginal productivity of soil reduced by the marginal cost of soil in terms of pollution taxation. Then, current marginal rent of soil λ grows over time as long as it is more profitable for farmer to let the soil non-exploited rather than to cultivate it.

The dynamics of the system can be represented within a (z, λ) diagram. Let D^1 be the locus of the (z, λ) points where $\dot{z} = 0$, formally $D^1 = \left\{(z, \lambda) \in \mathbb{R}^2_{+*} \mid \dot{z} = 0\right\}$. For any $(z, \lambda) \in D^1$, $h(u, z) = g$ so that z and u are constant since g is constant and function h is time independent. From (5), the equation of the D^1-demarcation curve and its slope write:

$$\lambda(z) \mid_{\dot{z}=0} = \frac{f_u(u, z) - c - \tau[\eta'(u) + \gamma h_u(u, z)]}{h_u(u, z)} \tag{7}$$

$$\lambda'(z) \mid_{\dot{z}=0} = \frac{h_u f_{uz} - [f_u - c + \tau\eta'(u)]h_{uz}}{(h_u)^2}. \tag{8}$$

where $[f_u - c + \tau\eta'(u)]$ is this part of the marginal profit that excludes the contribution of erosion. From (5), this last term equals $(\lambda + \tau\gamma)h_u$, which is positive for any λ. Hence, the D^1-demarcation curve is increasing in the (z, λ) plane and dynamics of z is

[3] From now, the time argument is suppressed for notational convenience.

[4] The farmer can invest a marginal unit of soil at rate r on a financial market rather than use it as input. This "harvesting" results in a diminution in the soil depth and in an increase of erosion by h_z. Then, the marginal return of soil is reduced by the effect of erosion and the net return rate of soil is $(r + h_z)$, where $r > 0$ and $h_z < 0$. Since the erosion magnitude is very small compared with the interest rate, we can assume $(r + h_z) > 0$.

as follows: (a) z is constant along the D^1-curve, (b) z decreases for any (z, λ) below the D^1-curve, (c) z increases for any (z, λ) above the D^1-curve. Similarly, define D^2, $D^2 = \left\{(z, \lambda) \in \mathbb{R}^2_{+*} \mid \dot{\lambda} = 0\right\}$. From (6) the equation of the D^2-curve and its gradient are, respectively:

$$\lambda(z) \mid_{\dot{\lambda}=0} = \frac{f_z(u, z) - \tau\gamma h_z(u, z)}{r + h_z(u, z)} \tag{9}$$

$$\lambda'(z) \mid_{\dot{\lambda}=0} = \frac{(r + h_z)f_{zz} - (r\gamma\tau + f_z)h_{zz}}{(r + h_z)^2}. \tag{10}$$

Since $(r + h_z)$ is positive, then $\lambda'(z) \mid_{\dot{\lambda}=0}$ is negative so that the D^2-curve is decreasing. The optimal dynamics of shadow price is the following: (a) λ is constant along the D^2-demarcation curve, (b) λ decreases for any (z, λ) below the D^2-curve, (c) λ increases for any (z, λ) above the D^2-curve.

[Figure 1 here]

The optimal dynamics of (z, λ) is depicted by Figure 1, in which E_1 denotes the steady-state of the system. Formally, let $(u_1^*, z_1^*, \lambda_1^*)$ be the the stationary values of (u, z, λ). This triplet is characterized by the following system of equations[5]:

$$g = h(u_1^*, z_1^*) \tag{11}$$

$$[r + h_z(u_1^*, z_1^*)]\, \lambda_1^* = f_z(u_1^*, z_1^* - \tau\gamma h_z(u_1^*, z_1^*) \tag{12}$$

$$h_u(u_1^*, z_1^*)\lambda_1^* = f_u(u_1^*, z_1^*) - c - \tau\left[\eta'(u_1^*) + \gamma h_u(u_1^*, z_1^*)\right] \tag{13}$$

Equation (11) means that optimal erosion must be balanced by pedogenesis to maintain a constant soil depth. Since (12) equalizes the marginal return of holding a unit of non-cultivated soil (left hand side) and the marginal contribution of soil in the farmer's profits (right hand side) then, at the stationary equilibrium, the farmer is indifferent to cultivate soil or not suggesting a constant marginal rent of soil. Similarly, from (13), the marginal benefit in terms of soil conservation the farmer is expected to earn by reducing its input use by one unit (left hand side) must be equal to the marginal profit he is expected to earn by increasing its input use by one unit (right hand side).

4 The environmental policy effect

4.1 Discussion on τ

First, as from (7) and (8), $\lambda(z) \mid_{\dot{z}=0}$ decreases and $\lambda'(z) \mid_{\dot{z}=0}$ increases with τ, a reduction of the unit tax results in an upward shift of the D^1-demarcation curve with a lower slope.

[5] It is easy to see that $(u_1^*, z_1^*, \lambda_1^*)$ exists if and only if $r + h_z(u_1^*, z_1^*) > 0$ and $f_u(u_1^*, z_1^*) - c - \tau[\eta'(u_1^*) + \gamma h_u(u_1^*, z_1^*)] \geq 0$. Under these conditions, $(u_1^*, z_1^*, \lambda_1^*)$ is proved to be a saddle point.

Second, from (9) and (10), $\lambda(z)\mid_{\dot{\lambda}=0}$ increases and $\lambda'(z)\mid_{\dot{\lambda}=0}$ decreases with τ so that a diminishing tax involves a downward shift of the D^2-demarcation curve with a more steep slope. Such moves are illustrated in Figure 2.

[Figure 2 here]

The stationary point E_2 refers to the optimal control problem without any environmental policy, i.e. when $\tau = 0$. Its comparison with E_1 reveals the positive effect of the taxation on the stationary soil depth: at the steady state, the environmental tax induces a more conservative farmer's behavior for soil management and the soil conservation increases as the environmental policy becomes restricting for the farmer. This global effect can be broken down as follows. From (2), erosion must be equal to pedogenesis at the steady-state. If the stationary soil level increases, then the stationary input use must also increase in order to maintain erosion constant. Hence, the environmental policy results in a more conserved soil and an higher intensity of input use. At the stationary equilibrium, the farmer can partially compensate the tax surcharge by improving the agricultural yield.

While the effect on z is clearly identified, the effect on e is ambiguous. To see that, differentiate totally the emission function:

$$\Delta e = \eta'(u)\,\Delta u + \gamma\left[h_u \Delta u + h_z \Delta z\right]. \tag{14}$$

Then the tax may prompt the farmer to diminish pollution emissions if and only if:

$$\frac{\Delta u}{\Delta z} < \frac{-\gamma h_z}{\eta'(u) + \gamma h_u}, \tag{15}$$

where $-\gamma h_z$ and $[\eta'(u) + \gamma h_u]$ denote respectively the marginal (negative) contribution of soil conservation and the marginal (positive) contribution of input use in the emission of pollution. Hence, the tax causes pollution to decrease if the increment of soil conservation due to the tax is important enough to balance the increment of pollution coming from an increase in the input use. In other words, the environmental policy acts for soil conservation as well as emission reduction only if the indirect "soil effect" overrides the direct "input effect".

4.2 Discussion on γ

As discussed in (15), the environmental effect of emission taxation is proved to be ambiguous. In particular, it depends on γ, which can be seen as a fragility index of soil faced to pollution. In Figure 3, we decompose the global effect of pollution to stress the contribution of soil erosion and the contribution of direct pollution (surface runoff) on soil conservation.

[Figure 3 here]

When the indirect effect of soil erosion on pollution emissions is null, i.e. $\gamma = 0$, the D^1-demarcation curve shifts upward and keeps the same slope whereas the D^2-curve shifts downward and have a more steep slope[6]. We obtain a new steady-state which is denoted by E_3 in Figure 3. The less the emission function depends on soil erosion, i.e. the smaller is γ, the more taxation acts as a regulator policy of environmental externalities by reducing pollution emissions and the less this environmental policy favors the soil conservation in the long run.

4.3 Pollution abatement

Let us assume now that the farmer can invest into abatement technologies. He can choose the level v_t of investment which will have an abatement effect on pollution coming only from the surface runoff. We consider that net pollution from surface runoff at date t is $\eta(u_t)/(1+v_t)$, where $1/(1+v_t)$ reads as a cleaning up factor and v_t as the abatement rate. The marginal cost of abatement $b > 0$ is constant. Then, the instantaneous profit function writes $\pi_t = f(u_t, z_t) - cu_t - bv_t - \tau e_t$ and the pollution emission function becomes:

$$e_t = \frac{\eta(u_t)}{1+v_t} + \gamma h(u_t, z_t). \tag{16}$$

Static first order conditions of the new farmer's program are:

$$f_u - c = \lambda h_u + \tau \left[\frac{\eta'(u)}{(1+v)} + \gamma h_u \right], \tag{17}$$

$$\tau \frac{\eta(u)}{(1+v)^2} = b. \tag{18}$$

Condition (17) has the same interpretation than (5). Condition (18) equalizes the marginal benefit of abatement expenditures and the marginal cost of this abatement. Equivalently, (17) writes $v = [\tau\eta(u)/b]^{1/2} - 1$: the optimal abatement intensity is an increasing function of the tax and the intensity of input use and a decreasing function of its marginal cost of abatement b. Since dynamic optimal condition (6) is unchanged, the

[6] Although the assumption $\gamma = 0$ is not realistic, it is considered here for technical conveniences since it might determine the boundary of the solution space in Figure 3.

abatement policy affects the dynamics of z and not the dynamics of λ. The equation of the D^1 representative curve becomes:

$$\lambda(z)^a \mid_{\dot{z}=0} = \frac{f_u(u,z) - c - \tau\left[\frac{\eta'(u)}{1+v} + \gamma h_u(u,z)\right]}{h_u(u,z)}, \tag{19}$$

where subscript a means that abatement effort acts as a control variable. After developments and simplifications, we obtain:

$$\lambda(z)^a \mid_{\dot{z}=0} = \lambda(z) \mid_{\dot{z}=0} + \left(\frac{v}{1+v}\right)\frac{\tau\eta'(u)}{h_u} > \lambda(z) \mid_{\dot{z}=0}, \tag{20}$$

where $\lambda(z) \mid_{\dot{z}=0}$ is defined by (7). Hence, the effect of abatement expenditures in addition to an environmental tax is the following: from the case without pollution abatement, the D^1-demarcation curve shifts upward whereas the D^2-demarcation curve shifts downward, as illustrated in Figure 4. Then, abatement expenditures involve a diminution of the stationary conservation of soil. This effect is proportional to $v/(1+v)$ and soil conservation decreases as v increases.

[Figure 4 here]

The trade-off between intensity culture and soil conservation remains the same: input use increases pollution emissions whereas soil conservation decreases them. Hence, the abatement expenditures and the environmental tax on pollution emissions have opposite effects. Abatement allows the farmer to reduce its emissions if and only if the resulting effect on pollution of a diminution in the input use overrides the effect on pollution of a diminution of the soil conservation. That can illustrated by differentiating totally the emission function:

$$\Delta e = \left[\frac{\eta'(u)}{(1+v)} + \gamma h_u\right]\Delta u - \frac{\eta(u)}{(1+v)^2}\Delta v + \gamma h_z \Delta z, \tag{21}$$

where $(1+v) = [\tau\eta(u)/b]^{1/2}$ and $\Delta v = (\tau/2b)[\tau\eta(u)/b]^{-1/2}\eta'(u)\Delta u$. After simplifications, it comes:

$$\Delta e = \left[\frac{\eta'(u)}{2}\left(\frac{\tau\eta'(u)}{b}\right)^{-1/2} + \gamma h_u\right]\Delta u + \gamma h_z \Delta z. \tag{22}$$

The first term of the right hand side of (22) is negative since the term in brackets is positive and Δu is negative in the case of an increase in abatement expenditures (see Figure 4). The second term is positive since $h_z < 0$ and $\Delta z < 0$. As a result, abatement expenditures contributes in the diminution of pollution if and only if:

$$\frac{\Delta u}{\Delta z} > \frac{-\gamma h_z}{\left[\frac{\eta'(u)}{2}\left(\frac{\tau\eta'(u)}{b}\right)^{-1/2} + \gamma h_u\right]}. \tag{23}$$

5 Conclusion

The study of environmental policy effects in agricultural context can not be dissociated from optimal soil management. This is due to the crucial relationship between, first, observed pollution and second, the weakening level of soil and the level of cultivation. By considering the pedological characteristics of soil and environmental externalities, we show that environmental tax induces two effects in the long run: (a) a more conservative farmer's behavior in the soil management and (b) an increase in the input use at the steady-state. To compensate the fiscal fees, the farmer improves his agricultural yield by preserving higher depth soil at the steady-state. This allows the farmer to use more input in the long run at the risk of increasing pollution emissions. Therefore, these effects depend on the contribution of soil erosion into the final emission of pollutants. The smaller this contribution, the larger is the positive effect of environmental policy on pollution and the smaller is the conservation of soil in the long run. Finally, the same mechanism can be obtained with abatement expenditures. Then, the efficiency of such environmental instruments (tax and abatement) to reduce pollution may be moderated by considering not only the flow of emissions, but also the dynamics of soil erosion.

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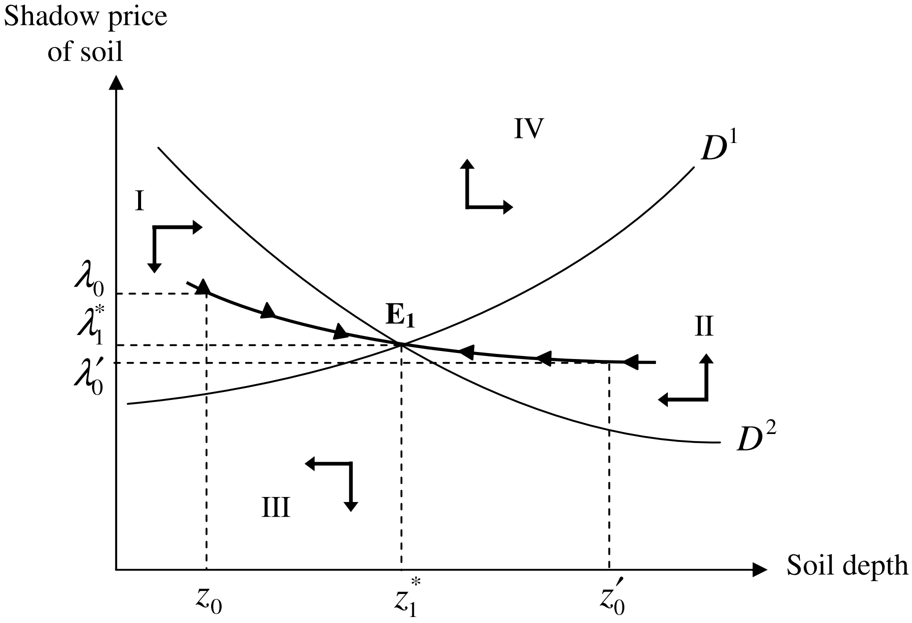

Figure 1: Dynamic optimal management of soil.

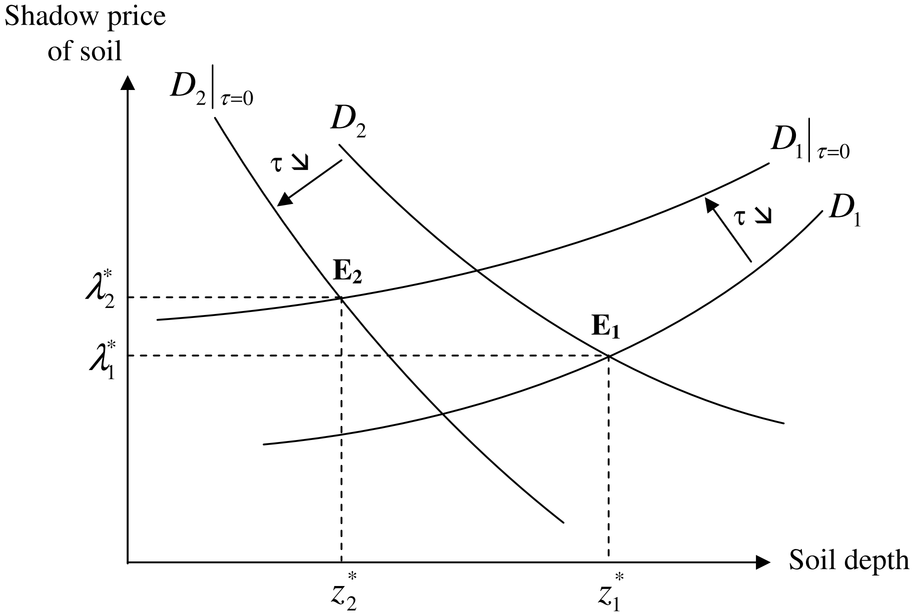

Figure 2: Effect of the environmental policy on optimal dynamics.

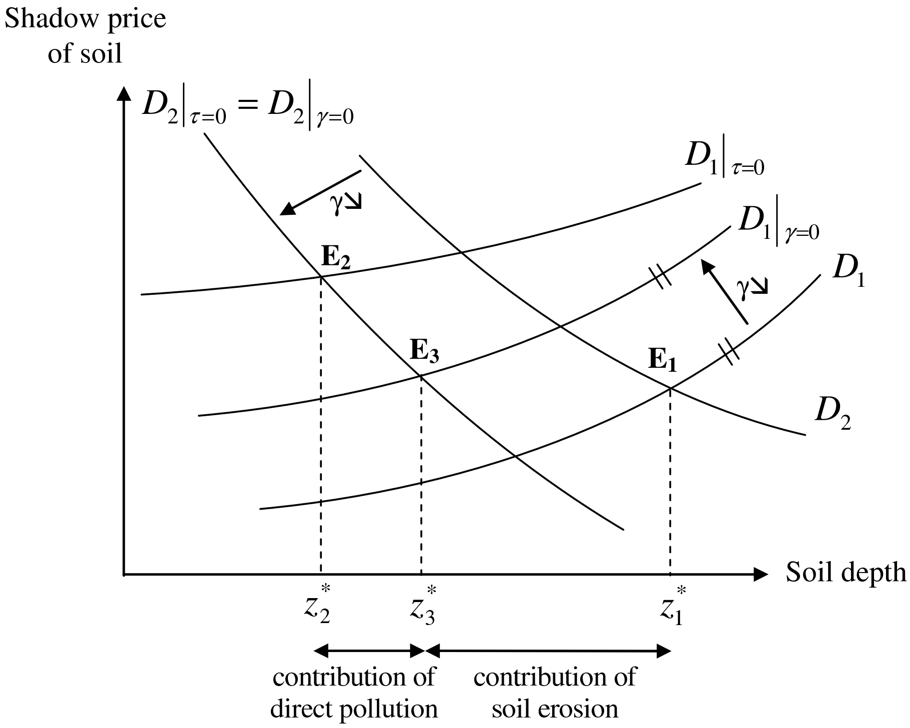

Figure 3: Soil erosion as pollution source.

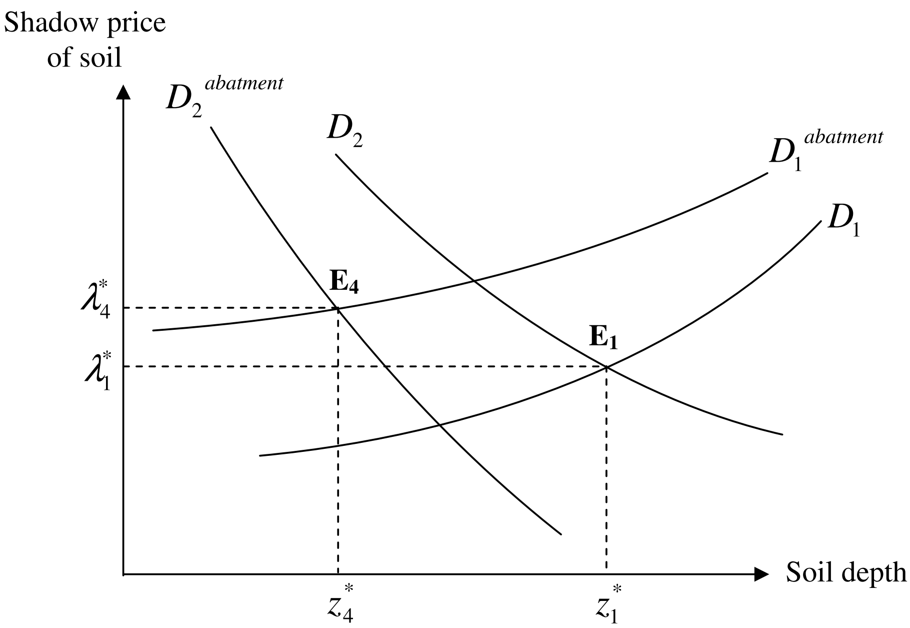

Figure 4: Effect of abatement technologies.