Optimal Soil Management and
Environmental Policy

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Summary

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. Therefore, inputs use induces a pollution which is accentuated by the soil fragility. We show, at the steady state, that the environmental tax induces a more conservative farmer behavior for soil, but in some cases it can exacerbate pollution. These effects can be moderated when farmers introduce abatement activity.

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1 Introduction

Soil erosion is a major problem for agriculture in most countries and particularly in developing context. If the rate of soil erosion exceeds the rate of soil genesis, then soil productivity is expected to decline. Many empirical studies on soil erosion (Papendick, and al., 1985; Troeh and al., 1991) showed that crop yields decrease with soil depth in the long run. This diminution of agriculture yields can be compensated by an expansion of the cultivated land area or an increase in the fertilizer inputs. However, these options are a sources of negative environmental externalities such as pollution of surface and ground water. Hence for an optimal soil management, environmental policy is required to take into account external effects as well as sustainable soil use.

In the literature, the problem of soil degradation is frequently analyzed within optimal control models, since the choice is inherently a dynamic one, involving both temporal and intertemporal trade-offs. Economic and biophysical factors, such as good prices and production costs, production technologies, intensity of cultivation, soil depth, and other productivity-related soil characteristics, determine the agriculture yield. All these factors have been introduced in dynamic models of resource management (McConnell,1983; Saliba, 1985; Barbier, 1990; LaFrance, 1992; Clarke, 1992; Barret, 1996; Grepperud, 1997; Goetz, 1998; Goetz and Zilberman, 2000). The aim of these dynamic models is the characterization of conditions for an optimal intertemporally use of soil as a production factor. While, soil erosion is not only a problem of resource degradation. It also causes negative agriculture externalities, such as water pollution and sedimentation. Expecting, Loehman and Randhir (1999) and Hediger (2003), there is no study which integrates optimal intertemporally soil use and off-farm effect of soil erosion.

In a two-sector model of rural-urban linkage, Loehman an Randhir (1999) study the types of public policies that satisfy social efficiency for soil erosion and pollution stock externality. The urban sector is assumed to be more wealthy than rural. The types of tax/subsidy policies examined range from central-

ization (with government determining taxes/subsidies) to complete decentralization (with government determination of an initial entitlement followed by market decision about pollution reduction). To traditional Pigouvian and bargaining solutions extended to a dynamic setting, a third alternative is government as a co-producer of environmental goods.

Hediger (2003) integrates the requirement for an intertemporally efficient and sustainable agricultural land use in the presence of soil erosion into analytical framework for the evaluation of sustainability at the farm level in which both on and off-farm effects are taken into account. To sustain the farm income, an agricultural Hartwick rule is proposed which addresses both effects. It requires the farmer to invest the soil rents into some suitably identified alternatives of capital. This implies a continuous substitution of alternative income sources (agricultural or non-agricultural) for traditional sources of income from crop production that induce persistent soil erosion. Under consideration of the optimally conditions from the dynamic erosion control problem, this investment rule enables the farmer to earn a constant income. A charge-subsidy provides an incentive for pollution control and allows farmers to earn a sustainable income. Under this scheme, the effluent charge revenues shall be earmarked to subsidize the retirement of cropland and conversion into extensively used grassland or forest land.

While their models consider both soil erosion and pollution externality, Loehman and Randhir (1999) and Hediger (2003) have not studied explicitly the effects of the environmental policy on the asymptotic soil management. The aim of this paper is to fill into this gap and to integrate in the same model, intertemporal efficiency management of soil and pollution externality. We analyze the effects of environmental tax on optimal soil use at the equilibrium with respect to different specifications of pollution emission in agriculture.

Obviously, soil erosion is a geological process, but the rate of erosion can be drastically increased by intensified agriculture activity. Under undisturbed vegetation there is normally a balance between the soil and the erosion. Cultivation of the land usually interrupts this balance because the vegetation cover is

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reduced. The soil provides the growth medium for the plants. As soil and nutrients are removed, the rooting depth for the plants is reduced. The consequence of lower rooting depth is more severe on shallow soils, which are predominant on sloping land, than on deep soils. The rate of soil loss, characteristics of the soil profile, climate and crop grown decide how much soil erosion lowers the productivity of land. On the back of this soil loss and related yield fall, erosion also causes surface-water pollution which induce an important social cost.

The surface-water pollution can be seen as point or diffuse pollution. The difference between them is not so apparent as it may seem at the first approach. In some senses, 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. In this paper, our analyze is limited to the case of a point pollution and fiscal environmental policy.

The remainder of the paper is organized as follows. In section 2 the general model is laid out and optimal conditions of soil use are derived. The dynamics analysis of the model and the steady-state characteristics are examined in section 3. Building on this dynamic framework, the environmental policy effects on soil management are studied with respect to different pollution emission specifications. Section 4 considers the case where farmer can spend on abatement technologies which reduces his direct emission. Finally, Section 5, summarizes the main findings.

2   The model

We consider a farm-level model which includes functional relationships and impacts among farm management choices and soil characteristics. Considered as state variable, soil characteristics incorporate soil depth and other productivity factors. We also include erosion productivity linkages which relate changes in soil characteristics to agricultural yield function. The latter supposes explicitly a possible substitution between soil characteristics and other inputs. The soil

characteristics constitute the farmer's capital stock whose dynamics is governed by a biophysical and economic process.

2.1 Assumptions

Let u_t be an index of inputs (the cultivation intensity), z_t, the overall soil depth and y_t, the physical yield per hectare of the crop at date t. The production function of a crop is then given by:

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

where f is defined in such a way that $f_u > 0$, $f_z > 0$, $f_{uu} < 0$, $f_{zz} < 0$ and $\left[f_{uu}f_{zz} - (f_{uz})^2 \right] > 0$. Inputs u and z are necessary to production: $f(0, z) = f(u, 0) = 0$. We impose $f_{uz} = f_{zu} > 0$, i.e. marginal productivity of soil increases with the input use. Finally, function f satisfies the asymptotic Inada conditions.

This production function is in line with the work of Saliba (1985), LaFrance (1992), Clarke (1992), and Hediger (2003). Unlike other studies such as Mc-Connell (1983) or Barett (1991), soil loss is not being considered as an argument of the function since it is a result of the choice of u as well as the development of the soil depth over time, rather than a choice variable for the farmer.

However, the soil depth not only affects crop yields, it also influences the magnitude of soil losses for a given amount of rain. Therefore, a per hectare erosion function given by $h(u, z)$ is introduced. We assume the following properties for erosion function : $h_u > 0$, $h_z < 0$, $h_{uu} > 0$, $h_{zz} > 0$, $h_{zz}h_{uu} - (h_{zu})^2 > 0$ and $h_{uz} = h_{zu} < 0$. Asymptotic Inada conditions about the behavior of marginal erosion functions are implicitly assumed to hold.

As the soil depth decreases the soil becomes finer textured and less friable. Furthermore, the low content of organic matter in the subsoil decreases the aggregate stability of the soil particles such that rain can destroy them more easily. Hence, reduced infiltration and permeability as well as the unstable structure of the soil aggregates together cause runoff and erosion of the subsoil to increase suggesting $h_z < 0$ [1].

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[1] See Troeh and al. (1991).

An increase in the production intensity will result in higher erosion rates, implying $h_u > 0$. The structural changes of soil due to water erosion help to determine the sign of h_{zz}. Rain drops disintegrate on the surface and produce a compact surface crust. Percolating rainwater dislocates suspended fine soil particles from the top soil to the subsoil. These changes amplify the magnitude of soil erosion as the soil layers decrease suggesting $h_{zz} > 0$. An augmentation of the production intensity leads to higher erosion rates. However, a simultaneous accretion of the soil adversely affects this increase which implies $h_{uz} < 0$.

The intertemporal change of the soil depth z at time t is described by:

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

where g is the pedogenesis rate, arbitrary taken as constant due to the length of geological cycles.

In addition to soil erosion, the agricultural activities induce a surface and ground water pollution. Mineral fertilizer and manure, at levels that exceed crop uptake, constitute the major sources of agriculture externalities. In territory where agricultural activities are intensive, this has resulted in phosphorus accumulation in surface runoff and soil erosion can accelerate the eutrophisation of surface water. This pollution is not taken into account by farmers, as long as they are not faced with the social cost of their activity. In practice there is two types of pollution: point and diffuse pollution. The difference between them is not so apparent as it may seem at first blush. From a political point of view, point sources are characterized by discrete discharge into the atmosphere or water environment, whereas diffuse sources do not have a clearly defined entry points[2].

In this paper, we concentrate our analyze on agriculture point pollution. According to Hediger (2003), we suppose that pollution flow is determined on the one hand by the rate of surface runoff $\eta\left(u_t\right)$, which progressively increases with u_t (such that $\eta'_u > 0$ and $\eta''_{uu} > 0$), and on the other hand by the proportional function of soil erosion rate $\gamma h\left(u, z\right)$. Altogether, this can be written

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[2]Shortle and Abler (2001), and O'Shea (2002) provide a survey on the economics of nonpoint-source pollution.

as:

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

where $\gamma > 0$ is the soil pollutant content (i.e. phosphorus) or the soil fixation rate, constant over time.

The real net revenue of farmer is given by:

$$\pi_t = pf(u_t, z_t) - cu_t - \tau e_t$$

where p and c are the prices of output and input, respectively and τ, the unit taxation of any positive emission. Given the perfect competition environment, prices are constant and are taken as given by farmers.

2.2 The farmer's program

The farmer is assumed to maximize the present discounted value of net returns from agricultural production with an infinite time horizon. Thus, the farmer's decision problem can be formulated as:

$$\max_{\{u_t\}} \int_0^{+\infty} [pf(u_t, z_t) - cu_t - \tau e_t] e^{-\rho t} dt \tag{4}$$

$$s.t. \quad \left| \begin{array}{l} \dot{z}_t = g - h(u_t, z_t) \\ z_0 > 0 \text{ given} \\ e_t = \eta(u_t) + \gamma h(u_t, z_t) \end{array} \right.$$

where ρ is the discount rate (real rate of interest). Without any loss of generality, we assume that p is a reference price equal to 1, $c > 0$ is the real unit cost of input use and τ the real unit tax.

Using Pontryagin's Maximum Principle, the associated Hamiltonian at date t in current value is:

$$H(u_t, z_t; \lambda_t) = f(u_t, z_t) - cu_t - \tau[\eta(u_t) + \gamma h(u_t, z_t)] + \lambda_t[g - h(u_t, z_t)]$$

where λ_t is the costate variable which can be interpreted as the shadow price of soil, or as the marginal rent of soil.

Optimal necessary conditions for interior solution writes:

$$\begin{aligned} f_u &= c + \lambda_t h_u + \tau[\eta'(u_t) + \gamma h_u] & (5) \\ \dot{\lambda}_t &= (\rho + h_z)\lambda_t - f_z + \tau\gamma h_z & (6) \end{aligned}$$

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and the transversality condition is:

$$\lim_{t \to +\infty} z_t \lambda_t e^{-\rho t} = 0. \tag{7}$$

By differentiating (5) with respect to time, it comes:

$$\dot{u}_t = \frac{h_u \dot{\lambda}_t + [(\lambda_t + \tau\gamma) h_{uz} - f_{uz}] \dot{z}_t}{[f_{uu} - \tau\eta''(u_t) - (\lambda + \tau\gamma) h_{uu}]} \tag{8}$$

where $\dot{z}_t$ and $\dot{\lambda}_t$ are determined by (2) and (6), respectively.

Static first order condition (5) tells that long any optimal trajectory, the marginal revenue of cultivation (i.e. the marginal productivity of input use) must be equal to the marginal cost of cultivation which is threefold: (a) the marginal cost c of using u_t units of input at time t, (b) the marginal cost of cultivation in terms of soil erosion, $\lambda_t h_u$, (c) the marginal cost of cultivation in terms of pollution marginal taxation, $\tau [\eta'(u_t) + \gamma h_u]$. Along the time path, u_t must be adjusted to satisfy at any time condition (5).

In the dynamic condition for optimality (6), $(\rho + h_z)$ reads as the marginal return rate of soil, or as the "soil discount rate"[3]. Then, $(\rho + h_z) \lambda_t$ is the marginal return of holding a unit of non-cultivated soil, λ_t being the unitary shadow price of soil. The other term of (6), $(f_z - \tau\gamma h_z)$, 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. Put differently, it denotes the marginal contribution of soil in the profit function. As a result, current marginal rent of soil λ_t grows over time as long as it is more profitable for farmer to let the soil non exploited rather than to cultivate it.

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[3]The farmer can invest a marginal unit of soil at rate ρ 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 $(\rho + h_z)$, where $h_z < 0$.

3 The environmental policy effect

3.1 Dynamic analysis

Our intention is to study the dynamics of the model described above, and to represent it within a (z, λ) diagram. The time argument t is suppressed for notational convenience. Beforehand, let $\widehat{u}(z)$ denote the optimal control under feedback form, solution of (5). The total derivation of (5) with respect to z and λ respectively, yields:

$$\frac{d\widehat{u}}{dz} = \frac{(\lambda + \tau\gamma) h_{uz} - f_{uz}}{f_{uu} - \lambda h_{uu} - \tau [\eta''(u) + \gamma h_{uu}]}, \tag{9}$$

$$\frac{d\widehat{u}}{d\lambda} = \frac{h_u}{f_{uu} - \lambda h_{uu} - \tau [\eta''(u) + \gamma h_{uu}]}. \tag{10}$$

Since $f_{uz} > 0$, $h_{uz} < 0$ by assumption and $\{f_{uu} - \lambda h_{uu} - \tau [\eta''(u) + \gamma h_{uu}]\} < 0$ by concavity of f and convexity of h, then $d\widehat{u}/dz > 0$ and $d\widehat{u}/d\lambda < 0$. Optimal intensity of input use increases with the soil depth and it decreases with the marginal rent of soil. Hence, the farmer becomes more conservative by reducing its input use as the soil weakens, which appreciates its marginal rent.

Define D^1 as the locus of the (z, λ) points where $\dot{z} = 0$, formally $D^1 = \{(z, \lambda) \in \mathbb{R}_{+*}^2 \mid \dot{z} = 0\}$. For any $(z, \lambda) \in D^1$, $h(u, z) = g$, where g is constant over time. Then, for any $(z, \lambda) \in D^1$, z and u are constant. From equation (5), we get the equation of the D^1-demarcation curve which is defined as follows:

$$\lambda(z) \mid_{\dot{z}=0} = \frac{f_u(u, z) - c - \tau [\eta'(u) + \gamma h_u(u, z)]}{h_u(u, z)}, \tag{11}$$

for any u such that $\dot{z} = 0$. The slope of this curve is measured by:

$$\lambda'(z) \mid_{\dot{z}=0} = \frac{h_u f_{uz} - [f_u - c + \tau\eta'(u)] h_{uz}}{(h_u)^2} \tag{12}$$

where $[f_u - c + \tau\eta'(u)]$ can be seen as the "direct" marginal profit of the farmer's, i.e. the part of the marginal profit which excludes the contribution of erosion. From (5), this last term equals $(\lambda + \gamma) h_u$, which is positive for any positive shadow price of soil. Hence, the D^1-demarcation curve is increasing in the (z, λ) plane. Finally, dynamics of z is 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, we define D^2, $D^2 = \left\{ (z, \lambda) \in \mathbb{R}^2_{+*} \mid \dot{\lambda} = 0 \right\}$. From (6), the equation of D^2-demarcation curve writes:

$$\lambda (z) \mid_{\dot{\lambda}=0} = \frac{f_z (u, z) - \tau \gamma h_z (u, z)}{\rho + h_z (u, z)}, \tag{13}$$

for any u such that $\dot{\lambda} = 0$. The gradient of this curve is determined by:

$$\lambda' (z) \mid_{\dot{\lambda}=0} = \frac{(\rho + h_z) f_{zz} - (\rho \gamma \tau + f_z) h_{zz}}{(\rho + h_z)^2}, \tag{14}$$

which is negative if $(\rho + h_z) > 0$. We assume $(\rho + h_z) > 0$ so that the D^2-demarcation curve is decreasing in the (z, λ) plane. The optimal dynamics of shadow price is the following: (a) λ increases 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. Optimal dynamics of (z, λ) is depicted in Figure 1.

[Place Figure 1 here]

The steady-state $(u_1^*, z_1^*, \lambda_1^*)$ of the optimal control problem is determined by the intersection of the D^1 and D^2-demarcation curves. Formally, it is characterized by the following equation system:

$$g = h (u_1^*, z_1^*) \tag{15}$$

$$[\rho + h_z (u_1^*, z_1^*)] \lambda_1^* = f_z (u_1^*, z_1^*) - \tau \gamma h_z (u_1^*, z_1^*) \tag{16}$$

$$h_u (u_1^*, z_1^*) \lambda_1^* = f_u (u_1^*, z_1^*) - c - \tau \left[\eta' (u_1^*) + \gamma h_u (u_1^*, z_1^*) \right] \tag{17}$$

Equation (15) means that optimal erosion must be balanced by pedogenesis to maintain a constant soil depth. Equation (16) tells that, at the stationary equilibrium, the farmer is indifferent to cultivate soil or not suggesting a constant marginal rent of soil. In fact, equation (16) 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). Similarly, from (17), 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). Combining equations (16) and (17), it comes:

$$\frac{\pi_u\left(u_1^*, z_1^*\right)}{\pi_z\left(u_1^*, z_1^*\right)} = \frac{h_u\left(u_1^*, z_1^*\right)}{\rho + h_z\left(u_1^*, z_1^*\right)} \tag{18}$$

where π_u denotes the marginal profit from using input and π_z, the marginal profit from cultivating soil. The necessary conditions for the existence of $(u_1^*, z_1^*, \lambda_1^*)$ are:

$$\rho + h_z\left(u_1^*, z_1^*\right) \;\; > \;\; 0, \tag{19}$$

$$f_u\left(u_1^*, z_1^*\right) - c - \tau\left[\eta'\left(u_1^*\right) + \gamma h_u\left(u_1^*, z_1^*\right)\right] \;\; \geq \;\; 0. \tag{20}$$

In other words, the soil discount rate and the marginal profit function must be positive at the stationary equilibrium.

This steady-state is represented by E_1 in the (z, λ) plane of Figure 1. For any initial soil depth, z_0, only one associated initial shadow price, λ_0, places the dynamic system along one of the two branches of the saddle-path which lead to stationary point E_1. Proposition 1 below summarizes all previous results.

Proposition 1 :

i) The optimal dynamic system (2)-(6)-(8) converges to a single steady-state $(u_1^*, z_1^*, \lambda_1^*)$ defined by equations (15), (16) and (17) if and only if conditions (19) and (20) are satisfied.

ii) Under the assumptions that the transversality condition holds and the assumptions that have been made on functions f and h, $(u_1^*, z_1^*, \lambda_1^*)$ is a saddle point (see proof in appendix).

3.2 Discussion on τ

Now, we undertake a sensitive analysis of parameter τ to drawn the effects of the environmental taxation on the optimal conservation of soil. First, as $\lambda(z)\mid_{\dot{z}=0}$ is decreasing in τ and $\lambda'(z)\mid_{\dot{z}=0}$ is increasing in τ (see equations (11) and (12) respectively), a reduction of the lump sum tax results in an upward shift of the D^1-demarcation curve with a lower slope. Second, since $\lambda(z)\mid_{\dot{\lambda}=0}$ is increasing in τ and $\lambda'(z)\mid_{\dot{\lambda}=0}$ is decreasing in τ (see equations (13) and (14) respectively),

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then a diminishing tax involves a downward shift of the D^2-demarcation curve with a more steep slope. Such moving are illustrated by Figure 2.

[Place Figure 2 here]

In Figure 2, 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, which is the purpose of proposition 2 below.

Proposition 2 : *At the stationary equilibrium, the environmental lump sum tax induces a more conservative farmer's behavior for soil management. The soil conservation increases as the environmental policy becomes restricting for the farmer.*

To really understand the complex effects of the environmental policy, it may be fitting to decompose them. First, from equation (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 compensate the tax surcharge by improving the agricultural yield.

While the effect on z is clearly identified, the effect on the level of e is ambiguous. In particular, it depends on the posological characteristics of soil, i.e. on function h and parameter γ. That can be emphasized by totally differentiating the emission function:

$$\Delta e = \eta'\left(u\right)\Delta u + \gamma\left[h_u \Delta u + h_z \Delta z\right]. \tag{21}$$

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

$$\frac{\Delta u}{\Delta z} < \frac{-\gamma h_z}{\eta'\left(u\right) + \gamma h_u}, \tag{22}$$

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where $-\gamma h_z$ and $[\eta'(u) + \gamma h_u]$ respectively denote the marginal (negative) contribution of soil conservation and the marginal contribution of input use in the emission of pollution. Hence, the lump sum tax causes pollution to decrease if the soil conservation the policy involves is important enough to balance the increment of pollution coming from an increase in the input use. In other words, the environmental policy exhibits a property of double dividend if the soil conservation effect overrides the intensity of input use effect which is risen by the policy in question.

3.3   Discussion on γ

As discussed in inequality (22), the environmental effect of emission taxation is proved to be ambiguous. In particular, it depends on parameter γ that 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.

[Place Figure 3 here]

When the indirect effect of soil erosion on pollution emissions is non-existent, i.e. $\gamma = 0$, then 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. 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   Pollution abatement

In this second version of the model, we assume that the farmer can invest into abatement technologies. Indeed, he must choose the level v_t of investment which will have an abatement effect on pollution coming only from the surface runoff. Net pollution from surface runoff at date t is then $\eta(u_t) / (1 + v_t)$ where

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$1/(1+v_t)$ reads as a cleaning up factor and v_t as the abatement rate. The marginal cost of abatement is b, assumed to be constant over time. The farmer's new program writes:

$$\max_{\{u_t,v_t\}} \int_0^{+\infty} \left[f\left(u_t,z_t\right) - cu_t - bv_t - \tau e_t\right] e^{-\rho t} dt \tag{23}$$

$$s.t. \quad \left| \begin{array}{l} \dot{z}_t = g - h\left(u_t,z_t\right) \\ z_0 > 0 \text{ given} \\ e_t = \frac{\eta(u_t)}{1+v_t} + \gamma h\left(u_t,z_t\right) \end{array} \right.$$

Static first order conditions are:

$$f_u - c = \lambda h_u + \tau \left[\frac{\eta'(u)}{(1+v)} + \gamma h_u\right], \tag{24}$$

$$\tau \frac{\eta(u)}{(1+v)^2} = b. \tag{25}$$

Condition (24) calls to the same comments than condition (5). Condition (25) equalizes the marginal benefit of abatement investment and the marginal cost of this abatement. Equivalently, (24) writes $v = \left[\tau\eta\left(u\right)/b\right]^{1/2} - 1$: the optimal abatement intensity is an increasing function of the lump sum tax and the intensity of input use and a decreasing function of its marginal cost b. Since dynamic optimal condition (6) remains unchanged, the abatement policy affects the dynamics of z and not the dynamics of λ. The equation of the D^1 representative curve becomes:

$$\lambda\left(z\right)^a \big|_{\dot{z}=0} = \frac{f_u\left(u,z\right) - c - \tau \left[\frac{\eta'(u)}{1+v} + \gamma h_u\left(u,z\right)\right]}{h_u\left(u,z\right)}, \tag{26}$$

for any u and v such that $\dot{z} = 0$ and where subscript a in $\lambda\left(z\right)^a$ means that abatement effort acts as a control variable. After developments and simplifications, we have:

$$\lambda\left(z\right)^a \big|_{\dot{z}=0} = \lambda\left(z\right) \big|_{\dot{z}=0} + \left(\frac{v}{1+v}\right) \frac{\tau\eta'(u)}{h_u} > \lambda\left(z\right) \big|_{\dot{z}=0} \tag{27}$$

where $\lambda\left(z\right) \big|_{\dot{z}=0}$ is defined by (11). 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 does not react as illustrated by Figure 4. Proposition 3 summarizes those effects.

[Place Figure 4 here]

Proposition 3 : *A positive investment into abatement technologies involves a diminution of the stationary conservation of soil. This effect is proportional to $v/(1+v)$ and soil conservation decreases as v increases.*

The trade-off between intensity culture and soil conservation remains the same: the input use increases pollution emissions and soil conservation decreases them. Hence, the effect of an abatement effort and the effect of the environmental tax on pollution emission are opposed. Abatement expenditures allow 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:

$$\Delta e = \left[\frac{\eta'(u)}{(1+v)} + \gamma h_u \right] \Delta u - \frac{\eta(u)}{(1+v)^2} \Delta v + \gamma h_z \Delta z \qquad (28)$$

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

$$\Delta e = \left[\frac{\eta'(u)}{2} \left(\frac{\tau\eta'(u)}{b} \right)^{-1/2} + \gamma h_u \right] \Delta u + \gamma h_z \Delta z \qquad (29)$$

The first term of the right hand side of (29) is negative since term in brackets is positive and Δu is negative in the case of an increase in the abatement effort (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:

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

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

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and the intensivity culture. 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.

To compensate the fiscal fees associated to environmental tax, 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 weight of erosion rate into the emission function. The smaller is this weight, the larger is the positive effect of environmental policy on pollution and the smaller is the conservation of soil in the long run. The same mechanism can be obtained with abatement expenditures.

An interesting extension of our model is to study other environmental policy instruments, such as quotas and tradable emission permits, in order to test the robustness of our main results.

Appendix: Stability of the steady-state

The stability properties of the steady-state that is characterized in Proposition 1 can be determined by linearizing the dynamic system in (z, λ) around (z_1^*, λ_1^*). First, define $F(z, \lambda)$ as follows:

$$F(z, \lambda) = \begin{pmatrix} \dot{z} \\ \dot{\lambda} \end{pmatrix} = \begin{bmatrix} g - h(u, z) \\ (\rho + h_z)\lambda - f_z + \tau\gamma h_z \end{bmatrix}. \tag{30}$$

The Jacobian matrix of $F(z, \lambda)$, formally $J(z, \lambda) = dF(z, \lambda)$, is:

$$J(z, \lambda) = \begin{bmatrix} -h_z - h_u \frac{du}{dz} & -h_u \frac{du}{d\lambda} \\ (\lambda + \tau\gamma)\frac{dh_z}{dz} - \frac{df_z}{dz} & (\rho + h_z) + (\lambda + \tau\gamma)\frac{dh_z}{d\lambda} - \frac{df_z}{d\lambda} \end{bmatrix} \tag{31}$$

where $dh_z/dz = h_{zz} + h_{zu}du/dz$, $df_z/dz = f_{zz} + f_{zu}du/dz$, $dh_z/d\lambda = h_{zu}du/d\lambda$ and $df_z/d\lambda = f_{zu}du/d\lambda$. Since $h_u du + h_z dz = 0$ at the steady-state, determinant of matrix $J(z, \lambda)$ evaluated at (z_1^*, λ_1^*) can be computed, after some rearrangements, as:

$$\det J(z_1^*, \lambda_1^*) = h_u \frac{du}{d\lambda}\left\{(\lambda + \tau\gamma)h_{zz} - f_{zz} - [(\lambda + \tau\gamma)h_{zu} - f_{zu}]\frac{du}{dz}\right\}. \tag{32}$$

Since $du/dz > 0$, $du/d\lambda < 0$ (see (9) and (10) respectively), $h_u > 0$, $h_{zu} < 0$, $h_{zz} > 0$, $f_{zu} > 0$ and $f_{zz} < 0$, then $\det J < 0$ which means that the product of the two eigenvalues of J is negative. As a result, eigenvalues of J are opposite signed and (z_1^*, λ_1^*) is a saddle point.

Since the dynamic system allows two converging director vector and two diverging director vectors, three cases are conceivable for any initial point (z_0, λ_0):

(a) in quadrant I and II of Figure 1, (z_0, λ_0) places the dynamic system along one of the two branches of the saddle path and the system converges to the steady-state;

(b) the dynamic system is initially located in quadrant III or it deviates towards quadrant III;

(c) the dynamic system is initially located in quadrant IV or it deviates towards quadrant IV.

One can check that cases (b) and (c) do not satisfy transversality condition (7) and then, the only feasible asymptotic solution is (z_1^*, λ_1^*) as depicted by E in Figure 1.
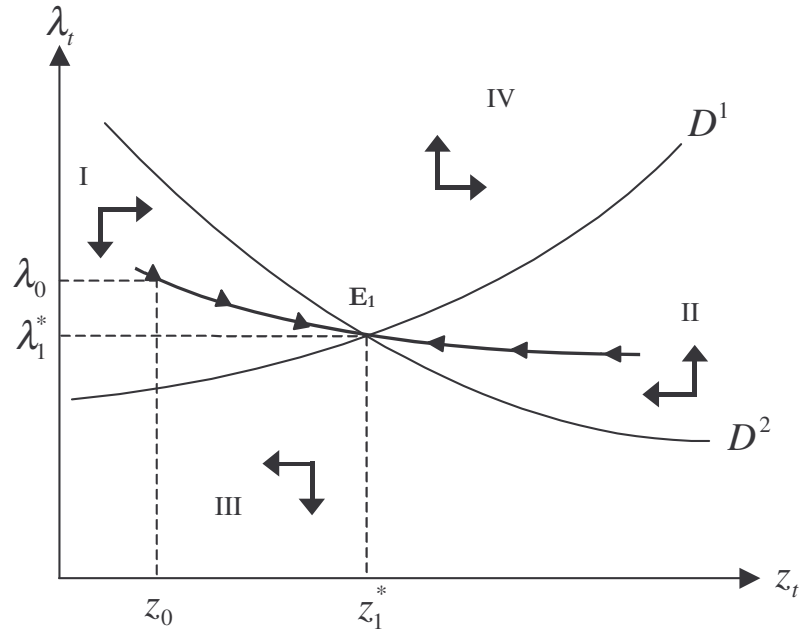
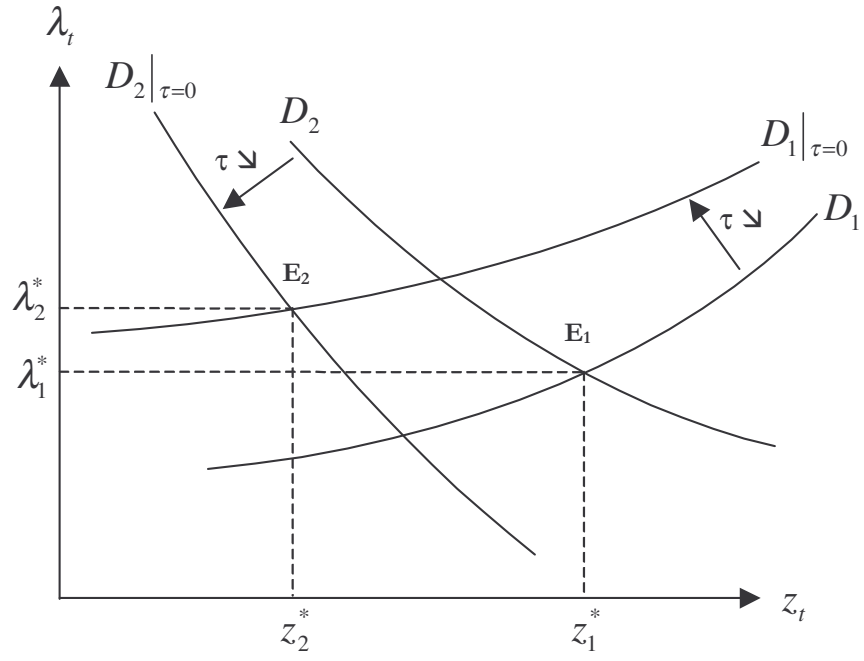Figure 1: Dynamic optimal management of soil erosion.

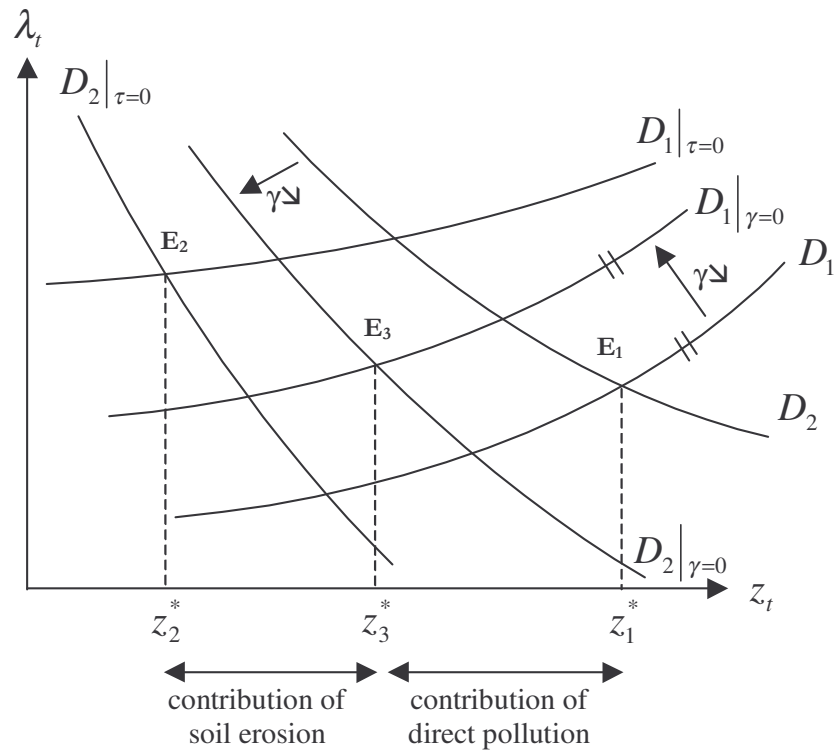Figure 2: Effect of the environmental policy on optimal dynamics.
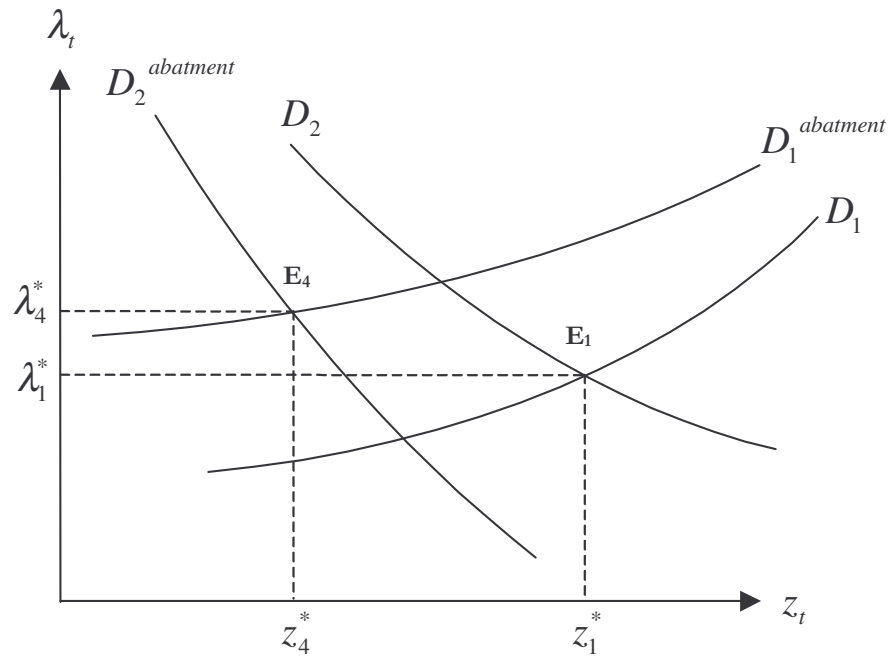
Figure 3: Soil erosion as pollution source.

Figure 4: Effect of abatement technologies.

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(lxvii) This paper has been presented at the international conference on "Tourism and Sustainable Economic Development – Macro and Micro Economic Issues" jointly organised by CRENoS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003

(lxviii) This paper was presented at the ENGIME Workshop on "Governance and Policies in Multicultural Cities", Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference "The Future of Climate Policy", Cagliari, Italy, 27-28 March 2003

(lxx) This paper was presented at the 9th Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004

(lxxi) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications", organised by Fondazione Eni Enrico Mattei and Consip and sponsored by the EU, Rome, September 23-25, 2004

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(lxxiv) This paper was presented at the ENGIME Workshop on "Trust and social capital in multicultural cities" Athens, January 19-20, 2004

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(lxxvi) This paper was presented at the 3rd Workshop on Spatial-Dynamic Models of Economics and Ecosystems held in Trieste on 11-13 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics

(lxxvii) This paper was presented at the Workshop on Infectious Diseases: Ecological and Economic Approaches held in Trieste on 13-15 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics.