Setting Pigouvian taxes correctly
an extension

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Abstract

This paper analyses the determination of an optimal pigouvian tax for an agricultural multioutput production process, where a negative production externality is present concurrent with the utilisation of a natural resource. In particular, the situation is analysed where the standard assumption that the quasirent is concave in the 'inputs' does not hold. The results show that the determination of the optimal pigouvian tax may require less information about the control and damage costs and can be calculated more easily in this case. The analysis is extended by a dynamic specification of the production process. As in the static case, the determination of the pigouvian tax may be facilitated considerably. However, it does not open the way for a reduction of the data requirement. An additional analysis of non-optimal intertemporal allocation of resources indicates that pigouvian taxes to correct this market failure can be obtained in a straightforward manner, if the socially desired intertemporal allocation is given.
1 Introduction

In contrast to conventional firm micro theory, cases of market failures such as externalities or the non optimal intertemporal allocation of natural resources employed in the production process are the focus of resource economic theory. If a production externality is present, Pigou (1932) suggested a pareto optimal solution by the imposition of a tax or subsidy related to the ‘emission’ which causes the negative or positive externality. An optimal tax or subsidy implies a zero price for the consumption of the externality and a nonzero price to the producer of the externality. In this way, the ‘costs’ for producing external benefits or damages resulting from external costs can be compensated (Baumol and Oates, 1988). As such, it is possible to simulate a ‘market’ for externalities to correct for the underlying cause of externalities – the lack of well-defined or appropriately defined property rights. It is quite clear that no normal market price can play this double role, and therefore an authority is needed to establish this ‘market’. Criticisms of the ‘pigouvian solution’ are numerous, see for example Pearce and Turner (1990). The application of pigouvian taxes seems to be particularly troublesome in the real world. Hence, non market mechanism (i.e. regulation) or voluntary bargains struck among the interested parties were also proposed to reduce or prevent externalities. However, pigouvian taxes can be considered as a first best environmental policy⁠¹ to achieve the socially desired ends if it would be possible to measure the costs and benefits associated with the externality (Cropper and Oates, 1990).

Traditionally, pigouvian taxes have been analysed where the externality originated from a production process of a single good. Yet, agricultural production is usually depicted by the simultaneous production of several goods and the intensive utilisation of natural resources like water, air or land. As a result of this setting, the paper characterizes situations where the traditional assumption on the concavity of the monetary benefit function in the inputs is questioned. It identifies the optimal pigouvian tax when the monetary benefit function is linear or convex in the ‘inputs’ where the natural resources employed in the production process are subject to an externality or they are not optimally allocated over time. In particular, conditions are stated where the pigouvian tax can be calculated easily and little information about the costs and benefits associated with the externality is needed. In the first section of the paper a static firm model is utilised for the analysis of optimal pigouvian taxes in the presence of production externalities. The second section extends this analysis to include the behaviour of the firm under dynamic specifications, with particular reference to the problem of the optimal intertemporal allocation of natural resources employed in the production process. A summary and conclusions close out the paper.

2 Pigouvian taxes for a static multioutput production process

Technical restrictions and the availability of fix factors preclude the inclusion of all feasible combinations of outputs in the farmers’ production possibility set. Generally, only a limited set of production alternatives are simultaneously available to the farmer. This set, termed
production system, is based on \( k \) production functions \( f \) given by

\[
y_j = f_j(x_1, x_2) \quad j = 1, \cdots, k
\]

where \( x_1 \) is a vector of inputs, \( x_2 \) a vector of flows of inputs from natural resources and \( y \) a vector of outputs. Following usual assumption about the qualitative properties of \( f \) it is proposed that \( \frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2} \leq 0 \). Let a set of production systems be characterized by a low, medium or high level of intensity for a cropping system on one hectare of land. Each production system may cause positive or negative production externalities. The following discussion, however, is framed in terms of negative production externalities in order to be more specific.

Some examples of negative externalities resulting from agricultural production are nitrate groundwater pollution, loss of biodiversity or in-stream and off-stream impacts caused by agricultural pollutants in surface waters such as phosphorus or pesticides run off. In case the property rights to ‘pollute’ are not assigned to the farmer he will be liable for negative production externalities, and it is suggested to tax the farmer (Zilberman and Marra, 1993). For the contrary it is proposed to subsidise the farmer.

It is assumed here that farmers are competitive price takers, and economically rational. It is further assumed that a price for every input associated with a cropping system with a low, medium or high intensity can be assigned. Thus, the private quasirent for a particular production system \( \phi \) can be calculated and is given by

\[
\phi = p \cdot y - v_1 \cdot x_1 - v_2 \cdot x_2
\]

where \( p \) is a vector of prices corresponding to \( y \), and \( v_1, v_2 \) are vectors of prices corresponding to \( x_1, x_2 \) respectively. Looking at the examples of negative production externalities given above, it is proposed that the intensification of the agricultural production leads in general to a more severe negative production externality, \( z \). The term, \( z \) is interpreted as the level of intensity of the agricultural production. Hence, a function \( g \) exists given by

\[
z = g(x_1, x_2)
\]

The increasing severity of the production externality caused by the intensification of the production suggests that \( \frac{\partial z}{\partial x_1} \) and \( \frac{\partial z}{\partial x_2} \) are positive. With these provisions, it is assured that the private quasirent \( \phi \) is a function of the level of the production intensity for a particular production system. That is,

\[
\phi = \varphi(z)
\]

The function \( g \) is a strictly monotonic transformation of the inputs. Hence, \( \varphi(z) \) will be concave with a unique maximum. In Figure 1 three examples of the function \( \varphi_i(z) \), \( i = 1, 2, 3 \) are presented by dashed lines reflecting a low, medium and high level of intensity of a production system. The private quasirent for all the three production systems \( \Phi \) is given by the envelope of the functions \( \varphi_i(z) \) for \( i = 1, 2, 3 \). For analytical purposes, the envelope will usually be approximated such that it is continuous and differentiable. Overall, it should present the essence of the quasirents for all considered production systems.
Usually $\Phi$ will be concave in $z$. However, if $z^i_0$, the maximum of $\varphi_i(z)$, $i = 1, 2, 3$, increases overproportionally and the intensification of the production system is limited by the flow of an input from a natural resource, the private quasirent $\Phi$ may be convex in $z$. Empirical evidence has shown that this is the case for agricultural production systems on peatlands (Goetz and Lehmann, 1994). Another example may be where sufficient precipitation limits a further intensification of the production in the convex range of $\Phi$.

In the presence of a negative production externality, the costs and benefits of abating the negative production externality need to be considered while maximizing $\Phi$. Thus, the social quasirent $\Psi$ is given by

\[ \Psi = \Phi - (c + d) \]

where $c = c(z)$ denotes the costs and $d = d(z)$ denotes the benefits of abating the negative production externality. The latter term is frequently called damage costs. In line with the literature it is proposed that $c + d$ is convex and $\Phi$ is concave, see for example Baumol and Oates (1988); Pearce and Turner (1990). A social planner who wants to maximise $\Psi$ would obtain the necessary condition,

\[ \Phi' - (c' + d') = 0 \]

for an interior solution. A solution for (6) exists and is unique as a result of the assumptions of the qualitative properties of $\Phi, c$ and $d$. Hence, the internalisation of the externality requires setting the pigouvian tax equal to the marginal costs at the socially optimal level.
The following three propositions state how to determine the optimal pigouvian tax, if $\Phi$ is convex or linear. Please note that in this case $\Phi$ will only take a unique maximum if it is defined on a closed interval, i.e. $z \in [0, b]$. 

**Proposition 1** If $\Phi'(b) \leq c'(b) + d'(b)$ and $\Phi'(0) \geq c'(0) + d'(0)$ then the optimal pigouvian tax should be set equal to $c'(z^*) + d'(z^*)$ where $z^*$ solves (6).

**Proof:** The derivatives of $\Phi, c$ and $d$ are monotonically increasing on the interval $[0, b]$. Hence, a comparison of their boundary values qualifies to show that the conditions stated in proposition 1 are sufficient for the existence and uniqueness of a solution for (6).

**Proposition 2** If $\Phi'(b) > c'(b) + d'(b)$ and $\Phi'(0) > c'(0) + d'(0)$ then the optimal pigouvian tax should be set to zero.

**Proof:** The conditions of this proposition and the positive signs of the derivatives of $\Phi, c$ and $d$ clearly suggests that an interior solution of (6) does not exist and $\Psi$ takes its maximum at the boundary of its domain, i.e. at 0 or $b$. Without loss of generality assume that $\Psi(0) = 0$. In case it does not hold, the coordinates need to be changed such that $\Psi(0) = 0$. The positive sign of $\Psi'$, and the conditions of this proposition assures that $\Psi(b)$ is positive. The socially optimal $z$ will be obtained by choosing $b$ which implies that the production system with the highest level of intensity should be chosen.

**Proposition 3** If $\Phi'(b) < c'(b) + d'(b)$ and $\Phi'(0) < c'(0) + d'(0)$ then the optimal pigouvian tax is equal to $\Phi(z)$.

**Proof:** As in the proof of proposition 2 a solution of (6) does not exist and $\Psi(0) = 0$. Taking account of $\Psi' > 0$ and the conditions of this proposition, results in $\Psi(b)$ being negative. Thus, the optimal $z$ is equal to zero. In case the coordinate were not changed it is proposed that no production should take place. Otherwise, the level of intensity should be chosen such that the negative production externality is zero.

This analysis shows that for the case of a linear or convex private quasirent function, when negative production externalities are present, the determination of the socially optimal pigouvian tax may; 1.) require less information with respect of the costs and benefits of abating the externality and 2.) be determined more easily. Propositions 2 and 3 indicate that only the signs of $\Phi', c'$ and $d'$ as well as their values at the points 0 and $b$ need to be known. In case proposition 2 or 3 do not hold, the required information and the effort for the determination of the optimal pigouvian tax coincides with a concave, linear or convex private quasirent function. In each case the functions $\Phi, c$ and $d$ and their derivatives need to be known for all $z \in [0, b]$.

In this section it has been assumed that the negative production externalities do not accumulate over time, or the flow of inputs from a natural resource is independent of the intensity of its previous utilisation. However, if it proves otherwise the time needs to be considered explicitly as it is done in the next section.
3 Pigouvian taxes for a dynamic multioutput production process

If the utilisation of a natural resource alters the state of the resource, i.e. degradation or melioration, the current production has an impact on the production in the future. Similarly, a negative production externality which 'discharge' accumulates over time influences the severity of the negative production externality in future time periods. Mathematically, the so called 'law of motion' can be described by

\[ \dot{s} = h(s(t), z(t), t) \]  

where \( s \) denotes the available stock, which is either the stock of a natural resource or of a negative production externality. The dot in (7) characterizes the derivative with respect of the variable \( t \) which respresents time. To simplify notation the argument \( t \) of the functions \( s, z \) and the function \( \lambda \) to be introduced later will be suppressed, unless it is necessary for an unambiguous notation. Although the farmer owns the property right for the utilisation of a natural resource a market failure may still occur, if the private and social discount rates differ or if a lack of information or uncertainty about the future prevents the farmer from an optimal intertemporal allocation of this natural resource. This may be the case for the resource soil and examples are given by: the erosion of the top layer of mineral soil on cultivated land, the subsidence of cultivated peatland, or the increasing salinity of cultivated land resulting from irrigation. This section will also include this kind of market failure in the analysis besides that of negative production externalities.

The social quasirent taking account of negative production externalities and the non-optimal intertemporal allocation of a private owned natural resource is given by

\[ 
\Psi = \begin{cases} 
\Phi & ; \text{intertemporal allocation of a resource} \\
\Phi - D & ; \text{negative production externality} 
\end{cases} 
\]

where \( D = D(z, s) \) takes account of the simultaneous influence of \( z \) and \( s \) on the control and damage costs. A social planer is thus confrontrated with the following optimal control problem:

\[ \max_\mathcal{Z} \int_0^T e^{-\rho t} \Psi(s, z, t) \, dt + e^{-\rho T} S(s(T)) \]  

subject to

\[ \dot{s} = h(s, z, t) \]
\[ s(0) = s_0 \quad z \geq 0 \]

where \( \rho \) respresents the social discount rate and \( S = S(s(T)) \) the value of the stock at the end of the planning horizon, \( T \). The corresponding current value Hamiltonian results in

\[ \mathcal{H} = \Psi(s, z, t) + \lambda h(s, z, t) \]
where $\lambda$ denotes the costate variable. The necessary conditions for a solution in the interior of the domain of $z$ are given by

$$
\begin{align*}
\mathcal{H}_z &= \Psi_z + \lambda h_z = 0 \\
\dot{\lambda} &= \rho \lambda - \mathcal{H}_s \\
\dot{s} &= h \\
s(0) &= s_0
\end{align*}
$$

and the transversality condition states that

$$
\lambda(T) = \begin{cases} 
S_s & ; \text{intertemporal allocation of a resource} \\
0 & ; \text{negative production externality}
\end{cases}
$$

where the subscript of a variable denotes its partial derivative.

A solution to the problem $P$ exists, if the values $z^*, s^*$ and $\lambda^*$ satisfy the necessary conditions and $\lambda^*(T)$ the transversality condition. These conditions will be sufficient for a solution of $P$ if $H$ is jointly concave in $s$ and $z$, (Seierstad and Sydsæter (1987), theorem 3, p. 182). Yet, in this general form it will not be possible to take the solution process much further than the mere statement of the necessary and sufficient conditions. As in the first section of this paper, the case where $\Psi$ is linear or convex in $z$ will be analysed with respect of the determination of the optimal pigouvian tax in particular. As it turns out, these qualitative properties of $\Psi$ may facilitate the solution process of $P$ and the specification of the optimal pigouvian tax to a great extent. As in the static case, the optimal pigouvian tax can be obtained by the solution of the necessary conditions, given by equations (11) and (12). Particular importance is given to the values of $\lambda$ which are called user costs and represent the marginal value or shadow price of the stock (Dorfman, 1969). In the case of a negative production externality, $\lambda$ represents the marginal value of a change in $s$. The user costs reflect the marginal value of the private quasirent and the marginal cost of the negative production externality as a result of a change in the accumulated 'discharge'. Hence, the optimal pigouvian tax is given by the part of the user costs which accounts for the marginal costs. Similarly, the optimal pigouvian tax for the case of a non optimal intertemporal allocation of a natural resource is given by the part of the user costs which considers only the over or under utilization of the resource in the particular time period. The following propositions characterize two classes of models which can be solved easily and allow to determine the optimal pigouvian tax. Please note that if $H$ is linear or convex in $z$ an upper bound, $b$, is required for the existence of a maximum of $H$. Hence, $H$ will be replaced by a Lagrangian $L$, simply requiring to append $\omega(b - z)$ in equation (10) where $\omega$ is a Lagrange multiplier. The condition $z \geq 0$ is not considered here since a non positive $z$ will not yield a maximum for problem $P$.

**Proposition 4** If the problem $P$ is autonomous and $\Psi$ and $h$ are linear in $s$ and $z$, the optimal pigouvian tax can be calculated from the solution of the differential equation

$$
\dot{\lambda} = \rho \lambda - \mathcal{H}_s(\lambda, s^*, b)
$$

The optimal pigouvian tax in case of a negative production externality will be constant and in case of a non optimal intertemporal allocation it will be increasing or decreasing exponentially.
Proof: Feichtinger and Hartl (1986) showed that under the provision of the conditions stated in proposition 4, \( z \) takes its optimal value at \( b \), the upper bound of its domain. Hence, the differential equation \( \dot{s} = h(s, b) \) can be solved by separation of the variables where the constant of integration is determined by the initial condition \( s(0) = s_0 \). Consequently, the necessary condition \( \dot{\lambda} = \rho \lambda - \mathcal{H}_s(\lambda, s^*, b) \) can be solved for \( \lambda \) where the constant of integration is determined by the transversality condition \( \lambda(T) = S_s(s^*(T)) \). The solution is given by

\[
\lambda = c_1 e^{\rho - b_3} + b_1 - b_2
\]

where the constant of integration, \( c_1 \), remains in this general form to simplify the notation. The parameter \( b_i, i = 1, 2, 3 \) are the linear factors of \( s \) in the private quasirent function, the control and damage costs function and the 'law of motion' respectively (see section 3.1 for more details). Thus, \(-b_2\) represents the marginal costs of the negative production externality which coincide with the optimal pigouvian tax. Looking at the case of the non optimal intertemporal allocation of \( s \) suggests that \( b_2 \) is equal to zero and the optimal pigouvian tax is given by \( \lambda \) times the units of the stock which are over or underused.

Proposition 5 If \( \Psi \) in problem \( P \) is strictly convex in \( z \), \( h = h_1(s, t) + h_2(s, t)z \) and the switching function \( \sigma(t) \) is not equal to zero for a positive time interval, the optimal pigouvian tax can be calculated from the solution of

\[
\dot{\lambda} = (\rho - h_s(s^*, t))\lambda - \Psi_s(s^*, b, t)
\]

Proof: The idea is to reduce the convex problem to the case of a linear one by the construction of a linear function \( \tilde{\Psi} \) whose graph lies above the one of \( \Psi \). This function is given by

\[
\tilde{\Psi} = \frac{\Psi(s, a, t)b - \Psi(s, b, t)a}{b - a} + \frac{(\Psi(s, b, t) - \Psi(s, a, t))}{b - a}z
\]

where \( a \) is the lower bound of \( z \) and is equal to zero according to problem \( P \). Please note that \( \Psi(a) = \tilde{\Psi}(a) \) and \( \Psi(b) = \tilde{\Psi}(b) \). The switching function \( \sigma \) is given by \( \mathcal{L}_z = 0 \) and states the necessary condition for an interior solution. Hence, the condition \( \frac{d}{dt}\sigma \neq 0 \) satisfied for all time intervals of positive lengths ensures that an interior solution will not occur. Theorem 3.3 of Feichtinger and Hartl (1986) stipulates that, under the conditions stated in proposition 5, the replacement of \( \Psi \) by \( \tilde{\Psi} \) in the decision problem \( P \) will yield the same optimal values \( s^*, z^*, \lambda^* \), and particularly \( z^* \) is given by \( b \). Consequently the differential equation, \( \dot{s} = h(s, b, t) \) can be solved and \( s^* \) is obtained. Thereafter, the nonhomogenous differential equation \( \dot{\lambda} = (\rho - h_s(s^*, t) - h_2(s^*, t))\lambda - \Psi_s(s^*, b, t) \) can be solved. The constants of integration for these two differential equations are again determined by the initial and the transversality conditions respectively. The optimal pigouvian tax in case of a non optimal intertemporal allocation is given by the solution of (14) where the control and damage costs are constantly zero. Thus, the optimal pigouvian tax in case of a negative production externality is given by the difference of the solution of (14) with and without control and damage costs.
The propositions 4 and 5 put two models forward where certain linearity or convexity conditions facilitate the solution process because $z$ takes its upper boundary value. As a result the simultaneous differential equation system in $s$ and $\lambda$ can be decoupled and solved successively. The optimal pigouvian tax can then be derived from $\lambda^*(t)$ and will also depend on time. In contrast to the case of the static multioutput production process it is not possible to identify situations where only the sign of the derivatives of the control and damage costs and its values at the boundary need to be known for the determination of the optimal pigouvian tax. The dynamic multioutput production process requires ‘full knowledge’ of the control and damage costs. However, the solution process may be considerably facilitated. The application of pigouvian taxes to correct for non optimal intertemporal allocation of resources seems to be more encouraging. If the socially desired utilisation of the resource is known, the optimal pigouvian tax can be easily obtained. This may be the case for a renewable resource like soil where sustainable agricultural production requires that $s = 0$, i.e. the soil erosion in tons per hectare should equate the soil genesis. However, if the socially desired utilisation of the resource is not exogenously determined, additional data is required in the form of a benefit function for this particular resource.

3.1 An example

Some specification of the models proposed in proposition 4 and 5 may illustrate its prospective applications. The Hamiltonian for a model according to proposition 4 reads as

$$\mathcal{H} = a_1z + b_1s - (a_2z + b_2s) + \lambda(a_3z + b_3s)$$

where the first two terms of the sum represent the private quasirent, the third and fourth the control and damage costs and the last two the ‘law of motion’. For the example of soil erosion $a_2$ captures the influence of the intensity on the depth or fertility of the top soil and would be expected to have a negative sign. The parameter $b_3$ would be positive and represents a factor for soil genesis. In the case of ground water pollution $a_3$ would be positive and depicts the pollutant ‘discharge’ where $b_3$ captures the constant decay of the stock of pollutant. Similarly, the model outlined in propositions 5 could be employed to model the applications just mentioned. Instead of constant factors, functions of $s$ and $t$ will be utilised. However, the underlying causalities remain the same and a further discussion is therefore not taken up.

4 Summary and conclusions

In the presence of market failures such as negative production externalities concurrent with the utilisation of natural resources, or the non optimal intertemporal allocation of natural resources, pigouvian taxes have been proposed to achieve efficient resource allocation. Their determination is analysed for a static agricultural multioutput production process where a flow of inputs from natural resources is utilised. All inputs are represented by a single
variable that captures the level of intensity of the production. A successive intensification of the production process enables the farmer to switch from a low, medium to a high intensive production system. As a result, a particular situation may occur where the quasirent of the farmer is linear or convex in the 'inputs' which is in contrast to the standard assumption of concavity. The results of the analysis show that the optimal pigouvian tax may be calculated more easily and less information about the control and damage costs are required. The extension of the analysis to the case of a dynamic agricultural production process shows some similarities to the static case. The determination of the optimal pigouvian tax is facilitated when appropriate linearity or convexity conditions hold. However, the control and damage costs need to be known completely. The additional analysis of non optimal intertemporal allocation of resources shows that pigouvian taxes can be derived easily, if the socially desired utilisation of the resource is determined exogenously. Thus, the argument against the employment of pigouvian taxes, requiring information which is difficult to obtain, does not apply here. Yet, if the socially optimal utilisation of the resource is not known, it needs to be determined endogenously. This might be accomplished by the specification of a benefit function for this resource, based on market or non market valuation methods, and the simultaneous consideration of private and social benefits. The simultaneous optimisation of private and social benefits in a dynamic setting is viewed as a fruitful and necessary perspective for further research.
Notes

1 Various other problems, e.g. the case of market imperfection may preclude the considerations of a pigouvian tax as a first best environmental policy. Yet, this paper will not consider these situations since it focuses on a particular extension of the determination of the optimal pigouvian tax.

2 The suggested analytical framework would also be suitable for positive production externalities. The results on the contrary cannot simply be transferred. An analysis of the necessary conditions in equations (6) and (11) with respect of the qualitative properties of a function capturing the positive production externality is indispensable.

3 The theoretical equivalence of both cases - taxes and subsidies - has been shown in the literature (Cropper and Oates, 1990). It should be noted however, that subsidies increase profits while taxes decrease them. Thus, the choice of the policy instrument can have quite different implications on the farmers' entry-exit decision which are not accounted for in this paper.

4 The stock may refer to the quantity such as the depth of the top soil layer, or to the quality suchlike soil fertility or the concentration of $NO_3$ in the groundwater.
References


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