The Optimal Intertemporal Management of the Soil and Phosphorus and the Equilibrium in Economic and Biophysical Models

Renan-Ulrich Goetz
e-mail: renan.goetz@udg.es

Alois Keusch

Paper prepared for presentation at the X[th] EAAE Congress
'Exploring Diversity in the European Agri-Food System',
Zaragoza (Spain), 28-31 August 2002

The Optimal Intertemporal Management of the Soil and Phosphorus and the Equilibrium in Economic and Biophysical Models

Renan-Ulrich Goetz*, University of Girona, Spain
Alois Keusch*, Credit Suisse, Zurich, Switzerland

mailing address:
Renan-Ulrich Goetz, Universitat de Girona, Departament d'Economia, Campus Montilivi, 17071 Girona, Spain, e-mail: renan.goetz@udg.es, tel: +34 972 418719, fax: +34 972 418032

The senior authorship is shared by both authors.

The Optimal Intertemporal Management of the Soil and Phosphorus and the Equilibrium in Economic and Biophysical Models

Abstract:
The paper proposes the use of meta models to determine the optimal intertemporal management of soil and phosphorus losses from agricultural land. This approach allows finding a equilibrium of the economic and biophysical system simultaneously. In contrast to the existing literature the model takes account of nonlinear relationships and of a large number of agricultural activities. The mathematical problems arising from this complex setup are addressed and the model is solved numerically. The results show that the second best policy in form of soil protection scores is highly inefficient, while another second best policy in form of land-use taxes is nearly as efficient as the first best policy.

Key words: Soil erosion; Phosphorus runoffs; Land-use tax; Soil protection scores, Dynamic optimization

The Optimal Intertemporal Management of the Soil and Phosphorus and the Equilibrium in Economic and Biophysical Models

1. Introduction

The cultivation of arable crops may causes soil losses, in particular at locations that are highly vulnerable. Soil losses lead to a decrease in productivity at the field level that can only be compensated in part by an increase in the amount of input (Lal, et al., 1983). Moreover, they cause runoff of particulate phosphorous into surface water which is responsible, together with soluble phosphorous, for the eutrophication of surface water (Wehrli and Wüest, 1996).
The intensification of agriculture, the expansion of arable land, the development of new agricultural land and the cultivation of erosive crops at vulnerable locations have aggravated the situation of soil losses in Switzerland.[1] Soil losses for arable crops vary for instance between 1 t/ha for grassland and 25 t/ha for corn within the watershed of Lake Baldegg. In average it is about 11 tons per hectare (Maurer, 1995). Generally soil erosion and phosphorous runoff are both of prime importance within the area of the watersheds of the lakes located in central Switzerland, particularly the area of Lake Baldegg, Sempach, and Hallwil.

While effects of soil losses leading to a reduction in productivity are of great importance for entire countries with periodically intensive rainfalls, the effects of phosphorous losses are in the center of interest for countries of the temperate zones, such as Switzerland. Moreover, often it is possible to restrict the problem of soil and phosphorous losses within these countries to a particular area.[2]

A number of studies indicate that the costs associated with the productivity loss, the so-called on-farm cost, are relatively low for agricultural farms within the temperate zones. According to Colacicco et al. (1989) the on-farm costs of soil erosion are negligible for the 10 analyzed regions within the United States. They are only at about 0.2 to 1 US$ per ton/acre of lost soil. Smith and Skaykewich (1990) obtain values of from 0 to 0.99 CA$ per ton/acre for different soils in Manitoba, Canada. Both studies analyzed a planning horizon of 100 years.
Schmid et al. (1997) situate the on-farm cost for Swiss conditions between 2 and 2.57 CHF ton/ha with a one year planning horizon. A longer planning horizon increases the on-farm costs for the initial year but decreases them for the later years. Overall, these studies demonstrate that on-farm costs for farmers in temperate zones on average are not significant and there is no incentive for farmers to employ erosion control measures.

In contrast, off-farm costs seem to be much higher. These costs consider the effects of soil erosions that occur beyond the limit of the farm, mostly as a result of the degradation of the water quality and/or sedimentation processes. For example these additional costs could arise due to additional purification and treatment costs for water utilities or additional maintenance cost for rivers, canals, dams and water reservoirs.

---

[1] Precipitations leading to soil erosion affects about 10-20% of the area of arable land. Strong precipitations may affect up to 40% of the land (Mosimann, et al., 1990).
[2] Putman et al. (1988) estimate that soil losses over 100 years only cause productivity losses of 2.3% within the entire US while 3% of the land will lose 10 % or more of its productive capacity.

Moore and McCarl (1987) calculated that the average off-farm costs per ha under agricultural use are 2.63 US$ per year for the Willamette Valley, Oregon, USA.

2. The meta model approach and the economic and biophysical equilibrium

Previous approaches in the literature to link an economic system with a biophysical system can be classified into three categories: A) economic models with biophysical parameters, B) economic models in combination with biophysical models and C) economic models with partial integration of biophysical models.

The works of Johnson (1993) and Moxey and White (1994) are examples of category A. Johnson (1993) evaluates the cost-effectiveness of nine different measures to reduce phosphorous runoffs from agricultural land in Norway. The economic data was obtained by a survey, and from agricultural statistics. The biophysical data is based on the statistical analysis of a large number of field trials. Moxey and White (1994) modeled the economic relationships by an economic decision model in form of a linear programming model. In this way the pure statistical approach, as chosen by Johnson (1993), was avoided and economic decision processes with respect to the intensive and extensive margin of the production were explicitly modeled. However, both works have in common that they use exogenously predetermined biophysical parameter. Consequently, the obtained economic equilibrium does not correspond to an equilibrium of the biophysical system. Changes in the biophysical system, as a result of the optimally chosen economic activities, would require adjusting the values of the biophysical parameters utilized previously in the economic model. Consecutively, the economic equilibrium has to be determined once again. Unfortunately, the continuation of this reciprocative process does not guarantee at all to find an equilibrium of economic and biophysical system.

Therefore, a new approach was proposed which links biophysical processes with economic decision models more closely. Representative for this kind of approach, classified as category B, are the works of Vatn et al. (1999), Louhichi et al. (1999), and Dabbert et al. (1999). Typically a serie of data, generated with a biophysical model, is employed in the economic decision model. The results of the economic model in turn change the biophysical bases of production. Thus, one has to generate once again biophysical data that can be passed on as input to the economic decision model. This process of mutual dependent interaction only comes to a rest if the economic equilibrium coincides with the biophysical equilibrium. In any case the iterative search of an economic and biophysical equilibrium is usually extremely time and resource consuming.

For this reason, current work is limited to a small number of iterations, i.e. we only observe an approximation to the economic and biophysical equilibrium but not the equilibrium of both systems. Yet, the simultaneous determination of an economic and biophysical equilibrium is indispensable since a disequilibrium of one system inevitably leads to a disequilibrium of the other system. For example, the determination of the least-cost strategy exclusively based on an economic model to comply with an exogenously specified environmental standard, will only yield a strategy, which is optimal for a short period of time, as the strategy itself alters the underlying biophysical system. Thus, on a long term perspectives the exogenously specified environmental standard will most likely not be met, and if it is met, only by chance.

Within this context it seems important to emphasize that the necessity to search for a common economic and biophysical equilibrium is not related to the question whether the model is statistic or dynamic. This necessity depends only on the interdependency of

the biophysical and economic model. However a dynamic model not only requires the search for a common economic and biophysical equilibrium for one particular point in time, as a static model does, but simultaneously over all points in time of the decision makers' planning horizon. On this account the computational requirements for the determination of the common equilibrium increase in such a way that the approach of category B computationally are hardly possible to realize.
To advance the previous interlocking of economic and biophysical models a new approach that is computationally feasible in practice was proposed. For this purpose, the economic model and the part of the biophysical model that is of interest were joint in one model. In fact a part of the physical model becomes an integral part of the economic model This approach is classified as category C and referred to as meta-modeling (Lakshminarayan, et al., 1996). The key element of this approach is the utilization of the interdependent reply functions of the economic and biophysical system.
The reply functions of the biophysical system are specified based on the results of carefully constructed series of simulations that are generated with process orientated biophysical models. Basically, the biophysical reply functions present the statistical evaluation of the series of simulations and are integrated in the economic model. The reply functions of the economic model are the outcome of the economic decision process. The economic reply in turn alters the values of the argument of the biophysical reply function, which produces new values of the integrated biophysical reply functions. Meta-models allow the greatest possible flexibility to evaluate the effects of different polices as it is not necessary to coordinate the economic and biophysical model. Thus, it allows saving resources and time. On the other hand the high degree of flexibility has its price. The amount of data obtained from the evaluation of the series of simulations increases rapidly with the number of different policies analyzed, such that the data management and the statistical evaluation of the data presents a challenge. Nevertheless, meta-models compared to the approach of category B are less time and resource consuming, and therefore are utilized for the work presented in this paper.

In this paper environmental policies are analyzed and compared with respect to their efficiency to induce a reduction in soil and phosphorous losses at the farm level. The economic analysis is based on a dynamic perspective. Moreover, in contrast to the previous literature nonlinear relationships between yield and solid depth on one hand and between soil losses, phosphorous losses and soil depth on the other hand are explicitly considered, and not linearly approximated (Baffoe, et al., 1986, Smith and Shaykewich, 1990, Wossink, 1993). There are examples in the literature where nonlinear biophysical relationships were taken into account; however, these studies were limited to the analysis of one (Yadav, 1997), or two crops (Goetz, 1997) on a field level or conceptual level respectively. Thus, they ignore the full effect of an optimally chosen crop rotation together with crop specific cultivation techniques on the abatement effort. In this respect the paper presents an extension of the current literature by taking account of non-linear biophysical relationships, and by considering simultaneously the determination of the optimal choice of crop, as encountered in farm management, as an endogenous problem.

Given this setup, the resulting economic model is non-linear and therefore a non-linear mathematical programming technique has to be used. In contrast to the method of linear programming the method of nonlinear programming is often related with the problems of existence and/or uniqueness of the solution. This problem is particularly present in this paper since the endogenous determination of the optimal crop rotation leads for most functions employed in economic analysis to a non-convex decision problem.

In order to guarantee that a unique solution of the economic model can be obtained a special production function (modified Cobb Douglas function) was chosen. Additionally the numerical optimization process was repeated with different initial values to verify the uniqueness of the previously obtained solution.

3. The economic model

Corresponding to the farm level approach of this work the economic model reflects the decision problem of a farmer. The meta-model was specified utilizing biophysical data, which was previously generated with a process orientated biophysical model (Erosion Productivity Impact Calculator, EPIC).[3] According to the approach of meta-modeling the generated data does not enter the economic part of the model in its unprocessed form but its processed form. The generated data helps to determine the functional relationships between yield, soil and phosphorous losses subjected to cultivated crops, biophysical characteristics (soil type etc), weather and cultivation techniques (Sharpley and Williams, 1990 a, Sharpley and Williams, 1990 b). These relationships were econometrically estimated and the obtained functions (reply functions) were integrated in the economic part of the model. The determination of the reply function on the base of empirical data is only difficult to imagine since the data is often not available or the existing time series does not allow isolating without ambiguity between endogenous variables and exogenous variables of interest (Goetz, et al., 1998). Moreover, empirical data would allow only reply functions, which are based on policies employed in the past. Thus, empirical data would exclude the economic evaluation of new policies

The model EPIC is able to reproduce the biophysical processes in the soil and the process of plant growth as a function of cultivation techniques and weather. EPIC consists of different sub-models that are sequentially and interactively connected. For the sub-model weather a so-called weather generator is available, which allows simulating weather according to previously fixed design parameters. With respect to erosion EPIC distinguishes between wind and water erosion where the latter one can be in the form of sheet and or gully erosion. The extent of soil erosion depends primarily on the conditions of the wind, the level and distribution of the precipitation during the year, the cultivated crop together with the chosen cultivation techniques, and the field conditions (Pimentel, 1997).[4] As the wind erosion has little importance for the region analyzed within this study the empirical part of the work considers exclusively the case of water erosion. Other sub-models include the processes of plant nutrition, plant growth and agricultural management (type of fertilizer, amount of fertilizer, timing of fertilization, soil cultivation techniques etc.). In the sphere of phosphorous the model reproduces the processes of mineralisation, immobilization, sorption, desorption, plant uptake of fertilization, runoffs of particulate phosphorous and transport of sediments of mineral and organic phosphorous.

---

[3] For more details see the model documentation (Sharpley and Williams, 1990 a) and the manual (Sharpley and Williams, 1990 b) of the EPIC model.

[4] Field conditions are determined for example by soil conditions (soil structure, humus content etc.) the slope of the field and the cultivated crop (root penetration, degree of soil cover during the year etc.).

For the economic part of the model we assume that the farmer maximizes his/her farm gross margin over the entire planning horizon T and he/she is risk neutral. The decision variables for the decision-maker are the type of fertilizer, the type of tillage and the choice of the crops. The farmer can choose between potatoes, corn, winter wheat, winter barley, summer oat, maize, annual or biennial grassland and summer oat with a cover crop over winter. The analyzed region is the watershed of Lake Baldegg, since soil and phosphorous losses are of great importance in this region and we can revert to previous experience with the utilization of EPIC for this region (Maurer, 1995). The specified farm model presents a typical farm in the watershed of the Lake Baldegg with 20 ha arable land. Given the regional focus of the analysis, the prices are not influenced by production decision and thus, they are exogenous. The dynamic economic decision can therefore be formulated as

$$\max_{y_{ijm}(t)} \int_0^T \sum_{i=1}^{9}\sum_{j=1}^{2}\sum_{m=1}^{2} e^{-\delta t}\left[\left(p_i f_{ijm}\left(n(t)\right) - c_i f_{ijm}\left(n(t)\right) - k_{ijm}\right) y_{ijm}(t)\right] dt \qquad (1)$$

subject to

$$\frac{dn}{dt} = \sum_{i=1}^{9}\sum_{j=1}^{2}\sum_{m=1}^{2}\left[\phi_{ijm}\left(n(t)\right) - \gamma_{ijm}\left(n(t)\right)\right] y_{ijm}(t)/\bar{y} \qquad n(0) = n_0 \qquad (2)$$

$$\sum_{i=1}^{9}\sum_{j=1}^{2}\sum_{m=1}^{2} y_{ijm} = \bar{y} \le y_{\max} \qquad (3)$$

$$I \sum_{i=1}^{9}\sum_{j=1}^{2}\sum_{m=1}^{2} y_{ijm}(t) \le \sum_{i=1}^{9}\sum_{j=1}^{2}\sum_{m=1}^{2} \alpha_{im} y_{ijm} \qquad (4)$$

$$\varphi \sum_{i=1}^{9}\sum_{j=1}^{2}\sum_{m=1}^{2}\left[\phi_{ijm}\left(n(t)\right) y_{ijm}(t)\right] \le \beta\, \bar{y} \qquad (5)$$

$$y_{ijm}(t) \in Y,\ \mathrm{Y} \subset \mathbb{R}^i, \quad i = 1,\cdots,9, \quad j = 1,2, \qquad \mathrm{m}=1,2\,. \qquad (6)$$

with the indices:

- i crop
- j type of fertilizer (mineral or organic fertilizer)
- m type of tillage (minimal or standard),

parameters:

- p_i price of the crop i
- c_i variable costs of crop i depending on the yield (harvest cost, drying cost etc.)
- k_{ijm} fix cost of crop i, (capital, labor and costs that depend on the type of fertilizer)
- Y set of crop rotation restrictions with respect to $y_{ijm}(t)$
- δ discount rate
- α_{im} soil protection scores of crop i with tillage m
- I minimal average soil protection scores per ha.
- β maximal average admissible phosphorus loss per ha.
- φ content and transfer coefficient with respect to bio-available phosphor per ton of eroded soil
- n_0 initial value of the soil depth
- $\bar{y}$ cultivated land
- $y_{\max}$ available land

variables:

$y_{ijm}(t)$ cultivated land in ha. of crop *i* with fertilizer *j* applied and tillage *m* as a function of calendar time *t*

$n(t)$ soil depth in millimeters, and

functions:

f_{ijm} production as a function of soil depth *n(t)*

ϕ_{ijm} erosion as a function of soil depth

γ_{ijm} soil genesis as a function of soil depth.

The differential equation (2) describes the change of the soil depth. Restriction (3) limits the area of cultivated crops to the area, which belongs to the farm. The fourth restriction puts an lower limit to the number of soil protection scores which have to be attained per hectare. Restriction (5) puts an upper limit on the average phosphorous loss per hectare. The restrictions concerning crop rotations are summarized in equation (6).
The functions f_{ijm} and ϕ_{ijm} were estimated based on the data generated with EPIC. In order to include weather induced yield variations and soil losses, particular weather conditions were selected. For the selection of the weather conditions we did not evaluate the weather itself but the distribution function of the events of soil losses which was known from an earlier study (Maurer, et al., 1995).
Thus, the average value of the lower 34%, the mid 46% and the upper 20% of this distribution were determined. Next, the weather conditions that have accompanied these erosion events were selected and utilized for the operation of the weather generator of EPIC. The simulated yield and soil losses, were weighted with the probabilities of the erosion events. Hence f_{ijm} and ϕ_{ijm} present weighted functions. The weight itself was selected based on the probability of the erosion event, since the erosion itself, as a trigger for phosphorus losses, is in the center of interest. Weighting according to weather conditions, for instance dry, normal and wet, might have resulted in wrongly specified functions f_{ijm} and ϕ_{ijm}, since a dry year may result in the same amount of soil losses as a wet year. This would be the case if the precipitation of the wet year are distributed equally over the years while those of the dry year are concentrated on a few days, for example at the beginning of the vegetation period.
To evaluate the long-term effects of soil erosion on soil productivity, phosphorus and soil losses, it would have been necessary to generate series of simulations over various centuries. Alternatively, it is possible to specify and use different depths of the soil horizon for the EPIC runs. The second option was chosen and the soil horizon was set at 105, 90, 70, 60 and 35 cm respectively. Together with the cut of the depth of the soil horizon the specification of the C/N ratio was adjusted to an actually eroded soil. According to the mathematical model and given the set of alternatively specified EPIC parameters one obtains 540 series of simulations, which are available for the estimation of the functions f_{ijm} and ϕ_{ijm} (9 crops x 2 types of fertilizer x 2 types of tillage x 3 weather conditions x 5 soil horizons = 540). The number of simulations could be reduced slightly since not all crops can be combined with the two different types of fertilizer and types of tillage. Nevertheless each series of simulation generate a plenitude of data (1 Mbyte), that required a very careful data management.
A unique solution to the nonlinear programming problem, specified in equations (1) to (6), can theoretically only be guaranteed if the decision problem is convex, i.e. the objective function has to be at least pseudo-concave in the case of maximization and the left hand side of the functions of the inequalities, put into normal form, are at least quasi-convex (Bazaraa, et al., 1993)).[5] The specification of the functions f_{ijm} and $\phi_{\mathrm{ijm},}$

[5] See Appendix 1 for details.

utilizing seven commonly employed functional forms in economics, Cobb Douglas, quadratic, transcendental, constant elasticity of substitution , translog, generalized Leontief or Miniflex Laurent, would violate the convexity requirement of the nonlinear programming problem (Keusch, 2000). The requirements from an analytical or numerical perspective, however, are not identical. In other words a convex problem might be hard to solve numerically even though convexity suggest that it should be solved easily. Equally, it may occur that a problem can be solved numerically easily although the problem is not convex. Ideally different solvers are used that are based on distinct algorithms to verify that the obtained solution corresponds to a global solution. Due to resource constraints we did not follow this path but decided to analyze the problem employing a modified Cobb Douglas function that guarantees that the optimization problem is convex. In this way it seems more likely to find the global optimum. The modified Cobb Douglas function in its general form is given by:

$$Q(\vec{X}^T, Y) = A + \omega * (\prod_{i=1}^{n} X_i^{c_i}) * Y^{1-\sum_{i=1}^{n} c_i} + \sum_{i=1}^{n} \zeta_i * X_i^{e_i} * Y^{1-e_i} - \sum_{i=1}^{n} \xi_i * X_i^{g_i} * Y^{1-g_i}, \qquad (7)$$

where i = 1, … , n denote the number of activities and $Q(\vec{X}^T, Y)$, output or erosion. The domain of the different parameter, specified by equation (D) below, is limited by the following restrictions

The variable X_i, Y and the parameter A denote the aggregate of input *i*, the aggregate of

$$\begin{aligned} &A = \{A \mid A \in \mathbf{R}\} && \zeta_i = \{\zeta_i \mid \zeta_i \geq 0\} \\ &\omega = \{\omega \mid \omega \geq 0\} && e_i = \{e_i \mid 0 \leq e_i < 1\} \\ &c_i = \{c_i \mid 0 \leq c_i < 1\} \wedge \sum_{i=1}^{n} c_i \leq 1 && \xi_i = \{\xi_i \mid \xi_i \geq 0\} \\ & && g_i = \{g_i \mid 1 \leq g_i\}. \end{aligned} \qquad (D)$$

input Y and the aggregate output with no input utilized, respectively. In other words the first term, A, of the sum of equation (7) presents the intersection with the y-axis, the second term a classical Cobb Douglas production function and the third and fourth term a concave and convex function respectively that allows to reflect the input output relation more precisely. The modified Cobb Douglas function is concave over the entire domain of the variables. The elasticity of scale like the elasticity of substitution are not constant. Thus, the function provides a high degree of flexibility. In the model presented by equations (1) – (6), however, n = 1, and thus, we obtain the desired quality of constant elasticity scale. Yet, the elasticity of substitution remains variable.

(Takayama, 1991, p. 115) noted that the requirement that the left-hand side of the functions of the inequalities, equations (3) - (6), put into normal form, are at least quasi-convex implies that the constraint set is convex. To test the convexity of this set the program MPROBE was employed.[6] This tool supports the mathematical analysis of a mathematical programming model by testing the effectiveness of the restrictions, the convexity of the constraint set, and it allows drawing iso-level curves of non-linear functions.

The parameters of the functions f_{ijm} and ϕ_{ijm} were both estimated based on algorithms for nonlinear least square regression techniques offered by the Software EVIEWS (Quantitative Micro Software, 1998). Before estimating, both functions were written in logarithmic form so that the relative and not the absolute deviations of the estimated

[6] See. Chinneck (forthcoming), and Chinneck (2000) http://www.sce.carleton.ca/faculty/chinneck/mprobe.html.

value from the observed value matter (Greene, 2000). Finally, the mathematical problem was programmed in AMPL (Algebraic Modeling Programming Language) (Fourer, et al., 1993) and solved with the solver MINOS (Murtagh and Saunders, 1995). Additionally AMPL can be linked directly to MPROBE. Furthermore, the economic model was qualitatively analyzed to verify that its implications are in line with the economic theory. This theoretical validation is by no means mathematical gimmick but an imperative for the utilization of the model in empirical research. Only in this way it is possible to interpret the results justly and to attribute them to the underlying data. The mathematical validation of the model makes it possible to rule out unintentable interferences between the specified model and the utilized data.

The described processes of the different components of the model and its relation among each other are presented schematically in Figure 1. It illustrates at the same time the temporal sequence and the interaction of the different components of the model.

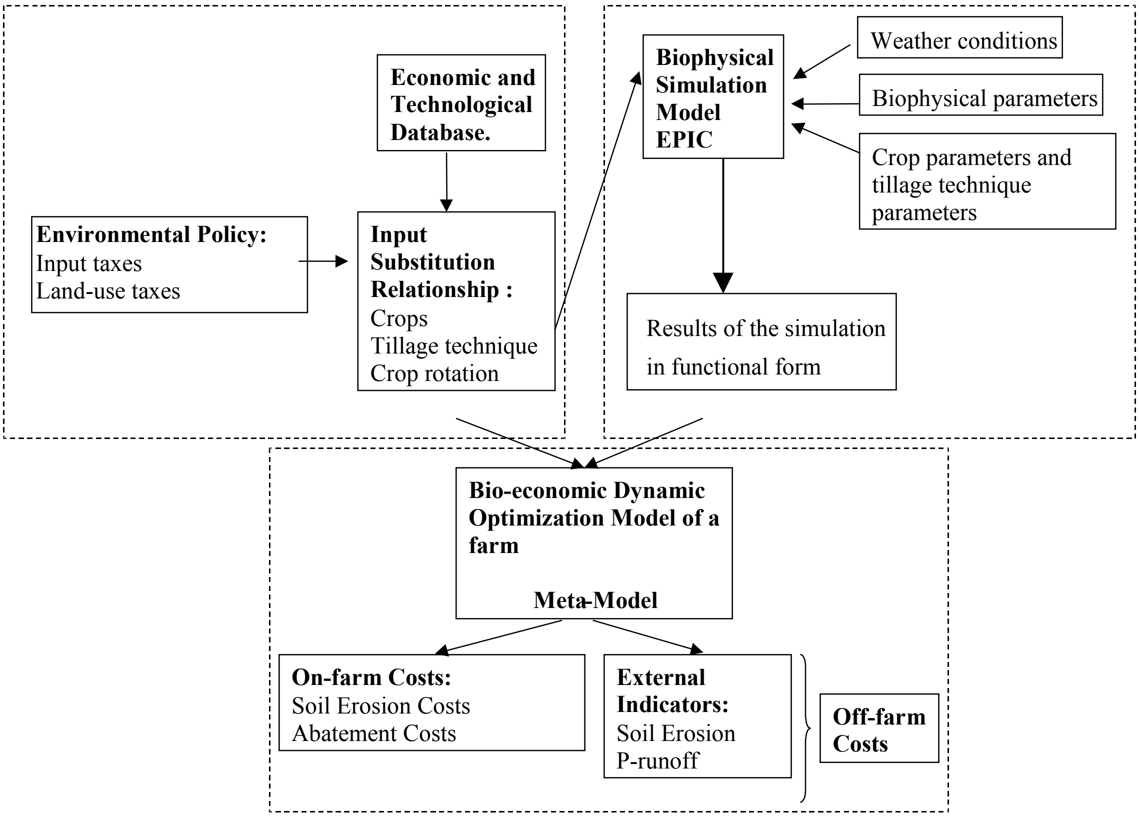

Figure 1: Components of the model and scheme of the economic analysis

3.1 Environmental policies

In the following section several polices aimed at reducing phosphorous and soil losses are compared with respect to their efficiency, i.e. with respect to the value of the abatement and damage costs. Other costs related to the different policies such as transaction, administration, control and enforcement costs are also important, however they do not form part of this analysis. The valuation of the damage cost often poses a serious, if not say unsolved, problem in practice. For this reason policymaker often apply standards in order to avoid the monetary valuation of the damage. This approach is also employed in this paper so that the value of abatement costs is the only criteria for the evaluation of the efficiency of different policies. Even thought there does not exist a threshold value, which has been defined explicitly by the legislator, the Swiss law of

water protection implicitly defines one. The law requires oxygen content of 4g O_2/m^3 in all parts of the watercourses. This threshold level in turn implies for the analyzed region that the phosphorous losses should not exceed 0.3 kg/ha. (Wehrli and Wüest, 1996). The analyzed farm has 20 ha. of arable land and the planning horizon of the farmer is assumed to comprise two generations, i.e. T= 66 years.
For our analysis we initially calculate the on-farm costs of soil erosion, to examine whether there are incentives to limit soil erosion. For this purpose we compare the value of the objective function with a short-term planning horizon with the value of the objective function with a long term planning horizon. The on-farm costs correspond to the difference of these two values, as a short-term planning horizon does not take account of the consequential costs of the soil erosion resulting from the decrease in soil productivity. Moreover, the on-farm costs serve as a point of reference for the off-farm costs, related to the abatement of phosphorus, calculated below.

If the planning horizon is classified as short term, the economic model is optimized recursively, i.e. given the value of the stock variable of the previous period, the economic model is optimized for every year individually in a sequence of 66 years.
For long-term planning horizon, however, we do not use recursive optimization but dynamic optimization. This approach allows optimizing over all 66-time periods simultaneously. The distinction between short-term and long-term planning horizon allows determining the relevance of the length of the planning horizon.
For a long-term planning horizon (dynamic optimization) our calculations show that the on-farm cost in the first year are between 138 (soil depth 105 cm) and 549 CHF (soil depth 35 cm). Thus the on farm cost are between 6.88 and 27.44 CHF per mm of lost soil and hectare, or in terms of tons/ha, between 0.49 and 1.96 CHF for a soil with a density of 1.4 t/m^3.
For a short term planning horizon (recursive optimization), however, the on-farm costs are between 7 and 31 CHF per mm of lost soil in the first year of the 66 years. Thus, on-farm costs are only from 0.36 to 1.53 CHF per hectare, or in terms of tons/ha between 0.03 and 0.10 CHF. Given these results one can conclude that the on-farm costs are, independent of the length of the planning horizon. They are too low to give incentives to apply soil conserving cultivation techniques or soil structure improving organic fertilizer. The consideration of the on-farm costs only lead to small change in the crop rotation when changing from a short-term to a long-term planning horizon.

Even though there is no reason to reduce soil losses from a private perspective it might be advantageous from a social perspective (McConnel, 1983). This is most likely the case if the soil erosion leads to damages, for example in form of phosphorous runoffs and the subsequent eutrophication of surface waters, that are not included in the private considerations (off-farm costs). Therefore, from a social perspective the question is raised how farmers can be induced to apply soil conserving and P-runoff reducing forms of cultivation.

In the following section different policies aimed at the reduction of P-runoffs are presented and are compared with respect to their efficiencies. The abatement costs are used as the point of reference for the comparison between these policies. Initially the abatement costs are calculated for the policy of the introduction of a P-emission standard and of a P-emission tax. Although these direct measures cannot be applied in the context of non-point source pollution, the calculated abatement costs are of great importance. They allow quantifying the inefficiency of indirect measure from a least-cost point of reference. As a indirect measures we analyze the concept of soil protection scores and land-use taxes.

3.1.1 P-emission standard and P-emission tax

As already mentioned above, the admissible P-emission standard for the analyzed region of the watershed of Lake Baldegg is 0.3 kg P/ha. This standard can be obtained in this model at the same abatement costs either with a P-emission standard or with a P-emission tax.

For a comparison of different environmental policies however, not only the abatement costs associated with a particular threshold value are of interest, but also the abatement costs as a function of different threshold values. The comparison of the different policies, based on the function of the abatement costs, allows a more general evaluation, since it is not only based on a single threshold value but on a wide array of possible values. The comparison of the different policies itself is based on the function of the marginal abatement costs. It supplies, apart from the marginal abatement costs, the abatement costs given by the area below the image of the marginal abatement costs function. The marginal abatement costs were determined for different threshold values, which result in different P-emission standards and P-emission taxes.

The reproduction of a P-emission standard is implemented in the model by the introduction of a P-runoff restriction that is reduced stepwise by 0.1 kg P-emission/ha. The starting point for the gradual reduction of the P-runoff restriction is the non-limiting P-runoff restriction of 1.2 kg P/ha. (free optimum).[7] The abatement costs of the P-emission standard result from the difference between the farm gross margin without a P-runoff restriction and that with a P-runoff restriction.

Alternatively to a P-emission standard one can also apply a P-emission tax. The value of the P-emission tax corresponds to the time dependent shadow value of the P-runoff restriction. For the implementation of this environmental policy the objective function needs to be modified such that the social cost, generated by observing the P-emission limit, are incorporated in the private objective function. By adding, the term - P-emission tax per kg $*$ P-emission in kg - in the private objective function, it is able to establish the socially desired outcome for a short-term as well as for a long-term planning horizon.

The results of the calculations of the model show that the shadow price of the P-emission standard of 0.3 kg P per ha produces the correct time-dependent P-emission tax, as the results of both environmental policies coincides (Keusch, 2000). To determine the function of the marginal abatement costs the different time dependent P-emission taxes are calculated according to the successively more restrictive P-emission limits.

Figure 2 shows the graph of the marginal abatement cost function per kg P in the first year given a short-term planning horizon. Marginal abatement costs for P-emissions for the entire farm increases from 200 to 6595 CHF, where en total 21 kg P are abated. The graph presents the least-cost marginal abatement cost and serves as a reference for the evaluation of other policies. Please note that the marginal abatement costs are taken directly from the outcome of the optimization process of the economic model.

[7] Without any P-runoff restriction the farm emits 22.48 Kg P, i.e. 1.12 Kg P/ha.

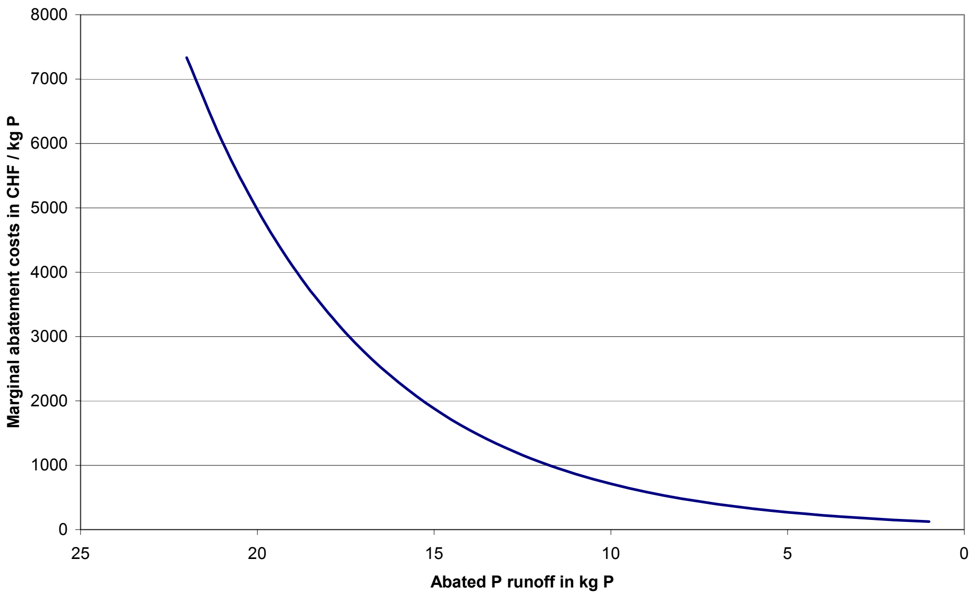

Figure 2: Marginal abatement cost of phosphorus at the farm level based on a P emission tax or a P standard

For this particular reason the marginal abatement costs do not coincide completely with the graph of the estimated marginal abatement cost function as presented in Figures 2. For the same account, Figures 3 to 6 display some differences between the estimated and cited values.

The abatement costs as derived from Figure 2 are identical for a P-emission standard and for a P-emission tax since we consider a single farm.[8] Our calculations show that the abatement costs are independent of the length of the planning horizon i.e. independent of the consideration of the on-farm costs. Short term and long term planning yields the same abatement costs in every year. However, the abatement costs are decreasing slightly over time. For a discount rate of 3% and a soil depth of 0.7m the abatement costs decrease from 645 CHF in the first year to 584 CHF in the 66th year. For this reason the marginal abatement cost function in Figure 2, as well as in the following Figures, is only presented for the first year and not for the following years. Likewise, we only depict the outcome of the short term planning horizon since the long term planning horizon does not yield a substantially different picture.

The abatement costs as a function of the reduced P-emission are estimated on the basis of an exponential function. With a short term planning horizon the function takes the following form.

$$F(P) = -534.27 + e^{0.194*P+6.26} \qquad R^2 = 0.994. \tag{8}$$

The marginal abatement costs function per kg P yield[9]

[8] The identity of these two policies with respect to the abatement costs also holds for the case of multiple farms provided that these farms are identical

[9] The marginal abatement cost can be determined according to the following approach

$$F(P(l_2)) - F(P(l_1)) = \int_{l_1}^{l_2} f(P(l))dP \qquad \frac{\partial F(P)}{\partial P} = f(P)$$

where

$$f(P) = 0.194 * e^{0.194*P+6.36}. \quad (9)$$

The invariance of the abatement cost with respect to the length of the planning horizon is due to the linearity of the only decision variable in the economic model. Thus, the social optimal outcome is quite robust with respect to changes in the on-farm costs. Even though the on-farm costs do not change the optimal outcome, they drive a wedge between the P-emission taxes based on a short-term and a long-term planning horizon. Given that a short-term perspective does not consider the on-farm cost the P-emission taxes have to higher in the myopic case than in the farsighted case. As time passes this difference decreases and vanishes completely in the 66 year. Thus, P-emission taxes derived from static or myopic economic analysis would impose taxes that are too high from dynamic or farsighted perspectives. The dynamic approach of this paper allows identifying this extra and unnecessary financial burden in comparison with a static approach and it allows to determinate the optimal adjustment of the P-emission taxes over time.

3.1.2 Soil protection scores

Indirect measures have been proposed as an alternative to direct measures since they can be applied more easily in practice. An example for such a measure is the concept of soil protection scores according to the regulation of integrated production (Bundesamt für Landwirtschaft, 1999). This regulation requires that farmers have to attain a minimum number of scores for the entire cultivated land. The scores relate to the unit of one hectare and they are differentiated according to the cultivated crop and the utilized tillage technique.

The regulation translates into the model by considering the following restriction

$\sum_i \sum_j \sum_m$ (cultivated area$_{ijm}$ in ha. $*$ soil protection scores$_{ijm}$ per ha.) $\geq$ (minimal soil protection score per ha. $*$ cultivated land in ha.), where i = crop, j = type of fertilizer, m = tillage technique.

The calculations show that P-runoffs recede only slightly even if the lower limit of the number of soil protection scores is raised. The average emissions over the entire planning horizon decrease from 1.12 kg P/ha. to 0.75 kg P/ha. Thus, it is not possible to reduce the emissions up to 0.3 kg P/ha as it is required to meet the Swiss water quality regulations, even though the lower limit of the number of soil protection scores is raised from 45 to 100. The shadow price of the land (1 ha.) is 2006 CHF with no minimum soil protection scores, 2077 CHF for scores of 45 to 79 and 3162 CHF for scores over 80.

Before estimating the abatement costs of this policy a relationship between abated P and the soil protection scores was established. Next, the abatement costs themselves were estimated based on a polynom of 3rd degree as a function of soil protection scores and as a function of abated P.

The abatement costs functions and their derivates are given by

---

F = abatement cost function

f = marginal abatement cost function

P = abated P-emission

l_i = P-emission standard per ha. i = 1,2

$$F(SPS) = -6092.67 + 385.95 * SPS - 8.12 * SPS^2 + 0.058 * SPS^3, \quad R^2 = 0.991 \qquad (10)$$

$$f(SPS) = 385.95 - 16.23 * BS + 0.174 * BS^2 \qquad (11)$$

where SPS = soil protection scores, and

$$F(P) = -313.253 + 1334.30 * P - 562.9 * P^2 + 76.47 * P^3 \quad R^2 = 0.991 \qquad (12)$$

$$f(P) = 1334.30 - 1125.78 * P + 229.42 * P^2, \qquad (13)$$

where P = P abated in kg

The graphs of these two marginal abatement costs functions are presented in Figures 3 and 4. They show that the marginal abatement costs surge with an increase in soil protection scores or in abated P.

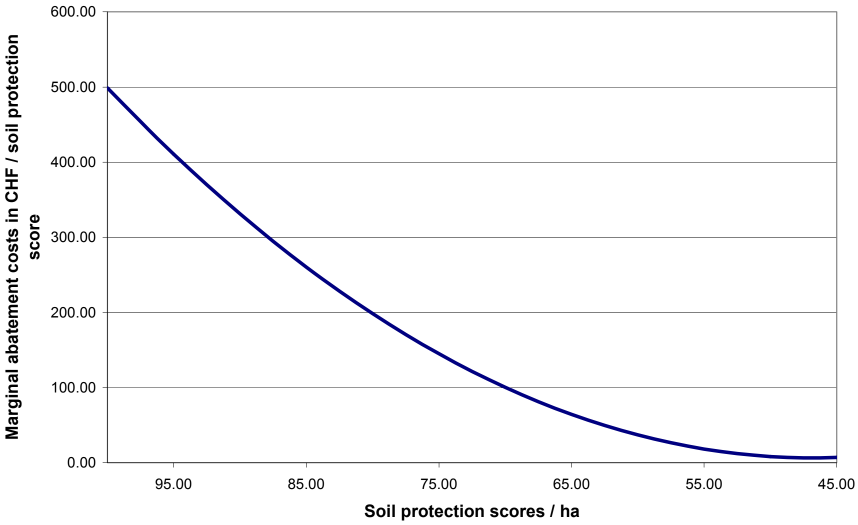

Figure 3: Marginal abatement cost of phosphorus at the farm level based on soil protection scores

A comparison of Figures 2 and 4 produces the evidence that the policy of soil protection scores is far more expensive than the benchmark solution. The reduction of P-runoffs by the introduction of soil protection scores, for example in 0.37 kg P/ha (from 1.12 kg P/ha to 0.75 kg P/ha), entails abatement costs of 8736 CHF for the entire farm. The introduction of a P-emission tax / standard, however, only produces farm abatement costs of 1888 CHF. Thus, soil protection scores imply a loss of efficiency equivalent to 6848 CHF. The comparison of the measures demonstrates that the current definition of the soil protection scores according to the integrated production regulation lessens the erosion and P-runoffs problem but in an inefficient way. Moreover, it is not capable to meet the standard aimed at by Swiss water regulations.

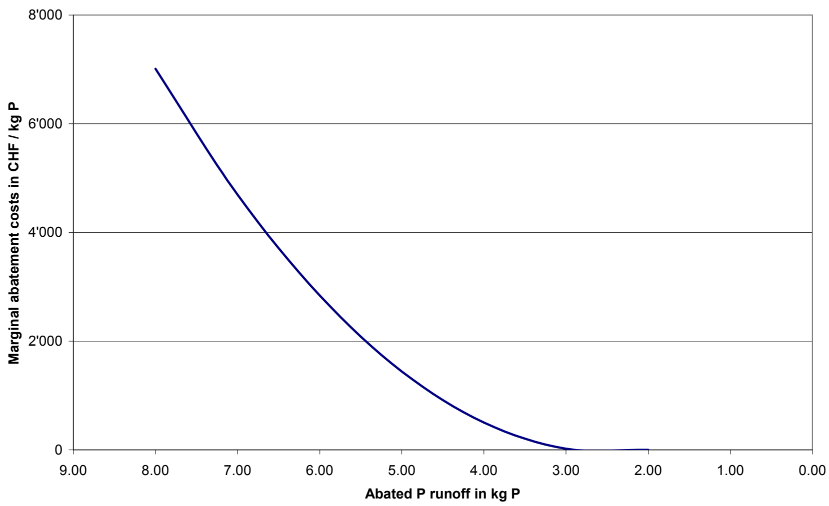

Figure 4: Marginal abatement cost of phosphorus at the farm level based on soil protection scores expressed as abated phosphorus

As in the benchmark case the abatement costs do not vary with the length of the planning horizon and only slightly over time. Moreover, the utilization of a dynamic approach showed that the consideration of the on-farm costs reduces the necessary P-emission taxes to induce the social optimal outcome compared to a static approach. Thus, the use of the dynamic approach allows reducing the lower limit of the soil protection scores in comparison with the use of a static approach, both in their infructuous effort to approach the benchmark solution.

3.1.3 Land-use taxes

A further alternative policy constitute the introduction of a land-use tax. This tax should be differentiated according to the P-runoff potential of each location. To asses it a wide array of different factors have to be considered, for example topographic aspects, the cultivated crop and the cultivation technique, the length of the field, physical and chemical aspects of the soil, and hydrological aspects of the receiving water body. All these factors should be considered in a land classification system that provides a basis for differentiating the land use tax according to the site vulnerability with respect P-runoffs. The Conservation Services of Natural Resources developed such a land classification system under the patronage of the US Department of Agriculture (Sharpley, 1995). For the actual calculation of the P site vulnerability the entire P-runoffs do not need to be considered but only the part of the P-runoffs, which reaches the water bodies and is bio-available. The translation of this policy into the economic model is obtained by adding the term, ($\sum_i \sum_j \sum_m$ cultivated area_{ijm} in ha. $*$ land-use tax_{ijm} per ha), where i = crop, j = type of fertilizer, m = tillage technique, to the objective function.

The economic model based on meta-modeling, allows to determine the shadow prices of the P-emissions depending on prespecified level of the P-emission restriction. The optimal land-use tax per hectare is given by the product of the crop and cultivation technique specific P-runoffs with the time-dependent shadow price for each prespecified P-runoff restriction. The crop and cultivation technique specific P-runoffs cause the land-use tax to be differentiated with respect to the cultivated crop, the cultivation technique and the employed type of fertilizer. The time-dependent shadow price conditions that the land-use tax is also time dependent.

The land-use tax differs strongly between the different crops and is directly proportional to the erosion / P-runoffs of the crop. This immediate relationship between erosion / P-runoffs of a crop and the land-use taxes causes that the land-use taxes are directly proportional to the changes in the optimal P-emission taxes. Land-use taxes however confront the legislator with the problem of the political acceptance of this measure since the taxes nearly eat up the entire profits of the farmers.

The optimal land-use tax gives sufficient incentives to the farmers to achieve the prespecified P-emission standard of 0.3 kg P/ha. (3.22 t for the entire farm).
The successive change of the prespecified P-emission standard and thus of the optimal land-use tax allows to determine the abatement costs for different tax rates.
The abatement cost function and its derivative are given by the following equations.

$$F(P) = -1064.12 + e^{0.164*P+6.73} \qquad R^2 = 0.98 \qquad (14)$$

$$f(P) = 0.164 * e^{0.164*P+6.72}, \qquad (15)$$

where P = P abated in kg.

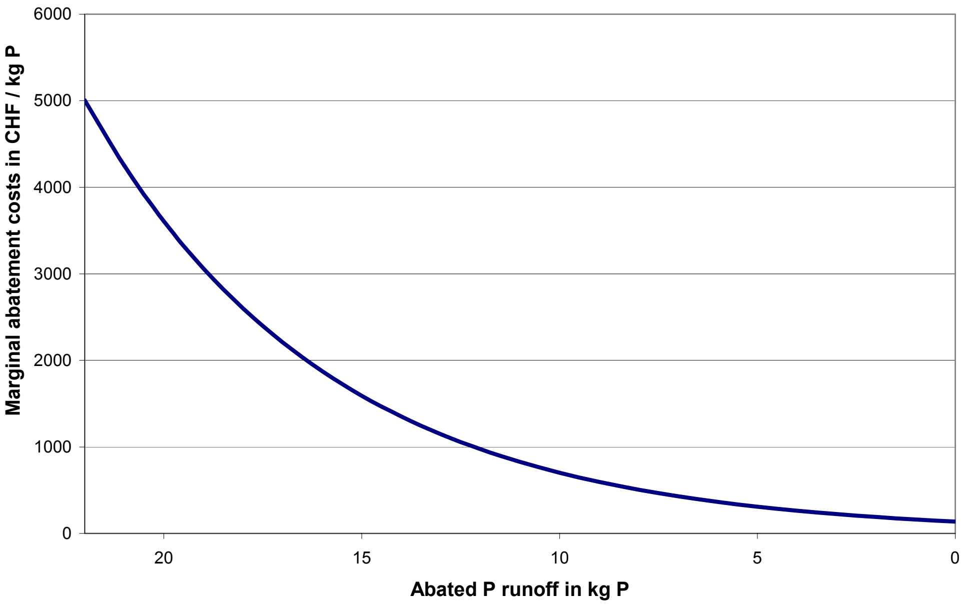

Figure 5: Marginal abatement cost of phosphorus at the farm level based on a land-use tax

Figure 5 shows the graph of the marginal abatement costs of the land-use tax. Figure 6 compares the abatement costs of the land-use tax with the benchmark case – P-emission tax / standard. It shows that the graphs are nearly identical and as such the land-use tax can be classified as an efficient instrument. Moreover, land use taxes can also be applied in practice since the use of the land is easily observable for the regulator.

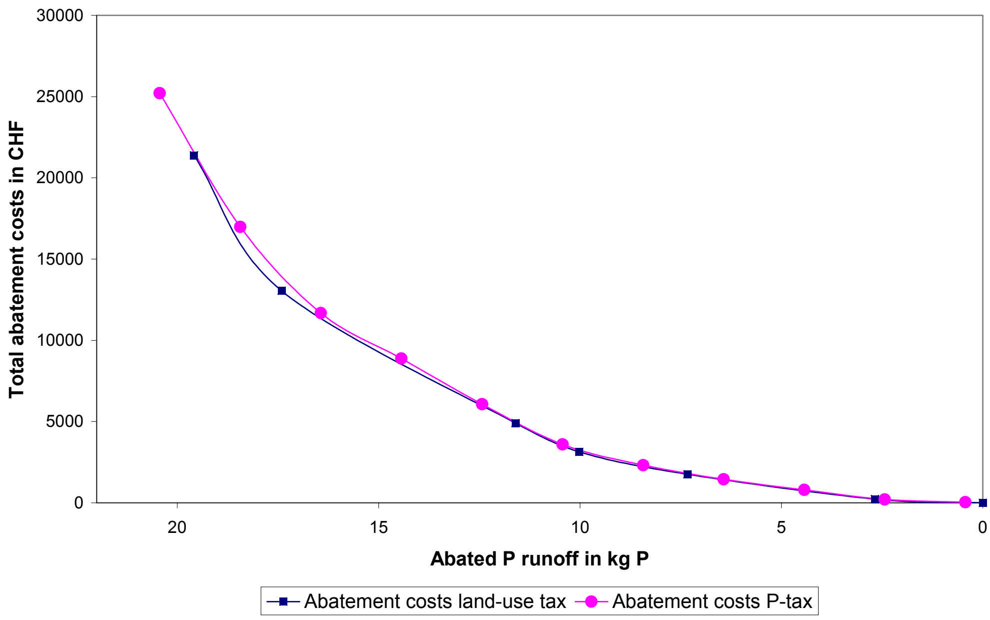

Figure 6: Marginal abatement cost of phosphorus at the farm level based on a land-use tax compared to P emission tax

With respect to the difference between static and dynamic approach we can employ the results we had in the previous two sections about other policies instruments. As such the calculations of the optimal land-use tax within a static model would result in land-use taxes, which are too high compared to the taxes that would result with the utilization of a dynamic model.

The results of the comparison of the two alternative policies are not affected by a change in the parameters. We analyzed different soil depths (0.35, 0.7 and 1.05m), and different discount rates (0%. 3% and 9%). None combination of these parameters reversed the order of the ranking of these policies with respect to efficiency.

4.Summary and conclusions

The utilization of an economic optimization model in combination with the results of a biophysical simulation model provides the basis for meta modeling. It is necessary to apply this approach for the analysis of environmental policy instruments since it allows to find the economic and biophysical equilibrium simultaneously. The dynamic analysis usually requires data, which is not available in empirical form. The use of biophysical simulation models extenuates this problem completely. The great importance of the biophysical processes suggests reflecting nonlinear relationships correctly, which in turn requires the utilization of nonlinear programming. As a consequence there may arise problems with the uniqueness of the obtained solution and therefore special attention has to be given to this problem.

Standard instruments such as emission standards or taxes cannot be employed in the context of non-point source pollution since the regulator cannot observe the emission. However, these instruments serve as least-cost reference for alternative measures. Land-use taxes, differentiated according to the cultivated crop, cultivation techniques and fertilizer type, are shown to be efficient. As the criteria for the differentiation are easily observable, land use taxes can be applied and differentiated in practice. As land-use taxes are fairly high and consume a large share of the farm profit one has to consider the possibility to reimburse farmer. One possibility might be to allow for special tax reduction in the tax declaration.

Appendix 1

Mathematically, pseudo-convexity is defined by:

Let S be nonempty open set in 3^n and let f: S → 3^1 be differentiable en S. The function f is pseudo-convex, if for any x_1, x_2 $\in S$ with $\nabla f(x_1)^t(x_2 - x_1) \geq 0$, $f(x_2) \geq f(x_1)$ or equivalently if $f(x_2) \prec f(x_1)$ $\nabla f(x_1)^t(x_2 - x_1) \prec 0$ holds (Bazaraa, et al., 1993, p. 113).

Convex and pseudo-convex functions share the characteristic that, if $\nabla f(\bar{x}) = 0$, the point $\bar{x}$ achieves a global optimum. Thus, the slope of the function has to be distinct from zero for all points other than $\bar{x}$. In contrast to convex functions, pseudo-convex functions may have an inflection point. However, the slope at this point has to be distinct from zero so that it cannot be a saddle point.

The decision problem, given by equation (1) – (6), requires for the objective function that the sum of products $(f(\cdot)_{ijm} y(\cdot)_{ijm})$ and of $\phi(\cdot)_{ijm} y(\cdot)_{ijm}$ have to be pseudo-convex. Given the fact that a sum of quasi-convex functions is not necessarily quasi-convex (Sydsaeter and Hammond, 1995, Thm. 17.16) one can easily deduce that a sum of pseudo-convex functions is not necessarily pseudo-convex. However, every nonnegative linear combination of convex functions is convex (Chiang, 1994). Thus, we need to require that the products of $(f(\cdot)_{ijm} y(\cdot)_{ijm})$ and $\phi(\cdot)_{ijm} y(\cdot)_{ijm}$ have to be strictly convex. Unfortunately, it turns out that the products, with f or ϕ based on seven different functions commonly employed in economics, is not strictly concave (Keusch, 2000, chp. 10). Concavity of these functions was tested by analyzing the sign of the principal minors of the Hessian matrix according to a test described by (Bazaraa, et al., 1993, p 90). For this purpose each principal minor was either minimized or maximized with Mathematica® to compare its sign with the sign required for concavity. Some functions, such as the Cobb Douglas can be formulated in such a way that the product of $(f(\cdot)_{ijm} y(\cdot)_{ijm})$ is concave, however, the parameters need to be restricted severely such that they loose a high degree of flexibility and are only of limited interest for an economic analysis.

References

Baffoe, J. K., D. P. Stonehouse, and B. D. Kay, 1986. A methodology for farm-level economic analysis of soil erosion effects under alternative crop rotational systems in Ontario. Canadian Journal of Agricultural Economics, 35(1), 55-73.

Bazaraa, M. S., H. D. Sherali, and C. M. Shetty, 1993. Nonlinear Programming: Theory and Algorithms. 2 ed. Vol. 1. Wiley, New York.

Bundesamt für Landwirtschaft, 1999. Richtlinien für den ökologischen Leistungs-nachweis (ÖLN). Koordinationsgruppe Richtlinien Deutschschweiz (KIP) c/o Landwirtschaftliche Beratungszentrale, Eschikon.

Chiang, C. A, 1994. Fundamental Methods of Mathematical Economics 3 ed. McGraw-Hill, New York.

Chinneck, J. W., forthcoming. Analyzing mathematical programs using MProbe. Annals of Operations Research. Special issue on Modeling Languages.

Chinneck, J. W., 2000. Discovering the Characteristics of Mathematical Programs via Sampling. Technical Report. Dept. of Systems and Computer Engineering. Carleton University, Ottawa.

Colacicco, D., T. Osborn, and K. Alt, 1989. Economic damage from soil erosion. Journal of Soil and Water Conservation 44, 35-39.

Dabbert, S., S. Herrmann, G. Kaule, and M. Sommer, 1999. Landschaftsmodellierung für die Umweltplanung. Springer-Verlag, Berlin.
Fourer, R., D. M. Gay, and B. W. Kernighan, 1993. AMPL: A Modeling Language for Mathematical Programming. The Scientific Press, Danvers.
Goetz, R. U. "Diversification in Agricultural Production, 1997. A dynamic model of optimal cropping to manage soil erosion. American Journal of Agricultural Economics 79(May), 342-356.
Goetz, R. U., A. Keusch, D. Schaub, S. Meier-Zielinski, H. Schmid, and B. Lehmann, 1998. A comment on: the intertemporal impact of soil erosion on non- uniform soil profiles: a new direction in analyzing erosion impacts. Agricultural Systems 58(4), 571-574.
Greene, W. H. "Econometric Analysis, 2000. 4th ed. Prentice Hall, Upper Saddle River.
Johnson, F. H., 1993. Economic analyses of measures to control phosphorus run-off from non-point agricultural sources. European Review of Agricultural Economics 20(4), 399-418.
Keusch, A., 2000. Modellierung ressourcenökonomischer Fragestellungen am Beispiel der Erosion im Gebiet des Baldeggersees. Dissertation, Eidgenössische Technische Hochschule Zürich, Zürich.
Lakshminarayan, P. G., P. W. Gassmann, A. Bouzaher, and R. C. Izaurralde, 1996. A Metamodeling Approach to evaluate agricultural policy impact on soil degradation in Western Canada. Canadian Journal of Agricultural Economics 44(3), 277-294.
Lal, R., F. Pierce, and R. Dowdy, 1983. The threat of soil erosion to long term crop production. Science 219, 458-465.
Louhichi, K., G. Flichman, and S. Zekri, 1999. Un modèle bio-économique pour analyser l'impact de la politique de conservation des eaux et du sol Le cas d'une exploitation agricole tunisienne. Économie Rurale 252(Juillet-Août), 55-64.
Maurer, B., 1995. Modellierung des langjährigen Rückganges der Bodenfruchtbarkeit durch Bodenerosion. Oberlehrerarbeit am Geographischen Institut der Universität Basel, Basel.
Maurer, B., D. Schaub, and R. U. Goetz, 1995. Simulation des langjährigen Rückganges der Bodenfruchtbarkeit durch Bodenerosion. Bulletin der Bodenkundlichen Gesellschaft der Schweiz 7, 25-30.
McConnel, K. E., 1983. An economic model of soil conservation. American Journal of Agricultural Economics 65(1), 83-89.
Moore, W. B., and B. A. McCarl, 1987. Off-site costs of soil erosion: a case study in the Willamette Valley. Western Journal of Agricultural Economics 12(1), 42-49.
Mosimann, T., A. Crole-Rees, A. Gaillard, J.-A. Neyroud, M. Thöni, A. Musy, and W. Rohr, 1990. Bodenerosion im schweizerischen Mittelland. Vol. 51. Schweizerische Nationalfonds, Liebefeld - Bern.
Moxey, A., and B. White, 1994. Efficient compliance with agricultural nitrate pollution standards. Journal of Agricultural Economics 45(1), 27-37.
Murtagh, B. A., and M. A. Saunders, 1987. MINOS 5.4 User's Guide. Technical Report SOL 83-20R, Dept. Operations Research, Stanford University, Stanford.
Pimentel, D., 1997. Soil erosion and agricultural productivity: the global population food problem. Gaia: Ecological Perspectives in Sciences, Humanities and Economics 6(3), 197-204.
Putman, J., J. Williams, and D. Sawyer, 1988. Using the erosion productivity impact calculator (EPIC) model to estimate the impact of soil erosion for the 1985 RCA Appraisal. Journal of Soil and Water Conservation 43, 321-326.
Quantitative Micro Software, 1998. EViews User's Guide. 2 ed. Vol. 1. Edited by Quantitative Micro Software. Quantitative Micro Software. Irvine.
Schmid, H., A. Keusch, R. Goetz, D. Schaub, and B. Lehmann, 1997. Management der Verschmutzung aus diffusen Quellen - Eine empirische Analyse anhand von Phosphorabträgen von landwirtschaftlich genutzten Flächen in einen Binnensee. Landwirtschaftsverlag, Münster-Hiltrup.

Sharpley, A., 1995. RCA III: Fate and Transport of Nutrients - Phosphorus. Working Paper 8. USDA, Agricultural Research Service, National Agricultural Water Quality Laboratory, Durant.

Sharpley, A. N., and J. R. Williams, 1990a. EPIC-Erosion/Productivity Impact Calculator: 1. Model Documentation. Vol. 1768. Technical Bulletin. U.S Department of Agriculture.

Sharpley, A. N., and J. R. Williams, 1990b. EPIC-Erosion/Productivity Impact Calculator: 2. User Manual. Vol. 1768. Technical Bulletin. U.S Department of Agriculture.

Smith, E. G., and C. F. Shaykewich, 1990. The economics of soil erosion and conservation on six soil groupings in Manitoba. Journal of Agricultural and Resource Economics 38, 215-231.

Sydsaeter, K., and P. Hammond, 1995. Mathematics for Economic Analysis. Prentice-Hall, Englewood Cliffs.

Takayama, A., 1991. Mathematical Economics. 2 ed. Cambridge University Press, London.

Vatn, A., L. R. Bakken, H. Lundeby, P. Botterweg, and E. Romstad 1999. ECECMOD: An interdisciplinary modeling system for analyzing nutrient and soil losses from agriculture. Ecological Economics 30(2), 189-205.

Wehrli, B., and A. Wüest, 1996. Zehn Jahre Seenbelüftung: Erfahrungen und Optionen. EAWAG Schriftenreihe Vol. 9, Dübendorf-Zürich.

Wossink, G. A.,1993. Analysis of future agricultural change. Economic Studies Vol. 27. Wageningen University, Wageningen.

Yadav, S. N., 1997. Dynamic optimization of nitrogen use when groundwater contamination is internalized at the standard in the long run. American Journal of Agricultural Economics 79(August), 931-945.