Gypsum amendment as a means to reduce agricultural phosphorus loading

Preliminary & incomplete draft

Marita Laukkanen, Antti Iho

Introduction

Phosphorus loads from agriculture deteriorate surface water quality. Most parts of the Baltic Sea, for instance, suffer from increased turbidity, mass blooms of toxic blue green algae and other symptoms of eutrophication which could be mitigated by reducing external nutrient loads entering the sea. Agriculture is the main source of anthropogenic loads of nitrogen and phosphorus, the two main nutrients accelerating algae growth.

Phosphorus is transported from agricultural land to surface waters in two major forms with different biochemical characteristics: dissolved reactive phosphorus (DP) and particulate phosphorus (PP). Long term phosphorus surpluses – differences between phosphorus fertilization and plant uptake – increase the stock of phosphorus reserves accumulated in soil (hereafter referred to as soil phosphorus). These reserves are the main driver of both crop response to phosphorus, and losses of dissolved phosphorus. Particulate phosphorus in turn is lost from fields within eroded soil.

The means to mitigate phosphorus loads typically focus on either on particulate or dissolved phosphorus. For a given soil structure, soil type and rainfall, the level of soil phosphorus determines the dissolved phosphorus loads. Hence, these loads can be mitigated by lowering soil phosphorus levels which, however, comes at the expense of crop yields and farm income. The most common means to mitigate erosion in turn are constructing vegetative filter strip on field edges bordering waterways and using soil conserving tillage technologies such as no till.

Recent results from field experiments suggest that applying gypsum ($CaSO_4$) on field surface would provide a novel, effective means to reduce both dissolved and particulate phosphorus loads. The method is currently being tested under a Finnish project TRAP.[1] The preliminary results from field experiments suggest that it might markedly reduce phosphorus loads from crop production. The impact is mainly due to sulphide ions which increase the ionic strength of soil solution. This causes

[1] contact information

the smallest soil particles – those most susceptible for erosion – to bond together. Such compounds are less likely to be carried from fields to receiving waters either by surface runoff or drainage flow. The changes in chemical characteristics of soil solution are also assumed to reduce dissolved phosphorus loads. The machinery required for gypsum application is identical to that used for lime. Because gypsum is a by-product of fertilizer production, its supply is stable.

The purpose of this paper is to complement the findings from field experiments by examining whether gypsum application provides socially desirable abatement method for phosphorus loads when its biophysical effect, cost and interaction with other abatement measures in the optimal policy mix are accounted for. The impact of environmental conditions on the economic performance of gypsym application is also addressed.

We analyze the socially optimal use and abatement of phosphorus when the choices available to the decision maker are the annual level of phosphorus fertilization, the width of vegetative filter strip and whether or not to treat fields with gypsum. Because phosphorus accumulates in soil over time, the choice of phosphorus fertilization rates and the optimal mix of abatement measures should be examined under a dynamic optimization framework.

The dynamically optimal use of phosphorus has been analyzed previously by for instance Schnitkey and Miranda 1993), Goetz and Zilberman (2000), Goetz and Keusch (2005) and Iho (2010). In the present study, we build on a framework created in Iho and Laukkanen (2009) who analyzed the potential of precision agriculture in phosphorus mitigation. We show how the initial soil phosphorus status and the differences in erosion susceptibility affect the optimal policies. In particular, we answer the following questions: how is the use of gypsum optimally adjusted with depleting/accumulating soil phosphorus towards its steady state level? How do we optimally combine the use of vegetative filter strips, precision phosphorus application and gypsum amendment?

The modelling framework

Consider a field parcel bordering a waterway. For simplicity, we assume that the parcel is square in shape and measures one hectare. A single crop is produced using phosphorus fertilizer as a variable input. The per hectare production function is $Y(s_t, x_t)$, where s_t denotes accumulated soil phosphorus and x_t phosphorus fertilizer applied in the current period. The soil phosphorus level changes from one period to the next according to the state transition function $s_{t+1} = \Gamma(s_t, x_t)$. The product and input prices are denoted by *p* and *w*, respectively, and are assumed to be constant. Operational costs per hectare are denoted by *F* and include costs such as seeds, labour and the rental or annualized cost of machinery.

Accumulated soil phosphorus and soil loss through erosion cause phosphorus loading from the field to the adjacent waterway. Phosphorus transport from fields to surface waters occurs in two main forms: dissolved phosphorus (DP) and particulate phosphorus (PP). The main determinant of DP loss is accumulated soil phosphorus, whereas PP loss is governed by erosion. Soil phosphorus also affects the bioavailability of PP (Sharpley 1993, Uusitalo et al. 2003).[2] In our model, total phosphorus load per hectare includes DP load and the bioavailable fraction of PP load. We consider the optimal mix of three phosphorus abatement measures: (i) precision phosphorus fertilizer application, where application rates are adjusted annually based on the current soil phosphorus level, (ii) gypsum treatment on field surface, and (iii) vegetative filter strips (VFS). Let a_t denote the share of the field parcel treated with gypsum, T the reduction in phosphorus loading provided by gypsum amendment, and b_t the VFS width in each period. For the hectare-sized square parcel considered here, the VFS width also determines the area of the VFS. The erosion susceptibility of land is indexed by field slope γ (see e.g. Wischmeier and Smith 1978). The total phosphorus load is then given by $L(s_t, b_t, \gamma)(1 - a_t T)$. The costs of gypsum treatment are given by Ga_t and the cost of planting and maintaining filter strips by $C(b_t)$. The costs of gypsum treatment include the costs of gypsum and the machinery and labour required for application; the costs of establishing VFSs include seed as well as the machinery and labour required for planting and for removing plant residues.. The per-period monetary damage resulting from phosphorus loading is given by $mL(s_t, b_t, \gamma)(1 - a_t T)$.

The per-period, per-hectare social net return from crop production is given by

$$\Pi(s_t, x_t, b_t, a_t) = \left[pY(s_t, x_t) - wx_t - F \right](1 - b_t) - C(b_t) - Ga_t - mL(s_t, b_t, \gamma)(1 - a_t T) \quad (1)$$

[2] Bioavailability describes the fraction of phosphorus that can be used by algae and that thus contributes to eutrophication. The bioavailability of PP has been estimated to range from 20 to 60 percent (see e.g. Sharpley 1993), while DP is considered fully bioavailable (see e.g. Ekholm and Krogerus 2003).

Multiplication by the term $(1-b_t)$ in (1) accounts for the fact that conversion of a fraction of arable land b_t into a vegetative filter removes that area from production. The private profit from farming is given by $\pi(s_t, x_t, b_t, a_t) = [pY(s_t, x_t) - wx_t - F](1-b_t) - C(b_t) - Ga_t$.

Dynamics of the phosphorus management problem

We are concerned with socially efficient fertilization, gypsum application and filter strip policies over time. Other inputs are assumed to be fixed. We assume that a social planner exists and first consider first the social planner's problem.. The social planner's problem is to maximize the present discounted value of rewards from production, equal to profits net of environmental damage. The farmer's problem is limited to the present discounted value of profits. The social planner's discrete-time, continuous-state decision problem is given by

$$\max_{x_t, b_t, a_t} \sum_{t=0}^{\infty} \beta^t \left\{ [pY(s_t, x_t) - wx_t - F](1-b_t) - C(b_t) - Ga_t - mL(s_t, b_t, \gamma)(1-a_tT) \right\} \tag{2}$$

subject to $s_{t+1} = \Gamma(s_t, x_t)$, $s_0 = S_0$, $x_t \geq 0$, $0 \leq a_t \leq 1$, and $0 \leq b_t \leq 1$. Parameter β is the discount factor corresponding to the social discount rate δ, with $\beta = \frac{1}{1+\delta}$, and S_0 denotes the initial soil phosphorus level. The farmer's intertemporal optimization problem is identical to that described by equations (2) and (3) with the exclusion of the term $mL(s_t, b_t, \gamma)(1-a_tT)$. Accounting for the constraints leads to the Lagrangian

$$\begin{aligned}\max_{x_t, b_t, a_t} \sum_{t=0}^{\infty} \beta^t \{ & [pY(s_t, x_t) - wx_t - F](1-b_t) - C(b_t) - Ga_t - mL(s_t, b_t, \gamma)(1-a_tT) \\ & + \mu_{1,t} x_t + \mu_{2,t} a_t + \mu_{3,t}(1-a_t) + \mu_{4,t} b_t + \mu_{5,t}(1-b_t) \}\end{aligned} \tag{2'}$$

Denote by $V(s)$ the maximum attainable sum of current and future net benefits given a current soil phosphorus level of *s*. Bellman's (1957) principle of optimality implies that the optimal policy must satisfy the functional equation

$$\begin{aligned} V(S) = \max_{x,b,a} \{ & [pY(s,x) - wx - F](1-b) - C(b) - Ga - mL(s,b,\gamma)(1-aT) \\ & + \mu_1 x + \mu_2 a + \mu_3(1-a) + \mu_4 b + \mu_5(1-b) + \beta V(\Gamma(s,x)) \}. \end{aligned} \tag{3}$$

The optimal fertilization rate *x*, gypsum application *a* and filter strip width *b* for each level of soil test phosphorus *s* must satisfy

$$[pY_x(s,x) - w](1-b) + \mu_1 + \beta\lambda(\Gamma(s,x))\Gamma_x(s,x) = 0 \tag{4}$$

$$-G + TmL(s_t, b_t, \gamma) + \mu_2 - \mu_3 = 0. \quad (5)$$

$$-\left[pY(s,x) - wx - F\right] - C_b(b) - mL_b(s,b,\gamma)(1-aT) + \mu_4 - \mu_5 \quad (6)$$

The envelope theorem applied to the same problem implies

$$\lambda(s) = \left[pY_s(s,x)\right](1-b) - mL_s(s,b,\gamma)(1-aT) + \beta\lambda\left(\Gamma(s,x)\right)\Gamma_s(s,x). \quad (7)$$

The equilibrium conditions do not involve the value function but its derivative $\lambda(s) \equiv V'(s)$, the shadow value of the soil phosphorus reserves. The first-order condition (4) states for an interior solution that at every soil phosphorus level fertilizer should be applied to the point where the sum of its marginal impact on profits in the current period and the marginal impact on the discounted value of the phosphorus reserve in the next period equals zero. Because the VFS and gypsum application do not affect the transition process, the partial derivatives Γ_b and Γ_a are zero and the first-order condition (5) and (6) collapse into a static optimality condition. Condition (5) indicates for an interior solution that the marginal cost of gypsum application should equal the marginal reduction in the monetary damage from phosphorus loading. However, since both the cost of gypsum application and the phosphorus loss function are linear in gypsum application, the optimal solution will be a corner solution: either the entire parcel is treated with gypsum (a=1), when the marginal reduction in monetary damage from phosphorus loading exceeds the marginal cost of gypsum treatment, or non of the parcel is treated (a=0) when the marginal reduction in damage falls below the marginal reduction in damage. The marginal reduction in damage depends on s and γ and the decision to apply gypsum or not will hence change over the soil phosphorus level and field slope. The filter strip width should be chosen so that the marginal reduction in profits from production equals the marginal reduction in the damage costs associated with phosphorus loading. Equation (7) indicates that the shadow value of soil phosphorus in the current period equals the sum of its marginal impact on the current period profits, net of the marginal impact on the costs of generated runoff, and the discounted value of the marginal increase in the phosphorus reserve in the following period.

The solution to the private farmer's problem is defined by equations (4) to (7) with the terms describing marginal damage set equal to zero. The shadow value of soil phosphorus in (7) now only accounts for the marginal impact of soil phosphorus on profits from production and on the phosphorus reserve in the following period. Thus, assuming that crop yield is concave in its arguments, the farmer would apply more fertilizer than the social planner. Furthermore, the marginal benefit of a vegetative filter strip is negative for the farmer, and the non-negativity constraint becomes binding. Hence, a private farmer will not construct filter strips without policy intervention.

The long-term development of rewards from production, soil phosphorus level, phosphorus losses and environmental damage can be characterized by a steady state towards which the process converges over time. The steady state for the social planner's problem is characterized by the fertilization rate x^*, gypsum application a^*, filter strip width b^*, soil phosphorus s^* and shadow price λ^*, which solve the equation system

$$\begin{aligned}
&\left[pY_x(s^*,x^*)-w\right](1-b^*)+\mu_1^*+\beta\lambda^*\Gamma_x(s^*,x^*)=0\\
&-G+TmL(s^*,b^*,\gamma)+\mu_2^*-\mu_3^*=0\\
&-\left[pY(s^*,x^*)-wx^*-F\right]-C_b(b^*)-mL_b(s^*,b^*,\gamma)(1-a^*T)+\mu_4^*-\mu_5^*=0\\
&\lambda^*=\left[pY_s(s^*,x^*)\right](1-b)-mL_s(s^*,b^*,\gamma)(1-a^*T)+\beta\lambda^*\Gamma_s(s^*,x^*)\\
&s^*=\Gamma(s^*,x^*).
\end{aligned}\qquad(8)$$

The envelope theorem applied to the same problem implies

$$\lambda(s)=\pi_s(s,x,b)-D_L\left(L(s,b,\gamma)\right)L_S(s,b,\gamma)+\beta\lambda\left(\Gamma(s,x)\right)\Gamma_s(s,x).$$

The solution to the farmer's problem is defined by equations (8), with the terms describing marginal damage set equal to zero.

The characteristics of phosphorus raise interesting empirical questions regarding optimal dynamic phosphorus policies. The optimal path of phosphorus reserves over time has to accommodate the trade-off between the roles that soil phosphorus plays in both crop growth and environmental degradation. If the initial soil phosphorus level is above the socially optimal level, what is the optimal mix of abatement through depletion of soil phosphorus reserves, gypsum application and erosion control? Does the optimal mix of the three abatement measures change along the optimal path, and how is this mix influenced by the key ecological characteristics of the site, such as susceptibility to erosion? To study these questions in a realistic setting, we construct a detailed bioeconomic model of crop production and phosphorus loading, with barley as the sample crop, and empirically evaluate optimal dynamic phosphorus policies.

Bioeconomic model and empirical illustration

Matching fertilizer application rates to soil phosphorus levels requires knowledge about the crop production and pollution generation processes. Our bioeconomic model considers the impact of soil phosphorus and phosphorus fertilization on yield and the accumulation of soil phosphorus as well as the link from soil phosphorus to phosphorus loading. The model is parameterized for sandy clay soils in southern Finland. We consider three representative field slopes: 0.5%, 2% and 7%. The average slope is 0-1% for some 57% of parcels in Finland; 1-3% for 26% of parcels; and greater than 7% for 3% of parcels (Puustinen et al. 1994). While the proportion of steeply sloped parcels is small, we include a steep slope in the analysis as an example of land with particularly high runoff potential. Throughout the empirical illustration, soil phosphorus level is expressed as agronomic soil test phosphorus (STP).

Crop production function

The yield response to phosphorus consists of the impacts of the fertilizer applied and the phosphorus accumulated in the soil. Following Myyrä, Pietola and Yli-Halla (2007), we specify the phosphorus response function for barley as

$$Y(s,x) = \alpha_1^Y (1 - \alpha_2^Y e^{-\alpha_3^Y s}) + (\alpha_4^Y - \alpha_5^Y s)\sqrt{x} + \frac{(\alpha_6^Y - \alpha_7^Y x)x}{s} + \alpha_8^Y \,. \tag{9}$$

From Myyrä, Pietola and Yli-Halla (2007), the parameter values for barley production in southern Finland are $\alpha_1^Y = 3367$, $\alpha_2^Y = 0.74$, $\alpha_3^Y = 0.37$, $\alpha_4^Y = 21.7$, $\alpha_5^Y = 0.414$, $\alpha_6^Y = 17.01$, $\alpha_7^Y = 0.1817$ and $\alpha_8^Y = 5.856$.

Transition function for soil phosphorus

Ekholm et al. (2005) model the relationship between the development of soil phosphorus and the phosphorus surplus, that is, the fertilizer applied to the land but not utilized by the crop. The phosphorus surplus is defined by $P_{bal}(s,x) = x - \Lambda(s)Y(s,x)$, where $\Lambda(s)$ is the phosphorus concentration of the crop yield. Saarela et al. (1995) provide information that allows specification of the phosphorus concentration of crop yield as a logarithmic function of the soil phosphorus. Following Ekholm et al. (2005), the change in soil phosphorus from one year to the next is then specified as follows:

$$\Gamma(s,x) = \alpha_1^\Gamma s + (\alpha_2^\Gamma + \alpha_3^\Gamma s)\left[x - (\alpha_4^\Gamma \ln(s) + \alpha_5^\Gamma)Y(s,x)\right], \tag{10}$$

where the term $\left[x - (\alpha_4^\Gamma \ln(s) + \alpha_5^\Gamma)Y(s,x)\right]$ is the phosphorus surplus and the term $\alpha_4^\Gamma \ln(s) + \alpha_5^\Gamma$ defines the phosphorus concentration of the crop yield. The parameter estimates α_1^Γ = 0.9816, α_2^Γ = 0.0032 and α_3^Γ = 0.00084 were obtained directly from Ekholm et al. (2005).[3] The parameter estimates $\alpha_4^\Gamma = 0.000186$ and $\alpha_5^\Gamma = 0.003$ were obtained from data in Saarela et al. (1995) through ordinary least squares estimation.[4]

Phosphorus load and abatement using gypsum and vegetative filter strips

The phosphorus load function $D\left(L(s_t, b_t, \gamma)(1 - a_t T)\right)$ expresses DP load and the bioavailable fraction of PP load net of VFS and gypsum abatement. Following Uusitalo and Jansson (2002), the annual DP load (kg ha^{-1}) from crop production is specified as a linear function of the soil phosphorus level:

$$L_{DP}(s) = \alpha_1^{DP} s - \alpha_2^{DP}. \tag{11}$$

In line with the universal soil loss equation (Wischmeier and Smith 1978), annual PP loss (kg ha^{-1}) is specified in turn as a quadratic function of field slope:

[3] The transition function presented by Ekholm et al. (2005) depicts changes in STP with a time step of 10-15 years with a constant phosphorus surplus over the period. Using a one-year time step predicts STP values in the long run that differ slightly from those predicted by the Ekholm et al. (2005) equation. For initial STP levels ranging from 2 to 40 mg l-1 and P surpluses from -5 to 25 kg ha-1 y-1, the differences in STP values for year 30 predicted by equation (10) with a constant phosphorus surplus and one- and ten-year time steps were 0 to 8%.

[4] The phosphorus concentration data in Saarela et al. (1995) were measured from dry matter. Their data were made commensurate with storage weight yield prior to the estimation.

$$L_{PP}(\gamma)=\alpha_1^{PP}\gamma^2+\alpha_2^{PP}\gamma+\alpha_3^{PP}. \quad (12)$$

As vegetative filter strips only retain nutrients in surface runoff, we distinguish PP load through surface runoff and through drainage water. We interpret the constant term in (12) as PP load in drainage, which should be independent of field slope. Accordingly, PP load via surface runoff is given by $L_{PP,S}(\gamma)=\alpha_1^{PP}\gamma^2+\alpha_2^{PP}\gamma$ and PP load via drainage by $L_{PP,D}=\alpha_3^{PP}$.

Following Lankoski, Ollikainen and Uusitalo (2006), the retaining of PP by filter strips is described by the function

$$R(b)=b^{\alpha_1^R}, \quad (13)$$

where $\alpha_1^R<1$. Vegetative filter strips also mitigate PP loss by placing erodible field area under a stable vegetative cover (see e.g. Dosskey 2001). In other words, no PP loss occurs in the VFS area *b*.

Only a proportion of PP contributes to the bioavailable phosphorus load. For simplicity, we assume a linear relationship between PP bioavailability and soil phosphorus level:

$$B(s)=\alpha_1^B s+\alpha_2^B. \quad (14)$$

Gypsum is assumed to reduce the loads of particulate and dissolved phosphorus by a given fixed percentage *T*. From equations (10)-(14), the total bioavailable phosphorus load is given by

$$L(s,b,\gamma)=\left\{L_{DP}(s)+B(s)(1-b)\left[L_{PP,D}+(1-R(b))L_{PP,S}(\gamma)\right]\right\}(1-aT). \quad (15)$$

The parameter estimates α_1^{DP}= 0.0567 and α_2^{DP}= 0.0405 for equation (11) were obtained by multiplying the estimates of DP concentration in mg l^{-1} in Uusitalo and Jansson (2002) by an estimated runoff volume of 270,000 l ha^{-1} (Ekholm et al. 2005) and converting the units to kg ha^{-1}. The data in Uusitalo et al. (2007) produce parameter estimates of $\alpha_1^{PP}=0.035$, $\alpha_2^{PP}=0.12$ and $\alpha_3^{PP}=0.37$ for equation (12). The parameter value $\alpha_1^R=0.3$ was obtained from Lankoski, Ollikainen and Uusitalo (2006), who used results from a Finnish study on grass filter strips (Uusi-Kämppä and Kilpinen 2000) in calculating their estimate. The data in Uusitalo et al. (2003) yield parameter estimates of $\alpha_1^B=0.48$ and $\alpha_2^B=19.7$ for equation (14). Finally, based on preliminary empirical reports on abatement through gypsum treatment, parameter *T* is set equal to 0.3.

Damage from phosphorus loading

By assumption, the damage from agricultural phosphorus loading is described by a linear damage function:

$$D\left(L(s,b,\gamma)\right)=\alpha_1^D L(s,b,\gamma). \qquad (16)$$

Based on Redfield et al (1963), Pitkänen et al (2007) and Kosenius (2010) we obtain the parameter value $\alpha_1^D = 348$ (EUR kg^{-1}). The derivation is presented in Appendix 1.

Prices and costs

Product price *p* and input price *w*, obtained from Myyrä, Pietola and Yli-Halla (2007), are 0.11 € kg^{-1} and 1.22 € kg^{-1}, respectively. The annual fixed costs of production, *FC*, were obtained from Helin, Laukkanen and Koikkalainen (2006) and equal 113 € ha^{-1}. The costs of gypsum application, G, are 61 € ha^{-1} (personal communication, Reetta Palva, 2010). The costs of establishing a vegetative filter strip derive primarily from removing plant residue each year in order to prevent phosphorus in the residue from leaching into the environment. The VFS cost function thus takes the form

$$(16) \qquad C(b)=\alpha_1^C b.$$

Palva (2003) and Pentti and Laaksonen (2005) estimated the costs in Finland to be 31 € ha^{-1} for mowing and 65 € ha^{-1} for baling and transportation, yielding a total of α_1^C = 96 € ha^{-1}. Finally, the discount rate was set at 5%.

Solution method

To determine the optimal phosphorus control policies over time, the dynamic program in (3) was solved numerically using the collocation method. This technique involves writing the value function approximant as a linear combination of n known basis functions $\varphi_1, \varphi_2, \ldots, \varphi_n$ whose coefficients $c_1, c_2, \ldots, c_n$ are determined by the equation

$$(17) \qquad V(s)\approx\sum_{j=1}^{n} c_j\phi_j(s)$$

The coefficients $c_1, c_2, \ldots, c_n$ are defined by requiring the value function approximant to satisfy the Bellman equation (3) at a finite set of collocation nodes. The solution was implemented using the

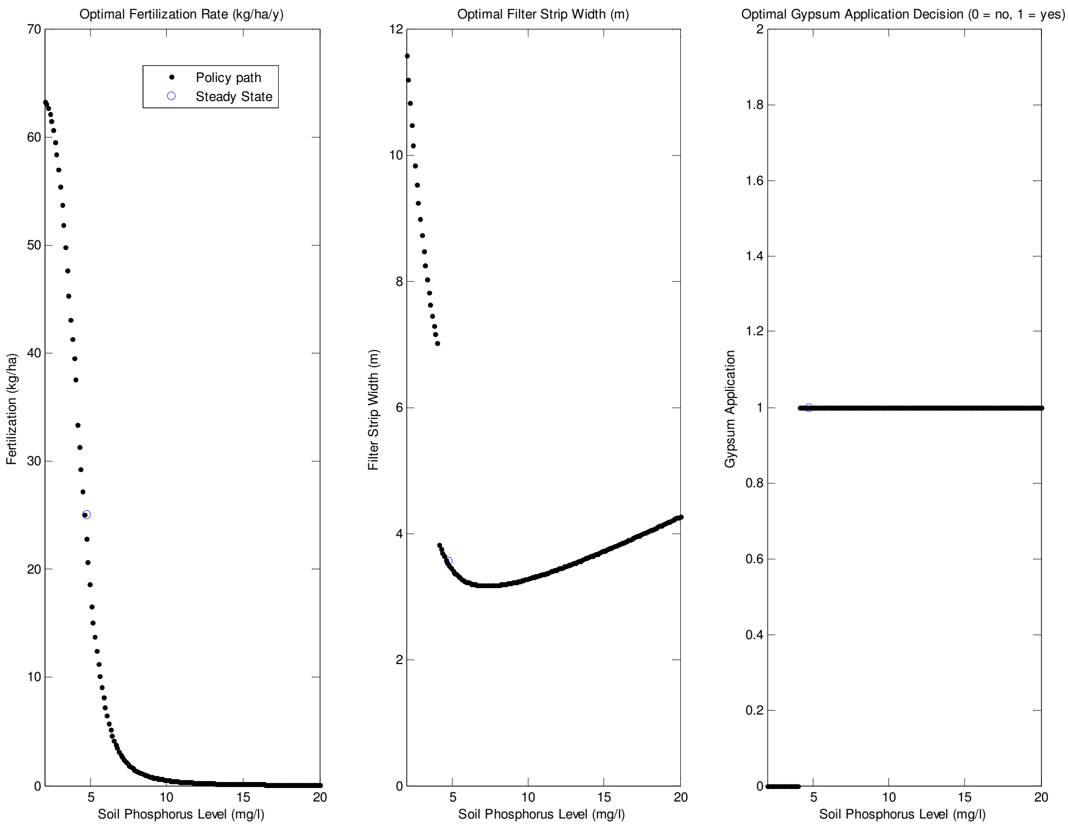
CompEcon Toolbox for Matlab.[5] The solution produces policy functions for $x(s)$, $a(s)$ and $b(s)$ that provide a mapping from the current soil phosphorus level to the optimal fertilization and VFS policies.

Results

The analysis is still unfinished. More results will be presented and discussed in the seminar

Optimal Policies

Figure 1 illustrates the core results of the present study. It presents the optimal policy for a steep parcel (slope 7 %). By presenting the results of the steepest parcel we are able to better illustrate the interesting links between optimal VFS width, STP values and gypsum application. The leftward panel denotes the optimal fertilization policies, the middle panel the optimal VFS policies and the rightmost panel the optimal gypsum application policy for each STP level. In each panel the small circle denotes the steady state.



[5] The Matlab code is available from the authors upon request. The CompEcon Toolbox is a library of Matlab functions, developed to accompany Miranda and Fackler (2002), for numerically solving problems in economics and finance. The library is downloadable at http://www4.ncsu.edu/~pfackler/compecon/toolbox.html.

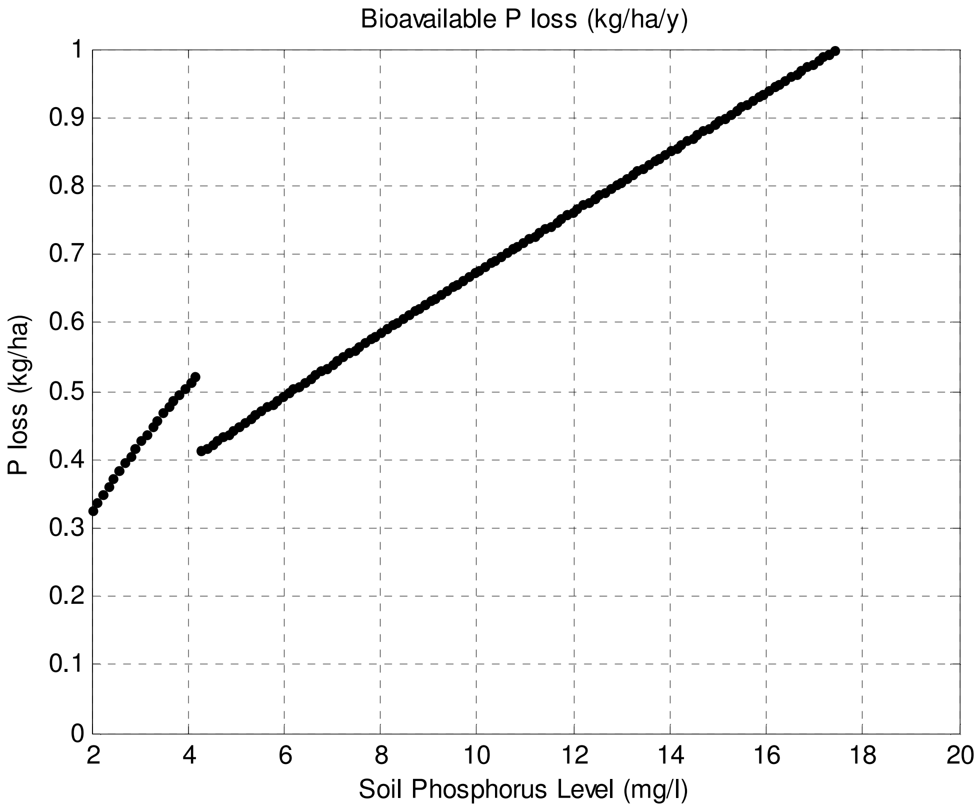
Figure 1 summarizes the key results of the present study. The leftward panel shows how the annual fertilization level is determined by the STP level. The application levels are negligible with STP above the steady state level. For STP values below the steady state the optimal fertilization levels are almost three times as high as at the steady state.

The two other panels are distinctly and directly connected – not only via STP level. VFS are used to reduce PP loads. Their costs are driven by the opportunity cost of land. This, on its behalf, is determined by the prevailing STP level. The higher the STP, the more valuable the land, and the more costly it is to allocate it away from production. However, the higher the STP, the more bioavailable the PP load. Therefore, the optimal VSF starts to increase again after certain STP threshold level. These two effects – costs and bioavailability increasing with STP, form the curvature seen in the middle panel.

This curvature is truncated at the STP level where gypsum amendment is brought into play. At STP levels above about 3 mg/l it will optimal to apply gypsum on field surface. This enables the social planner to decrease the VFS width and obtain more land on production.

Figure 2 presents the phosphorus loading associated with optimal phosphorus and gypsum application and VFS widths, as a function of STP level.

Figure 2. Bioavailable phosphorus load



The curve is truncated at the point of introducing gypsum application. Furthermore, the slope of the phosphorus loss is less steep when gypsum is applied.

In figre 3 we compare phosphorus application levels to constraints posed by the Finnish agri-environmental program. A optional measure "Reduced Fertilization" sets STP-dependent limits on phosphorus use. Figure 3 compares them ageainst the optimal application levels.

Figure3 compares the optimal fertilization policy with the constraints posed by the Finnish agri-environmental program