

DYNAMICS OF PHOSPHORUS FERTILIZATION AND LIMING UNDER LAND TENURE INSECURITY

Sami Myyrä and Kyösti Pietola

MTT Agrifood Research Finland Economic Research
Luutnantintie 13, FI-00410 Helsinki, Finland
e. sami.myyra@mtt.fi and kyosti.pietola@mtt.fi
t. +358-9-56080 f. +358-9-5608 6264



Paper prepared for presentation at the 99th seminar of the EAAE

(European Association of Agricultural Economists),

*'The Future of Rural Europe in the Global Agri-Food System', Copenhagen, Denmark,
August 24-27, 2005*

Copyright 2005 by Myyrä and Pietola. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

DYNAMICS OF PHOSPHORUS FERTILIZATION AND LIMING UNDER LAND TENURE INSECURITY

Abstract: This article solves and characterizes optimal decision rules to invest in irreversible land improvements conditional on land tenure insecurity. Economic model is a normative dynamic programming model with known parameters for the one period returns and transition equations. The decision rules are solved numerically conditional on alternative scenarios on the likelihood that the lease contract and, thus, farmer access to land is either renewed or expired. The model parameters represent Finnish soil quality and production conditions. The results suggest that irreversible land improvements decrease quickly and the yields decline gradually when the farmer is confronted with land tenure insecurity caused by uncertain renewal of the lease contract.

Keywords: Agriculture, Dynamic Programming.

JEL: Q15, Q21

1. Introduction

Economic literature analysing implications of land tenure insecurity focuses for the most part in developing countries. In these countries land tenure insecurity has large implications, not only on land improvements, but also on the household and society welfare as a whole. In many empirical studies the effects of land tenure insecurity could not, however, be strongly identified in these countries, because household access to farming inputs and output markets can be severely retarded by other institutional, financial, and economic factors than by land tenure insecurity alone (Holden and Hailu 2002).

In the context of rich countries, land tenure insecurity has not received much attention in the economics literature. Even if land tenure insecurity is not yet a dominating problem in these countries it may become such, particularly in Less Favoured Areas (LFA), where production costs are high and yields decrease quickly if land improvements are delayed. The trend towards more liberalized food market and internationally harmonized agricultural policies decrease Marginal Value Products (MVP) for agricultural inputs in the LFA areas, where farmer options to adjust to these trends are rare. There are good reasons to expect that in the LFA areas of Northern Europe land improvements may decrease below the socially optimal levels¹, if farmers are confronted with significant land tenure insecurity. Land insecurity problem is also strongly linked to the efficiency of agri-environmental programs of maintaining open landscape, maintaining fertility of arable land, and decreasing nutrient runoffs from agriculture. The reason is that long term land improvements are necessary for reaching the goals of these programs.

In Finland, for example, signals on market failures, caused by land tenure insecurity, are emerging in agricultural input market and in the amount of irreversible land improvements. Land improvements have generally decreased, and they have decreased most in land parcels that have been cultivated under lease contracts (Yearbook of Farm Statistics 2003; Myyrä *et al.* 2003). The observed data suggest that market failures resulting from land insecurity problem have not been solved on land cultivated under lease contracts. The problem is not linked only to yields and food supply but also on efficiency of agri-environmental programs that require irreversible investments on land improvements that have long pay-back periods.

The potential land tenure insecurity problem on leased land is becoming more and more extensive. In 1995 in Finland the share of land cultivated under a lease contract was 18% and in 2003 it was increased to 33%.

This article is to solve and characterise optimal decision rules to invest in irreversible land improvements conditional on land tenure insecurity. Economic model is a normative dynamic programming model with known parameters for the one period returns and transition equations. The decision rules are solved numerically conditional on alternative scenarios on the likelihood that the lease

¹ The socially optimal level of land improvements refers to a level, which is reached in competitive markets equilibrium without land tenure insecurity (Mas-Coell *et al.* 1995 p. 325-328). The social optimum gives the maximum welfare for society as a whole, including land owners and tenants.

contract and, thus, farmer access to land is expired. The model parameters represent Finnish conditions and they are based on field experiments. The results suggest that land improvements decrease quickly and the yields decline gradually when the continuation of the lease contract is uncertain.

2. The model

The Bellman equation

The grain grower optimization problem is modelled as a recursive finite horizon (T) dynamic programming problem that is solved numerically by iterating on the following Bellman's equation (Bellman 1957):

$$V_t(z_t) = \max_{u_t} \left\{ R_t(z_t, u_t) + \beta E_t [V_{t+1}(z_{t+1}) | \Omega_t] \right\}, \quad t = 0, 1, \dots, T \quad (1)$$

subject to
 transition equations: $z_{t+1} = g(z_t, u_t)$, and
 initial state: z_0 given

where the optimal value function (V_t) is the function of the current state vector (z_t); u_t is the control (also called as the decision rule or policy function); $R_t(\cdot)$ is the one period net return function; β is the discount factor; and $E_t[\cdot]$ is the conditional expectations operator, conditioned on current information (Ω_t). The optimal value function is constrained by the transition equations, in which $g(\cdot)$ is a function. It determines the connection between the current state and control and the next period state. The optimal solution is pinned down by the initial state z_0 . It has to be noticed that z_t and u_t have separate transition equations and contributions to the net return. This specification generalizes the models presented in Kennedy (1986).

The problem is normalized to one hectare and the crop grown is spring barley which is the most common cereal grown in Finland. The soil types are fine-textured *Vertic Cryaquepts*² and medium-textured *Oxyaquic Eutrocryepts*². The model represents land that has sufficient quality and the long run equilibrium is to keep soil *pH* and soil phosphorus status at satisfactory³ levels from the society perspective, i.e. without land tenure insecurity. In more marginal land areas, the land tenure insecurity problem is not the only institutional factor that is decreasing the irreversible soil improvements in a high cost country with sparse rural population, such as Finland.

The problem is specified and solved separately for phosphorus and lime applications. The time horizon was set at 100 years which guaranteed that not only the decision rules but also the stock variables converged.

Economic implications of land tenure insecurity are modelled through a sequence of fixed duration (τ) land leasing contracts. We simulate a five year ($\tau=5$) cash lease contract, which is the standard duration for the lease contracts in Finland. Five year contracts and commitments are often

² Soil taxonomy

³ The values of *pH* and soil phosphorus status are divided into seven classes as follows: poor, rather poor, fair, satisfactory, good, high and excessive (Viljavuuspalvelu Oy – Soil Analysis Service Ltd. 2000). The class limits are based on extensive number of field experiments. Satisfactory is the target class, considered sufficient for normal yields of field crops such as cereals and ley. Phosphorus is extracted with an acid (*pH* 4,65) ammonium acetate solution, closely resembling the well-known Morgan method, and Soil *pH* is determined in water suspension.

required in agri-environmental programs. Longer than 10 year contracts are forbidden by law (Maanvuokralaki). The most common lease payment is a fixed cash payment, since the land owners can auction the cash payments with low information requirements. The short term land rent can be maximized simply by leasing the land for a farmer who pays the highest cash lease.

The signed contract continues, and farmer has access to land, by certainty until the contract's next expiration date $t=n\tau$, for $n=1,2,3,\dots,20$. At each expiration date $t=n\tau$, the continuation of the contract is uncertain and it is renewed by an exogenously given probability $Prob_{n\tau}$. Because continuation and expiration are mutually exclusive, the probability that the lease contract expires is $(1-Prob_{n\tau})$ and, once the contract expires, the one period returns are assumed to stay at zero forever. Thus, the expiration is assumed irreversible so that, if the contract expires, it can never be renewed. Under these conditions, taking the expectations results in the Bellman equation

$$V_t(z_t) = \max_{u_t} \left\{ R_t(z_t, u_t) + \beta Prob_t V_{t+1}(z_{t+1}) \right\}, \quad t = 0, 1, \dots, T \quad (2)$$

subject to $z_{t+1} = g(z_t, u_t)$
 z_0 given, $T=100$
 where $0 \leq Prob_t \leq 1$ for all $t=n\tau$, and $Prob_t=1$ otherwise.

The state vector (z_t) consists of nutrient stock (x_t) and prices of outputs (p_t) and the price of the control variable (w_t). Prices are assumed deterministic such that the current prices prevail in the future. Thus, the transition equations for prices are simply

$$p_t = p_{t+1} = \bar{p} \quad \text{and} \quad w_t = w_{t+1} = \bar{w} \quad (3)$$

The transition equations (*i.e.* the carry-over effects) for phosphorus and soil *pH* are defined separately in subsequent sections. The one period net return (R_t) is the difference between the one period revenue from selling the yield minus the expenditure of purchasing the control. Because other factors are hold fixed in the analysis, they can be suppressed and the one period return function is:

$$R_t(z_t, u_t) = p_t y(x_t, u_t) - w_t u_t \quad (4)$$

where $y(x_t, u_t)$ is a deterministic yield response function, specified separately for phosphorus and lime below. The last term, $w_t u_t$ is the expenditure of using inputs *i.e.* lime and phosphorus fertilizer.

Phosphorus (P): yield response and carry-over

The yield (y) and phosphorus control (u^p) are expressed as kilograms per hectare (kg/ha), whereas the phosphorus stock (x^p) is expressed by milligrams of easily soluble phosphorus per litre of soil (mg/l).

Phosphorus has a direct flow effect and an indirect stock effect on the yield. The direct flow effect is the fraction of the current phosphorus fertilization that is utilized by the crop at the same period as the nutrient is applied in soil. Indirect stock effect is from phosphorus stock accumulated in soil as unused residues of previous phosphorus applications. It can be depleted gradually without phosphorus fertilization, reflected as a decline of the Soil test P value. It is common that 10-25% phosphorus taken up by a crop comes from the same year's fertilizer application, the rest originating from the stock of the Soil build up earlier (Sharpley 1986). The yield response to the phosphorus stock in the soil is described by a Mitscherlich function (Myyrä *et al.* 2003)

$$y(x_t^p, u_t^p) = 3367 - 2492 e^{-0.37 x_t^p} \quad (5)$$

and the yield response to phosphorus application (u^p) is specified as an exponential function (Saarela *et al.* 1995)

$$dy(x_t^p, u_t^p) / du_t^p = 5.85 + (21.7 - 0.414x_t^p)\sqrt{u_t^p} + (17.01u_t^p - 0.1817) \frac{u_t^p}{x_t^p} \quad (6)$$

The transition equation is assumed to be

$$x_{t+1}^p = 0.01u_t^p + (1 - 0.02)x_t^p \quad (7)$$

The transition equation imposes an average annual decay rate of 2% in the stock of phosphorus, which can be seen when u_t^p is put to zero. Assumption is made, even if it is known that the decay rate has large annual variation (Yli-Halla 1989). The initial state for the stock is given at $x_0^p = 7.8 \text{ mg/l}$, which was estimated to be an average on leased plots in central and northern Finland (Myyrä *et al.* 2003).

The fit of the equation system matches to the generalized results of Mäntylähti (2002) so that an annual phosphorus application of 14-15 kg/ha converges the phosphorus stock at around 7.5 mg/l. Less than 15 kg/ha phosphorus application is a common standard in meeting the terms of the Finnish agri-environmental program. The resulting average yield level is 3,500 kg/ha, which also corresponds to the observed average yields of spring barley in Finland (Yearbook of Farm Statistics 2003).

Lime (L): yield response and carry-over

The liming control (u^l) is measured as tonnes per hectare (t/ha) and the stock of lime (x^l) is measured in terms of soil pH . Liming has only an indirect effect on yield via soil pH . The yield response to the soil pH is described by Mitscherlich function (Kempainen 1993; Myyrä *et al.* 2003)

$$y(x_t^l, u_t^l) = 3748 - 29147862 e^{-3.85 pH_t} \quad (8)$$

The transition equation describing the carry over effect and the effects of liming to the soil pH is (Kempainen 1993)

$$x_{t+1}^l = pH_{t+1} = 0.049u_t^l + pH_t - 0.015 \quad (9)$$

With no liming the average annual decay rate in the soil pH is 0.015 pH -units, which implies that annual amount of liming required for maintaining the existing pH level is in average 0.3 tonnes per hectare. The initial state is imposed at $x_0^l = pH_0 = 5.8$, which was estimated to be an average on leased plots in central and northern parts of Finland (Myyrä *et al.* 2003). The prices and the scope of the model are summarized in Table 1.

Table 1. Prices and the scope of the optimization problem.

Price of barley ^a	110 €/tonne
Price of phosphorus ^a	1,220 €/tonne
Price of lime ^a	
if applied 1-3 tonnes/ha	42.69 €/tonne
if applied 4-15 tonnes/ha	33.61 €/tonne
Discount factor (β)	1/1.05
Time horizon (T)	100 years
Duration of single contract (τ)	5 years

^a The prices are at farm gate. The price of liming includes also distribution on the field because the standard is that the distribution is bought from a contractor and, therefore does not involve sunk cost from the farmer perspective. Distribution incurs extra cost per tonne at low application levels.

3. Results

Phosphorus

When there is no land tenure insecurity, *i.e.* the land is owned by the farmer or the lease contract is repeatedly renewed by certainty, the steady state equilibrium⁴ for the phosphorus application is estimated to be 18 kg/ha (Figure 1). The likelihood for expiration of the lease contract has considerable effects on the optimal phosphorus fertilization, particularly, when the contract is reaching the edge of expiration/renewal date. If, for example, the odds are slightly in favour of contract renewal ($Prob=0.6$), the optimal phosphorus fertilization stays between 10 and 11 kg/ha until the third year before the renewal date. This level of application is as much as 44-39 percent lower than the long run equilibrium without land tenure insecurity. Thereafter and towards the end of the current contract, the phosphorus fertilization drops to 9-8 kg's per hectare. If the expiration of the contract is certain, the phosphorus fertilization goes towards 2 kg/ha quickly as the expiration date approaches.

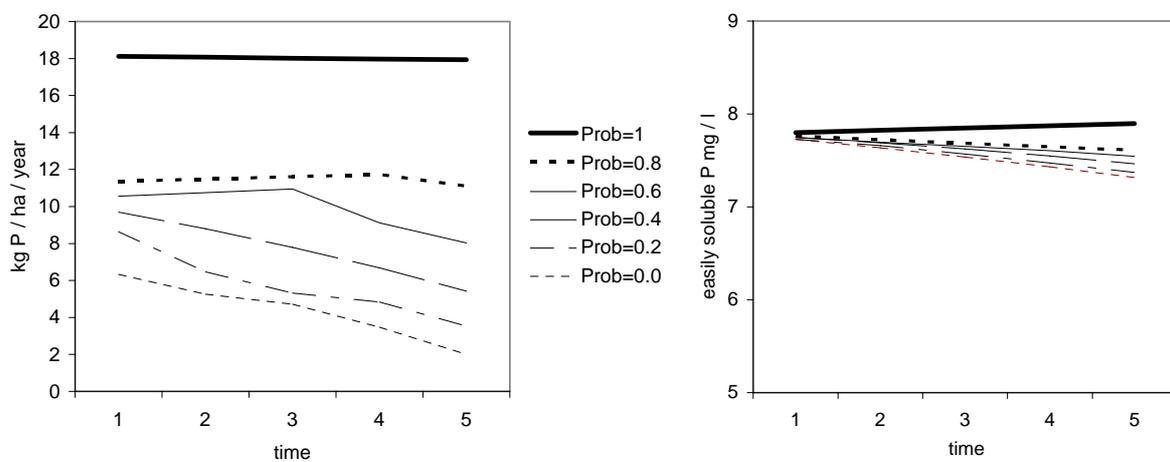


Figure 1. Phosphorus fertilization (u_t^p) (left) and consequent values of easily soluble P in soil (right) as a function of the remaining duration in the contract before its expiration/renewal date, conditional on the probability ($Prob$) that the contract is renewed at the expiration date. If $Prob=1$ ($Prob=0$), the contract is renewed (terminated) by certainty. Please note that Phosphorus state (z_t) is not yet converged by the period of $t=5$. Crop is spring barley.

When there is no land tenure insecurity the steady state (*i.e.* the state which you have to keep to achieve the maximum profit) for soil phosphorus is 8.5 mg/l, which is substantially below the amount needed for producing the maximum yield (13 mg/l)(Figure 2). If uncertainty over continuation of each five year contract is large such that the odds are strongly against of contract renewal ($Prob=0.2$), the steady state soil phosphorus is estimated at 5.5 mg/l, which definitely represents a lower soil phosphorus status that required for the maximum yield. Even if the odds are slightly in favour of the contract renewal ($Prob=0.6$) the steady state soil phosphorus decreases to 6.8 mg/l. The analysis is based on estimated⁵ connection between soil phosphorus and expected yield presented in equation 5. In the equation 5 decreasing soil phosphorus have quite small influence to yield until soil phosphorus decreases below 7 mg/l. When the soil phosphorus status declines below 7 mg/l, the yield decreases rapidly. Thus, the profit maximising soil phosphorus levels are substantially lower compared to the maximum yield levels under large uncertainty over contract renewal ($Prob < 0.4$).

When the phosphorus state is converged, the steady state equilibrium for the phosphorus application is estimated between 16 and 18 kg/ha (Figure 2). The optimal use of phosphorus fertilizer has decreased slightly, because of increased phosphorus stock. Changes, caused by uncertainty, in

⁴ Which we call as the socially optimal level in chapter 1.

⁵ Functional form is a fundamental guest in estimating connection between fertilization and yield (Bäckman et al. 1997). A thorough discussion about the functional specification can be found in Myyrä et al. (2003).

phosphorus stock have also implications to the tenants fertilizing behaviour. There is incentive to use phosphorus fertiliser at the beginning of the lease contracts, even if uncertainty over continuation of each five year contract is large ($Prob=0.2$), because of the low levels of phosphorus stock. Incentives disappear sharply as the expiration date approaches (Figure 2).

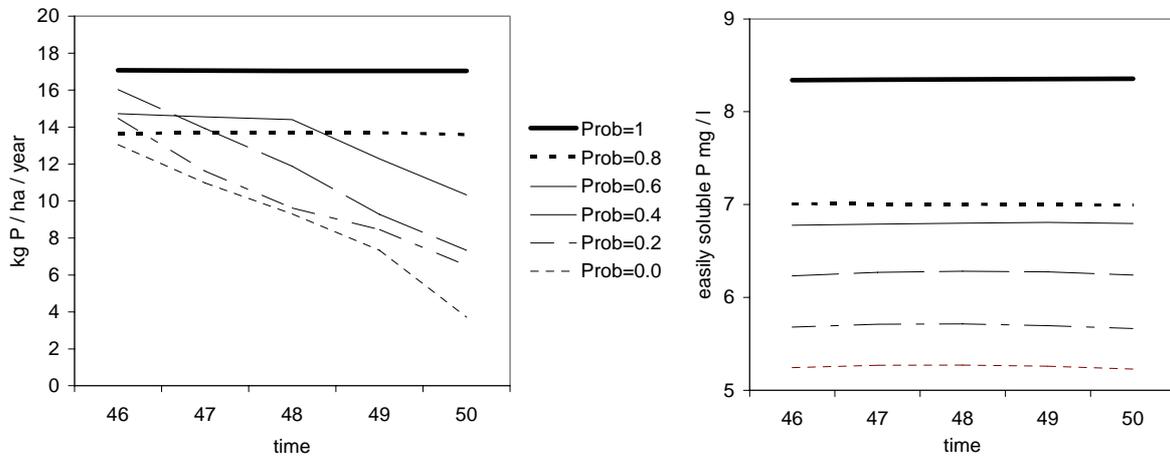


Figure 2. Phosphorus fertilization (u_t^p) (left) as a function of the remaining duration in the contract before its expiration/renewal date and converged values of easily soluble P in soil (right), conditional on the probability ($Prob$) that the contract is renewed at the expiration date. If $Prob=1$ ($Prob=0$), the contract is renewed (terminated) by certainty. Phosphorus state (z_t) is converged during $46 \leq t \leq 50$. Crop is spring barley.

Gradually decreasing soil phosphorus stock will eventually decrease yields (*ceteris paribus*). Figure 3 traces out the yields during two five years contracts, which are located in the optimization horizon at $1 \leq t \leq 5$ and $46 \leq t \leq 50$. In the latter period the soil phosphorus has converged to steady state values as given in Figure 2. When the land has been cultivated under several subsequent five year lease contracts and the likelihood for contract renewal has been repeatedly at stake, the yield will start to decrease significantly and converge to around 3,100 kg/ha. The yield decrease from the 3,400 kg/ha steady state equilibrium without land tenure insecurity is 300 kg/ha and in relative terms 10 per cents. Even if the odds are slightly in favour of contract renewal ($Prob=0.6$) the steady state yield will be decreased by 100 kg/ha (3%) to 3,300 kg/ha.

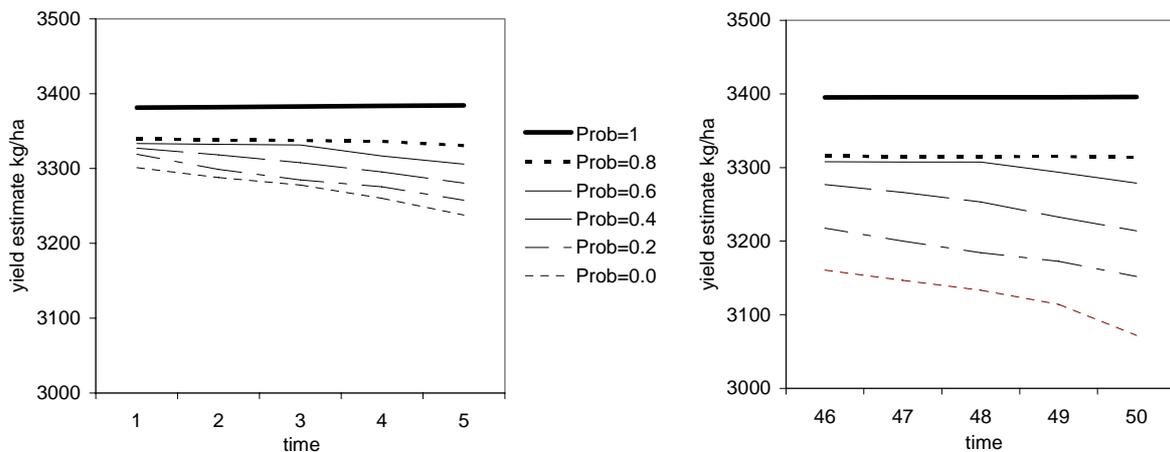


Figure 3. The predicted yield response to optimal phosphorus fertilization under alternative probabilities ($Prob$) for renewal of each five year lease contract (*ceteris paribus*). Phosphorus state (z_t) is converged during $46 \leq t \leq 50$ (right). Crop is spring barley.

Liming and soil pH

Liming represents even a longer term land improvement than phosphorus fertilization. Liming is also to some extent lumpy so that it is expensive to distribute small amounts of lime (see the price thresholds in Table 1). Therefore, if the initial soil pH is in biological target range, which is in our simulations 5.8, the land tenure insecurity does not make a difference in the optimal liming rules (Figure 4). It does not pay to distribute lime on land with pH level exceeding 5.4, except when the farmer access to land certainly continues, either through repeated contract renewals or land ownership. In this case the decision rule converges with optimal behaviour around long run equilibrium without land tenure insecurity, which is also optimal for the society. More demanding crops than spring barley would likely benefit from higher pH values.

But when the initial pH level decreases and soil acidity increases, decisions to lime diversify according to the uncertainty over continuation of the lease contract (Figure 4). If the contract is going to expire by certainty, it pays to lime at the beginning of a five year contract only if the soil pH is below an extremely low value of 5. If the odds are slightly in favour of contract renewal ($Prob=0.6$) it pays to lime at the beginning of the five year contract if the soil pH is below 5.2.

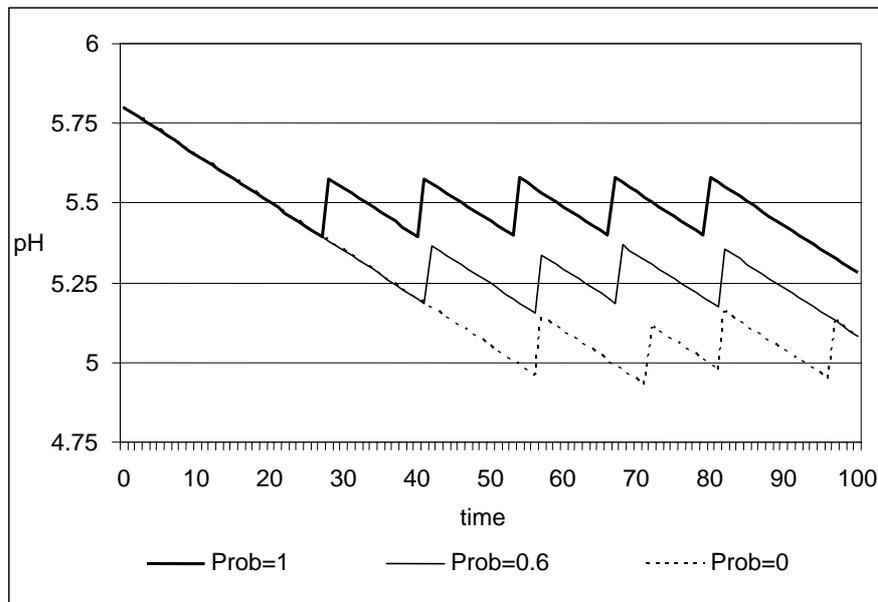


Figure 4. Development of soil pH in a sequence of 5 year lease contracts, conditional on alternative contract renewal probabilities ($Prob$). The upward sloping jumps in soil pH indicate points where lime is applied. Downward sloping line traces the soil pH , when lime is not applied.

The steady state, long run equilibrium, without land tenure insecurity is to maintain soil pH above 5.4, representing a “fair” soil pH status in the soil type studies. When the likelihood for contract renewal is likely (e.g. $Prob>0.5$), it is still advantageous to maintain the soil pH above 5.2. Optimal timing is to apply liming immediately after the new contract is signed. Nevertheless, when likelihood for contract renewal decreases and the odds are in favour of contract termination ($Prob<0.5$), the soil pH is allowed to decrease below 5.2, which in the soil studies most commonly represents the fertility class “rather poor” or “poor”⁶.

⁶ The class limits depend on the particle size distribution and the organic matter content of the soil.

Neglected liming results in gradually decreasing soil pH , which will eventually decrease yields (*ceteris paribus*). Figure 5 traces out patterns of consequent five year contracts, which sum up to a 100 year period. When the land has been cultivated under several subsequent five year lease contracts and the likelihood for contract renewal has been repeatedly at stake, the yield will start to decrease significantly and converge to around 3,300 kg/ha. The yield decrease from the 3,670 kg/ha steady state equilibrium without land tenure insecurity is 230 kg/ha and in relative terms 6 per cent. If the odds are slightly in favour of contract renewal ($Prob=0.6$) the steady state yield will be decreased only by 120 kg/ha (3%) to 3,550 kg/ha.

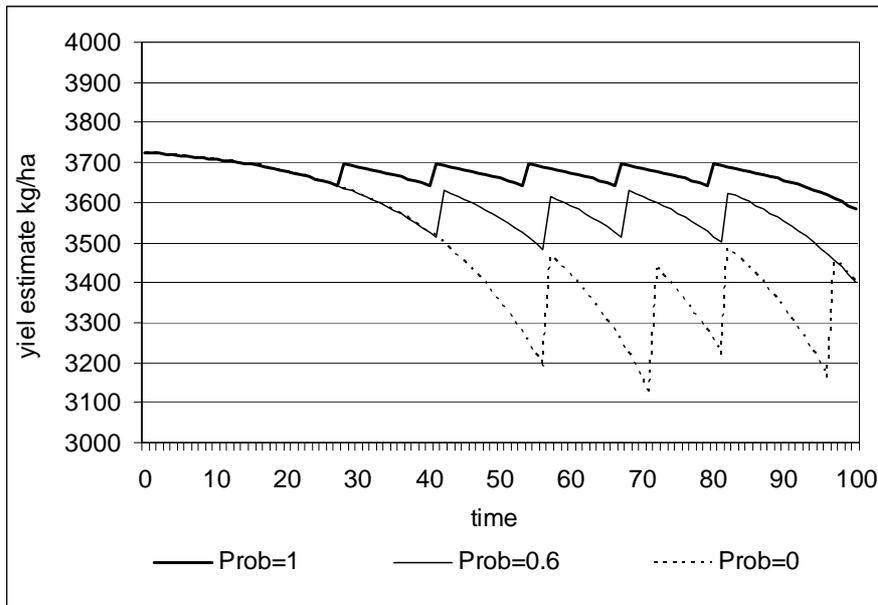


Figure 5. Predicted yield response to optimal liming under alternative probabilities ($Prob$) for a renewal of each five year lease contract (*ceteris paribus*). The means are computed over the years $t \geq 18$.

Conformity of the predicted yield in two separately calculated models is not complete (Figures 2 and 5). This is because of separate data sources for the yield response and carry-over parameters. Still both models give signals that the land tenure insecurity harms the goal to increase productivity in Finnish crop farming.

4. Concluding remarks

The results of our normative dynamic programming model, solved with known parameters, highlight that the optimal decision rules on irreversible land improvements, with long pay-back periods, substantially diversify according to the extent of land tenure insecurity. Land improvements decrease below the optimum for the society, when the likelihood for contract renewal decreases and likelihood of having future access to land decreases. Therefore, the current tendency of gradually increasing share of land cultivated under simple fixed duration cash lease contracts poses a problem in maintaining land improvements and soil fertility that are sufficient for maximizing society welfare. This will finally turn into decreased yields and weakened supply for food. Further, the incentive problem caused by land tenure insecurity will hamper the efficiency of environmental programs to decrease nutrient runoffs since the standard is that implementing these programs requires irreversible investments on land with long payback periods.

The results also give justified concerns and reasons to expect that prominent land tenure insecurity is posing more severe problems to land improvements than currently revealed by the observed statistics on soil pH and stock of phosphorus in soil (soil phosphorus status). In positive approaches, the insecurity problem has had statistically significant effects on the soil pH and soil phosphorus, but

the diversification in the stock variables according to land tenure status (leased vs. owned) has, so far, been modest (Myyrä *et al.* 2003). The modest differences found in the positive modelling may have been shrink by data censoring. For example, the time when the land has become to the rental market was unobserved in the statistical tests of Myyrä *et al.* (2003).

Nevertheless, the substantial implications, as suggested by our normative model, are supported by aggregate market behaviour even if this behaviour cannot, due to data limitations, be directly linked to individual plots of certain tenure status. The demand for lime and phosphorus fertilizers has been decreasing rapidly as the share of land cultivated under lease contracts has been increasing. It has to be noted, however, that the market trends have been affected also by other institutional and economic factors, such as decreasing Marginal Value Product for lime and phosphorus.

Our results hold only to cash lease contracts where the likelihood of contract renewal is exogenous. The results do not generalize to repeated dynamic games, in which the reputation effect has significant implications to the optimal decision rules. Thus, our analysis does not account for the possibility that land improvements may be used to increase likelihood for contract renewal.

One of the main goals of CAP is to increase productivity in agriculture. The results signal that reaching this goal may be seriously hampered by gradually increasing land leasing unless the land tenure insecurity problem can not be solved by better contract design.

References:

- Bellman, R. (1957). *Dynamic Programming*. Princeton University Press. New Jersey.
- Bäckman, S.T., Vermeulen, S., Taavitsainen, V-M. (1997). Long term fertilizer field trials: comparison of three mathematical response models. *Agricultural and Food Science in Finland* 6(2): 151-160.
- Holden, S., Hailu, Y. (2002). Land redistribution, tenure insecurity and intensity of production: A Study of farm household in southern Ethiopia. *Land Economics* 78 (4): 573-590.
- Kemppainen, E., Jaakkola, A., Elonen, P. (1993). Peltomaiden kalkitustarve ja kalkituksen vaikutus viljan ja nurmen satoon. Abstract: Effect of liming on yield of cereals and grass. *Maatalouden tutkimuskeskuksen tiedote* 15/93. ISSN 0359-7652.
- Kennedy, J. (1986). *Dynamic programming. Applications to agriculture and natural resources*. Elsevier Applied Science Publishers LTD. England.
- Maanvuokralaki. (Law of land leasing) (Downloadable from webside <http://finlex1.edita.fi>.) Referred 08.10.2003.
- Mas-Coell, A., Winston, M. D., Green, J. R. (1995). *Microeconomic Theory*. Oxford University Press. New York.
- Yearbook of farm statistics (2003). Maa- ja metsätalousministeriön tietopalvelukeskus. Helsinki.
- Mäntylähti, V. (2002). "Peltojen ravinnetilan kehitys 50 vuoden aikana." (In Finnish). Title in English: "*Development of the nutrient status of fields over 50 years*". In: Uusitalo, R., Salo, R. (eds.). *Tutkittu maa - turvalliset elintarvikkeet*. Maa- ja elintarviketalous 13: 5-13.
- Myyrä, S., Ketoja, E., Yli-Halla, M. (2003). "Pellon hallintaoikeuden yhteys maanparannuksiin - esimerkkinä kalkitus ja fosforilannoitus" (In Finnish). Abstract: Land tenure and land improvements in Finland -the case of liming and phosphate fertilization. *MTT:n selvityksiä* 37.
- Saarela, I., A. Järvi, H. Hakkola, and K. Rinne. (1995). "Fosforilannoituksen porraskokeet 1977-1994. Vuosittain annetun fosforimäärän vaikutus maan viljavuuteen ja peltokasvien satoon monivuotisissa kenttäkokeissa." Abstract: Phosphorus fertiliser rate trials, 1977-1994. Effects of the rate of annual phosphorus application on soil fertility and yields of field crops in long-term field experiments. *Maatalouden tutkimuskeskuksen tiedote* 16/95.
- Sharpley, A. N. (1986). Distribution of fertilizer phosphorus applied to winter wheat. *Soil Science Society of American Journal* 50:953-958.

Viljavuuspalvelu. (2000). Viljavuustutkimuksen tulkinta peltoviljelyssä. (In Finnish. Title in English: Interpretation of soil test results in field crop production). Finland, Mikkeli.

Yli-Halla, M. (1989). Effect of different rate of P fertilization on the yield and P status of soil in two long-term fiel experiments. *Journal of agricultural science in Finland* 61:361-370.