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Nitrate Leaching Regulation as a Nonpoint Source Pollution Problem: A Conceptual Framework

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Abstract

We develop a stylized agricultural production model, where fertilizers and irrigation, cause water stock depletion and leaching that pollutes the aquifer. Nitrate accumulation causes environmental damages and possibly has adverse effects on individual farmers production processes. The agricultural model embodies elements from current EU agricultural policies such as subsidies for land-set-aside and direct transfers to farmers. The regulator wants to regulate leaching but cannot observe individual leaching since this is a nonpoint source (NPS) problem. The regulator seeks to transform the NPS problem into a PS problem by gathering information and trying to estimate an expected loading factor that relates fertilizers use with expected individual nitrate emissions. We set up the regulator's problem as an optimal control problem, which determines policies regarding, fertilizers use; water use; land-set-aside and associated subsidies; direct transfers to farmers; management practices; information gathering policies; and the allocation of a limited budget among land-set-aside subsidies, direct transfers to farmers and information gathering expenses. We develop first the conceptual model and then we propose an approach for estimating individual loading factors by minimizing an entropy metric and an approach for solving the optimal control model. The conceptual model is used to develop a case study.

Contents

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[1] This report was submitted to the coordinator on the 30th of August 2005 and circulated among partners for final comments and modifications to be made by December 2005, as suggested by the coordinator, in view of the additional 3 months granted by the Commission at the time that the contract was signed.

1 Executive Summary[2]

When the project was conceived, the European Commission had already admitted that, among the factors responsible for a series of adverse environmental services of agricultural activities, the various CAP measures could be included (Baldock D. et al, 2002). Such a formal recognition of the problem stressed the need for policy makers to account for both environmental issues and the recent developments in environmental regulatory policy in the design of the common agricultural policy.

In this context lies the contribution of Partner 6 within Work Package 3 under the Project GENEDEC. **Work Package 3** (WP3) is entitled: *New development and linkage between farm models and partial market model and environment* and has set the following objectives (see, Technical Annex I, pg 17):

Objective 1: Develop a set of models that would describe the interactions between EU and world markets (the “small country” assumption is irrelevant for the EU).

Objective 2: Improve the assessment provided by farm-type models (in WP2) by sharpening land opportunity cost thanks to land market modelling.

Objective 3: Examine the effects of decoupling on structural change in farming (e.g. farms number and size, full or part-time farming, entry-exit).

Objective 4: Determine the relationship between EU agricultural production and its physical environment.

Objective 5: Study Non point source pollution problems, which are typical environmetal problems associated with agricultural activities.

The work to be undertaken under the WP3 can be described as follows.

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- To fulfil the first objective a set of models that would describe the interaction between EU markets and the world will be developed. Then EU prices will be adjusted to world prices using a simplified FAPRI-like model, i.e. AgMeMod.

  Land market will be modelled under condition of non-tradable premium rights using shadow prices from WP2.

  Series of historical transition probabilities will be developed and a non-stationary Markov Chain model, which could be coupled to models reviewed in WP2, will be implemented. It may be necessary to supplement the Markov Chain model with some farmer-decision models to examine issues such as succession and labour allocation.

  The coupling of economic and biophysical models will be developed to get an improved technical approach, to spatialize land use and production localisation. Theoretical approach related to the implementation of environmental policies will be tackled through the transformation of a non point source pollution problem into a point source one.

Work Package 3 will provide two **deliverables**:

D4: List of prices and land opportunity costs, projections concerning number of farms, proportion of full and part-time farming on a member state basis, technical indicators, extensification indicator like the average productivity of land, agro-technical and cross reference data bases and maps.

D5: Report or article on theoretical aspects concerning the implementation of environmental policies.

Regarding the **milestones and expected results** the technical Annex I (pg 17) involves:

Prices adjusted to world market and land opportunity costs are meant to implement exogenous prices in farm-type models.

Objectives 3 and 4 will provide necessary materials to feed WP4 and WP5.

The contractual obligation of Partner 6 under the Work Package 3 consists of objective 5 (see Technical Annex I, pg 20) that results in Deliverable 5 (D5): *Report or article on theoretical aspects concerning the implementation of environmental policies*, consisting of two parts:

D5.1: Conducting of an extensive survey of current issues and policies regarding environmental pressures and regulation in European agriculture.

D5.2: Development of a conceptual framework under which information gathered by an environmental regulating agency can be used to estimate individual emissions in an agricultural non-point source pollution (NPS) problem.

The present document constitutes the second part of Deliverable 2.

Deliverable 5 will provide material for Work Package 4: *Quantitative assessment of socio-economic impacts of the Commission proposal of decoupling* and Work Package 5: *Ex-ante evaluation of the economic effects of decoupling on structural change at farm and regional level.* The more specific contribution of Deliverable 5 to the other workpackages of the project is to provide a solid theoretical foundation for assessing policy impacts using either the framework of differentiative production function or the linear programming framework under appropriate modifications.

2 Introduction

One of the most important and widely discussed agricultural pollution problems is nitrate leaching (NO_3) which basically involves nitrate removal from the soil under the influence of water (Owen et al., 1998). The phenomenon of leaching , includes both leaching below the crop's roots due to the downward movement of water (percolation) and leaching due to the flow of water over the surface of the land (runoff).

The mechanism behind leaching is that the negative electrical charge of the clay particles of soil attracts the positively charged ions of nutrient elements, while it does not retain negatively charged ions very well (Owen et al., 1998). Therefore, if too much nitrogen fertilizers are applied to a crop only the nitrogen ions bond on clay particles are available for plant uptake, preventing leaching, while the rest are not taken by the crop. This residual nitrogen may be lost in the environment and results in potential inflows to underground water aquifers, or lakes and reservoirs in the surface where it is accumulated causing contamination (Classen and Horan, 2001; Helfand and House, 1995). Notable is a US study according to which the amount of fertilizer nitrogen taken by crops is rarely greater than 70% and it is typically closer to 50%, while the 90% of applied nitrogen may be lost to the environment when crop yields are near optimum levels (Classen and Horan, 2001).

Among the environmental costs associated with nitrogen flows is water pollution, that poses a threat to both freshwater and marine ecosystems (Huhtala and Laukkanen, 2004) and reduces water's value to humans and nature (Owen et al., 1998).[3] The potential for surface water pollution from ground water contaminated with leached nitrates is an important environmental concern (Johnson et al., 1991) since approximately 30% of surface water stream flow is coming from groundwater sources (Fleming and Adams, 1997). Surface water pollution threatens aquatic life and may turn into an ecological disaster (Millock and Zilberman, 2004). Eutrophication of slow flowing rivers, lakes, reservoirs and marine areas appears through the proliferation of algae bloom, which degrades bottom fauna, fish stock and wetlands (Huhtala and Laukkanen, 2004; Isik, 2004). Among the effects of such a bloom is the destruction of lake's aesthetic furthermore, chemicals released by blue-green algae are poisonous to fish, cattle and humans (Owen et al., 1998).

Even though it seems that farmers could eliminate the majority of nitrate leaching by more careful management of nitrogen and water applications, they face a more complex problem since there are factors affecting nitrate residuals which are out of their influence. In general, nitrate emissions depend on management decisions, environmental variables and site characteristics (soil type and topography) (Horan et al.,

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[3] Nitrogen flows are also associated with soil and air pollution. In particular soil is at a high risk of eutrophication in cases where excessive nitrogen deplete oxygen in the soil, affecting micro-organisms proper functioning and soil's fertility. Eutrophied soils are also a source of N_2O - a powerful greenhouse gas.

1998; Shortle et al., 1998). Thus even though individual farmers could influence the distribution of their nitrate emissions (Shortle et al., 1998) through their management decisions, the associated uncertainty regarding environmental variables, imperfect knowledge, and heterogeneity regarding the physical environment of their cultivations tend to result in excessive nitrate leaching.

The factors that contribute to excess nitrate pollution include: imperfect knowledge about soil moisture levels; imperfect knowledge about soil fertility levels; uncertainty about future weather-related events; location and physical attributes of agricultural land; the risk characteristics of the agricultural production process; and the risk of under applying inputs, resulting in excess nitrate applications. Regarding the EU agriculture, factors that affect European agricultural management and have resulted in intensification, marginalization, concentration and specialization of farming, have led to an unbalance in the agriculture-environment relationship and indirectly in nitrate leaching.

The environmental costs associated with nitrate leaching, and the evidence that farmers' decisions have led to excess nitrate emissions suggest that regulation of nitrate leaching is in order. There is however a serious obstacle in applying conventional instruments of environmental regulation, since nitrate leaching is a typical nonpoint source (NPS) pollution problem.

A pollution problem is a *"pure" NPS problem* if the regulatory body has no knowledge of the location of polluting sources or the individual contribution in aggregate pollution (Kaplan et al., 2003). In general NPS pollution can be characterized as an information and/or an uncertainty problem where informational issues are the core of NPS externalities analysis (Legras, 2004) and the question "*What information is available at what cost?*" plays crucial role in the determination of the best regulatory mechanism (Cabe and Herriges, 1992).

Potentially the most important feature of NPS problems is the associated uncertainty about the decision makers (polluters) actions and the degree of each agent's contribution to total pollution, a fact that eliminates emission-based instruments from the set of available NPS pollution instruments (Shortle et al., 1998). In short the origins of this uncertainty can either be attributed to stochastic influences affecting fate and transport of pollutants, the great number of sources of pollution emissions that can be either stationary (farms, households) or mobile (vehicles), and/or the regulator's inability to infer individual emissions from ambient pollution levels or inputs used (Xepapadeas, 1995).

The NPS pollution problem associated with nitrate leaching is mainly characterized by: (i) multiple dischargers and diffuse, potentially stochastic, pollution processes - the effects of nitrate leaching can be felt and measured (if at all) after they have entered the ecosystem, but identifying polluting sources and their contribution to total ambient pollution, may be impossible (Chambers and Quiggin, 1996; Kampas and White, 2004) since agricultural pollutants does not enter waterbodies at a defined point (Helfand and House, 1995), they dissipate quickly and the area vulnerable to pollution is extensive (Johnson et al., 1991); (ii) monitoring and measurement inefficiency, since monitoring individual leaching is costly, technically difficult and the regulator is usually operating under a budget constraint, and (iii) informational asymmetries associated with moral hazard with hidden actions, which basically induces farmers to emit nitrates in excess of the socially desirable level, and adverse selection that could preclude the regulator from knowing the individual farmers' characteristics, an information necessary to design efficient regulation.

Nevertheless, the classification of an individual source of pollution as NPS may change over time as monitoring technology advances and the cost of monitoring declines (Millock et al., 2002). In this case if information about individual leaching become available through certain types of monitoring technology or information gathering, the NPS pollution problem can be transformed to point source (PS) problem in which case regulation can be carried out by conventional instruments, such command and control performance standards, emission taxes or tradable permits. The impact of information gathering and investment in monitoring with the purpose of transforming a NPS pollution problem to a PS pollution problem have been examined for example by Kaplan et al., (2003); Millock et al., (2002); Dinar and Xepapadeas (2002). This study follows this approach and aims at providing a conceptual framework and a supporting case study for the case of nitrate leaching NPS pollution, where a regulator seeks to regulate nitrate leaching by transforming the NPS problem to a PS problem through costly information gathering.

In particular a stylized agricultural production model is developed, where application of fertilizers and irrigation by pumping water from an underground aquifer, cause water depletion and leaching that pollutes the aquifer, through the accumulated stock of nitrates. Nitrate accumulation causes environmental damages and could also have adverse effects on individual farmers' production processes. The agricultural model embodies elements from current EU agricultural policies since it includes subsidies for land-set-aside and direct transfers to farmers. The regulator wants to regulate leaching by using as potential instruments, land-set-aside programs, direct transfers, and possibly command and control methods or quantity instruments, such as tradable quotas associated with fertilizers use, water use, and subsidies related to management practises. However the regulator cannot observe individual leaching since the particular pollution problem is a NPS problem. The regulator seeks to transform the NPS problem into a PS problem by gathering information and trying to estimate an expected loading factor that relates fertilizer use with expected individual nitrate emissions. This factor depends on water used, land-set-aside, management practices, and soil composition and evolves through time as its determinants change in response to policy changes. Information gathering that could allow the estimation of this loading factor is costly and the regulator has to allocate a limited budget between land-set-aside subsidies, direct transfers and information gathering costs.[4]

We set up the regulator's problem as an optimal control problem. If the regulator: (i) knows the production structure and the natural processes associated with water flows and nitrate flows in the aquifer, (ii) can observe individual decisions related to fertilizer use, water use, management practise, land-set-aside, and (iii) can estimate through in-

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[4] This approach is similar to the one taken by Kaplan et al. (2003).

formation gathering or monitoring the individual expected nitrate loading factors, then the optimal control problem can be solved to determine policies regarding fertilizers use; water use; land-set-aside and associated subsidies; direct transfers to farmers; management practices; information gathering policies; and the allocation of a limited budget among land-set-aside subsidies, direct transfers to farmers and information gathering expenses.

We develop first the conceptual model and then we propose an approach for estimating individual loading factors by minimizing an entropy metric (Kaplan et al.. 2003) and an approach for solving the optimal control model. The conceptual model is used to develop a case study for a region in Thesally, Greece where nitrated leaching occurs and affects the water quality of an underground aquifer.

3 The Agricultural Model

Let the agricultural production function for farmer $j = 1, ..., J$ at time t be

$$y_j(t) = f(x_j(t), w_j(t), L_j(t) - R_j(t), N(t)) \tag{1}$$

where $x_j(t)$: fertilizers used; $w_j(t)$: applied water pumped from an underground aquifer; $L_j(t)$: land used; $R_j(t)$: land set-aside by the farmer, $R_j(t) \geq 0$. The production function is increasing and concave at an economically relevant domain of inputs, $x_j(t)$, $w_j(t)$, $L_j(t) - R_j(t)$. $N(t)$ is total accumulated nitrates in the aquifer. This is a fairly general formulation allowing for impacts from accumulated nitrates on the production function. If there is an impact on the production function then $\partial f / \partial N \neq 0$, but this is largely an empirical issue. The flow of profits accruing to farmer j is defined, after omitting t to simplify notation, as:

$$\pi_j = pf(x_j, w_j, L_j - R_j, N) - c_j x_j - r_j(W) w_j + bR_j(t) + T_j \tag{2}$$

where p : the price of the agricultural product; c_j : per unit fertilizer cost; $r_j(W)$: unit pumping cost for farmer j as a function of the total water stock in the aquifer $W(t)$, with $r_j^{'}(W) < 0$; to allow for negative stock effects, b : subsidy given per unit of land set-aside; T_j : direct transfer to farmer j.

Total nitrate leaching at time t that reach the underground aquifer are

$$E(t) = \sum_{j=1}^{J} e_j(t) \tag{3}$$

Total leaching $E(t)$ is observed but individual runoff $e_j(t)$ is not observed. The regulator has subjective expectations about individual leaching denoted by the vector

$$\bar{\mathbf{e}}(t) = (\bar{e}_1(t), \bar{e}_2(t), ..., \bar{e}_J(t)) \tag{4}$$

where

$$E(t) = \sum_{j=1}^{J} e_j(t) = \sum_{j=1}^{J} \bar{e}_j(t) \tag{5}$$

Following Kaplan et al. (2003), we assume that the expected individual leaching can be expressed as a function of the fertilizers used by farmer j, or

$$\bar{e}_j(t) = l_j(\mathcal{E}(\alpha_j(t)), x_j(t)) \tag{6}$$

where $\alpha_j(t)$ is a stochastic loading factor and $\mathcal{E}$ is the expectation operator.

The evolution of the loading factor can be expressed as a function of agricultural practices followed by farmers $z_j(t)$, the applied water used $w_j(t)$, the specific soil characteristics ξ_j and the actual land used by the jth farmer $L_j(t) - R_j(t)$. Let $s = 1, ..., S$ denote the state of the world associated with the loading factor of the jth farmer. That is high loading factor, medium, low and so on. Thus if $s = 1$ denotes a high loading factor, then the farmer $j1$ will be a farmer associated with high leaching per unit of fertilizers used if state $s = 1$ occurs. The evolution of the loading factor can be written in general terms as:

$$\frac{d\alpha_{js}(t)}{dt} \equiv \dot{\alpha}_{js}(t) = \beta_j\left(z_j(t), w_j(t), L_j(t) - R_j(t), \xi_j\right)\alpha_{js}(t) \quad (7)$$

Let $p_{js}(t)$ denote the probability that the farmer j is in state s at time t. This probability can be updated by information gathering effort (or monitoring effort) $m(t)$ applied by the regulator at time t, or

$$\dot{p}_{js}(t) = \gamma_j(m(t), p_{js}(t)) \quad (8)$$

Monitoring or information gathering provides information about the loading factor. So the expected loading parameter is:

$$\mathcal{E}(\alpha_j(t)) = \sum_{s=1}^{S} p_{js}(t)\,\alpha_{js}(t) \quad (9)$$

while the entropy metric is

$$A(p(t)) = \frac{-\sum_j \sum_s p_{js}(t)\ln p_{js}(t)}{J\ln S} \quad (10)$$

The regulator has a total available annual budget $\hat{G}(t)$, that needs to be allocated among land-set-aside subsidies b, direct transfers T_j and monitoring or information gathering costs. Thus the budget constraint becomes

$$\hat{G}(t) = b\sum_{j=1}^{J} R_j(t) + \zeta m(t) + \sum_{j=1}^{J} T_j(t) \quad (11)$$

where ζ is cost per unit of monitoring effort.

The above described agricultural model that embodies many important features from the current EU agricultural policy can be used as a basis for designing optimal regulation in the region.

4 Optimal Regulation

The regulator seeks to maximize the total net present value from agricultural production in the region less the environmental costs of agricultural production. Environmetal costs are associated with nitrate pollution due to leaching in the area and can be approximated by a strictly increasing and convex damage function $D(N)$, $D' > 0$, $D'' \geq 0$. The regulator's control variables are $x_j(t), w_j(t), R_j(t), T_j(t), m(t)$. That is, the regulator seeks to maximize the total net present value by formulating a fertilizer policy, a water use policy, a land-set-aside policy, a direct transfer policy and a monitoring policy. The problem can be stated as follows:

Objective

$$\max_{\{x_j(t),w_j(t),R_j(t),T_j(t),m(t)\}} V = \tag{12}$$

$$\int_0^\infty \exp(-\rho t) \left\{ \sum_{j=1}^{J} [pf(x_j, w_j, L_j - R_j, N) - c_j x_j \right.$$

$$\left. -r_j(W) w_j + bR_j(t) + T_j] - D(N) \right\} dt \tag{13}$$

Constraints

$$\dot{N}(t) = E(t) - \delta N(t) \quad , E(t) = \sum_{j=1}^{J} \bar{e}_j(t) \text{ or}$$

$$\dot{N}(t) = \sum_{j=1}^{J} l_j(\mathcal{E}(\alpha_j(t))), x_j(t) - \delta N(t) \tag{14}$$

$$\mathcal{E}(\alpha_j(t)) = \sum_{s=1}^{S} p_{js}(t) \alpha_{js}(t) \tag{15}$$

Constraints (14) and (15) describe the evolution of the stock of nitrates in the aquifer, where $\delta \geq 0$ indicates the aquifer's self cleaning capacity.

$$\dot{W}(t) = F(t) - \sum_{j=1}^{J} w_j(t) - \sigma W(t) \tag{16}$$

This constraint describes the evolution of the water stock in the aquifer. $F(t)$ denotes the rate of natural water inflows and σ reflects the rate of natural outflows.

$$\dot{\alpha}_{js}(t) = \beta_j \left(z_j(t), w_j(t), L_j(t) - R_j(t), \xi_j \right) \alpha_{js}(t) \;\; \forall j, s \tag{17}$$

$$\dot{p}_{js}(t) = \gamma_j (m(t), p_{js}(t)) \;\; \forall j, s \tag{18}$$

These are the loading factor evolution and the probability update constraints.

By setting the total direct transfers at a predetermined level T^0, the annual budget constraint can be written as:

$$b \sum_{j=1}^{J} R_j(t) - \zeta m(t) \leq G(t) = \hat{G} - T^0 \tag{19}$$

The maximum principle under pure control constraints implies that the following Lagrangean function can be defined by maximizing the Hamiltonian function associated with problem (12) - (18) subject to the budget constraint (19).

$$\begin{aligned}
\mathcal{L} = {} & pf(x_j, w_j, L_j - R_j, N) - c_j x_j - r_j(W) w_j + bR_j(t) + T^0 - D(N) + \\
& \lambda(t) \left[\sum_{j=1}^{J} l_j \left(\sum_{s=1}^{S} p_{js}(t) \alpha_{js}(t), x_j(t) \right) - \delta N(t) \right] + \\
& \mu(t) \left[F(t) - \sum_{j=1}^{J} w_j(t) - \sigma W(t) \right] + \\
& \sum_{j=1}^{J} \sum_{s=1}^{S} \phi_{js} \beta_j \left(z_j(t), w_j(t), L_j(t) - R_j(t), \xi_j \right) \alpha_{js}(t) + \\
& \sum_{j=1}^{J} \sum_{s=1}^{S} \eta_{js} \gamma_j (m(t), p_{js}(t)) + \\
& v(t) \left[G - b \sum_{j=1}^{J} R_j(t) + \zeta m(t) \right]
\end{aligned} \tag{20}$$

First order necessary conditions (FONC), omitting t to simplify notation, imply for the controls:

$$\frac{\partial \mathcal{L}}{\partial x_j} = 0 : p\frac{\partial f_j}{\partial x_j} - c_j + \lambda \frac{\partial l_j}{\partial x_j} = 0 \tag{21}$$

$$\frac{\partial \mathcal{L}}{\partial w_j} = 0 : p\frac{\partial f_j}{\partial w_j} - r_j\left(W\right) - \mu + \sum_{s=1}^{S} \phi_{js} \frac{\partial \beta_j}{\partial w_j} = 0 \tag{22}$$

$$\frac{\partial \mathcal{L}}{\partial R_j} = 0 : -p\frac{\partial f_j}{\partial R_j} + b - vb - \lambda \frac{\partial l_j}{\partial R_j} - \sum_{s=1}^{S} \phi_{js} \frac{\partial \beta_j}{\partial R_j} = 0 \tag{23}$$

$$\frac{\partial \mathcal{L}}{\partial m} = 0 : \sum_{j=1}^{J} \sum_{s=1}^{S} \eta_{js} \frac{\partial \gamma_j}{\partial m} - v\zeta = 0 \tag{24}$$

$$v\left[G - b\sum_{j=1}^{J} R_j\left(t\right) + \zeta m\left(t\right)\right] = 0, v \geq 0 \tag{25}$$

The FONC can be interpreted in various ways. For example from (23) - (25) we obtain for the optimal allocation of constrained funds between land-set-aside subsidies and monitoring expenses as:

$$\frac{1}{b}\left[-p\frac{\partial f_j}{\partial R_j} + b - \lambda \frac{\partial l_j}{\partial R_j} - \sum_{s=1}^{S} \phi_{js} \frac{\partial \beta_j}{\partial R_j}\right] = \frac{1}{\zeta}\left[\sum_{j=1}^{J} \sum_{s=1}^{S} \eta_{js} \frac{\partial \gamma_j}{\partial m}\right] \tag{26}$$

The evolution of the costate variables is determined as:

$$\dot{\lambda} = \left(\delta + \rho\right)\lambda - p\sum_{j=1}^{J} \frac{\partial f_j}{\partial N} + D'\left(N\right) \tag{27}$$

$$\dot{\mu} = \left(\delta + \sigma\right)\mu + w_j \sum_{j=1}^{J} \frac{\partial r_j}{\partial W} \tag{28}$$

$$\dot{\phi}_{js} = \rho\phi_{js} - \lambda \frac{\partial l_j}{\partial \mathcal{E}\left(\alpha_j\left(t\right)\right)} p_{js} - \phi_{js}\beta_j\left(z_j, w_j, L_j - R_j, \xi_j\right) \ , \forall js \tag{29}$$

$$\dot{\eta}_{js} = \rho\eta_{js} - \lambda \frac{\partial l_j}{\partial \mathcal{E}\left(\alpha_j\left(t\right)\right)} \alpha_{js} - \eta_{js} \frac{\partial \gamma_j}{\partial p_{js}} \ , \forall js \tag{30}$$

The system of algebraic equations (21) - (25) and the differential equations (14), (16), (17), (18) and (27) - (30) determine the solution of the optimal control problem along with the appropriate transversality conditions at infinity. At this level of generality the solution of the problem does not provide specific information about policy rules and regulation. Our approach will be to examine ways of solving the optimal control problem by estimating the specific function involved. Solution of the problem will provide the required policy functions and optimal regulation rules.

5 Estimation Issues

If we knew the functional forms and the parameters of the functions involved in the problem we could have solved the full optimal control problem, or some appropriately defined linear quadratic approximation, and derive the optimal policy functions for fertilizers, water use, land-set-aside, transfers and monitoring. The policy functions could also provide information about the impacts of changes of policy instrument on the whole system, or about the ways that management practices affect the system.

Some of the function involved can be estimated directly through econometric methods. These could include:

1. The production function $f\left(x_j, w_j, L_j - R_j, N\right)$
2. The unit pumping cost function $r\left(W\right)$
3. The hydrological relationship describing the water stock in the aquifer $\dot{W} = F\left(t\right) - \sum_{j=1}^{J} w_j\left(t\right) - \sigma W\left(t\right)$

Furthermore the environmental damage function $D\left(N\right)$ can be approximated either by direct estimations in the area or by using data from comparable studies,

However expected individual leaching $\bar{e}_j\left(t\right) = l_j\left(\mathcal{E}\left(\alpha_j\left(t\right)\right)\right), x_j\left(t\right)$, $E\left(\alpha_j\left(t\right)\right) = \sum_{s=1}^{S} p_{js}\left(t\right)\alpha_{js}\left(t\right)$ is not observed. The non observability of individual leaching is what makes the problem a NPS pollution problem. The purpose here is to estimate individual leaching using the problem structure defined above. Individual leaching is determined by the equations

$$\dot{\alpha}_{js}(t) = \beta_j\left(z_j(t), w_j(t), L_j(t) - R_j(t), \xi_j\right)\alpha_{js} \tag{31}$$
$$\dot{p}_{js}(t) = \gamma_j(m(t), p_{js}(t)) \ \forall j, s \tag{32}$$
$$\bar{e}_j(t) = l_j(\mathcal{E}(\alpha_j(t))), x_j(t), \tag{33}$$
$$\mathcal{E}(\alpha_j(t)) = \sum_{s=1}^{S} p_{js}(t)\alpha_{js}(t) \tag{34}$$
$$\sum_{s=1}^{S} p_{js}(t) = 1 \tag{35}$$
$$\sum_{j=1}^{J} \bar{e}_j(t) = E(t) \ , \ E(t) : \text{observed} \tag{36}$$

We can make the following approximation after combining equations (31) and (32) and using discrete time formulation[5]

$$\mathcal{E}(\alpha_{jt}) = \mathcal{E}(\alpha_{jt-1})\left[\gamma_j(m_t) - \beta_j\left(z_{jt}, w_{jt}, L_{jt} - R_{jt}, \xi_j\right)\right] + \varepsilon_{jt} \tag{37}$$
$$\ln \bar{e}_{jt} = \mathcal{E}(\alpha_{jt}) \ln x_{jt} \tag{38}$$
$$\sum_{j=1}^{J} \bar{e}_j(t) = E(t) \ \ E(t) : \text{observed} \tag{39}$$

where ε_{jt} is the usual stochastic error term. Then we can a make linear specifications of the $\mathcal{E}(\alpha_{jt})$, and the $\gamma_j(m_t)$ and $\beta_j\left(z_{jt}, w_{jt}, L_{jt} - R_{jt}, \xi_j\right)$ functions as follows:

$$\mathcal{E}(\alpha_{jt}) = \sum_{s=1}^{S} p_{jst}\alpha_{jst} \ \forall j, \ \gamma_{jt} = \sum_{s=1}^{S} \pi^{m}_{jst} m_s \ \forall j, \tag{40}$$
$$\beta_{jt} = \sum_{s=1}^{S} \pi^{z}_{jst} z_{js} + \sum_{s=1}^{S} \pi^{w}_{jst} w_{js} + \tag{41}$$
$$\sum_{s=1}^{S} \pi^{R}_{jst}(L_{js} - R_{js}) + \sum_{s=1}^{S} \pi^{\xi}_{js}\xi_{js} \ \forall j$$
$$\sum_{s=1}^{S} p_{jst} = \sum_{s=1}^{S} \pi^{z}_{jst} = \sum_{s=1}^{S} \pi^{w}_{jst} = \sum_{s=1}^{S} \pi^{R}_{jst} = \sum_{s=1}^{S} \pi^{\xi}_{js} = 1 \tag{42}$$

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[5] See also Kaplan et al. (2003).

In the above set up $\left\{\alpha_{jst}, m_s, z_{js}, w_{js}, \left(L_{js}-R_{js}\right), \xi_{js}\right\}$ are support values for the corresponding probability distributions and indicate the values that the corresponding variable could take in state s, for farmer j, while the corresponding probability indicates the probability of occurrence of that state for farmer j.

Given a range of support values for these variables the task is to use the entropy method to estimate the corresponding probabilities. The entropy method seeks to estimate probabilities that will minimize the entropy metric, given the support values and prior probabilities as initial values. The problem can be stated as:

$$\min_{\left(p_{jst},\pi_{jst}^{z},\pi_{jst}^{w},\pi_{jst}^{R},\pi_{jst}^{\xi}\right)} \mathbf{E} = \tag{43}$$

$$\sum_{j=1}^{J}\sum_{s=1}^{S} p_{jst}\ln\left(\frac{p_{jst}}{p_{jst-1}}\right)+\sum_{j=1}^{J}\sum_{s=1}^{S}\pi_{jst}^{z}\ln\left(\frac{\pi_{jst}^{z}}{\pi_{jst-1}^{z}}\right)$$

$$+\sum_{j=1}^{J}\sum_{s=1}^{S}\pi_{jst}^{w}\ln\left(\frac{\pi_{jst}^{w}}{\pi_{jst-1}^{w}}\right)+\sum_{j=1}^{J}\sum_{s=1}^{S}\pi_{jst}^{R}\ln\left(\frac{\pi_{jst}^{R}}{\pi_{jst-1}^{R}}\right) \tag{44}$$

$$+\sum_{j=1}^{J}\sum_{s=1}^{S}\pi_{jst}^{\xi}\ln\left(\frac{\pi_{jst}^{\xi}}{\pi_{jst-1}^{\xi}}\right)+\sum_{j=1}^{J}\sum_{s=1}^{S}\pi_{jst}^{\varepsilon}\ln\pi_{jst}^{\varepsilon}$$

subject to constraints (37) - (42) the range of the support values chosen for $\left\{\alpha_{jst}, m_s, z_{js}, w_{js}, \left(L_{js}-R_{js}\right), \xi_{js}\right\}$, and initial prior probabilities corresponding to the vector $\left(p_{jst-1}, \pi_{jst-1}^{z}, \pi_{jst-1}^{w}, \pi_{jst-1}^{R}, \pi_{jst-1}^{\xi}\right)$. Initial prior probabilities can be taken to correspond to the uniform distribution with value $1/S$. The support values for the error term is largely arbitrary.

If the probabilities are estimated, we can proceed along two different ways:

- We can obtain an estimate $\mathcal{E}^{es}\left(\alpha_{jt}\right)$ of $\mathcal{E}\left(\alpha_{jt}\right)$ using estimates $\hat{p}_{jst}$ of p_{jst} as

$$\mathcal{E}^{es}\left(\alpha_{jt}\right)=\sum_{s=1}^{S}\hat{p}_{jst}\alpha_{jst} \tag{45}$$

and then use it to estimate individual expected leaching, $\bar{e}_{jt}$ by assuming a proportionality relationship between $\mathcal{E}^{es}(\alpha_{jt})$ and the observed values of fertilizers used by the jth farmer, or

$$\bar{e}_{jt} = \mathcal{E}^{es}(\alpha_{jt})\, x_{jt} \tag{46}$$

If we assume that this loading parameter is time stationary we can solve the control problem:

$$\begin{aligned} &\max_{\{x_j(t), w_j(t), R_j, T_j, m\}} V = \\ &\int_0^\infty \exp(-\rho t) \left\{ \sum_{j=1}^{J} \left[pf(x_j, w_j, L_j - R_j, N) - c_j x_j \right.\right. \\ &\left.\left. -r_j(W)\, w_j + bR_j(t) + T_j \right] - D(N) \right\} dt \end{aligned} \tag{47}$$

subject to

$$\dot{N}(t) = \sum_{j=1}^{J} \mathcal{E}^{es}(\alpha_{jt})\, x_{jt} - \delta N(t) \;\;, E(t) = \sum_{j=1}^{J} \mathcal{E}^{es}(\alpha_{jt})\, x_{jt}$$

$$\dot{W}(t) = F(t) - \sum_{j=1}^{J} w_j(t) - \sigma W(t) \tag{48}$$

$$b\sum_{j=1}^{J} R_j - \zeta m \leq G(t) = \hat{G} - T^0 \tag{49}$$

If we assume a quadratic specification for the production function then this is linear-quadratic problem that can be solved using standard methods. Furthermore policy functions can be recovered as stable manifolds associated with saddle point equilibria. Since the problem is linear-quadratic the manifolds are linear and can be determined as part of the solution. In this problem however the estimated $\mathcal{E}^{es}(\alpha_{jt})$ depend on the values of R_j, T_j, m and z_j. Since these variables are controls, chosen by the regulator they can be regarded as control parameters. Different choices of these parameters produce a different estimate for $\sum_{j=1}^{J} \mathcal{E}^{es}(\alpha_{jt})$. We can explore the impact of changing these control parameters that represent policy instruments on the value of the problem, as well as the implied optimal paths for fertilizer, water use and run-off, by solving the control problem (47) for different values of these control parameters..

- We can use the estimated probabilities to approximate the functions

$$\dot{\alpha}_{js}(t) = \left(\sum_{s=1}^{S} \pi^{z}_{jst} z_{js} + \sum_{s=1}^{S} \pi^{w}_{jst} w_{js} + \right. \tag{50}$$

$$\left. \sum_{s=1}^{S} \pi^{R}_{jst} (L_{js} - R_{js}) + \sum_{s=1}^{S} \pi^{\xi}_{js} \xi_{js} \right) \alpha_{js}(t) \tag{51}$$

$$\dot{p}_{js}(t) = \left(\sum_{s=1}^{S} \pi^{m}_{jst} m_{s} \right) p_{js}(t) \tag{52}$$

Then we can try to solve the full control problem:

$$\max_{\{x_j(t), w_j(t), R_j(t), T_j(t), m(t)\}} V = \tag{53}$$

$$\int_0^\infty \exp(-\rho t) \left\{ \sum_{j=1}^{J} \left[pf(x_j, w_j, L_j - R_j, N) - c_j x_j \right. \right.$$

$$\left. \left. -r_j(W) w_j + bR_j(t) + T_j \right] - D(N) \right\} dt \tag{54}$$

subject to

$$\dot{N}(t) = \sum_{j=1}^{J} \mathcal{E}(\alpha_j(t)) \ln x_j(t) - \delta N(t) \tag{55}$$

$$\mathcal{E}(\alpha_j(t)) = \sum_{s=1}^{S} p_{js}(t)\, \alpha_{js}(t) \tag{56}$$

$$\dot{W}(t) = F(t) - \sum_{j=1}^{J} w_j(t) - \sigma W(t) \tag{57}$$

$$\begin{aligned} \dot{\alpha}_{js}(t) = \Bigg(& \sum_{s=1}^{S} \pi^{z}_{jst} z_{js}(t) + \sum_{s=1}^{S} \pi^{w}_{jst} w_{js}(t) + \\ & \sum_{s=1}^{S} \pi^{R}_{jst} (L_{js}(t) - R_{js}(t)) + \sum_{s=1}^{S} \pi^{\xi}_{js} \xi_{js} \Bigg) \alpha_{js}(t) \end{aligned} \tag{58}$$

$$\dot{p}_{js}(t) = \left(\sum_{s=1}^{S} \pi^{m}_{jst} m_s(t) \right) p_{js}(t) \tag{59}$$

$$b \sum_{j=1}^{J} R_j(t) - \zeta m(t) \leq G(t) = \hat{G} - T^0 \tag{60}$$

This problem can be solved in principle if it has a linear quadratic structure and the policy functions can be derived in the same conceptual framework as above.

6 Concluding Remarks

In this study we develop a conceptual model for regulating nitrate leaching as a non point source pollution problem. We consider a stylized model of irrigated agriculture, where application of fertilizers and water creates nitrate leaching that accumulates in an aquifer and causes environmental damages. The model embodies characteristics of the current agricultural policies of the European Union, such as land-set-aside subsidies and direct transfers to farmers. Our approach is to try to transform the NPS problem to a PS problem by estimating a stochastic loading factor that determines individual nitrate emissions as proportions of the fertilizers used by the farmers. This factor depends on water, used land-set-aside, management practices, and soil composition and evolves trough time as its determinants change in response to policy changes.

We develop a model of optimal regulation which if solved can provide policies for water use, fertilizer use, land-set-aside, direct transfers and management practices. The solution of the model depends however on the estimation of the loading factor for nitrate emissions. We provide a theoretical framework for the estimation of this factor in the context of minimizing an entropy metric and we show how this estimation can be used to solve the optimal regulation model.

The next step of our study is to provide an application of our conceptual framework by developing a case study of optimal regulation for a region in Thesally, Greece.

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