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The Use of Organic vs. Chemical Fertilizer with a Mineral Losses Tax: The Case of Dutch Arable Farmers

ELI FEINERMAN[1,]* and MARINUS H. C. KOMEN[2]
[1]*Department of Agricultural Economics and Management, The Hebrew University, 12, 76100 Rehovot, Israel;* [2]*Agricultural Economics and Rural Policy Group, Wageningen University, Wageningen, The Netherlands; *Author for correspondence (e-mail: feiner@agri.huji.ac.il)*

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Abstract. The paper focuses on farm-level nitrogen fertilization strategies of Dutch arable farmers for analyzing the substitution of organic fertilizers (manure) with chemical fertilizers. The model developed investigates the impact of the major parameters affecting the inferiority of manure compared with chemical fertilizers, including the low availability and non-uniformity of the nitrogen in manure, and the low level and high non-uniformity of plant-available nitrogen supplied via manure. The sensitivity of the optimal fertilization decisions and its associated environmental impact to product price, manure cost, and environmental tax is also examined. The theoretical analysis is applied to a representative Dutch grower of ware potatoes in the northern part of the Netherlands. The results suggest that in the absence of a subsidy the representative farmer will prefer to apply nitrogen only via chemical fertilizers.

Key words: Dutch growers, environmental tax, fertilization strategies, manure inferiority, non-used nitrogen, ware potatoes

JEL classifications: D21, Q12, Q18, Q58

1. Introduction

A growing international demand for animal products and a favorable EU common agricultural policy has dramatically increased livestock production (in particular pigs and poultry) in western European countries such as Belgium, Denmark, France, and the Netherlands. As a result of price support for cereals in the EU and the absence of import levies, the importing of tapioca, soybeans, citrus pulp, and maize gluten became attractive options for Dutch livestock producers, who exploited their proximity to the port of Rotterdam. The positive trade balance in feedstuffs led to high pressure being put on the environment through an excess supply of minerals. This causes denitrification and leaching the soil of

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phosphate and nitrogen, thereby polluting surface water and ground water.

Mineral policies are increasingly being implemented, both at the national level and the EU level (see Johnsen 1993; Vermersch et al. 1993; Komen and Peerlings 1998). In the 1980s and 1990s, the Dutch government started to introduce some policies for reducing mineral problems, involving a limitation of the amount of minerals from manure that can be produced (phosphate production rights) and applied to land, depending on soil type, land use (crop) and the time period of the year. Initially, however, this policy proved not to be completely effective in reducing the production of minerals, since total production rights were set at a level higher than actual production. Later, the government decided to fix limits for permitted mineral *losses*, instead of permitted mineral *application*, per hectare. These losses have to be calculated using a mineral (phosphate and nitrogen) accounting system (MINAS). In this system, the deliveries of minerals to the farm in the form of livestock, feed, manure, and fertilizer, in addition to the removal of minerals from the farm in the form of products and manure are recorded. The net difference is the mineral loss, which, above a certain threshold, is subject to a levy. The MINAS system has been operational since 1998. Although it was originally intended for intensive livestock farming only, since the first of January 2002 it is being applied for arable farming also.

Although MINAS works rather well, the Dutch government recently took additional measures in the form of manure outlet contracts, mainly under pressure from the EU Nitrates Directive. A manure-producing farm should discharge its manure surplus, based on a mineral application norm, by contracting a party who is willing and allowed to use the manure as fertilizer. While the manure-producing parties are mainly intensive pig and poultry farms (in the south), the manure-receiving parties are generally arable farms and extensive dairy farms that use manure as a substitute for chemical fertilizer (in the north). However, arable farmers, who absorb the bulk of the manure surplus, are rather reluctant to use manure as a substitute for chemical fertilizer. Specifically, the degree of acceptance of manure (by arable farmers) is commonly defined as the share of manure actually applied to a specific crop planted in a specific field from the theoretical amount of applied manure which maximizes crop yield (e.g., Staalduinen et al. 2002). This degree is dependent on the source of manure (poultry, cows, pigs), its quality (e.g., percentage of dry matter, nitrogen and phosphate contents and more), environmentally oriented legislation and manure price. Empirical studies show that the degree of acceptance of manure on farms where the manure is produced is close to 100 percent. However, on arable farms, Luesink et al. (2004) report values within the range of 53% to 92%.

The main reasons for their reluctance relate to the lack of homogeneity of manure, the technical limitations to applying manure uniformly and without damaging top soil, and the unidentified mineral contents. Moreover, the relatively high mineral losses from manure due to leaching make it unattractive from the MINAS perspective. While there seems to be equilibrium in the market for manure at the moment, this equilibrium is rather fragile and very much dependent on the acceptability rate of manure by arable farmers (see Staalduinen et al. 2002). This is illustrated by the fact that manure producers sometimes pay to discharge manure, which implies a negative price for arable farmers for obtaining minerals from manure. Since it is likely that environmental regulations will become stricter under pressure from the EU Nitrates Directive, the acceptability of manure by arable farmers forms a crucial role in future mineral policy and development of intensive livestock farming.[1] After all, the only way to avoid a further reduction in the production level of animal farming is to distribute more manure to arable farms (and extensive dairy farms) as a substitute for chemical fertilizer.

There is some scientific literature focused on the specific Dutch case: Komen and Peerlings (1998) on national economic effects of reducing the mineral surplus in the Netherlands using an output restriction; Oude Lansink and Peerlings (1997) on the effects of an N-surplus tax in Dutch arable farming; Fontein et al. (1994) on levies to reduce the nitrogen surplus at Dutch pig farms. Another branch of literature focuses on optimal mineral application strategies (e.g. Feinerman and Voet 1995; Feinerman and Falkovitz 1997; Bontems and Thomas 2000) and the regulation of livestock waste (Innes 2000; Feinerman et al. 2004). However, the issues of absorbing livestock mineral surpluses by arable farming as a substitute for chemical fertilizer has received little attention. In this paper we focus on the fertilization strategies of Dutch arable farmers to analyze the extent to which they are willing to substitute organic fertilizer for chemical fertilizer. In the model developed, we take into account the most important variables affecting the farm-level strategies, i.e. the availability and non-uniformity of nitrogen in organic fertilizer (manure), the non-uniformity of soil nitrogen available for crop uptake, the timing of manure application, the taxation of nitrogen leaching, and the prices of inputs and output. In doing so, we gain insight into the decision-making process of a representative arable farmer, and identify the most important decisive variables, which generates useful information for policy makers.

The remainder of this paper is organized as follows. Section 2 introduces the conceptual framework of the model and elaborates on comparative statics with respect to relevant parameters. Section 3 derives optimal fertilization strategies at the farm level. Section 4 illustrates the analytical findings using a numerical example, and evaluates the sensitivity of the optimal fertilization strategies to various parameters. Finally, Section 5 discusses some caveats and derives conclusions.

2. Conceptual Framework

Consider a Dutch arable farmer who is reviewing the fertilization strategy of a field for a crop that is planted in spring and harvested in fall, and has to choose between applying manure and/or chemical fertilizer (see Figure 1).

To simplify the analysis, we will focus only on nitrogen and will not take into account any side effects of manure.[2] We assume an agricultural field of H hectares (ha) of clay soil and a two-dimensional spatially variable function, $\tilde{N}(x)$, where $x \in H$ represents the coordinate vector of a point in the field. Specifically, $\tilde{N}(x)$ is the initial stock of plant-available nitrogen in the root zone below point x, after harvesting the preceding crop. We subdivide the field domain into a set of S sub-plots of equal area, $h = H/S$ ha, and denote by $\tilde{N}_i$ the value of $\tilde{N}(x)$ at the ith sub-plot.[3] The distribution of $\tilde{N}_i$ over the field area is assumed to be known with certainty via available spatial field tests for nitrogen. Nitrogen is an essential nutrient for plant growth and can be applied via both chemical fertilizers and animal manure.

Following cultivation practices commonly used in the Netherlands, we assume that animal manure can be applied by pre-planting only either in fall or in spring, while chemical fertilizers can be applied by pre-planting either in spring and/or during the growing season as a side-dressing.

The timing of manure application plays a crucial role in the decision-making process at the farm level. Application of manure in spring inflicts damage to the top soil, resulting in a reduction in the crop yield, while application in the fall does not involve any soil damage. However, on average, about 65% of nitrogen applied via manure in the fall will not be available for crop-uptake, and a significant part of this amount may be leached below the root zone and pollute water resources, while the average rate of unavailable nitrogen applied (via manure) in spring is "only" about 30%. Thus, we can conclude, a priori, that *it is inefficient to apply manure pre-planting* ***both*** *in the fall* ***and*** *in spring*. Once the farmer applies even a small amount of manure in spring, the top soil will be damaged. Given that the damage has already been done, a profit-maximizing farmer will apply all the manure he wants in spring (when "only" 30% of its nitrogen content will be unavailable) rather than in the fall (when as much as 65% of the nitrogen will become unavailable).[4] Another reason for the inefficiency of two successive

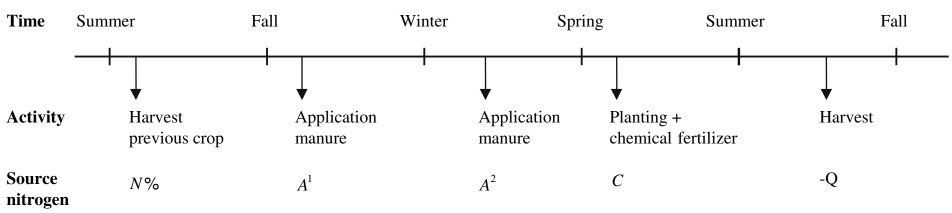

Figure 1. Fertilization strategy field crop.

manure applications is the fixed costs associated with each application. A single application of A kg of manure to a given field is cheaper than two applications of 0.5 A kg each.

Let A^1 and A^2 be the total amounts of manure, in kg, applied to the field in the fall and in spring, respectively. The amount applied to each sub-plot is therefore equal to $a^k = A^k/S$, $k = 1,2$. The above discussion implies that if $A^2 > 0$ then $A^1 = 0$, and if $A^1 > 0$ then $A^2 = 0$. Obviously, a fertilization strategy under which a profit-maximizing farmer applies only chemical fertilizers (i.e., $A^1 = 0$ and $A^2 = 0$) should also be examined. Typically, the quantity of nitrogen contained at a given volume of manure is quite variable, and the application of manure over the field is non-uniform, implying non-uniform, or spatially variable, distribution of nitrogen (applied via manure) over the field area. The degree of non-uniformity is independent of the time of application. We account for this non-uniformity by a positive random variable, θ, the distribution of which is affected by both the variability of nitrogen contained in manure and the non-uniformity of manure application. Specifically, we assume that the mean and variance of θ are given by $E(\theta_i) = E(\theta_j) = E(\theta) \equiv \bar{\theta}, \forall i,j$ and $\mathrm{Var}(\theta_i) = \mathrm{Var}(\theta_j) \equiv V(\theta) =, \forall i,j$, respectively. The random level of nitrogen applied to the ith sub-plot is $a^k\, \theta_i = (A^k/S)\theta_i$, where θ_i is the realization of θ with respect to the manure applied to this plot.

The effective plant-available nitrogen from manure in the root zone of the ith sub-plot is given by $\delta_i^k\, (A^k/S)\theta_i$, $k = 1,2$, where $0 < \delta_i^k < 1$ is the percentage of total nitrogen supplied via the manure applied at time k that is actually available for crop uptake during the current growing season. The value of δ_i^k is affected by spatially variable soil properties, weather conditions (e.g. rainfall), slow release processes, and non-uniformity of application. Consequently, the farmer will not know its realized value before the manure has been applied. We treat δ_i^k as a random variable, with mean and variance given by $E(\delta_i^k) = E(\delta_j^k) = \bar{\delta}^k, \forall i,j,$ and $\mathrm{Var}(\delta_i^k) = \mathrm{Var}(\delta_j^k) \equiv V(\delta^k) =, \forall i,j,$ respectively (in the case considered here, $\bar{\delta}^1 \approx 0.35$ and $\bar{\delta}^2 \approx 0.70$). We additionally assume that δ_i and θ_i are independent random variables. From the total amount of nitrogen applied to the ith sub-plot, $(1 - \delta_i^k)(A^k/S)\theta_i$ kg are not used by the plant.

The total level of chemical nitrogen (in kg N), applied to the field is denoted by C. Advanced application technologies of chemical fertilizers allow us to assume that C is applied uniformly over the field area. Chemical or mineral nitrogen available for plant uptake is βC, $(0 < \beta < 1)$, whereas the rest, $(1-\beta)C$, is assumed to be leached below the root zone. Without loss of generality, we assume hereafter that due to rainfall, there is no carry-over of organic and mineral nitrogen to the next growing period and that all unused nitrogen is leached beyond the root zone and contaminates water resources.[5]

Plant-available nitrogen in the ith sub-plot, and expected quantity of nitrogen not used by the plant at the field level are thus given respectively by

$$N_i^k = \tilde{N}_i + \delta_i^k (A^k/S)\theta_i + \beta C/S; k = 1, 2 \tag{1}$$

and

$$L^k = (1-\beta)C + A^k(1-\bar{\delta}^k)]\bar{\theta}; k = 1, 2 \tag{2}$$

The inferiority of manure relative to chemical fertilizers implies, among other things, that

$$\frac{\partial EN_i^k}{\partial C} = \frac{\beta}{S} > \frac{\partial EN_i^k}{\partial A^k} = \frac{\bar{\delta}^k \bar{\theta}}{S}, \forall i, k.$$

The connection between the economic optimization problem and the physical distribution of plant-available nitrogen is made via a yield response function. Specifically, crop yield (in kg of dry matter: DM) at the ith sub-plot is assumed to depend on N_i^k,[6] and is represented by the production function

$$q_i^k = f(N_i^k) \cdot \phi^k = f(\tilde{N}_i + \delta_i^k (A^k/S)\theta_i + \beta C/S) \cdot \phi^k, k = 1, 2, \tag{3}$$

where ϕ^k is a parameter of yield reduction as a result of soil damage if manure is applied in spring. Namely,

$$\phi^k = \begin{cases} 1 & \text{if } k = 1 \\ < 1 & \text{if } k = 2. \end{cases} \tag{4}$$

The function f is assumed to be strictly concave and twice differentiable. We further assume f to be monotonically increasing in N_i^k up to some threshold level, say $\underline{N}$, and it decreases when N_i^k exceeds this threshold. Obviously, q_i^k is a random variable depending stochastically on δ_i^k and θ_i.

Total yield over the field area is given by:

$$Q^k = \sum_{i=1}^{S} q_i^k = \sum_{i=1}^{s} f(\tilde{N}_i + \delta_i^k (A^k/S)\theta_i + \beta C/S) \cdot \phi^k, k = 1, 2. \tag{5}$$

The expectation of the yield function f is given by

$$\begin{aligned} & E\{f(\tilde{N}_i + \delta_i^k (A^k/S)\theta_i + \beta C/S) \cdot \phi^k\} = E_{\delta_i^k}\{E_{\theta_i}[f(\cdot)] \\ & = \phi^k \int_{\delta_i^k} \left\{ \int_{\theta_i} f(\tilde{N}_i + \delta_i^k (A^k/S)\theta_i + \beta C/S) \cdot \phi^k) g(\theta_i) d\theta_i \right\} h^k(\delta_i^k) d\delta_i^k, \Big\} \end{aligned} \tag{6}$$

where $g(\theta_i)$ and h^k (δ_i^k) are the probability density functions of θ_i and δ_i^k, respectively.

It is useful for the analysis below to identify the approximate relationships between the expected yield and the means and the variances of the random variables θ_i and δ_i^k. These relationships can be obtained by employing a second order Taylor expansion of $f(\cdot)$, about $\bar{\theta}$ and $\bar{\delta}^k$ which yields:

$$E\{f(\tilde{N}_i+\delta_i^k(A^k/S)\theta_i+\beta C/S)\cdot\phi^k\}\approx f(\tilde{N}_i+\bar{\delta}^k(A^k/S)\bar{\theta}+\beta C/S)\cdot\phi^k + \frac{1}{2}\phi^k f''_{N_i^k}(\bar{\theta},\bar{\delta}^k)\cdot\frac{(A^k)^2}{S^2}[(\bar{\delta}^k)^2V(\theta)+\bar{\theta}^2V(\delta^k)], \tag{7}$$

where E is the expectation operator over δ_i^k and θ_i,

$$f''_{N_i^k}(\bar{\theta},\bar{\delta}^k)\equiv\frac{\partial^2 f(\tilde{N}_i+\bar{\delta}^k(A^k/S)\bar{\theta}+\beta C/S)\cdot\phi^k}{\partial(N_i^k)^2}, \tag{8}$$

and N_i^k is defined in equation (1). The assumed strict concavity of f implies that $f''_{N_i^k}(\bar{\theta},\bar{\delta}^k)$ is negative. The sign of the third derivative of f with respect to N_i^k is dependent on the specific assumed functional form. Here we assume that the second order Taylor expansion is a good approximation of f, which implies that $f''_{N_i^k}(\bar{\theta},\bar{\delta}^k)$ is a negative constant, the absolute value of which is denoted by b^k. Inspection of (7) shows that expected yield increases in the mean values of the random variable (as long as $N_i^k\leq\underline{N}$) and decreases in its variances.

3. Optimal Fertilization Strategies at the Farm Level

As stated in our example, the farmer will not apply pre-planting manure in **both** the fall **and** in spring. So, in the analysis below we define k to be either 1 or 2. In principle, the optimization problem should be solved twice, first with $k=1$ and then with $k=2$. Comparing the level of expected profits under each of the two cases will determine the choice of the preferred application date.

For a given date of manure application (i.e., for a given k), the optimization problem of a risk-neutral farmer is to choose A^k and C to maximize expected profit. Utilizing the approximation in (3), the problem is formulated as follows

$$\max_{\{A^k,C\}} E\Pi^k = P_Q\phi^k\sum_{i=1}^{s}\left\{f(\tilde{N}_i+\bar{\delta}^k(A^k/S)\bar{\theta}+\beta C/S) - \frac{1}{2}b^k\cdot\frac{(A^k)^2}{S^2}[(\bar{\delta}^k)^2V(\theta)+\bar{\theta}^2V(\delta^k)]\right\} - wA^k - P_CC - t[(1-\beta)C+A^k(1-\bar{\delta}^k)\bar{\theta}], \tag{9}$$

where P_Q is income net of non-nitrogen variable costs per unit of yield (€/kg DM); w is the sum of purchase price, variable transportation costs, and variable application costs per unit of manure (€/kg N); P_C is the per unit price of chemical fertilizer (€/kg N); t is tax per unit of nitrogen loss, (€/kg N). If the farmer gets paid for the manure used, then w might be negative. The first order conditions for optimal A^k and C are:

$$\begin{aligned}\frac{\partial E\Pi^k}{\partial A^k} = P_Q\phi^k\Bigg[(\bar{\delta}^k\bar{\theta}/S)\sum_{i=1}^{S}\Bigg[f'_{N_i^k}(\tilde{N}_i + \bar{\delta}^k(A^k/S)\bar{\theta} + \beta C/S) \\ - b^k\cdot((\bar{\delta}^k)^2V(\theta) + \bar{\theta}^2V(\delta^k))\frac{A^k}{S^2}\Bigg] - w \\ - \bar{\theta}(1-\bar{\delta}^k)t \leq 0; \text{but} = 0 \quad \text{if } A^k > 0; \text{and}\end{aligned} \tag{10a}$$

$$\begin{aligned}\frac{\partial E\Pi^k}{\partial C} = P_Q\phi^k(\beta/S)\sum_{i=1}^{S}f'_{N_i^k}(\tilde{N}_i + \bar{\delta}^k(A^k/S)\bar{\theta} + \beta C/S) \\ - P_C - t(1-\beta) \leq 0, \text{but} = 0 \quad \text{if } C > 0,\end{aligned} \tag{10b}$$

where $f'_{N_i^k} = \frac{\partial f}{\partial N_i^k}$. In principle, it may well be that in the optimal solution, the marginal product of N_i^k for some of the plots will be negative.

3.1. FERTILIZATION STRATEGIES

Let (A^{k*},C^*) be the optimal input levels maximizing (9). Since nitrogen is an essential nutrient for crop growth, we ignore the possibility that both A^{k*} and C^* are equal to zero. Thus, the farmer is left with a choice of three fertilization strategies, presented below.

Strategy 1: Mixed application of manure and chemical fertilizers: $C^* > 0$, $A^{k*} > 0$.

Utilizing the first order conditions (10a) and (10b), the optimal input levels (A^{k*},C^*) under this strategy is determined simultaneously by equations (10a)′ and (10b)′ below:

$$\begin{aligned}\frac{1}{S}\cdot\sum_{i=1}^{S}f'_{N_i^k}(\tilde{N}_i + \bar{\delta}^k(A^{k*}/S)\bar{\theta} + \beta C^*/S) = \frac{A^{k*}\cdot b^k\cdot((\bar{\delta}^k)^2V(\theta) + \bar{\theta}^2V(\delta^k))}{S\bar{\delta}^k\bar{\theta}} \\ + \frac{[w + \bar{\theta}(1-\bar{\delta}^k)t]}{P_Q\phi^k\bar{\delta}^k\bar{\theta}}\end{aligned} \tag{10a$'$}$$

and

$$\frac{1}{S}\cdot\sum_{i=1}^{S}f'_{N_i^k}(\tilde{N}_i + \bar{\delta}^k(A^{k*}/S)\bar{\theta} + \beta C^*/S) = \frac{[P_C + t(1-\beta)]}{\beta\phi^kP_Q}. \tag{10b$'$}$$

Equations (10a)′ and (10b)′ enable us to solve explicitly for A^{k^*}:

$$A^{k*} = \frac{S\{\bar{\delta}^k\bar{\theta}[P_C + t(1-\beta)] - \beta[w + \bar{\theta}(1-\bar{\delta}^k)t]\}}{b^k \cdot ((\bar{\delta}^k)^2 V(\theta) + \bar{\theta}^2 V(\delta^k))\beta P_Q \phi^k}. \tag{11}$$

Note that a sufficient condition for A^{k^*} to be positive is:

$$\bar{\delta}^k\bar{\theta}[P_C + t(1-\beta)] > \beta[w + \bar{\theta}(1-\bar{\delta}^k)t]. \tag{12}$$

Inspection of (11) shows that A^{k^*} decreases in the variances $V(\theta)$ and $V(\delta)$, in the crop-uptake rate of chemical fertilizer, β, in ϕ^k and in w. Counter intuitively, A^{k^*} also decreases in income per unit of output, P_Q. This can be explained, however, by noting that using manure involves a penalty that is related to the fact that $\beta > \bar{\delta}^k\bar{\theta}$, and to the uncertainty expressed by $V(\theta)$ and $V(\delta^k)$. Since we are dealing with a given plot, in the optimal solution an increase in the output price will lead to a higher level of plant-available nitrogen, N_i, (see (1)). In our model, this can be achieved by increasing the amount of applied chemical fertilizer and/or manure. Recalling that the expected gross revenues per land unit is given by $P_Q\, E[f(N_i^k)\phi^k]$ and noting from (7) that $\frac{\partial E[f(N_i^k)\phi^k]}{\partial C} > \frac{\partial E[f(N_i^k)\phi^k]}{\partial A^k}$, implies that the higher the output price, the higher the penalty (i.e., the reduction in expected gross revenues) associated with the use of manure, compared to the use of chemical fertilizer[7]. Hence, the increase in plant-available nitrogen will be obtained through an increase in chemical fertilizer, **which exceeds the** reduction of manure.

It can also be easily verified that A^{k^*} increases with the price of chemical fertilizer, P_C. The sign of the partial derivative of A^{k^*} with respect to the tax level t, is equal to the sign of $(\bar{\delta}^k - \beta)$, which is likely to be positive. The impact changes in $\bar{\theta}$ and in $\bar{\delta}^k$ on A^{k^*} are generally indeterminate and are dependent on specific parameter values.

Substituting for A^{k^*} in (10b)′ and noting that, *ceteris paribus*, increase in A^{k^*} implies a decrease in C^*, allows us to conduct comparative statics with (10b)' and to evaluate the impact of changes in various parameters on C^*. It can be easily verified that C^* increases in $V(\theta)$, $V(\delta^k)$, w, P_Q, and decreases in P_C. If $\frac{\partial A^{k*}}{\partial t} > 0$ then $\frac{\partial C^*}{\partial t} < 0$, but if A^{k^*} decreases in t, the sign of $\frac{\partial C^*}{\partial t}$ is indeterminate. The impact on C^* of changes in $\bar{\theta}$, $\bar{\delta}$ and β is generally indeterminate.

Strategy 2: Application of chemical fertilizers only: $C^* > 0$, $A^{k^*} = 0$.

This strategy will be adopted by the farmer when $\bar{\delta}^k\bar{\theta}[P_C + t(1-\beta)] < \beta[w + \bar{\theta}(1-\bar{\delta}^k)t]$, (see (12)). The optimal level of C^* is determined by equations (10b)′, with $A^{k^*} = 0$. Namely,

$$\sum_{i=1}^{S} f'_{N_i^k}(\tilde{N}_i + \beta C^*/S) = \frac{[P_C + t(1-\beta)]S}{\beta\phi^k P_Q} \tag{13}$$

Comparative statics shows that C^* decreases in P_C and t, and increases in P_Q,ϕ^k and in β.

Strategy 3: Application of manure only: $C^* = 0,\ A^{k^*} > 0$.

This strategy will be chosen in cases when (see (10b))

$$P_Q \phi^k (\beta/S) \sum_{i=1}^{S} f'_{N_i^k} (\tilde{N}_i + \bar{\delta}^k (A^k/S)\bar{\theta}) < P_C + t(1-\beta)$$

The optimal level of A^{k^*} is determined by equation (10a)′ with $C^* = 0$. Namely,

$$\begin{aligned} &\frac{1}{S} \cdot \sum_{i=1}^{S} f_{N_i^k} (\tilde{N}_i + \bar{\delta}^k (A^{k*}/S)\bar{\theta}) - \frac{A^{k*} \cdot b^k \cdot ((\bar{\delta}^k)^2 V(\theta) + \bar{\theta}^2 V(\delta^k))}{S \bar{\delta}^k \bar{\theta}} \\ &\quad - \frac{[w + \bar{\theta}(1 - \bar{\delta}^k)t)]}{P_Q \phi^k \bar{\delta}^k \bar{\theta}} = 0 \end{aligned} \tag{14}$$

Comparative statics with the above equation show that A^{k^*} decreases in the variances $V(\theta)$ and $V(\delta)$ and in w and increases in P_Q. The signs of $\frac{\partial A^{k*}}{\partial \bar{\theta}}$ and $\frac{\partial A^{k*}}{\partial \bar{\delta}^k}$ are both indeterminate.

3.2. THE CHOICE OF MANURE APPLICATION DATE

Recall that ϕ^k is a parameter of yield reduction as a result of soil damage if manure is applied in spring. Namely,

$$\phi^k = \begin{cases} 1 & \text{if } k = 1 \\ < 1 & \text{if } k = 2. \end{cases}$$

Also recall that manure will be applied only once (if at all), either in the fall ($k = 1$) or in spring ($k = 2$). So, in order to choose the date of application that is most profitable for the farmer, the optimization problem in (9) should be solved twice, once with $k = 1$ and once with $k = 2$. Then, the choice of timing should be made as follows:

- If $\bar{\Pi}^{1*}(A^{1*} > 0, C^* \geq 0) > \bar{\Pi}^{2*}(A^{2*} > 0, C^* \geq 0) \Rightarrow$ then choose to apply manure in the fall, at a level of A^{1^*}. In that case there will be no soil damage (i.e., $\phi^1 = 1$).
- If $\bar{\Pi}^{2*}(A^{2*} > 0, C^* \geq 0) > \bar{\Pi}^{1*}(A^{1*} > 0, C^* \geq 0) \Rightarrow$ then choose to apply manure in spring, at a level of A^{2^*} at a cost of some soil damage (i.e. $\phi^2 < 1$).

The advantage of fall application as opposed to spring application is offset by the fact that the nitrogen loss associated with the former is greater than the one associated with the latter (i.e., $\bar{\delta}^1 > \bar{\delta}^2$).

4. Numerical Analysis

The theoretical analysis is demonstrated for ware potatoes, one of the main field crops grown on clay soils in the northern part of the Netherlands. For the estimation of the yield function we utilized an existing, agronomically oriented, biological–physical model, QUAD-MOD, documented by Ten Berge et al. (2000). QUAD-MOD makes it possible to simulate the response of total dry-matter yield of a specific crop to the applied nitrogen dose, taking into account soil characteristics, weather conditions, general agronomic practices, and nutrient management. Specifically, it quantifies the response of crop yield (denoted by Y in the document of Berge et al) to nitrogen input (denoted by A) on the basis of the partial response of Y to nitrogen uptake (denoted by U), Y(U), and of the partial response of U to A, U(A). Both responses are quantified over two domains, using different functions U(A) and Y(U) in each domain. Domain I applies to the lower range of nitrogen availability with a linear U(A) function. Domain II is the upper range of nitrogen availability, using a concave functional form for U(A). The transition between the two domains in a given nitrogen response experiment occurs at the so called "critical point" and is governed by the nitrogen concentration in the crop. Also, the function Y(U) is non-linear in the upper range (Bos 2002). We used the QUAD-MOD model to simulate the response of dry matter of ware potatoes to seasonal plant-available nitrogen in a representative farm, assuming average weather conditions and commonly used agricultural practices. Using the simulated data set, we estimated the following quadratic yield function in the absence of soil damage (t values in parentheses):

$$Q^1 = \underset{(236.0)}{10636.4} + \underset{(29.9)}{10.3}\,N - \underset{(-25.3)}{0.0148}\,N^2, \quad (R^2 = 0.94)$$

where yield, Q^1, is measured in kg dry matter (DM) per ha, and N is measured in kg of available nitrogen per ha.

To further parameterize the model developed in Section 2, we used data characterizing the most common current practice under which a pig manure surplus is used as an organic fertilizer by arable farmers. We assume a representative field of $H = 1$ ha and subdivide its domain into a set of $S = 20$ sub-plots of equal area, $h = 1/20$ ha. The *average* initial stock of nitrogen in the root zone of each of the sub-plots is assumed to be 4.5 kg (= 90/20, see Table I below). Then the values of $\tilde{N}_i, i = 1, \ldots, 20$, were simulated via random number generator, assuming that $\tilde{N}_i$ is normally distributed over the field with variance of 0.81 square kg of nitrogen (implying a coefficient of variation of 0.20). The main parameter values and sources are reported in Table I.

Table I. Benchmark values for the numerical analysis

Parameter	Explanation	Value	Source
$\tilde{N}_i$	Average Stock of nitrogen at plot i (in kg N per plot)	4.5	Ten Berge et al. 1999, table 3.4 (potatoes on clay soil)
$cv(\tilde{N}_i)$	Coefficient of variation of $\tilde{N}_i$	0.20	Own approximation
$\bar{\theta}$	Nitrogen content pig manure in kg N / kg manure	0.0072	PAV, 1999, table 7.1;
$cv(\theta)$	Coefficient of variation of θ	0.35	PDLT, 2003, table C
β	Efficiency coefficient $N^{fertiliser}$ applied in spring	0.9	Own approximation
$\bar{\delta}^1$	Efficiency coefficient N^{manure} applied in the fall	0.35	PAV, 1999, footnote 1, table 7.2
$\bar{\delta}^2$	Efficiency coefficient N^{manure} applied in spring	0.70	PAV, 1999, table 7.2
$cv(\delta)$	Coefficient of variation of δ	0.30	Approximated from Ten Berge et al. 1999, table 3.7
P_Q	Price of ware potatoes (in € per kg DM)	0.64	Bos, 2002, appendix 7
P_C	Price of fertilizer (in € per kg N)	0.51	Bos, 2002, appendix 7

4.1. RESULTS

The vast majority of Dutch farmers who use manure choose to apply it in the fall ($k = 1$). Hence, we choose the fall application as our benchmark. Utilizing the parameter values in Table I and assuming a tax of $t = 0.25$ € per kg of N loss (about 50% of the price of chemical fertilizer), the effects of per unit costs of manure purchase, transportation, and application, w (€/kg manure) on optimal fertilization decisions and their environmental consequences (via nitrogen loss) are illustrated in Table II.

Currently, manure application by contract labor in the Netherlands costs about 0.003 €/kg. The results in the first row of Table II suggest that even if a representative arable farmer is offered manure free of charge at the gate of a manure-producing farm, he will not use it. In other words, if transportation and application costs are not subsidized, the farmer will prefer to apply nitrogen via chemical fertilizers only. As long as actual costs of manure to the arable farmer, w, exceed 327.5×10^{-6} Euros per kg, the optimal fertilization strategy is to apply only chemical fertilizers. When w ranges between 209.95×10^{-6} and 327.49×10^{-6} (€/kg), mixed application of manure and chemical fertilizer is the preferred fertilization strategy (Table II). If w drops below 209.95×10^{-6} (€/kg), the optimal fertilization strategy is to apply manure only.

Table II. The role of manure cost, w ($k = 1$)

w(€/kg)	A (kg/ha)	$\bar{\delta}^1\bar{\theta}A \equiv N(A)$ (kg N/ha)	C (kg N/ha)	$N(A)+\beta\ C$ (kg N/ha)	Non-used nitrogen = L^1 (kg N/ha)
300×10^{-5}	0	0	260	234	25
327×10^{-6}	397	1	258	234	28
303×10^{-6}	19841	50	204	234	113
277×10^{-6}	39683	100	148	234	201
265 $\times 10^{-6}$	**49603**	**125**	**121**	**234**	**244**
252×10^{-6}	59524	150	93	234	288
227×10^{-6}	79365	200	37	234	357
210×10^{-6}	92359	233	1	234	432

Obviously, the above ranges are highly sensitive to some of the other parameter values, especially to the level of the environmental tax on nitrogen loss t, and should be treated with caution. If, for example, t were to increase from 0.25 to 0.5 (€/kg N), manure will be applied only if w becomes negative, i.e. smaller than -772.5×10^{-6} (€/kg). Namely, the representative arable farmer will use manure only if he gets paid for it, possibly by manure-producing farmers who are obliged to discharge their manure surplus (see below). More specifically, with $t = 0.5$ (€/kg N), the mixed application of manure and chemical fertilizer will be adopted when $w \in [-772.5 \times 10^{-6}, -889.3 \times 10^{-6}]$. If w drops below -889.3×10^{-6} (€/kg), the optimal fertilization strategy is to apply manure only.

The total contribution of fertilization to the plant-available nitrogen, $\bar{\delta}^1\bar{\theta}A + \beta C$, is independent of w and equal to 233.65 kg/ha (column 5, Table II). However, as expected, the lower w is, the higher the level of A is, and the lower the level of C. The additive relationship between A and C in the expected yield function (equation (7)), implies that the substitution between A and C is large. Increasing w by 56% (from 209.95×10^{-6} to 327.49×10^{-6}) reduces the optimal A/C ratio from 92539 to a low of 1.5.

While the impact of w on the value of the objective function in (9) is very low, its environmental-associated impact might be significant. As illustrated in the last column of Table II, the sensitivity of the level of non-used N, or nitrogen loss, $L^1 = 0.10C + 0.00468A$, is significant. Much of the increase in L^1 resulting from a decrease in w is attributed to the large changes in manure application that are accompanied by much smaller changes in the value of C. Although the marginal impact of C on L^1 ($\partial L^1/\partial C = 0.1$) is 21 times larger than the marginal impact of A ($\partial L^1/\partial A = 0.00468$), the impact of the latter on total non-used nitrogen is much higher than the impact of the former. For example, with $w = 264.59 \times 10^{-6}$ the "contributions" of A and C to total nitrogen-loss are 232 kg and 12 kg, respectively. The above result has an important implication on policy. As mentioned, manure-producing (poultry and pig) farms are required to discharge their surplus via land application. It may well be that it is more price efficient for at least some of them, who face high treatment cost for their manure, to pay arable farmers in order to discharge the excess manure. This would result in greater substitution, but can still be socially optimal. Policy makers should be aware of the fact that the substitution of chemical fertilizer by manure may yield significant environmental costs, but it can still be a socially desired action.

As shown above, this substitution is quite sensitive to the level of environmental tax, t, imposed by the government. *Ceteris paribus*, an increase in the tax rate implies a significant reduction in the amount of applied manure. Thus, the positive environmental contribution associated with that increase is offset by the potential loss to manure-producing farmers who are obliged to get rid off their excess manure via land application (or otherwise to reduce the level of their livestock).

Recall that spring application of manure inflicts damage to the top soil, resulting in reduction of crop yield, but much lower nitrogen loss $((1-\bar{\delta}^2) = 0.30)$ relative to fall application $((1-\bar{\delta}^1) = 0.65)$. Thus, the higher the tax rate levied on nitrogen loss, the higher the relative advantage of spring application.

In the absence of accurate data on yield reduction caused by spring application (given by $\phi^{k=2}$ (<1) in our theoretical analysis), we compared the profitability of fall and spring applications by calculating "profit equivalent" levels of $\phi^{k=2}$, denoted by $\hat{\phi}^2$, for the various levels of w. Specifically, for each value of w we calculated the level of $\hat{\phi}^2$ under which expected profits associated with the optimal fertilization strategy, when manure is applied in the spring, is equal to the optimal expected profits associated with fall application. With $t = 0.25$, all levels of $\hat{\phi}^2$ were higher than 0.9935, implying yield reductions which are lower than 0.65%. Namely, if actual yield reduction associated with spring application of manure exceeds 0.65%, then fall application of manure is preferred to spring application. A corollary of this is that if the actual yield reduction falls short of 0.65%, fall application of manure is not attractive. Given the type of soil and normal weather conditions in the Netherlands, in combination with current application technologies, the actual yield loss commonly exceeds 0.65%, which explains why most Dutch arable farmers who apply manure prefer the fall application.

4.2. THE ROLE OF ENVIRONMENTAL TAX, t

To examine the sensitivity of the optimal fertilization strategy to changes in t, we chose as a benchmark the results associated with fall application of manure ($k = 1$), with $w = 264.59 \times 10^{-6}$, (see Table II). Then, we solved the optimization problem in (9) for t values ranging between 0 and 2. The results are summarized in Table III. The optimal level of applied manure is quite sensitive to the tax rate. For low tax values ($0.2376 > t \geq 0$) the preferred strategy is to apply manure only ($C = 0$). When t increases from 0 to 0.2376, the levels of A, $N(A)$, and non-used nitrogen reduces by about 9.3%. Mixed application of manure and chemical fertilizer is optimal only for a small range of t values ($0.2643 \geq t \geq 0.2376$). Within this range, the substitution between A and C is extreme: increasing the tax rate by 11% causes A to decline from a high of about 92.4 tons per hectare to almost zero (0.4 tons/ha), accompanied by a sharp increase in the value of C from 1 to 258 (kg N/ha). The environmental impact of this substitution is quite large; the level of non-used nitrogen is reduced from 432.48 to only 27.71 (kg N/ha) when t increases from 0.2376 to 0.2643.

When t exceeds 0.2643, the optimal fertilization strategy is to apply only chemical fertilizer (i.e., $A = 0$), and a significant increase in t causes only a small decline in both C and the value of non-used nitrogen. In conclusion, the results in Table III suggest that the impact of the environmental tax on the level of non-used nitrogen is moderate for low values of t (under which $A > 0$ and $C = 0$), extreme for a small range of higher t values (under which $A > 0$ and $C > 0$), and almost negligible for high t values (under which $A = 0$ and $C > 0$).

We also examined the sensitivity of the ''profit equivalent'' threshold $\hat{\phi}^2$ to the tax level. Specifically, for each value of t presented in Table III, we calculated the level of $\hat{\phi}^2$ under which expected profits associated with the optimal fertilization strategy – when manure is applied in the spring – equals the optimal expected profits associated with fall application. The farmer is indifferent between applying manure in spring or fall, when the yield loss is

Table III. The impact of environmental tax, t (with $k = 1$ and $w = 264.59 \times 10^{-6}$)

t(/kg N)	A(kg/ha)	$\bar{\delta}^1\bar{\theta}A \equiv N(A)$ (kg N/ha)	C (kg N/ha)	$N(A) + \beta\, C$ (kg N/ha)	Non-used nitrogen = L^1 (kg N/ha)
0.0	101880	257	0	257	477
0.05	99962	252	0	252	468
0.15	96112	242	0	242	450
0.238	92388	233	1	234	432
0.25(basic)	**49603**	**125**	**121**	**234**	**244**
0.264	397	1	258	234	28
0.30	0	0	259	234	26
0.50	0	0	258	232	26
1.00	0	0	255	229	25
2.00	0	0	248	223	25

equal to $(1 - \hat{\phi}^2)$, hereafter: "acceptable yield loss". In Figure 2, $(1 - \hat{\phi}^2)$ is plotted as a function of t.

At $t = 0$ (and $w = 264.59 \times 10^{-6}$), the farmer applies manure only in the fall application. Since nitrogen loss associated with spring application is significantly smaller than that associated with fall application, only a small yield loss is acceptable to make the farmer indifferent. When the tax increases, less manure will be applied in the fall application. Hence, it is more attractive to switch to spring application where mineral losses (and tax payments) are lower, implying a larger acceptable yield loss. When the tax level rises to such an extent that manure applied in the fall is substituted by fertilizer in spring, switching to spring application becomes even more attractive and the acceptable yield loss reaches its highest point. Further increases in tax cause the manure application in the fall (but not in the spring) to vanish. At these higher tax rates, the application of manure in spring also becomes less attractive. Hence, the acceptable yield loss to make the farmer indifferent between fall and spring application becomes smaller. At very high tax levels, spring application also vanishes (i.e., completely substituted by chemical fertilizer) and manure is no longer relevant. Hence, the acceptable yield loss is reduced to 0.

4.3. SENSITIVITY ANALYSIS FOR THE FALL APPLICATION

To examine the sensitivity of the results to product price (P_Q), and the variances of $\theta(V(\theta))$ and $\delta^1(V(\delta^1))$, we choose as a benchmark the results of fall application with $w = 264.59 \times 10^{-6}$ (see Table II). We start with the product price. Recall from equations (11) and (15) that manure application decreases in P_Q when the mixed application strategy is optimal (i.e., $A > 0$, $C > 0$), and decreases in P_Q when application of manure only is optimal ($A > 0$, $C = 0$). Chemical fertilizer increases in product prices under both the

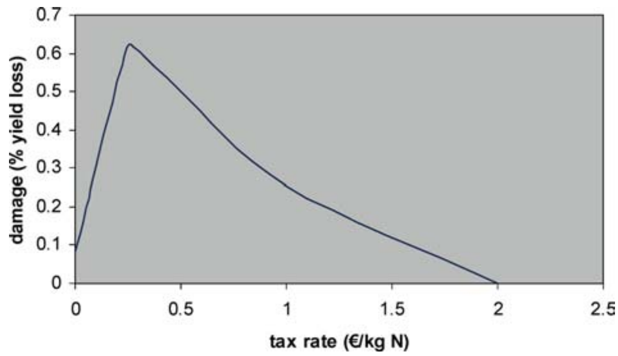

Figure 2. Acceptable yield loss resulting from spring application manure at different tax rates.

mixed application strategy and the strategy to apply only chemical fertilizers. We changed P_Q within the range of 0–3 € per kg DM. With $w = 264.59 \times 10^{-6}$ €/kg, the optimal strategy was to apply manure only for product prices smaller than 0.38 € per kg DM and to adopt the mixed application strategy for the rest of the assumed range of product prices. The results are summarized in Figure 3.

Inspection of Figure 3 illustrates the inferiority of A relative to C under the mixed application. As P_Q increases, less of A and more of C is used while the total amount of applied nitrogen increases. This is due to the fact that the use of manure involves a penalty, which is attributed to the relatively high nitrogen loss $(1 - \bar{\delta}^1 = 0.65 > 1 - \beta = 0.1)$ and to the variances $V(\theta)$ and $V(\delta)$. The higher the output price, the higher the penalty.

The sensitivity of the results of the benchmark case to mean preserving spreads in the distribution of δ and θ, expressed by the coefficients of variation (CV), is illustrated in Figures 4 and 5, respectively.

We changed $CV(\delta)$ within the range of 0–0.7. With $w = 264.59 \times 10^{-6}$, the mixed application strategy was optimal for the whole range. As $CV(\delta)$ increases, the higher the disadvantage of manure relative to commercial fertilizer becomes, implying that less of A and more of C is used, while the total amount of applied nitrogen, $N(A) + \beta\ C$, is held fixed at a level of 233.65 kg N/ha. The substitution of A by C yields a significant reduction in the level of non-used nitrogen (from 404.6 (kg N/ha) when $CV(\delta) = 0$ to only 101.7 (kg N/ha) when $CV(\delta) = 0.7$). Increasing the uniformity of manure application and improving cultivation practices may reduce the value of $CV(\delta)$ and, consequently, increase the level of applied manure. This suggests that subsidizing of advanced cultivation and/or application technologies will

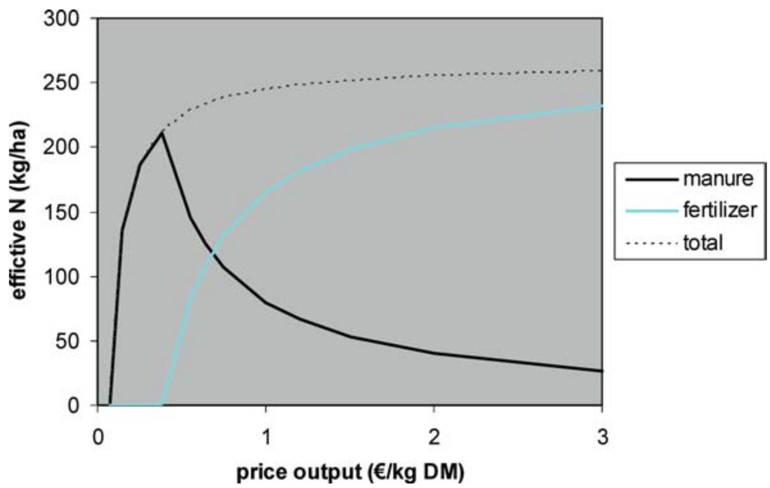

Figure 3. Manure (A) and fertilizer (C) as function of output price P_Q.

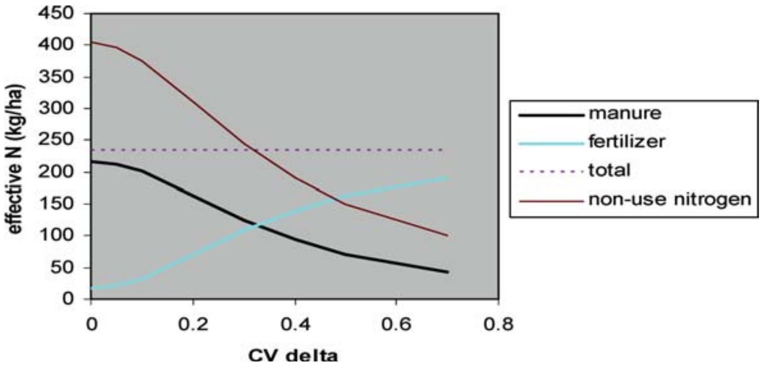

Figure 4. Manure (A) and fertilizer (C) as function of $CV(\delta)$.

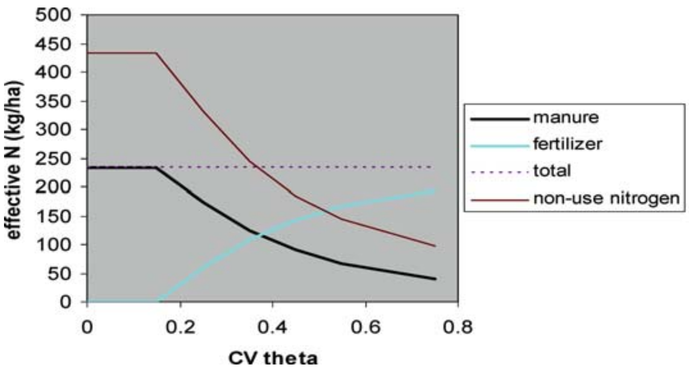

Figure 5. Manure (A) and fertilizer (C) as function of $CV(\theta)$.

result in higher environmental damage caused by higher levels of non-used nitrogen. Similar results were obtained with respect to the variance of θ (Figure 5).

With $w = 264.59 \times 10^{-6}$ €/kg, the optimal fertilization strategy is to apply only manure as long as $CV(\theta)$ is lower than a threshold level of about 0.155. As $CV(\theta)$ exceeds this threshold level, the mixed application strategy becomes optimal, and manure is gradually substituted by chemical fertilizer. Due to this substitution, the higher $CV(\theta)$, the lower the level of non-used nitrogen. In other words, *ceteris paribus* – the more homogeneous the manure content is, the lower is its relative disadvantage, and the higher the level of manure application, implying a higher level of non-used nitrogen.

5. Summary and Conclusions

This paper has focused on farm-level nitrogen fertilization strategies of Dutch arable farmers for analyzing the substitution between organic fertilizers (i.e. manure) and chemical fertilizers. The model developed captures and analyzes the major parameters affecting the inferiority of manure compared with chemical fertilizer, including the low availability and non-uniformity of the nitrogen in manure, the low level and high non-uniformity of plant-available nitrogen supplied via manure, and the potential damage to top soil associated with spring application. The sensitivity of the optimal fertilization decisions and their associated environmental impacts on product price, manure cost, and environmental tax was also examined. The theoretical analysis was applied to a representative Dutch grower of ware potatoes in the northern part of the Netherlands.

The core of the problem is that manure-producing farms in the Netherlands are compelled to discharge their manure surplus, based on mineral application norms, by contracting arable farmers who are willing to use the manure as fertilizer. Arable farmers, however, are subject to nitrogen regulation as a result of the EU Nitrates Directive (environmental tax on nitrogen loss in this study) and, for a variety of reasons, are reluctant to use manure as a substitute for chemical fertilizer. The inferiority of manure compared to chemical fertilizer can be attributed to the relatively high nitrogen loss, and to the high non-uniformity of nitrogen content in manure, as well as of manure nitrogen available for crop uptake.

The empirical analysis has demonstrated that even if a representative arable farmer is offered manure free of charge at the gate of a manure-producing farm, she will not do it. The reason being, that if transportation and application costs are not subsidized, by manure-producing farms for example, the farmer will prefer to apply nitrogen only via chemical fertilizers. We also found that the optimal fertilization strategy is quite sensitive to the cost of manure, (w), and to the environmental tax levied on non-used nitrogen, (t).

The mixed application of manure and chemical fertilizer is the preferred fertilization strategy under relatively narrow ranges of w and t. Within these ranges, the substitution between the two fertilizers is considerable. Policy makers should be aware of the fact that the substitution of chemical fertilizer by manure may yield significant environmental costs. *Ceteris paribus*, an increase in the tax rate or in the cost of manure implies a significant reduction in the amount of applied manure. Thus, the positive environmental contribution associated with that increase is offset by the potential loss to manure-producing farmers, who are obliged to get rid off their excess manure via land application (or otherwise to reduce the level of their livestock).

The comparison of fall and spring applications of manure shows that the former is preferred as long as actual yield reduction associated with spring application exceeds 0.65%. Given the type of soil and normal weather conditions in the Netherlands, in combination with current application technologies, the actual yield loss commonly exceeds 0.65%, which explains why the vast majority of Dutch arable farmers prefer the fall application. We also found that the higher the non-uniformity of the nitrogen content in manure and/or of manure-nitrogen available for crop uptake, the higher the disadvantage of manure relative to commercial fertilizer, implying a lower level of non-used nitrogen.

The study presented here represents only a first step in a comprehensive analysis of the market for manure and of alternative agri-environmental policies aimed at regulating nitrogen use. Clearly, expanding the analyzed economic unit from a single arable farmer to a multi-farm framework, and modeling the decision-making process of manure-producing farms would be a significant improvement. It will make it possible to investigate the market for excess manure and the impact of alternative regulation policies on the price at which it will be traded. Assuming an institutional setting under which the allocation of costs and benefits between manure producers and consumers is determined through bargaining via game-theoretic setup is another area that deserves further analysis. The analysis presented here could be used as a building block in such analyses. Beyond that, the analysis can be extended by taking explicit account of the side effects associated with manure application; like the contribution to organic matter in the soil, the phosphate and potassium content of manure, the weeds included in manure, and its unpleasant odor.

Notes

1. Stricter environmental regulations will work in two ways. Firstly, manure-producing farmers will need to conform to stricter standards with respect to mineral losses, which will increase their surpluses. Secondly, arable farmers who also have to meet stricter standards, will be less likely to accept manure that is subject to leaching.
2. Potential relevant positive side effects are the increased phosphate and potassium content and the contribution to organic matter in the soil. Negative side effects are, for example, that manure may contain weeds, and that it has an unpleasant odor.
3. The selected number of sub-plots should be large enough so that the distribution of the initial nitrogen stock over the (small) area of each sub-plot, $h = H/S$, is approximately uniform.
4. The analysis here assumes average or "normal" weather conditions under which the soil is not too wet and application of manure in spring is technically feasible. In cases where the probability that application in spring is technically prohibitive is significant, it may well be that the producer would like to apply manure in both the fall and spring, reflecting the trade-off between guaranteed application in the fall to uncertain application in spring. The issue of split nitrogen application and stochastic weather is investigated in Feinerman et al. (1990) and it is beyond the scope of this paper.
5. Our theoretical analysis is applied to ware potatoes grown in the northern part of the Netherlands. Given the weather conditions in this region, the assumption that all nitrogen not used by the crop is leached below the root zone is reasonable. Alternatively, we could assume in the theoretical analysis that only part of the unused nitrogen is leached below

the root zone (and contaminates water resources) whereas the remainder is carried over to the beginning of the next growing period, affecting the initial stock of $\tilde{N}_i$ in that period. However, this (more general) assumption will only affect the *values* of the parameters δ_i^k and β, and has no impact on the qualitative results of our analysis.

6. Obviously, in reality the producer uses other inputs as well; however she is assumed to use "best management practices" for non-nitrogen inputs, like labor, machinery, herbicides and other fertilizers. That is, these other inputs are assumed to be fixed, and we focus only on the application decisions of nitrogen.
7. In the original equilibrium for both chemical fertilizer (10b)' and manure (10a)', the marginal cost of an additional unit of applied input is equal to its marginal benefit. Since manure is a rather inferior substitute for fertilizer, it will be used only where w is low enough to compensate for the penalty that is related to the use of manure.

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