Nitrate Pollution and Efficiency Measurement in Intensive Farming Systems: A Parametric By-Production Technology Approach

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Abstract

This paper develops a novel empirical framework for estimating individual emission levels in a non-point source (NPS) pollution problem. For doing so we incorporate into the GME model suggested by Kaplan et al., (2003) a specific theoretical structure describing both crop production technology and nature's residual generating mechanism based on the multiple production relations model suggested by Murty et al, (2012) fitted into a parametric stochastic framework. Our model is applied to a nitrogen leaching problem in a sample of 257 small-scale greenhouse farms in Crete, Greece during the 1999-00 cropping period. Empirical results indicate a great dispersion of individual nitrate leaching levels which are associated with low and high profit margins. However, improvements in nitrate leaching and fertilizer application efficiency can decrease significantly individual leaching levels providing a more cost effective way to improve water quality in the area.

Keywords: nitrogen leaching, multiple production relations, Generalized Maximum Entropy, greenhouse farming, Crete
JEL Codes: C40, Q12, Q24, Q25.

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Introduction

Nitrate leaching and the associated water contamination have become a major concern in developed countries' agriculture, mainly due to the intensification of agricultural production and the associated excessive application of nitrogen fertilizers and organic wastes. On the other hand, although many agricultural systems in developing countries are still nitrogen deficient, recently rising nitrogen concentrations in water reservoirs have also been detected in some regions where agricultural production has intensified with increasing use of chemical and organic fertilizers. High concentrations of nitrogen in drinking water causes serious health threat to humans.[1] The most familiar problem is nitrate poisoning of infants less than one year of age (i.e., blue baby syndrome) who have more sensitive and underdeveloped gastrointestinal tracts converting nitrate into nitrite (Golden and Leifert 1999).[2] Nitrate intake in drinking water has also been implicated circumstantially in a greater incidence of stomach cancer and childhood diabetes (Gao et al., 2012).[3] In addition, eutrophication, the overenrichment of water by nitrogen and the resulting harmful algal blooms and hypoxia are also a major source of pollution of coastal waters, oceans and closed seas, lakes, rivers, and estuaries. Surveys by the International Lake Environment Committee Foundation showed that 54% of the lakes in Asia are eutrophic, along with 53% in Europe, 48% in North America, 41% in South America, and 28% in Africa. To protect human health and aquatic environments, world and national health organizations have established water standards, limiting nitrogen concentration to a maximum of 50 mg NO_3^- l^{-1} (World Health Organization, 1984).

Across EU nationally averaged groundwater nitrate concentrations are all below the *Nitrates and Drinking Water Directives* limit of 50 mg NO_3^- l^{-1} but in several occasions above recommended standards of 11.3 mg NO_3^- l^{-1}. National aggregation, however, masks considerable variation at the scale of individual groundwater monitoring stations, with approximately 13% of groundwater monitoring stations across Europe, in 2009, exceeding the 50 mg NO_3^- l^{-1} limit. Between 1992 and 2009 this figure has remained relatively stable, lying between 5% and 10%. However, more than 25% of groundwater reservoirs in several EU countries exhibit statistically significant rising trends (Eurostat, 2012). In a US study conducted in Wisconsin, nitrogen concentrations exceeding 10 mg NO_3^- l^{-1} (the threshold for drinking water set by the US Environmental Protection Agency) were found in 10% of 800,000 wells, and 17-26% of wells in the agricultural production areas exceeded the limit (Postle, 1999). On the other hand, Townsend *et al.*, (1996) found that high nitrate

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[1] High concentrations of nitrogen in drinking water are also toxic to livestock and can cause *methemoglobinemia* and abortions in cattle.

[2] As nitrite circulates in the body, it produces *methemoglobin* which prevents the release of oxygen into the bloodstream.

[3] Forman et al., (1985) reported additional consequences among people who consumed drinking water containing high levels of nitrates: enlargement of the thyroid gland, increased incidence of 15 types of cancer and two kinds of birth defects, and even hypertension.

concentrations (12-60 mg NO_3^- l^{-1}) in groundwater in the southwest of Kansas resulted from high application rates of nitrogen fertilizer to sugar beet fields. Thorburn *et al.*, (2003) investigated groundwater nitrogen concentrations in intensive agriculture areas of northeast Australia and found that 14-21% of the wells were contaminated by nitrate, and in about half of these the nitrate was derived from fertilizer application. A survey conducted by the Chinese Academy of Agricultural Science in the provinces of Beijing, Tianjin, Hebei, Shandong and Shanxi showed that about 45% of 600 groundwater samples exceeded the WHO and European limit for nitrate in drinking water of 50 mg NO_3^- l^{-1}, with the highest nitrate concentration reaching 113 mg NO_3^- l^{-1} (Zhang *et al.*, 2004).

Nitrate leaching is a typical non-source pollution (NPS) problem, as only the ambient concentration of nitrogen is observed, posing serious challenges in policy formation and regulation. The main reasons are informational asymmetries between the regulator and the individual farmers, along with the coexisting uncertainty related to farm technologies and natural conditions. In policy formulation, these informational asymmetries induce moral hazard and adverse selection problems. Under moral hazard, as monitoring and measurement of individual nitrate emissions is not possible, farmers can always increase their profits by choosing higher than the socially desirable nitrogen emissions levels. On the other hand, under adverse selection, individual farmers may have incentives not to reveal their specific characteristics or farming type to the regulator if this is profitable for them.[4] As the empirical evidence worldwide reveals, in such situations the standard environmental policy instruments cannot be used to internalize external damages or to obtain the Pareto optimal outcome. The inadequacy of the standard instruments of environmental policy to deal with NPS problems has resulted in increasing effort to develop policy schemes appropriate for such problems.[5] Recently the focus of applied research is on the possibility of measuring individual emissions by applying monitoring technologies as increased observability of individual emissions enables the use of standard policy instruments to regulate NPS pollution to some, or even to a full, extent.

Along this line, our aim in this paper is to approximate individual nitrate leaching levels in intensive farming activities using the approach suggested by Kaplan et al., (2003) and Farzin and Kaplan (2004). They develop a budget constrained NPS problem model allowing for information acquisition and learning combined with a sequential entropy filter to deal with the ill-posed NPS pollution data problems. Extending their approach, we impose into a generalized entropy filter a specific theoretical structure describing both crop production technology and nature's nitrogen residual generating mechanism. The theoretical model is based on the multiple production relations model developed by Murty et al., (2012) that identifies appropriately the features of by-production

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[4] For a more detailed discussion on these issues see Segerson (1988) and Shortle and Horan (2001).

[5] Xepapadeas (2011) provides a thorough review of all approaches developed so far to deal with NPS pollution problems.

of pollution in intended output production activities which is adapted for nitrate leaching occasions in intensive crop production. To our knowledge this is the first attempt to empirically apply a parametric by-production technology model in a NPS pollution problem. The model, which eventually allows for the presence of inefficiencies in both technologies, is applied to a sample of 257 randomly selected greenhouse farms in the Ierapetra Valley in Crete, Greece during the 1999-00 cropping season. If farmers are indeed inefficient, then policy measures aimed to improve individual know-how on both crop production and nature's nitrogen residual mechanism, may be proved cost-effective in reducing water contamination close to recommended standards.

The rest of the paper is structured as follows. Next section analyzes the nitrogen residual generation mechanism and how nitrates from fertilization contaminate underground water reservoirs. Third section develops a theoretically consistent model for nitrogen polluting farm technology followed by the econometric model used together with a description of the survey data and the empirical model adopted to approximate farm technology and natural conditions. The next section presents and discusses the estimation results and finally, the last section concludes the paper.

The Nitrogen Residual Generation Mechanism

The use of nitrogen fertilizers is one of the main contributors to the increased agricultural production all over the world in the past few decades. Nitrogen plays an important role in crop plants: it is involved in plant growth, leaf area-expansion and biomass-yield production. It can also improve root growth, increase the volume, area, diameter, total and main root length, dry mass and subsequently increase nutrient uptake and enhance nutrient balance and dry mass production. Accordingly, global nitrogen fertilizer consumption increased from nearly zero in the 1940's to about 80,310 Mg N y^{-1} in 1996 (FAO, 2010). In a global scale today, the use of chemical fertilizers is more than 100 million metric tons, and is projected to grow to approximately 171 million metric tons in 2050 (Wood et al., 2004). The role that fertilizer plays in agricultural production can be emphasized by the fact that, while in the first half of the 20th century, mineral fertilizer acted for less than 5% of total nitrogen input into soil for food production, today it supplies approximately 45%. The remaining supply of nitrogen comes from soil organic nitrogen, biological fixation and organic inputs.[6] However, the nitrogen applied or fixed is not all taken up by plants: a large proportion is incorporated into the soil organic matter, lost to the atmosphere, or leached into the ground or surface water (Blum et al., 2013). Smil (1999) analyzing the fate of nitrogen introduced in global agro-ecosystems, estimates that most of it is further distributed as reactive nitrogen to other systems: 50% as harvested crop,

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[6] Biological fixation is the process by which the *rhizobium*, a genus of Gram-negative soil bacteria, converts nitrogen (N_2) in the atmosphere to ammonia (NH_3). The organic inputs are generally a large quantity of organic wastes that is applied to agricultural land for disposal and nutrient recycling.

23% as leached into the aquifers, 6% as volatilized NH_4, and 6% as volatilized NO_x and N_2O. Only about 10% is converted to un-reactive nitrogen by denitrification.

Chemical fertilizers containing NO_3 (i.e., ammonium nitrate) are mainly responsible for increased nitrate leaching into groundwater reservoirs.[7] Several experimental studies conducted worldwide generally agree that nitrogen uptake by plants rarely exceed the 50% of nitrogen applied in plants during the cropping season (e.g., Khosla et al., 2002; Cambouris et al., 2005; Galloway, 2008). Leaching occurs mainly because the mineral nitrogen present in the soil in the form of nitrate NO_3^- is negatively charged. However, most soils in the temperate areas around the world are also negatively charged. Due to this mutual repulsion at molecular level, when precipitation and irrigation is high or when NO_3^- concentration rise too much, NO_3^- is not retained by soil and it is transported together with water in the underlying soil layers or, if the depth of the water table is not too high, to the shallow aquifer.[8] Hence, nitrate leaching occurs when two conditions are satisfied: first, there is a significant amount of NO_3^- in the soil profile and second, enough rainfall or irrigation water is applied to the plants moving nitrates beyond the root zone into the shallow aquifer. Nitrate is leached to groundwater mostly during low evapotranspiration periods, such as fall and winter, when precipitation or ground water recharge exceeds the water holding capacity and coincides with high residual soil NO_3^- levels at the end of the growing season.

The nutrient leaching problem is most severe in areas with sandy soils and heavy rains or intensive irrigation. A survey of 40 agriculutral ecosystems on three continents indicated that with application of less than 150kg N ha^{-1} leaching equaled about 10% of fertilizer nitrogen, while with additions of more than 150 kg N ha^{-1} about 20% of added nitrogen was lost (Hansen and Djurhuus, 1996). Losses of 15-25% of initial nitrogen were also measured with repeated applications of cattle feedlot manure (Chang and Entz, 1996). Higher leaching rates, on sandy soils, may remove over 60% of nitrogen applied. Sandy soils usually have a low retention of nutrients and 20-80% of applied nutrients or chemicals leach or runoff to ground and surface waters (Manevski et al., 2015). Clayey soils tend to have a higher water-holding capacity and retain NO_3^- available to plants and microbes for a longer time and therefore, they may reduce NO_3^- leaching (Tully et al., 2016).

The NO_3^- leaching losses are usually less from fine-textured soils than from coarse-textured soils, because of slower drainage and greater potential for denitrification. Fine-textured soils have usually less permeability (water needs more time to reach the water table) and more capacity to retain water (high water content favors denitrification). The depth of soil above groundwater level

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[7] As noted by Liu *et al.*, (2007), ammonium sulfate or urea exhibit slow conversion to NO_3^- especially in cool climates or seasons. However, ammonia volatilization loss is greater with urea or ammonium sulfate compared to that from ammonium nitrate, and so the fertilizer efficiency is generally lower. This implies that these kinds of chemical fertilizers are not favoured by individual farmers.

[8] Chemical inhibition of nitrifiation can improve nitrogen use efficiency and reduce NO_3^- leaching (Zerulla et al., 2001). Nitrification inhibitors (e.g., nitrapyrin) slow down the conversion of NH_3 to NO_3^- and should be used with NH_4-forms of fertilizer if application is made pre-plant.

or above gravels is also an important factor, with NO_3^- reaching the underground aquifer quicker in shallow soils than in deep soils.[9] Macro pores, e.g. earthworm channels, root channels, and large cracks, can have an impact on solute transport and NO_3^- leaching (Silva et al., 2000). When the soil is dry, for instance, nitrogen fertilizer applied on the soil surface can be washed through large soil cracks or channels by irrigation water or rainfall, by passing through the fine pores. While macro pores may only constitute a small fraction of the total porosity of a soil (e.g., 5%), they can have a significant impact on the transport of water, NO_3^- and other solutes (Russo et al., 2017).

A Model for Nitrogen Polluting Technology

As posed at the outset, our theoretical framework is based on the multiple production relations model developed by Murty et al., (2012).[10] We consider a crop production process that uses a vector of variable inputs $x^v \in \Re_+^m$ together with chemical fertilizers $x^q \in \Re_+$ and irrigation water $x^w \in \Re_+$, to produce a single crop denoted by $y \in \Re_+$.[11] Yet nitrogen application through chemical fertilization results in NO_3^- leaching (i.e., nitrous oxide) that contaminates water reservoirs denoted by $q \in \Re_+$.[12] Following the relevant literature, we assume that the extent of nitrate leaching into the groundwater aquifers depends on irrigation water application, the soil characteristics of the farm (e.g., soil texture and density) denoted by the vector $s \in \Re_+^k$, and farmers' ability to apply appropriately chemical fertilizers to the plants which is determined by farm's human capital denoted by $h \in \Re_+$.[13]

Under this general setup, the crop production technology and the nature's nitrogen residual generating mechanism can be represented by the following closed, non-empty sets:

$$T^y = \{(x^v, x^q, x^w, y, q, s, h) : \ (x^v, x^q, x^w) \text{ can produce } y \text{ for a given level of } h\} \tag{1a}$$

$$T^q = \{(x^v, x^q, x^w, y, q, s, h) : \ x^q \text{ can pollute by } q \text{ for a given level of } (x^w, s, h)\} \tag{1b}$$

Given that the contaminated with nitrogen, underground water used for irrigation purposes,

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[9] The vadose zone may be very shallow (<1m) or very deep (extending over hundreds of meters or more) depending on the depth to the water table. The thickness of the vadose zone has been demonstrated to be the most significant factor affecting the NO_3^- concentrations in groundwater (Juntakut et al., 2019).

[10] Murty et al., (2012) framework builds on the factorially determined multi-output model developed by Frisch (1965), as it was further elaborated by Førsund (2009; 2018), that captures the physical process of generation of residuals allowing for some inputs and outputs that exhibit technological non-rivalness/jointness.

[11] To keep the notation simple, we develop the model for a scalar output technology which is consistent with our empirical application focusing on a single crop. However, the extension to a multi-output case is largely notational.

[12] Nitrate runoff may also contaminate surface water like rivers, lakes etc. Since our empirical application is focused on aquifer contamination we do not account for those cases.

[13] Human capital is also affecting crop production.

does not have an effect on crop yield, crop technology set does not impose any constraint on q:[14]

$$\text{if } (x^v, x^q, x^w, y, q, s, h) \in T^y \text{ then } (x^v, x^q, x^w, y, \bar{q}, s, h) \in T^y \quad \forall \bar{q} \in \Re_+$$

Further, variable inputs (including chemical fertilizers and irrigation water) and crop output are strongly disposable in farm production:

$$\begin{aligned}
&\text{if } (x^v, x^q, x^w, y, q, s, h) \in T^y \wedge \bar{x}^v \geq x^v \text{ then } (\bar{x}^v, x^q, x^w, y, q, s, h) \in T^y \\
&\text{if } (x^v, x^q, x^w, y, q, s, h) \in T^y \wedge \bar{x}^q \geq x^q \text{ then } (x^v, \bar{x}^q, x^w, y, q, s, h) \in T^y \\
&\text{if } (x^v, x^q, x^w, y, q, s, h) \in T^y \wedge \bar{x}^w \geq x^w \text{ then } (x^v, x^q, \bar{x}^w, y, q, s, h) \in T^y \\
&\text{if } (x^v, x^q, x^w, y, q, s, h) \in T^y \wedge \bar{y} \leq y \text{ then } (x^v, x^q, x^w, \bar{y}, q, s, h) \in T^y
\end{aligned}$$

that is, inputs are not congesting crop output[15] and reduction in crop output is always possible if inputs are reduced (or remain constant).

In order to capture the fact that nitrate leaching is an output of crop production whose disposal is not free, the nitrogen residuals generating natural technology satisfies *costly disposability* of nitrate emissions (Murty, 2010):

$$\text{if } (x^v, x^q, x^w, y, q, s, h) \in T^q \wedge \bar{q} \geq q \wedge \bar{x}^q \leq x^q \text{ then } (x^v, \bar{x}^q, x^w, y, \bar{q}, s, h) \in T^q$$

The above monotonicity property allows the possibilities of inefficiencies in nitrate emissions into the aquifer (i.e., T^q is bounded from below).[16] Any given level of chemical fertilizers application may create a minimal level of nitrate leaching but it can always generate a greater amount of leached nitrogen if farmers are ignorant about the nature's residual generating mechanism.

Hence, overall farm technology may be described as the intersection of the two sub-technologies

$$T = T^y \cap T^q$$

reflecting both the transformation of inputs into crop output (as shown by the definition in (1a)) and the nitrogen pollution generating mechanism resulting from crop fertilization (as shown by the definition in (1b)). According to Murty et al., (2012), the unified crop technology violates free disposability with respect to chemical fertilizers application (i.e., pollution-generating input),

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[14] Water contaminated with nitrogen do not harm palnt growth. instead it may affect positively crop yields as long as fertilization is absent (Poinke and Urban, 1985).

[15] In other words if inputs are increased (or not reduced) then the crop farm technology set will not shrink.

[16] As noted by Murty et al., (2012) there may be also an upper bound of water contamination with nitrogen. This depends on chemical fertilizer on field. Nevertheless for the econometric estimation of farm technology and efficiency measurement only the lower bound is important.

satisfies free disposability with respect to crop output and variable inputs use, and it satisfies cost-disposability with respect to nitrogen water pollution. In effect, if crop production is inefficient, farmers can always decrease variable input use without changing fertilizer use that generates nitrogen pollution in the aquifer. On the other hand, if nitrogen pollution is inefficient, then farmers can decrease nitrate leaching without altering variable input use and crop output by improving their knowledge about nature's pollution generating mechanism.

Using a functional representations and assuming that farmers are technical inefficient in both crop production and nitrate leaching, then crop production technology and nature's nitrogen generation mechanism may be defined as

$$T^y = \{(x^v, x^q, x^w, y, q, s, h) : \; y \leq f(x^v, x^q, x^w, h)\, \theta^y\} \tag{2a}$$

$$T^q = \{(x^v, x^q, x^w, y, q, s, h) : \; q \geq g(x^q, x^w, s, h)\, \theta^q\} \tag{2b}$$

where $f(x^v, x^q, x^w, h) : \Re_+^{m+3} \to \Re_+$ is a continuous and, strictly increasing, twice differentiable concave production function representing maximal crop output obtained from variable input, chemical fertilizers and irrigation water use with farm's human capital at h. Similarly, $g(x^q, x^w, s, h) : \Re_+^{k+3} \to \Re_+$ is also a continuous and twice-differentiable *emissions* function providing minimum nitrate leaching levels attained from chemical fertilizer application and irrigation water use given soil characteristics and farm's human capital. It is non-decreasing and convex in fertilizer application, soil nitrate absorption characteristics (e.g., soil texture and density) and irrigation water application, and non-increasing and concave with respect to farmers' ability to apply properly chemical fertilizers. It also holds that $q = 0$ if $x^q = 0$, that is when chemical fertilizers are not applied on field nitrate leaching is zero regardless of the other factors affecting by-production.[17] Finally, θ^y whose range is restricted to lie in $\in (0, 1]$ represents the percentage of maximal output realized by farm households in the presence of technical inefficiency in crop production.

Similarly, $\dfrac{\theta^q - 1}{\theta^q} \in (0, 1]$ represents the percentage of excess nitrates leached into the aquifer due to inefficiency in fertilizers and irrigation water application through nature's residual generation mechanism.[18] Apart of wrong application of chemical fertilizers within farming activities, farmers who are unaware of the natural processes may further intensify water contamination through nitrate leaching. For instance, less frequent fertilization in dry soils at increased doses may increase leaching potential of nitrogen through extensive irrigation schemes. Similarly inappropriate irrigation technology for the soil conditions prevailing on farm, may enhance the leaching process through soil layers. Hence, apart of utilizing an appropriate input mix during farm production exploring fully

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[17] Nitrogen leaching may be non-zero in cases that farmers do not apply fertilizers at all due to the existing nitrogen stock in the soil. However, since our primary focus is on estimating individual leaching levels we do not take that into account.

[18] It holds that $\theta^q \geq 1$ as nitrate is leached in excess.

the potential of crop technology, farmers should be also aware of the natural processes that trigger nitrate leaching in their own fields. Different soil conditions require different fertilizer and irrigation water application or even irrigation technology. Failure of doing so may result to increased nitrate leaching into the water aquifer.

Still, wrong application fertilizers application still enhance water contamination with nitrogen. If farmers fail to utilize efficiently crop technology they are doing so in fertilizer application. Excess use of fertilizers result in increased levels of nitrogen leached into the aquifer. If $\theta^{yq} \in (0,1]$ defines efficiency in fertilizer application then it should holds:

$$g\left(x^q, x^w, s, h\right) \geq g\left(\theta^{yq} x^q, x^w, s, h\right)$$

Finally, the unified farm technology may be defined now

$$T = \left\{ \left(x^v, x^q, x^w, y, q, s, h\right) : \; g\left(x^q, x^w, s, h\right)\theta^q \leq \frac{y}{\theta^y} \; \wedge \; f\left(x^v, x^q, x^w, h\right)\theta^y \geq \frac{q}{\theta^q} \right\} \tag{3}$$

that is observed nitrate leaching points lie below the crop production frontier and observed crop production points lie above the minimum nitrate leaching frontier.[19] Using the implicit function theorem, Murty et al., (2012) proved that the relationship between crop output and nitrate leached into the aquifer is non-negative as chemical fertilizers affect positively both crop output and nitrate leaching. In other words, the marginal product of fertilizers is non-negative in crop production, while at the same time more fertilizers applied on field increase nitrate leaching for any given soil characteristics and irrigation water use.

Econometric Setup

Functional Representations

However, there is a serious obstacle in applying conventional instruments to approximate parametrically the unified farm technology in (3) since nitrate leaching is only detectable and measurable after it has entered the ecosystem. To overcome this problem we utilize the *Generalized Maximum Entropy* (GME) method of inference[20]. GME is is an information-theoretic approach and was initially devised for ill-posed problems of inference where the sample sizes are limited, since it is robust to the problem of multicollinearity, and eventually became a popular econometric tool (Golan et al., 1997). In summary, the GME principle refers to minimizing a generalisation of *Shannon's entropy*

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[19] As noted by Førsund (2018) scaling of y and q is necessary to avoid the intersection of the two sets to be empty. We resolve that in the econometric setup of the model.

[20] The usual scenario of its application is the estimation of unobserved quantities when the parametric function that have generated them is (assumed to be) known.

$I(\mathbf{p}) = \mathbf{p}\ln\mathbf{p}$ subject to a set of constraints, where $\mathbf{p}$ encodes some parameters to be estimated. GME has also been extended to other problems, such as estimation of parameters in regression models (Calcagni et al., 2019) and stochastic frontier models (Campbell et al., 2012). In those cases, GME is advantageous over maximum likelihood because it does not assume a distribution for the random disturbances, nor the estimated efficiencies (in the stochastic frontier models). Further, from a theoretical point of view GME was shown to have excellent properties. Golan and Perloff (2002) proved that GME, unlike Renyi-GME and Tsallis GME, satisfies all five axioms they considered crucial. Specifically, GME estimates satisfy completeness, transitivity and uniqueness, permutation invariance, scaling, as well as subset and system independence.

To make the model empirically operational, and to apply GME, we need to assume specific functional representations for crop production and nitrogen residual generating technology. Starting from farm production, we choose the following *transcendental logarithmic* (translog) specification to approximate crop production technology:

$$\begin{aligned}\ln y_i &= \beta_0 + \sum_m \beta_m^v \ln x_{mi}^v + \frac{1}{2}\sum_m \sum_l \beta_{ml}^{vv} \ln x_{mi}^v \ln x_{li}^v + \ln h_i \left(\beta^h + \frac{\beta^{hh}}{2} \ln h_i + \sum_m \beta_m^{hv} \ln x_{mi}^v \right) \\ &+ \ln x_i^q \left(\beta^q + \frac{\beta^{qq}}{2} \ln x_i^q + \sum_m \beta_m^{qv} \ln x_{mi}^v + \beta^{qw} \ln x_i^w + \beta^{qh} \ln h_i \right) \\ &+ \ln x_i^w \left(\beta^w + \frac{\beta^{ww}}{2} \ln x_i^w + \sum_m \beta_m^{wv} \ln x_{mi}^v + \beta^{wh} \ln h_i \right) + \varepsilon_i^y\end{aligned} \qquad (4)$$

where subscript $i = 1, \ldots, n$ indicates farms, β's are the associated parameters and, $\varepsilon_i^y = \epsilon_i^y - u_i^y$, is the composed error term in stochastic frontier terminology with ϵ_i^y denoting random disturbances, and u_i^y capturing technical inefficiency in crop production obtained from $\theta_i^y = \exp(-u_i^y)$.

Accordingly, following Knapp and Schwabe (2008), Wang and Baerenklau (2014) and an extensive soil science literature, we may define nitrate emission function as follows:

$$q_i = \frac{-\delta_i^q x_i^q + \delta_i^{qq} \left(x_i^q\right)^2}{1 + \exp\left(-\delta_i^w x_i^w\right)} \exp\left(\varepsilon_i^q\right) \qquad (5)$$

with

$$\delta_i = \alpha_0 + \sum_k \alpha_k^s s_{ki} + \alpha_h h h_i \quad \text{and} \quad \varepsilon_i^q = \epsilon_i^q + u_i^q \qquad (6)$$

where again subscript $i = 1, \ldots, n$ indicates farms, α's are the associated parameters, s_k is the k$^{\text{th}}$ soil nitrate absorption characteristic (e.g., soil texture and density), ϵ_i^q is the usual random term and u_i^q captures technical inefficiency in nitrate emission function obtained from $\theta_i^q = \exp(u_i^q)$.

Finally given (4) we can estimate input-specific efficiency in fertilizer application using the formula suggested by Reinhard et al., (1999) and Karagiannis et al., (2003):

$$\theta_i^{yq} = exp\left[\frac{\varepsilon_i^f + \sqrt{(\varepsilon_i^f)^2 - 2u_i^y\beta^{qq}}}{\beta^{qq}}\right] \tag{7}$$

where ε_i^f is the crop output elasticity of chemical fertilizers and β^{qq} the corresponding parameter from (4). Once θ_i^{yq} is computed, it can be plugged into the estimated nitrate leaching function in (5) to obtain nitrogen emissions under efficiency in fertilizer application.

The GME Estimator

Starting from the production frontier in (4), the GME principle dictates that the k-th regression coefficient of $\left(\beta_0, \beta_m^v, \beta_{ml}^{vv}, \beta^q, \ldots, \beta_m^{vh}\right)$, should be written in the form of a weighted combination of J plausible real values $\mathbf{z}^{\beta_k} = \left(z_1^{\beta_k}, z_2^{\beta_k}, \ldots, z_J^{\beta_k}\right)$ for β_k as[21]

$$\beta_k = \mathbf{z}^{\beta_k}\mathbf{p}_k^{\beta_k}$$

such that $\beta_k \in \left[z_1^{\beta_k}, z_J^{\beta_k}\right]$ and the J non negative weights $\mathbf{p}^{\beta_k} = \left(p_1^{\beta_k}, p_2^{\beta_k}, \ldots, p_J^{\beta_k}\right)'$ sum to unity, $\sum\limits_j p_j^{\beta_k} = 1$. Accordingly, the vector of random disturbances in (4) may be expressed as

$$\boldsymbol{\epsilon}^y = \mathbf{Z}^{\epsilon^y}\mathbf{p}^{\epsilon^y} = \begin{bmatrix} \mathbf{z}_1^{\epsilon^y} & 0 & \ldots & 0 \\ 0 & \mathbf{z}_2^{\epsilon^y} & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & \mathbf{z}_n^{\epsilon^y} \end{bmatrix} \begin{bmatrix} \mathbf{p}_1^{\epsilon^y} \\ \mathbf{p}_2^{\epsilon^y} \\ \vdots \\ \mathbf{p}_n^{\epsilon^y} \end{bmatrix} \tag{8}$$

where $\mathbf{z}_i^{\epsilon^y} = \left(z_{i1}^{\epsilon^y}, z_{i2}^{\epsilon^y}, \ldots, z_{ij}^{\epsilon^y}\right)$ refers to the support values of the i-th random disturbance, $\mathbf{p}_i^{\epsilon^y} = \left(p_{i1}^{\epsilon^y}, p_{i2}^{\epsilon^y}, \ldots, p_{iJ}^{\epsilon^y}\right)'$, and the matrix $\mathbf{Z}^{\epsilon^y}$ is of dimensions $n \times nJ$. Similarly, we will denote by $\mathbf{Z}^{u^y}$ the matrix of support values of the technical inefficiencies in crop production.

Following (8), we can express the regression coefficients of the nitrate emission function in a similar manner. We denote by $\mathbf{z}^{a_k^q}$ and $\mathbf{z}^{a_k^{qq}}$ the support values of the constant and slope coefficients of δ_i^q and δ_i^{qq} respectively, that appear in the numerator of (5). Similarly we denote by $\mathbf{z}^{a_k^w}$ the support values of the constant and slope coefficients of δ_i^w that appear in the denominator of (5), whereas the matrix of support values of the random disturbances and inefficiencies of the emission

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[21] The subscript k collects all superscripts and subscripts of Equation (4). It runs from 1 up to the total number of parameters that appear in (4). On the other hand J is the number of support values assumed for the regression coefficients.

function will be denoted by $\mathbf{Z}^{\epsilon^q}$ and $\mathbf{Z}^{u^q}$ respectively.

Let us now re-write the two constraints that form the unified farm technology (3) as

$$f_i(\cdot)\exp\left(-u_i^y\right) \geq g_i(\cdot) \quad \text{and} \quad f_i(\cdot) \geq g_i(\cdot)\exp\left(u_i^q\right) \quad \forall\ i = 1,\ldots,n \tag{9}$$

Since GME requires only equality constraints we introduce two non-negative valued slack variables to turn the inequalities above into equalities. Expressing both the production and emission functions in log-scale, the constraints in (9) become

$$\ln f_i(\cdot) - u_i^y - \ln g_i(\cdot) = s_i^1 \quad \text{and} \quad \ln f_i(\cdot) - \ln g_i(\cdot) - u_i^q = s_i^2 \quad \forall\ i = 1,\ldots,n \tag{10}$$

Again, slack variables can be expressed in a similar form to Equation (8) and their matrix of support values will be denoted by $\mathbf{Z}^{s^1}$ and $\mathbf{Z}^{s^2}$.

The production function in (4) is the first set of equations that must hold true for every $i = i,\ldots,n$. The second set of equations (actually one equation only) comes from the fact that the sum of the individual leaching, attributed to each farmer, Q^N has been recorded and hence $\sum\limits_i q_i = Q^N$. The last two sets of equality constraints are given by (10). Summing up the above information, the GME problem in our specification is to minimize *Shannon's* entropy $I(\mathbf{p})$ subject to four sets of equality constraints as follows.

$$\begin{aligned}
\min_{\mathbf{p}} I(\mathbf{p}) \quad = \quad & \min_{\mathbf{p}} \left\{ \sum_k^K \sum_j^J p_j^{\beta_k} \ln p_j^{\beta_k} + \sum_{i=1}^n \sum_j^J p_{ij}^{\epsilon^y} \ln p_{ij}^{\epsilon^y} + \sum_{i=1}^n \sum_j^J p_{ij}^{u^y} \ln p_{ij}^{u^y} \right. \\
& + \sum_l^L \sum_j^J p_j^{\alpha_k^q} \ln p_j^{\alpha_k^q} + \sum_l^L \sum_j^J p_j^{\alpha_k^{qq}} \ln p_j^{\alpha_k^{qq}} + \sum_j^J p_j^{\alpha_k^w} \ln p_j^{\alpha_k^w} \\
& \left. + \sum_{i=1}^n \sum_j^J p_{ij}^{\epsilon^q} \ln p_{ij}^{\epsilon^q} + \sum_{i=1}^n \sum_j^J p_{ij}^{u^q} \ln p_{ij}^{u^q} + \sum_{i=1}^n \sum_j^J p_{ij}^{s^1} \ln p_{ij}^{s^1} + \sum_{i=1}^n \sum_j^J p_{ij}^{s^2} \ln p_{ij}^{s^2} \right\}
\end{aligned}$$

subject to[22]

$$\ln y_i = \ln f_i(\cdot) + \epsilon_i^y - u_i^y \quad \forall\ i = 1,\ldots,n \tag{11a}$$

$$Q^N = \sum_i^n g_i(\cdot)\exp\left(\epsilon_i^q + u_i^q\right) \tag{11b}$$

$$s_i^1 = \ln f_i(\cdot) - \ln g_i(\cdot) - u_i^y \quad \forall\ i = 1,\ldots,n \tag{11c}$$

$$s_i^2 = \ln f_i(\cdot) - \ln g_i(\cdot) - u_i^q \quad \forall\ i = 1,\ldots,n \tag{11d}$$

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[22] We have omitted the summation to unity constraints of the probabilities as their Lagrangean multipliers vanish. However these constraints have been taken into consideration in the computations.

Introducing Lagrangean multipliers $\lambda^y = (\lambda_1^y, \ldots, \lambda_n^y)$, λ^q, $\lambda^1 = \left(\lambda_1^1, \ldots, \lambda_n^1\right)$ and $\lambda^2 = \left(\lambda_1^2, \ldots, \lambda_n^2\right)$, the optimization problem becomes

$$\begin{aligned}
\min_{\mathbf{p}} \quad I(\mathbf{p}, \lambda^y, \lambda^q, \lambda^1, \lambda^2) = \min_{\mathbf{p}} \Bigg\{ & \sum_k^K \sum_j^J p_j^{\beta_k} \ln p_j^{\beta_k} + \sum_{i=1}^n \sum_j^J p_{ij}^{\epsilon y} \ln p_{ij}^{\epsilon y} + \sum_{i=1}^n \sum_j^J p_{ij}^{u^y} \ln p_{ij}^{u^y} \\
& + \sum_l^L \sum_j^J p_j^{\alpha_k^q} \ln p_j^{\alpha_k^q} + \sum_l^L \sum_j^J p_j^{\alpha_k^{qq}} \ln p_j^{\alpha_k^{qq}} + \sum_j^J p_j^{\alpha_k^w} \ln p_j^{\alpha_k^w} \\
& + \sum_{i=1}^n \sum_j^J p_{ij}^{\epsilon_i^q} \ln p_{ij}^{\epsilon_i^q} + \sum_{i=1}^n \sum_j^J p_{ij}^{u^q} \ln p_{ij}^{u^q} + \sum_{i=1}^n \sum_j^J p_{ij}^{s^1} \ln p_{ij}^{s^1} + \sum_{i=1}^n \sum_j^J p_{ij}^{s^2} \ln p_{ij}^{s^2} \\
& + \sum_{i=1}^n \lambda_i^y \left(\ln y_i - \ln f_i(\cdot) - \epsilon_i^y + u_i^y\right) + \lambda^q \left(\sum_i^n g_i(\cdot) \exp\left(\epsilon_i^q + u_i^q\right) - Q^N \right) \\
& + \sum_{i=1}^n \lambda_i^1 \left(\ln f_i(\cdot) - \ln g_i(\cdot) - u_i^y - s_i^1\right) + \sum_{i=1}^n \lambda_i^2 \left(\ln f_i(\cdot) - \ln g_i(\cdot) - u_i^q - s_i^2\right) \Bigg\}
\end{aligned}$$

We will use the following notation to present the expressions for the probabilities in a more compact form. We denote by $\mathbf{X^g}$ and $\mathbf{X^f}$ the design matrices with the explanatory variables used in (5) and (4), respectively and by x_{ki}^g and x_{ki}^f the i-th element of the k-th column of the $\mathbf{X^g}$ and $\mathbf{X^f}$ matrices, respectively. Then the estimated probabilities of the regression coefficients, random disturbances and technical inefficiencies associated with the crop production function are given by:

$$\begin{aligned}
p_j^{\beta_k} &= \frac{\exp\left(\sum_{i=1} \left(\lambda_i^y - \lambda_i\right) z_j^{\beta_k} x_{ki}^f \right)}{\sum_{j=1} \exp\left(\sum_{i=1} \left(\lambda_i^y - \lambda_i\right) z_j^{\beta_k} x_{ki}^f \right)} \\
p_{ij}^{\epsilon^y} &= \frac{\exp\left(\lambda_i^y z_{ij}^{\epsilon^y}\right)}{\sum_{j=1} \exp\left(\lambda_i^y z_{ij}^{\epsilon^y}\right)} \quad \text{and} \quad p_{ij}^{u^y} = \frac{\exp\left(\left(-\lambda_i^y + \lambda_i^2\right) z_{ij}^{u^y}\right)}{\sum_{j=1} \exp\left(\left(-\lambda_i^y + \lambda_i^2\right) z_{ij}^{u^y}\right)}
\end{aligned}$$

Accordingly, the probabilities of the regression coefficients, random disturbances and of the inefficiencies associated with the emission function are given by:

$$p_j^{\alpha_k^q} = \frac{\exp\left(\lambda^q \sum_{i=1} z_j^{\alpha_k^q} x_i^q x_{ki}^g \exp\left(\varepsilon_i^q\right) \xi_i^{-1} \right)}{\sum_{j=1} \exp\left(\lambda^q \sum_{i=1} z_j^{\alpha_k^q} x_i^q x_{ki}^g \exp\left(\varepsilon_i^q\right) \xi_i^{-1} \right)}$$

$$
\begin{aligned}
p_j^{\alpha_k^{qq}} &= \frac{\exp\left(\lambda^q \sum\limits_{i=1} z_j^{\alpha_k^{qq}} \left(x_i^q\right)^2 x_{ki}^g \exp\left(\varepsilon_i^q\right) \xi_i^{-1}\right)}{\sum\limits_{j=1} \exp\left(\lambda^q \sum\limits_{i=1} z_j^{\alpha_k^{qq}} \left(x_i^q\right)^2 x_{ki}^g \exp\left(\varepsilon_i^q\right) \xi_i^{-1}\right)} \\
p_j^{\alpha_0^w} &= \frac{\exp\left(\lambda^q \sum\limits_{i=1} z_j^{\alpha_0^w} d_i^q \exp\left(d_{1i}^w\right) \xi_i^{-2}\right) + \exp\left(\sum\limits_{i=1} \lambda_i z_j^{\alpha_0^w} \exp\left(d_{2i}^w\right)\right)}{\sum\limits_{j=1} \left[\exp\left(\lambda^q \sum\limits_{i=1} z_j^{\alpha_0^w} d_i^q \exp\left(d_{1i}^w\right) \xi_i^{-2}\right) + \exp\left(\sum\limits_{i=1} \lambda_i z_j^{\alpha_0^w} \exp\left(d_{2i}^w\right)\right)\right]} \\
p_j^{\alpha_k^w} &= \frac{\exp\left(-\lambda^q \sum\limits_{i=1} z_j^{\alpha_k^w} d_i^q x_{ki}^g x_i^w \exp\left(d_{1i}^w\right) \xi_i^{-2}\right) + \exp\left(\sum\limits_{i=1} \lambda_i z_j^{\alpha_k^w} x_{ki}^g x_i^w \exp\left(d_{2i}^w\right)\right)}{\sum\limits_{j=1} \left[\exp\left(-\lambda^q \sum\limits_{i=1} z_j^{\alpha_k^w} d_i^q x_{ki}^g x_i^w \exp\left(d_{1i}^w\right) \xi_i^{-2}\right) + \exp\left(\sum\limits_{i=1} \lambda_i z_j^{\alpha_k^w} x_{ki}^g x_i^w \exp\left(d_{2i}^w\right)\right)\right]} \\
p_{ij}^{\epsilon^q} &= \frac{\exp\left(-\lambda^q z_{ij}^{\epsilon^q} g_i(\cdot) \exp\left(\varepsilon_i^q\right)\right)}{\sum\limits_{j=1} \exp\left(-\lambda^q z_{ij}^{\epsilon^q} g_i(\cdot) \exp\left(\varepsilon_i^q\right)\right)} \quad \text{and} \quad p_{ij}^{u^q} = \frac{\exp\left(-\lambda^q z_{ij}^{u^q} g_i(\cdot) \exp\left(\varepsilon_i^q\right) - \lambda_i^2 z_{ij}^{u^q}\right)}{\sum\limits_{j=1} \exp\left(-\lambda^q z_{ij}^{u^q} g_i(\cdot) \exp\left(\varepsilon_i^q\right) - \lambda_i^2 z_{ij}^{u^q}\right)}
\end{aligned}
$$

with $\lambda_i = \lambda_i^1 + \lambda_i^2$, $d_i^q = -\delta_i^q x_i^q + \delta_i^{qq} \left(x_i^q\right)^2$, $d_{1i}^w = d_{2i}^w + \varepsilon_i^q$, $d_{2i}^w = \delta_0^w - \delta_i^w x_i^w$, and $\xi_i = 1 + \exp\left(d_{2i}^w\right)$.

Finally, the probabilities associated with the unified farm technology constraints are expressed as:

$$
p_{ij}^{s^1} = \frac{\exp\left(\lambda_i^1 z_{ij}^{s^1}\right)}{\sum\limits_{j=1} \exp\left(\lambda_i^1 z_{ij}^{s^1}\right)} \quad \text{and} \quad p_{ij}^{s^2} = \frac{\exp\left(\lambda_i^2 z_{ij}^{s^2}\right)}{\sum\limits_{j=1} \exp\left(\lambda_i^2 z_{ij}^{s^2}\right)}
$$

We solve the problem with respect to the probabilities, which are a function of the Lagrangean multipliers, using an iterative scheme. We begin with some initial values in the Lagrangean multipliers, we then compute the associated probabilities and solve each set of equations (11a)-(11d) serially. We update the Lagrangean multipliers and the associated probabilities and then we solve those equations again. We repeat this process until convergence[23] and then using the probabilities we estimate all regression parameters. The support values of the parameters is a crucial point for successful implementation of the GME. In our econometric setup we used $J = 5$[24] for each regression coefficient, for the random disturbances, the inefficiencies and the slack variables. For the production function, our starting point was the stochastic frontier model, assuming a half normal distribution for the technical inefficiencies. We centred the support values for the β coefficients at

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[23] In our case convergence was achieved when the change between two successive vector of estimates of the production function was tiny.

[24] Golan et al., (1996) after several Monte Carlo simulation concluded that 5 support values are sufficient enough.

the stochastic frontier model estimates and we added a small perturbation from left and right. We examined the range of the random disturbances to construct the support values for the random disturbances, and used the estimated inefficiencies as initial values in our GME formulation. On the contrary, we decided upon the support values of the emission function parameters and of the slack variables based on trial-and-error as no prior information is available.

Survey and Empirical Data

In greenhouse-based intensive vegetable production, excessive nitrogen supply and consequent nitrate NO_3^- leaching loss commonly occur as reported in several regions worldwide (e.g., Castilla, 2002; Meisinger et al., 2008). Given that vegetable production in relatively simple plastic greenhouses is an essential and rapidly growing industry in southern Greece, the problem of nitrate leaching has become a major concern.[25] All data were obtained through a primary survey financed by the *Agricultural Department of the Region of Crete.* The stratified sample consists of 257 randomly selected multi-output farms located in the Ierapetra Valley during the 1999-2000 cropping season. Using *Agricultural Census* and data from local *Extension Agencies*, farms in the area were stratified according to their size and soil quality.[26] The survey was designed to examine empirically the effectiveness of irrigation water application in the Ierapetra Valley and elaborate on issues related with nitrate leaching from greenhouses. Water resources in this semi-arid area of the Mediterranean basin are limited and maintaining a sufficient level of good quality water reserves has been an important issue of public concern over the last decades. This concern has been further reinforced in the recent years by the continuous increase in the total acreage of greenhouses in the area. The total acreage of greenhouse vegetable crops in Ierapetra Valley alone was 1,550 hectares in 2011 which corresponds to the 25 per cent of the total acreage in Greece.

Surveyed farmers were asked to recall key variables related to their farming operation in the same year (i.e., production patterns, input use, gross revenues, irrigation water use and cost, structural and demographic characteristics). All information was collected using questionnaire-based field interviews. The interviews were conducted by the extension personnel of the *Regional Agricultural Directorate.* The cropping period in greenhouse cultivation starts at the end of August/beginning of September until the end of May with significant fluctuations in crop yield during the season. Personal interviews took place at the beginning of June right after the end of the cropping season in our sample. The water supply comes from the local public irrigation network using the water from a shallow aquifer in the valley. Approximately 90 per cent of greenhouse farms in the valley rely

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[25] In general, greenhouses in the Mediterranean Basin have plastic cladding, passive climate control, and low energy inputs.

[26] See below for details on soil data.

on this public irrigation network for their water supply. The remaining farms have their own water wells using though water from the reservoir. Local authorities monitor regularly the level of nitrates into the aquifer as the same water reserves are used for domestic consumption. During the year of the survey nitrogen levels in the aquifer exceeded the recommended EU limit as they were 14.37 mg NO_3^- l^{-1}, whereas in 2010 it has been further increased to 19.73 mg NO_3^- l^{-1} underlying the severity of water contamination in the area (see Table 1). The whole valley has been declared as a *Nitrate Vulnerable Zone* requiring crop management practices that reduce aquifer contamination. Since these values refer to total water contamination, we use stratification variables to obtain individual nitrate emission levels for farms in the sample. Since surveyed farms are representative in the area given their size and soil quality characteristics, this is a reasonable proxy used our GME framework.

For the empirical approximation of farm technology, we consider one output and four variable inputs together with irrigation water (summary statistics of these variables are presented in Table 1). Greenhouse farmers produce four different kinds of vegetables: tomatoes, peppers, cucumbers and aubergines.[27] Different crops (including quantities sold off the farm and quantities consumed by the farm household during the crop year) are aggregated into a single aggregate *Tornqvist* output index with the revenue shares of each crop defining the relevant weights. The cultivation methods used are not found to vary across crops while the water requirements of these four vegetables are quite similar. Therefore, the aggregation across crops is not expected to bias our estimations. On average, total crop production for sample participants is 17,052 Kgs varying significantly among farms. Farm labor is defined as the total working hours devoted to supervision and organizational activities as well as to field activities such as harvesting, planting, fertilization, spraying and irrigation water application. Farm labor includes farm owner, family members and hired workers with either permanent or seasonal occupation status.[28] On average, farmers devote 418 hours in their greenhouses in all farming activities.

Land input includes the value of the total acreage (rented or owned) under greenhouses measured in stremmas. Given the nature of greenhouse cultivation which is an intensive farming activity, greenhouse farms are small, with 17.3 stremmas on average. Chemical fertilizers include mostly ammonium nitrate and to a lesser extent urea or ammonium sulfate. The different categories of chemical fertilizers are aggregated into a single input index using again *Tornqvist* procedures with cost shares as weights. On average, farms in the sample applied 7,281 Kgs of chemical fertilizers in their greenhouses. Irrigation water is measured in m^3 using the individual water meters installed in each farm. During the whole cropping period, farmers in the sample used 230.5 m^3 of irrigation

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[27] According to the local *Agricultural Experimental Stations* in the Ierapetra Valley 46.5 per cent of greenhouses cultivate tomatoes, 30.2 per cent peppers, 14.2 per cent cucumbers and the remaining 9.1 per cent aubergines. In sample stratification we took into account this specific crop distribution in the area.

[28] Given the competitive local labor market conditions we assume that family and hired labor are perfect substitutes, implying that returns to farm and off-farm work are equal.

water. Finally, we used farmer's age reflecting on-farm experience as a proxy of human capital and individual perceptions of proper farm management practices. On the average, surveyed farms were 49.3 years old. To avoid problems associated with units of measurement, all variables were converted into indices, with the basis for normalization being their maximum value. This way, all values, including crop output, are within the $(0, 1]$ range.

Soil characteristics were proxied by extension personnel during the field personal interviews using also information from previous field experiments undertaken by the *Extension Services* in several locations throughout the Ierapetra Valley on the saturated hydraulic conductivity[29] of water in soil or the intrinsic permeability of the soil together with soil's dry bulk density[30] (van Bavel and Kirkham, 1949). The soil of the greenhouses is an artificial layered soil, consisting of a 30 cm layer of imported silty loam textured soil placed over the original sandy soil and a 10 cm layer of fine gravel (mostly 2-5 mm diameter) placed on the imported soil as a mulch. At the beginning of the cropping period at the end of August, and before adding the final gravel layer, mature sheep manure (60-70% dry matter, 2-5% nitrogen content and 0.7 Mg m^3 density) is mixed into the top layer of the imported soil following local practices (Olympios, 2002). Soil bulk density among greenhouse farms in the sample varies between 1.290 and 1.569 gr cm^{-3} with an average value of 1.417 gr cm^{-3}. The clay content of the soil is on the average 23% ranging from a minimum of just 8% to a maximum of 41% (see Table 1).

Empirical Results

The estimated parameters of the translog production frontier along with those of the nitrate leaching function appear in Table 2 together with their corresponding standard errors obtained using non-parametric bootstrapping. The fit of the crop technology specification is assessed in Figure 1, that visualizes the estimated against the observed crop production levels. The three ellipsoidal curves correspond to the 90, 95 and 99 per cent confidence levels produced assuming a bivariate normal distribution, and the blue cross denote the mean values. The relevant *Pearson* correlation equal 0.928 and hence overall, the model captures a high percentage of the variability of the observed data, yielding a very satisfactory fit. The first-order parameters of variable inputs, chemical fertilizers and irrigation water are statistically significant at least at the 5 per cent level with their magnitudes being bounded in the unity interval. The bordered *Hessian* matrix is found to be negative semi-definite at the point of approximation and for the 85 per cent of observations. Hence, concavity

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[29] The hydraulic conductivity of soil is a measure of the soil's ability to transmit water when submitted to a hydraulic gradient.

[30] Bulk density is the density of a volume of soil as it exists naturally, it includes air space, organic matter, and soil solids. The optimal and critical limits of soil bulk density are dependent on soil texture, particle size, management practices, and organic matter content. A bulk density of less than or equal to 1.3 gr cm^{-3} is good, between 1.3 and 1.55 gr cm^{-3} is fair, and greater than 1.8 gr cm^{-3} is considered extremely bad (Reichert et al., 2009).

of the production function is satisfied with respect to all variable inputs, fertilizer application and irrigation water, implying positive and diminishing marginal products among greenhouse farmers in the sample.

Concerning nitrate leaching function all the estimated parameters are statistically significant at least at the 5 per cent significance level, having the anticipated sign and magnitude. The bordered *Hessian* matrix is found to be positive semi-definite for the 90% of the observations implying that it is convex with respect to both chemical fertilizers and irrigation water application. Overall unified greenhouse technology appears on Figure 2, where the blue curve represents crop production technology and the red curve nature's nitrate residual generation mechanism with respect to chemical fertilizers application. As the parameter estimates of both models imply, the desired output (crop production) is concave and the by-product (leaching) is convex with the respect to the fertilizer application. What it is evident from the graph is that greenhouse farms are both production and emission inefficient with respect to both technologies. This is more evident in high higher chemical fertilizers application.

Based on the parameter estimates of the translog production frontier, output elasticities of variable inputs, chemical fertilizers and irrigation water are estimated and presented in Table 3. Chemical fertilizers together with labour input are found to have the greatest percentage impact on farm's crop production with their corresponding mean output elasticities being 0.3992 and 0.2127, respectively. In contrast, crop production output is found to be less responsive to changes in utilized agricultural area with a point estimate of 0.1377. Finally, the corresponding point estimate for irrigation water is 0.0274, which is an expected result for water demanding crops like vegetables. In total, returns-to-scale were found to be decreasing (0.7768 on the average), implying that farmers in the sample are operating beyond their optimal scale. In turn, this implies that the average farm size of 17.3 stremmas is bigger than the farm size that would maximize the ray average productivity. Conventional LR-test validates this finding as the hypothesis of constant returns-to-scale in crop technology is rejected at the 5 per cent significance level.

Estimated individual leaching ranges from a minimum of 0.0037 mg NO_3^- l^{-1} to a maximum of 0.8622 mg NO_3^- l^{-1} with an average value of 0.0767 mg NO_3^- l^{-1} (see Table 5). The frequency distribution of these values depicted in Figure 3 reveal a smooth pattern with the majority of farms exhibiting leaching levels up to 0.0400 mg NO_3^- l^{-1}. However, there is a group of farms with severe nitrate emission problems exhibiting values above 0.2000 mg NO_3^- l^{-1}. Specifically, a large portion of farmers 39% of sample participants) pollute by a relatively small degree, whereas the 9 per cent of surveyed farms are responsible for more than 0.2000 mg NO_3^- l^{-1} as depicted by the histogram in Figure 3. The majority of these greenhouse farms belong either to the first or to the fourth profit quartile pollute more the water reservoir (average nitrate leaching levels are above sample mean).

Small farms with lower profit margin are more keen to use excess chemical fertilizers and paying less attention to water contamination. This is also true for more profitable greenhouse farms who take the full advantage of the common water resource.

Nitrate leaching elasticities reported also in Table 3 show that chemical fertilizers are the foremost important factor (positively correlated with profit margins) especially in farms with low soil bulk density and less clay content. Our estimates are in line with the survey of Hansen and Djurhuus (1996) who found higher nitrate leaching rates associated with increased use of chemical fertilizers from large farms. Wrong irrigation schedules combined with excess fertilization and adverse soil conditions intensify further the water contamination problem. Nitrate leaching elasticity of irrigation water application is 0.0012 on the average, with an increasing trend over nitrate leaching quartiles. An important finding coming out from the parameter estimates of the nitrate leaching function is that farmer's experience (as proxied by farmers' age) has a significant effect in leaching mechanism. This implies that the human capital asset is an important factor but farmers' experience alone is not enough and they should further seek external knowledge if nitrate leaching should be lessened, i.e. agronomist advice with respect to the evolving soil characteristics.

Point estimates of both crop production and nitrate emission technical efficiencies are presented in Table 4 per estimated individual nitrate leaching quartile. Kernel densities and beeswarm boxplots of all types of inefficiencies are shown in Figure 4. First, crop production efficiency was found 72.03 per cent on average ranging from a minimum of 50.21 per cent to a maximum of 88.66 per cent. These values exhibit a clear increasing trend over individual nitrate leaching quartiles indicating that abatement efforts directed to small greenhouse farms should be accompanied with measures aimed to improve utilization of crop production in greenhouses. Concerning technical efficiency in nitrate leaching, average value is 69.05 per cent, lower than the corresponding value in crop production. Greenhouse farms are doing less efficient job in realizing nature's nitrate residual generation mechanism. However, the relevant range of these point estimates is considerably lower ranging from a minimum of 69.05 per cent to a maximum of 76.63 per cent.

This is also evident from Figure 4 as the distribution of nitrate leaching technical efficiency scores is very concentrated around the mean, whereas that of crop technical efficiency is more spread but displays a shift to higher average values. Finally, using relation (7) we estimated input specific technical efficiency in fertilizer application as the main determinant of nitrate leaching on field. If fertilizer application is associated with higher leaching levels, then if farmers are not utilizing this specific input efficiently will enhance water contamination of the shallow aquifer in the Valley. On average chemical fertilizer technical efficiency was found to be 81.19 per cent following the same spread pattern of crop technical efficiency (with a higher mean value though). The minimum value is 59.55 per cent, whereas the maximum value 95.12 per cent. The mean value implies that on the average greenhouse farms in the sample can decrease chemical fertilizer use by 18.81 per cent still being able to produce the same level of aggregate vegetable output. The kernel density and the beeswarm boxplot of individual estimates shown in Figure 4 reveal a similar clustering with crop technical efficiency.

Using estimates of fertilizer and nitrate leaching inefficiency we calculate the associated reductions in individual leaching for greenhouse farms in the sample. Improving farmers know how on the appropriate use of chemical fertilizers and nature's nitrate residuals generating mechanism may be proved more effective in reducing water contamination in the aquifer. The summary of individual calculations are presented in Table 5 per farm profit quartile together with estimated individual nitrate leaching levels. If greenhouse farms in the sample become efficient in nitrate leaching through improvements in their information set about natural mechanism and information about the specific soil conditions in their field, nitrates leached into the aquifer will be reduced from 0.0767 mg NO_3^- l^{-1} to 0.0549 mg NO_3^- l^{-1}.

Reduction will be higher for farms belonging to the first and fourth profit quartile. Similarly, if farmers are informed about proper chemical fertilizer application becoming efficient with respect to fertilizer specific technical efficiency, individual leaching will be reduced to 0.0475 mg NO_3^- l^{-1}. This is more effective for large farms belonging to the fourth profit quartile. Overall, if surveyed farms become efficient with respect to both indices, nitrated leached into the underground aquifer will be reduced by 55.20 per cent or to 0.0340 mg NO_3^- l^{-1} on the average. This is clearly depicted in Figure 5 that shows reductions in nitrates leached for all farms in the sample according to chemical fertilizer use. It is evident that there are good practices in chemical fertilizer application among large farms although some of them exhibit severe inefficiency problems intensifying water contamination in the Valley.

Concluding Remarks

In this paper we develop an empirical framework for measuring individual leaching levels in a well established NPS pollution problem of nitrate leaching and underground water contamination. We adapt the GME approach suggested by Kaplan et al., (2003) which is incorporated into a specific theoretical structure describing both crop production technology and nature's nitrate residual mechanism based on the multiple production relations model developed by Murty et al., (2012). The model assumes a specific parametric structure of both technologies using an extensive soil science literature and the model suggested by Knapp and Schwabe (2008) and Wang and Baerenklau (2014). Using this complex modeling structure we are able to convert the NPS pollution problem into a PS one approximating individual nitrate leaching levels among 257 greenhouse farms from the Ierapetra Valley in Southern Crete, Greece.

Our empirical results provide a good proxy of the unified greenhouse technology accommodating appropriately both crop production and nature's nitrogen residual generating mechanism. Individual nitrate leaching levels vary from a minimum of 0.0037 mg NO_3^- l^{-1} to a maximum of 0.8622 mg NO_3^- l^{-1}. Farms in the sample, belonging to the lowest and highest profit quartiles, pollute more the underground water resources indicating the group of farmers that appropriate policy measures should be directed for. However, good farming practices are observed among large farms that can be used as a benchmark to lessen nitrate leaching levels in the area. Still the majority of the farms are facing severe inefficiency problems according to all technical efficiency indices. Mean values are 72.30, 69.05 and 81.19 per cent for crop production, nitrate leaching and fertilizer specific technical efficiency, respectively. Improvements in technical efficiency can bring significant benefits in water quality as nitrogen leached into the aquifer can be reduced by 55.20 per cent on the average.

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Tables and Figures

Table 1: Descriptive Statistics of Variables

Variable	Mean	Min	Max	St. Dev.
Vegetable Production (in Kgs)	17,052	4,381	46,349	8,606
Land (in stremmas[1])	17.3	5.7	45	8.1
Labour (in hrs)	418	141	1,076	195
Irrigation Water (in m^3)	230.5	46.2	871	121.6
Chemical Fertilizers (in Kgs)	7,281	2,033	32,105	5,270
Farmer's Age (in years)	49.3	25.0	85.0	13.5
Soil's Bulk Density (in gr cm^{-3})	1.417	1.290	1.569	0.069
Soil's Clay content (in %)	0.230	0.080	0.410	0.075
			2000	2010
Nitrogen Levels in the Aquifer (in mg NO_3^- l^{-1})			14.37	19.73
No of farms in the area			7,987	8,105

[1] one stremma equals 0.1 ha.

Figure 1: Observed and Estimated Crop Production Levels.

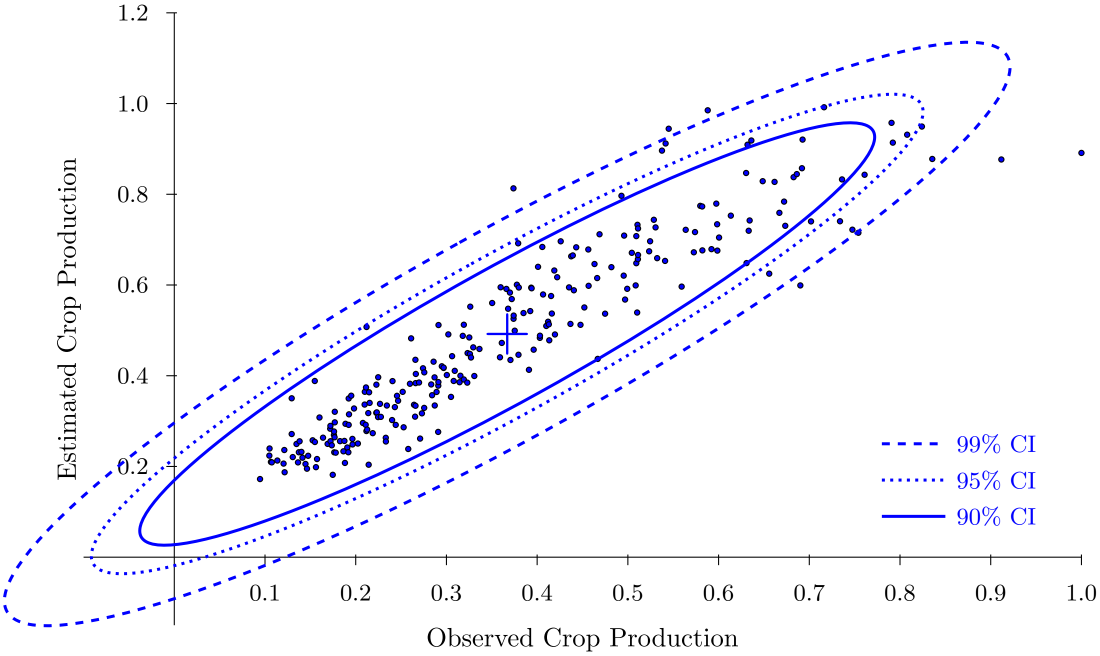

Figure 2: Production Frontier and Nitrate Leaching Function.

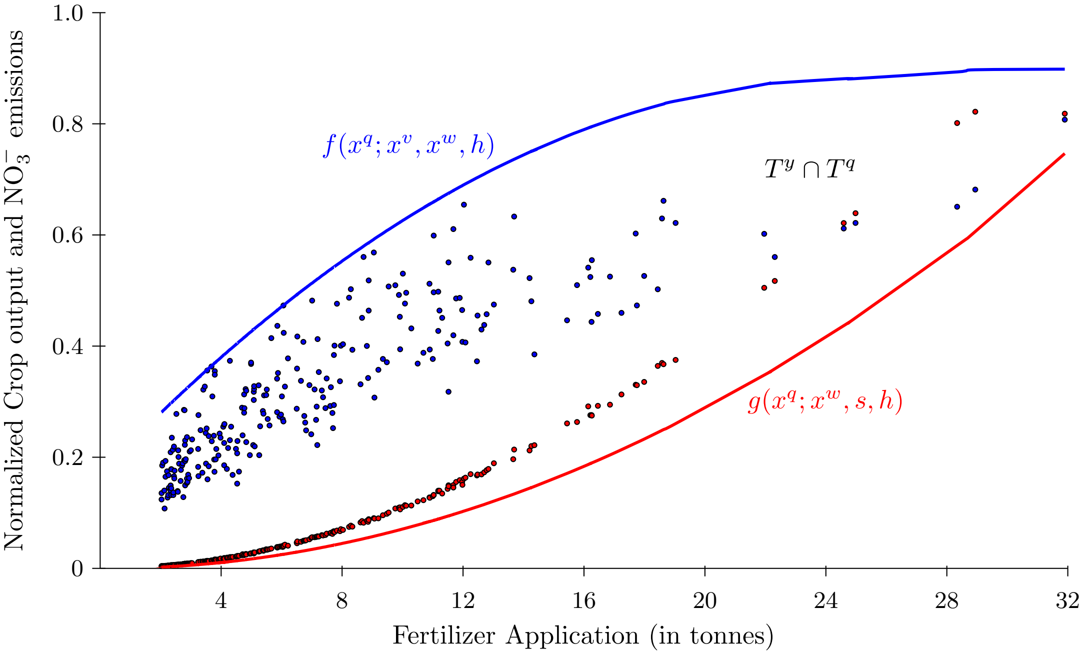

Figure 3: Frequency Distribution of Individual Nitrate Leaching Levels.

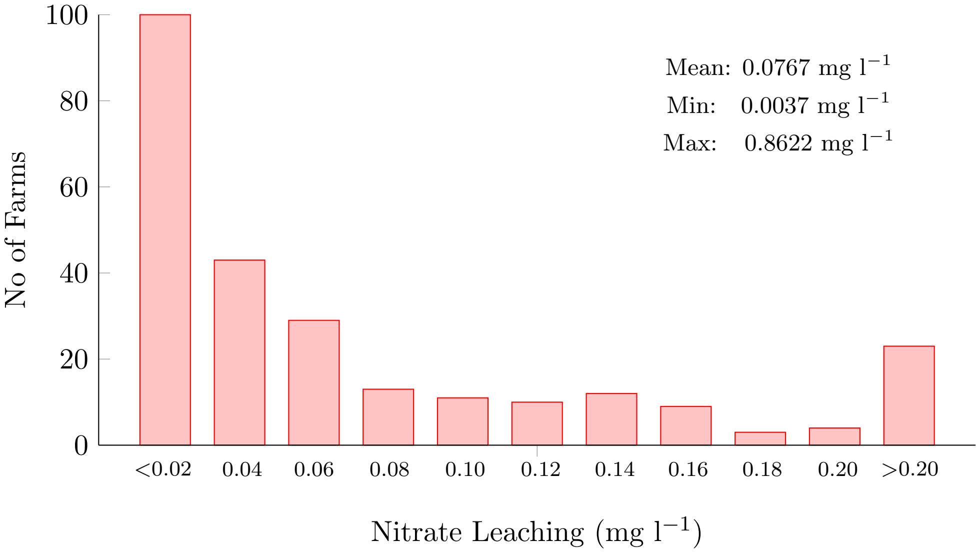

Table 2: Parameter Estimates of the Translog Production and Nitrate Leaching Frontiers.

Parameter	Estimate	Std Error	Parameter	Estimate	Std Error
Crop Production Frontier			Nitrate Leaching Frontier		
β_0	0.2856	0.0013	δ_0^q	0.0473	0.0005
β_A^v	0.4313	0.0018	δ_H^q	0.0428	0.0001
β_L^v	0.1787	0.0024	δ_B^q	0.0238	0.0013
β^q	0.2078	0.0011	δ_C^q	0.0050	0.0001
β^w	0.0235	0.0003	δ_0^{qq}	1.7267	0.0102
β^h	0.1759	0.0020	δ_H^{qq}	1.4994	0.0002
β_{AA}^{vv}	-0.6762	0.0030	δ_B^{qq}	0.3464	0.0009
β_{LL}^{vv}	-0.1180	0.0042	δ_C^{qq}	0.3488	0.0003
β^{qq}	-0.2339	0.0023	δ_0^w	0.7051	0.1233
β^{ww}	-0.2569	0.0019	δ_H^w	0.5000	0.0001
β^{hh}	-0.0193	0.0003	δ_B^w	0.0500	0.0001
β_{AL}^{vv}	-0.0141	0.0001	δ_C^w	0.0700	0.0001
β_A^{qv}	0.0344	0.0003			
β_L^{qv}	0.3298	0.0029			
β^{qw}	-0.0204	0.0015			
β^{qh}	-0.0905	0.0039			
β_A^{wv}	0.3715	0.0030			
β_L^{wv}	-0.2294	0.0028			
β^{wh}	0.1567	0.0038			
β_A^{hv}	0.2645	0.0050			
β_L^{hv}	-0.0750	0.0049			
Number of obs.	257			257	

where A stands for area, L for labour, B for soil bulk density and, C for soil's clay content. The corresponding standard errors are obtained using non-parametric bootstrap.

Figure 4: Densities and Beeswarm Boxplots of Production, Fertilizer and Nitrate Leaching Efficiencies.

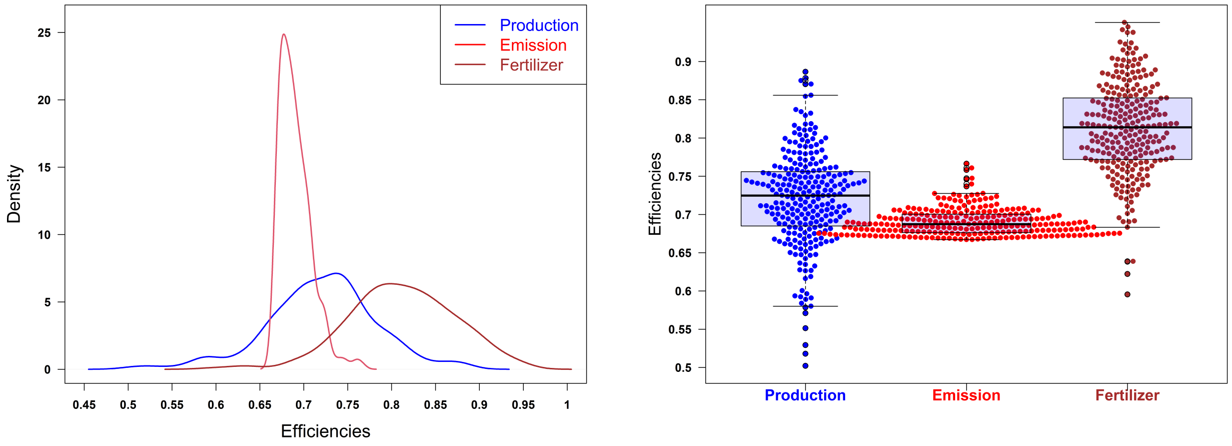

Table 3: Crop Output and Nitrate Leaching Elasticities, Returns-to-Scale and Farm Size per Nitrate Leaching Quartile.

	Crop Output Elasticities					Emission Elasticities		Farm Size
	Area	Labour	Fertilizers	Water	RTS	Fertilizers	Water	(in str)
1st Quartile	0.2790	0.0615	0.4965	0.0008	0.8378	0.0963	0.0001	10.6
2nd Quartile	0.0895	0.1983	0.4093	0.0714	0.7685	0.1840	0.0003	15.4
3rd Quartile	0.1147	0.2242	0.3755	0.0193	0.7337	0.3267	0.0008	20.2
4th Quartile	0.0653	0.3691	0.3141	0.0186	0.7671	0.6694	0.0035	23.3
Mean	0.1377	0.2127	0.3992	0.0274	0.7768	0.3182	0.0012	17.3
Std Error	0.0180	0.0221	0.0104	0.0123	0.0172	0.0270	0.0003	

Elasticities are computed at the mean values of all exogenous variables and distortion parameters. The standard errors were obtained via non-parametric bootstrap.

Table 4: Production, Fertilizers and Nitrate Leaching Technical Efficiencies per Nitrate Leaching Quartile.

	Technical Efficiency in:		
	Crop Production	Nitrate Leaching	Fertilizer Application
1st Quartile	0.6985	0.6721	0.8339
2nd Quartile	0.7204	0.6817	0.8176
3rd Quartile	0.7311	0.6930	0.8112
4th Quartile	0.7317	0.7155	0.7844
Mean	0.7203	0.6905	0.8119
Min	0.5021	0.6671	0.5955
Max	0.8866	0.7663	0.9512

Table 5: Indiviual Nitrate Leaching per Farm Profit Quartile.

	Individual Nitrate Leaching				Leaching
	Estimated	Leaching Efficient	Fertilizer Efficient	Leaching&Fertilizer Efficient	Reduction (in %)
1st Quartile	0.0942	0.0678	0.0591	0.0425	54.88
2nd Quartile	0.0639	0.0455	0.0388	0.0276	56.81
3rd Quartile	0.0663	0.0472	0.0399	0.0284	57.16
4rd Quartile	0.0820	0.0590	0.0521	0.0374	54.39
Mean	0.0767	0.0549	0.0475	0.0340	55.20
Min	0.0037	0.0024	0.0019	0.0013	38.91
Max	0.8622	0.6607	0.5298	0.4060	77.22

Figure 5: Estimated and Fully Efficient Individual Nitrate Leaching Levels.