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Environmental Performance and Shadow Value of Polluting on Swiss Dairy Farms

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Better understanding the trade-offs/synergies between desirable and environmentally harmful (undesirable) farm outputs is relevant for future targeting and tailoring of agri-environmental policy measures. We use a hyperbolic distance function to represent the production technology employed by Swiss dairy farms in mountainous regions, thus allowing for simultaneous expansion of desirable outputs (milk and non-milk) and contraction of undesirable output (nitrogen surplus). We calculate the farm-specific shadow price of the undesirable output. The obtained shadow prices (mean value with respect to milk output was equal to 28 Swiss francs per kg of nitrogen) provide quantitative information on farmers' costs of reducing nitrogen pollution.

Key words: dairy farms, environmental performance, hyperbolic distance function, shadow prices

Introduction

Agriculture, as a sector that is particularly interrelated with the environment, has considerable potential to generate environmentally detrimental by-products. Since the 1990s, there has been a growing public concern with the environmental issues associated with agriculture, including water pollution with nitrates and phosphorus, air pollution with ammonia and nitrogen oxides, impairment of human health or the environment from use of pesticides, and soil erosion. Relevant policies in most European countries encourage farmers to adopt more environmentally friendly agricultural practices. Despite the environmental improvement achieved in the last decades, existing regulations have not been sufficient to meet environmental targets (OECD, 2013).

Switzerland introduced environmental regulations in agriculture in the early 1990s. Since 1999, receiving direct payments[1] has been conditional on the fulfillment of the "proof of ecological performance" (PEP). In 2005, 97% of the utilized agricultural area of Switzerland was farmed under the PEP regulation (FOAG, 2007). One of the requirements of this regulation is that nitrogen and phosphorus balances must be equilibrated at the farm level. Nevertheless, Switzerland has missed its main agri-environmental target of reducing losses of environmentally harmful nitrogen compounds in agriculture by 23% by 2005 compared to the base year 1994 (FOAG, 2008). Nitrate levels in groundwater were decreasing until 2002, but they have started to rise again (FOAG, 2008).

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[1] Until 2013, the Swiss direct payment system distinguished between general and ecological direct payments. General direct payments remunerate farmers for ensuring food supply, maintaining the landscape, and contributing to the preservation of social structures in rural areas. These payments are linked to the farm area and to the number of animals. Ecological direct payments compensate farmers for particular environmental services, such as managing extensive meadows, managing permanently flowering meadows, or organic farming (FOAG, 2004). Ecological direct payments make up about 21%, 17%, and 11% of total direct payments received by farmers in the plain, hill, and mountainous regions, respectively (FOAG, 2012).

Ammonia emissions have not decreased since 2000, and, hence, the target gap remained unchanged (FOEN/FOAG, 2008). Although the Swiss target for phosphorus losses at the national level was met by 2005, there are still phosphorus surpluses at the regional level (FOAG, 2010).

Considering this evidence, the recently reformed Swiss agricultural policy (AP 14–17) emphasizes the need to improve farmers' environmental performance beyond general requirements. Goals such as improvement of nitrogen use efficiency, reduction of nitrogen surpluses, and alleviation of ammonia losses are important parts of the reformed Swiss agricultural policy (FOAG, 2012). A key point for this new policy is to implement targeted measures for reducing the environmental impact of agriculture. Targeting of these policy measures poses new challenges for micro-level (farm-level) analyses of environmental performance as well as for assessing farm-specific economic costs caused by compliance with the policy (e.g., quantifying the pollution abatement costs for farmers).

Considering environmentally detrimental by-products (negative externalities) in the assessment of farm performance has been attracting growing attention in the last decades. Two conflicting points of view exist in the literature regarding the way that conventional methods of productivity and efficiency analysis should be adjusted to incorporate those by-products into the representation of the production technology: (i) as an input or (ii) as an output. The studies that model by-products as an input (Reinhard, Lovell, and Thijssen, 1999; Fernández, Koop, and Steel, 2002; Atkinson and Dorfman, 2005) follow the idea that the relation between desirable outputs and detrimental by-products is similar to that between conventional inputs and desirable outputs: higher amounts of by-products are associated with higher production levels of desirable outputs. The studies that include by-products as undesirable outputs apply either the Shephard distance function (Shaik, Helmers, and Langemeier, 2002; Van Ha, Kant, and Maclaren, 2008; Zaim, 2004; Zhou, Ang, and Poh, 2006, 2008; Ferjani, 2011; Tamini, Larue, and West, 2012) or the directional distance function (Färe et al., 2005; Färe, Grosskopf, and Weber, 2006; Färe, Grosskopf, and Pasurkajr, 2007; Picazo-Tadeo and Prior, 2009; Vardanyan and Noh, 2006; Skevas, Lansink, and Stefanou, 2012).[2] While the Shephard distance function treats all outputs/inputs symmetrically (the measure is based on maximal possible proportional expansion of all outputs or contraction of all inputs), the directional distance function allows for a particular direction of expansion/contraction for each output/input. Similar to the directional distance function, the hyperbolic distance function can describe technology that seeks to contract undesirable output and expand desirable outputs at the same time.[3]

Against this background, this study assesses the performance of Swiss dairy farms considering an undesirable output (nitrogen surplus) and estimates farm-specific abatement costs of nitrogen pollution. In particular, the study seeks to answer the following research questions: (i) How efficient are Swiss dairy farms when an environmentally detrimental by-product (nitrogen pollution) is integrated into the representation of the production technology?; and (ii) What are the shadow prices of pollution reduction (costs of reducing nitrogen pollution in terms of forgone desirable output) for Swiss dairy farms?

We represent the production technology of Swiss farms using a hyperbolic distance function, which allows for simultaneous expansion of desirable outputs and contraction of undesirable outputs. Allowing for asymmetric treatment of different types of outputs, the hyperbolic distance function provides a useful framework for modeling by-products (undesirable outputs) and measuring farm-level environmental performance. Our choice of the hyperbolic representation is also motivated by the fact that—in contrast to the directional distance function—the hyperbolic distance function can assume a flexible translog functional form, which is the most widely used specification in the

[2] The concept of the directional distance function was introduced by Chambers, Chung, and Färe (1996) and was further elaborated by Chung, Färe, and Grosskopf (1997), Chambers, Chung, and Färe (1998), Färe and Grosskopf (2000), and Färe et al. (2005).

[3] Färe, Grosskopf, and Lovell (1985) introduced the hyperbolic distance function, which measures producers' efficiency in terms of the ability to expand outputs and contract inputs at the same time. Later, Färe et al. (1989) used the hyperbolic distance function to model undesirable outputs and measure producers' environmental performance.

empirical literature. In addition, as a robustness check regarding the assumptions imposed by the hyperbolic distance function, we also employ an enhanced hyperbolic distance function (Cuesta, Lovell, and Zofío, 2009), which allows for simultaneous adjustment of inputs, desirable outputs, and undesirable outputs.

Several studies apply a hyperbolic efficiency measure. For example, Soboh, Oude Lansink, and Van Dijk (2012) measured the efficiency of dairy processing firms using the hyperbolic distance function in the framework of data envelopment analysis (DEA). However, only a few studies have employed hyperbolic distance functions to measure environmental performance (Färe et al., 1989; Cuesta, Lovell, and Zofío, 2009). To our knowledge, only Suta, Bailey, and Davidova (2010) used a parametric hyperbolic distance function for measuring environmental performance in the farming context.

The contribution of this paper is threefold. First, this paper presents an overall measure of performance of Swiss dairy farms that includes an environmentally detrimental by-product in the representation of the production technology. Second, the efficiency measures used in this analysis are less restrictive than those applying the usual output or input distance functions (which hold either inputs or outputs fixed). Third, we estimate and analyze farm-specific shadow prices for undesirable output (nitrogen pollution), providing valuable information on farms' costs of pollution reduction in terms of forgone desirable outputs.

Theoretical Concepts

Hyperbolic and Enhanced Hyperbolic Distance Functions

Shephard input and output distance functions provide a convenient way to represent a multiple-input multiple-output production technology. The Shephard input distance function $D_I(\boldsymbol{x},\boldsymbol{y})$ gives the maximum amount by which the input vector ($\boldsymbol{x}$) can be radially contracted while still being capable of producing a given output vector ($\boldsymbol{y}$). The Shephard output distance function $D_O(\boldsymbol{x},\boldsymbol{y})$ gives the maximum linear expansion of an output vector for a given input vector.

Shephard distance functions have been used intensively for measuring the technical efficiency of decision-making units. The input-oriented technical efficiency is defined as $TE_I = 1/D_I(\boldsymbol{x},\boldsymbol{y})$ and the output-oriented technical efficiency as $TE_O = D_O(\boldsymbol{x},\boldsymbol{y})$. Both of these measures assume values on the unit interval. The input- and output-oriented measures of technical efficiency coincide in the case of a technology with constant returns to scale (CRS). However, when the production technology exhibits variable returns to scale (VRS), results on efficiency may differ considerably between the input and output orientations.

Färe, Grosskopf, and Lovell (1985) proposed a hyperbolic distance function, which measures technical efficiency along a hyperbolic path from the firm's current location inside the production possibilities set toward the production frontier, as an alternative to the Shephard distance function. Hyperbolic efficiency (HE) is defined as producers' ability to expand outputs and contract inputs at the same time. Therefore, this measure is less restrictive since it simultaneously takes into account the adjustability of both inputs and outputs. Furthermore, in contrast to input- and output-oriented measures, the hyperbolic measure of efficiency avoids results that might depend on the slope of the production function (Wilson, 2012).

Considering both desirable and undesirable outputs, the technology of a farm can be described using a hyperbolic distance function (D_H), which gives the maximum linear expansion of a desirable output vector ($\boldsymbol{y}$) and contraction of an undesirable output vector ($\boldsymbol{b}$) for a given input vector ($\boldsymbol{x}$). It is formally defined as (Färe et al., 1989; Cuesta, Lovell, and Zofío, 2009)

$$D_H(\boldsymbol{x},\boldsymbol{y},\boldsymbol{b}) = \min\left\{\theta : \left(\boldsymbol{x}, \frac{\boldsymbol{y}}{\theta}, \boldsymbol{b}\theta\right) \in T\right\}. \tag{1}$$

Therefore, in the hyperbolic specification, desirable and undesirable outputs change by the same proportions but in opposite directions.

Similarly, an enhanced hyperbolic distance function (D_{ENH}) seeks to expand desirable outputs and contract both inputs and undesirable outputs. It is defined as (Cuesta, Lovell, and Zofío, 2009)

$$(2) \qquad D_{ENH}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{b}) = \min\left\{\theta : \left(\boldsymbol{x}\theta, \frac{\boldsymbol{y}}{\theta}, \boldsymbol{b}\theta\right) \in T\right\}.$$

Both measures of efficiency capture the technical relations between inputs and desirable and undesirable outputs. In this paper we use the term "hyperbolic efficiency" to represent technical efficiency in the context of the hyperbolic distance function. Farms are said to be fully efficient if $D_H = 1$. Further, we use the term "enhanced hyperbolic efficiency" to represent technical efficiency in the context of the enhanced hyperbolic distance function. Farms for which $D_{ENH} = 1$ are fully efficient. If the value of the distance functions is less than 1 ($D_H < 1$ or $D_{ENH} < 1$), then the farm is inefficient.

Initially, the concept of the hyperbolic distance function was developed using mathematical programing methods (i.e., in the non-parametric framework of data envelopment analysis (DEA)). Recent studies have also used stochastic frontier analysis (SFA) to estimate parametric hyperbolic distance functions (Cuesta and Zofío, 2005; Cuesta, Lovell, and Zofío, 2009).

Parametric Estimation of Hyperbolic Distance Functions

With available data on inputs and desirable and undesirable outputs for farm *i*, its hyperbolic efficiency (HE) is defined as

$$(3) \qquad HE_i = D_H(\boldsymbol{x}_i, \boldsymbol{y}_i, b).$$

The hyperbolic distance function with desirable and undesirable outputs (equation 2) is almost homogeneous of degrees 0, 1, −1, 1 (Cuesta, Lovell, and Zofío, 2009). This property can be expressed as follows:

$$(4) \qquad D_H\left(\boldsymbol{x}, \lambda\boldsymbol{y}, \frac{\boldsymbol{b}}{\lambda}\right) = \lambda D_H(\boldsymbol{x},\boldsymbol{y},\boldsymbol{b}) \quad \forall \quad \lambda > 0.$$

The almost homogeneity property (equation 4) can then be used to derive an estimable form of the hyperbolic distance function: since expression (4) is true for any $\lambda > 0$, setting $\lambda = 1/y_M$ (where y_M is, without loss of generality, the Mth output) leads to

$$(5) \qquad D_H\left(\boldsymbol{x}_i, \frac{\boldsymbol{y}_i}{y_M}, \boldsymbol{b}_i \cdot y_M\right) = \frac{1}{y_M} D_H(\boldsymbol{x}_i, \boldsymbol{y}_i, \boldsymbol{b}_i).$$

After taking logarithms of both sides we get

$$(6) \qquad \ln D_H(\boldsymbol{x}_i, \boldsymbol{y}_i, \boldsymbol{b}_i) = \ln D_H\left(\boldsymbol{x}_i, \frac{\boldsymbol{y}_i}{y_M}, \boldsymbol{b}_i \cdot y_M\right) + \ln y_M.$$

We can substitute expression (6) back into equation (3) to get an estimable form of the hyperbolic distance function, after appending an error term, v_i, which captures statistical noise:

$$(7) \qquad -\ln y_M = \ln D_H\left(\boldsymbol{x}_i, \frac{\boldsymbol{y}_i}{y_M}, \boldsymbol{b}_i \cdot y_M\right) - \ln HE_i + v_i.$$

Similarly, the enhanced hyperbolic distance function (D_{ENH}) is almost homogeneous of degrees −1, 1, −1, 1:

$$(8) \qquad D_{ENH}\left(\frac{\boldsymbol{x}}{\lambda}, \lambda\boldsymbol{y}, \frac{\boldsymbol{b}}{\lambda}\right) = \lambda D_H(\boldsymbol{x},\boldsymbol{y},\boldsymbol{b}) \quad \forall \quad \lambda > 0.$$

An estimable form of the enhanced hyperbolic distance function can be derived in the same way as described for the hyperbolic distance function in equations (3)–(7).

Shadow Prices

The duality between distance functions and cost, profit, or revenue functions allows retrieving the shadow prices associated with undesirable outputs, for which a well-defined market rarely exists. Below, we describe the derivation of shadow prices from a hyperbolic distance function, which is dual to the profitability (return to dollar) function (Färe, Grosskopf, and Zaim, 2002).[4]

Consider a vector of quantities of desirable outputs $\boldsymbol{y}$ with corresponding prices $\boldsymbol{p}$. Following Cuesta, Lovell, and Zofío (2009) but restricting attention to the case of a single undesirable output, the problem of maximizing the profitability function is

$$\max_{\boldsymbol{y},b} \frac{\sum_{m=1}^{M} p_m y_m}{q \cdot b} \quad \text{s.t.} \quad D_H(\boldsymbol{x},\boldsymbol{y},b) = 1, \tag{9}$$

where q is the (unknown) price of the undesirable output.

The first-order conditions for this problem are

$$\frac{p_m}{q \cdot b} = \lambda \frac{\partial D_H}{\partial y_m}, m = 1,\ 2,\ \ldots,\ M; \qquad -\frac{\sum_{m=1}^{M} p_m y_m}{q \cdot b^2} = \lambda \frac{\partial D_H}{\partial b}. \tag{10}$$

By taking the ratio of the last condition to any first-order condition in the first set we obtain:

$$\frac{\sum_{m=1}^{M} p_m y_m}{b} = -\frac{\frac{\partial D_H}{\partial b}}{\frac{\partial D_H}{\partial y_1}} p_m. \tag{11}$$

Because the locus of points for which the distance function is equal to unity represents the frontier of the production possibilities set, the ratio of partial derivatives on the right-hand side of equation (11) can be expressed as the slope of the relationship between y_m and b at the frontier. That is, by applying the implicit function theorem on the distance function we get

$$-\frac{\frac{\partial D_H}{\partial b}}{\frac{\partial D_H}{\partial y_m}} p_m = p_m \left.\frac{dy_m}{db}\right|_{D_H=1}, \tag{12}$$

which can be interpreted as the shadow price of b in terms of y_m. This shadow price shows how much revenue from production of y_m will have to be reduced if b is reduced by one unit when the point $(\boldsymbol{x},\boldsymbol{y},b)$ is on the production frontier. These equations suggest that if producers are both technically efficient ($D_H = 1$) and allocatively efficient (all first-order conditions are satisfied), then the shadow price of a unit of b should be the same irrespective of which first-order conditions have been used to calculate it.

When the point $(\boldsymbol{x},\boldsymbol{y},b)$ is not on the frontier, (i.e., when the farm is technically inefficient) the shadow price of b should, theoretically, be zero because a reduction in b could technically

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[4] Georgescu-Roegen's "return to the dollar" measure is defined as $\frac{py}{wx}$, where p and w denote output and input prices, respectively. When py is interpreted as observed revenue and wx is observed cost, it is not necessary to know output and input prices to estimate the return to the dollar (Färe, Grosskopf, and Zaim, 2002, p. 673). The "return to the dollar" provides a profitability interpretation of the Malmquist productivity index (Färe, Grosskopf, and Zaim, 2002, p. 672). Färe, Grosskopf, and Zaim (2002) show that "return to the dollar" (profitability function) is dual to the hyperbolic technical efficiency measure. In our study, we consider both desirable and undesirable outputs and thus we work with the following profitability function: $\pi(x,p,q) = \max_{y,b}\{py/qb : D_h(x,y,b) \leq 1\}$, where p and q denote prices of desirable and undesirable outputs, respectively.

occur without a reduction in y_m. However, when restrictions with respect to undesirable outputs are imposed on an inefficient farm, it would be unreasonable to assume that these will be addressed entirely by the farm becoming more efficient. It appears much more likely that the trade-off between y_m and b will persist even when the farm is located inside the feasible set. The implicit rate of substitution between desirable and undesirable outputs when holding the level of inefficiency constant may be different than the one that holds on the frontier, but the two should be similar in magnitude, especially for farms which are highly efficient.

Data

The dataset used in this this study consists of 507 dairy farms located in the mountainous region of Switzerland, observed in 2010. This is a cross-sectional sample from the Swiss Farm Accountancy Data Network (FADN). For the definition of a dairy farm we rely on the farm typology of the Swiss FADN (Mouron and Schmid, 2012). According to this typology, farm type 21 (dairy farm) is defined as a farm which has a share of cattle in total livestock units higher than 75%, a share of milk cows in cattle stock higher than 25%, and a share of arable land in total agricultural area not higher than 25%. Our sample consists of both conventional and organic farms. The share of conventional farms is 77%. 76% of the farms in the sample are full-time farms (i.e., farms with a share of off-farm income in total household income less than 50%).

We use nitrogen balance as a proxy for the environmental impact ("harm") generated by nitrogen use.[5] The OECD soil-surface approach (Parris, 1998; OECD, 2001) defines nitrogen balance as the difference between nitrogen input (inorganic fertilizer, livestock manure, biological nitrogen fixation, atmospheric deposition, and seeds and planting materials) and nitrogen contained in output (arable crops, vegetables, fruits, grass and fodder). Since farm-level data on nitrogen use are not directly available in Switzerland, nitrogen input and output elements for the soil-surface balancing approach are indirectly assessed on the basis of accountancy and/or structural variables from the Swiss FADN. This indirect-assessment approach is validated on the basis of a small subsample of farms (n=24) for which a nitrogen balance has been estimated according to both the direct (based on collected data for all required nitrogen input and output elements) and indirect approaches. A strong correlation (r>0.80) is found between estimates from these two approaches for all nitrogen input and output elements (Appendix A presents more details on the nitrogen balance approach used in this study).

Because of data limitation, we only employ cross-sectional data on mountainous dairy farms, for which nitrogen surpluses can be estimated based on only few assumptions (i.e., the applied nitrogen balancing is expected to be most exact for these farms). The data limitation is also a cause for some inconsistency regarding system boundaries between the economic and environmental assessment in this study. For the economic assessment, we consider the farm as a whole, including all relevant inputs and outputs. For the environmental assessment, we use soil-surface nitrogen balance, which considers the conversion of nitrogen (entering the soil) into harvestable crop nitrogen (leaving the soil). However, conversion of nitrogen into animal products is only partly factored into the nitrogen balancing. This data limitation should be borne in mind when interpreting results obtained in this study.

The analyzed dairy farms use, on average, 29 hectares of land and owned 25 livestock units. The average share of general and ecological direct payments in total farm output is 37%. The mean value

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[5] Schröder et al. (2003) distinguish between means- and goal-oriented indicators for assessing environmental impact at the farm level. Whereas goal-oriented indicators are directly related to the ultimate goal pursued (for example, eutrophication reduction), means-oriented indicators are only very weakly related to this goal, as they focus on production means (e.g., livestock density, nitrogen input via manure; Schröder et al., 2003). Nitrogen balance holds an intermediate position between these indicator types (Schröder et al., 2003). Owing to this characteristic, and because this indicator can be estimated on the basis of the data available for the present study, we use nitrogen surplus as a proxy for the environmental impact generated by nitrogen use on the farms.

of nitrogen surplus in the sample is 53 kg per hectare. The average nitrogen use efficiency (defined as the ratio of nitrogen output to nitrogen input) is equal to 71%. We provide descriptive statistics of the inputs and outputs, as well as other farm characteristics, in Appendix B (table A1).

Empirical Specification of the Models

Both hyperbolic and enhanced hyperbolic distance functions are specified in two desirable outputs, one undesirable output, and five inputs. Since outputs produced on Swiss farms are very heterogeneous (even on specialized dairy farms), we decide to separately model two different desirable outputs: (i) milk output and (ii) non-milk output, including direct payments, which compensate farmers for provision of public services. The empirical literature does not provide a consistent guiding rule on the way that direct payments should enter the production models. If direct payments are assumed to be fully decoupled from production, they can be modeled as an exogenous factor in the production function (e.g., Bezlepkina, Lansink, and Oskam, 2005; Zhu and Lansink, 2010). In contrast, McCloud and Kumbhakar (2007) suggested modeling subsidies endogenously, as "facilitating" inputs. Several papers (e.g., Ferjani, 2008; Jan, Lips, and Dumondel, 2010, 2012) model direct payments as an output in the production technology. In the case of Switzerland, direct payments are not fully decoupled from production and considerably influence farmers' allocation of inputs. Most direct payments remunerate Swiss farmers for the provision of environmental services that require the use of additional inputs and/or the extensification of production. In our sample, direct payments account for 37% of total output, on average. Therefore, we include direct payments in the representation of the production technology as outputs (as part of non-milk output). As a robustness check, we also run models that treated direct payments as an additional input rather than as part of non-milk output; these results are presented in Appendix B. There are considerable differences between the two specifications, especially regarding shadow prices. However, the models that treated direct payments as an input produce many inconsistent signs in the distance function parameters.

The considered undesirable output is farm-level nitrogen surplus, which is measured in kg of nitrogen. The five inputs are land, labor, capital, livestock, and materials. Land is measured in hectares of farm area. Labor is measured in annual working units and includes both family and hired labor. Capital is measured in Swiss francs and consists of depreciation of buildings and machinery, interest on debt and on owned capital, and rent paid for buildings. Materials are measured in Swiss francs and consist of expenses for fertilizer, purchased feed, etc.

The translog specification of the hyperbolic distance function (D_H) with two desirable outputs (y_m), one undesirable output (b), and five inputs (x_k) yields the following expression (based on expression 7):

$$
\begin{aligned}
-\ln y_{1i} = \; & \alpha_0 + \sum_{k=1}^{5} \alpha_k \ln x_{ki} + \frac{1}{2}\sum_{k=1}^{5}\sum_{l=1}^{5} \alpha_{kl} \ln x_{ki} \ln x_{li} + \beta_2 \ln \frac{y_{2i}}{y_{1i}} + \frac{1}{2}\beta_{22}\left(\ln \frac{y_{2i}}{y_{1i}}\right)^2 \\
& + \gamma_o \ln(b_i y_{1i}) + \frac{1}{2}\gamma_{oo}(\ln(b_i y_{1i}))^2 + \sum_{k=1}^{5} \delta_{k2} \ln x_{ki} \ln \frac{y_{2i}}{y_{1i}} \\
& + \sum_{k=1}^{5} \omega_{ko} \ln x_{ki} \ln(b_i y_{1i}) + \xi_{2o} \ln \frac{y_{2i}}{y_{1i}} \ln(b_i y_{1i}) + u_i + v_i,
\end{aligned} \tag{13}
$$

where k and l index different inputs and i is farm index.

The translog enhanced hyperbolic distance function (D_{ENH}) yields the following expression:

$$
\begin{aligned}
-\ln y_{1i} &= \alpha_0 + \sum_{k=1}^{5} \alpha_k \ln(x_{ki}y_{1i}) + \frac{1}{2}\sum_{k=1}^{5}\sum_{l=1}^{5} \alpha_{kl} \ln(x_{ki}y_{1i}) \ln(x_{li}y_{1i}) + \beta_2 \ln \frac{y_{2i}}{y_{1i}} \\
&\quad + \frac{1}{2}\beta_{22}\left(\ln \frac{y_{2i}}{y_{1i}}\right)^2 + \gamma_o \ln(b_i y_{1i}) + \frac{1}{2}\gamma_{oo}(\ln(b_i y_{1i}))^2 + \sum_{k=1}^{5} \delta_{k2} \ln(x_{ki}y_{1i}) \ln \frac{y_{2i}}{y_{1i}} \\
&\quad + \sum_{k=1}^{5} \omega_{ko} \ln(x_{ki}y_{1i}) \ln(b_i y_{1i}) + \xi_{2o} \ln \frac{y_{2i}}{y_{1i}} \ln(b_i y_{1i}) + u_i + v_i.
\end{aligned} \tag{14}
$$

We use stochastic frontier analysis (SFA) to estimate both hyperbolic functions. The error terms in expressions (13) and (14) consist of two components: a random symmetric error term (v_i) and a non-negative inefficiency term (u_i). We use the half-normal model, which assumes a normal distribution for v_i and a half-normal distribution for u_i. Moreover, we allow both u_i and v_i to be heteroskedastic (Kumbhakar and Lovell, 2000):

$$\sigma^2_{u,i} = e^{\boldsymbol{z}_i' \boldsymbol{\rho}}; \tag{15}$$

$$\sigma^2_{v,i} = e^{\boldsymbol{w}_i' \boldsymbol{\tau}}, \tag{16}$$

where $\boldsymbol{z}_i$ and $\boldsymbol{w}_i$ are vectors of variables that affect the variance of the two error terms and $\boldsymbol{\rho}$ and $\boldsymbol{\tau}$ are vectors of parameters to be estimated. Because the distribution of u_i is not symmetric around zero, a larger value of $\sigma^2_{u,i}$ implies lower efficiency. That is, a positive ρ would indicate that the associated variable in $\boldsymbol{z}$ has a negative effect on efficiency. On the other hand, variables in $\boldsymbol{w}$ do not affect efficiency, but they do have an impact on the variance of the noise component of the error term. Thus, a positive τ would indicate that the associated variable has a tendency to reduce production risk.

The estimated total error term $\hat{\varepsilon}_i = v_i + u_i$ contains some information on u_i, which can be extracted by using the conditional distribution of u_i given ε_i (Kumbhakar and Lovell, 2000). Farm-specific hyperbolic efficiency scores are calculated using the point estimator proposed by Battese and Coelli (1988):

$$HE_i = E(e^{-u_i} | \varepsilon_i), \tag{17}$$

where E is the mathematical expectation operator.

Following the empirical literature, we use several farm characteristics to explain the variance of technical inefficiency across farms. We hypothesize a negative influence of part-time farming (z_1) on farm technical efficiency because off-farm income may decrease farmers' motivation to manage their farms efficiently. We hypothesize a negative effect of the share of agricultural output of the total farm output (z_2) on technical efficiency because more diversified farmers may utilize their time better by allocating it to different farm activities. We expect organic farming (z_3) to have a positive effect on farm technical efficiency because organic farms are more labor-intensive than conventional farms and, therefore, may have less time to be detracted from their main activity: agricultural production. We hypothesize a positive influence of higher mountain zone (z_4) on technical efficiency because farmers in higher zones are required to have lower livestock per hectare and therefore may be more motivated to use their resources efficiently. We expect higher efficiency of farmers who have higher milk yields (z_5), which may indicate having more productive cows in the herds. Finally, we hypothesize a positive effect of direct payments (z_6 and z_7) on technical efficiency because a higher share of these payments may indicate farmers' higher compliance with current technology, which implies a high share of public goods and services in total farm output.

To model heteroskedasticity of v_{it} we use the following variables:[6] part-time farming (w_1); share of rented land (w_2); share of hired work (w_3); and mountain zone (w_4). These variables might affect production risk of farms. A negative sign of an estimated parameter would indicate that the respective variable reduces variance of the error term (v_{it}), leading to lower production risk. We expect part-time farming (w_1) and share of rented land (w_2) to lower production risk of farms. On the other hand, share of hired work (w_3) and mountain zone (w_4) might be associated with higher production risk of farms.

Calculating Shadow Prices

Based on the estimated technology parameters, we calculate the farm-specific shadow prices of undesirable output (nitrogen surplus) with respect to both desirable outputs, as described in equations (11)–(12). This is easier to do using the expression in the right-hand side of equation (11) rather than equation (12) because the derivatives of the distance function with respect to desirable and undesirable outputs can be expressed as linear functions of the estimated parameters after transforming the derivatives to elasticities. Because the two desirable outputs in the model are measured in monetary units, the output prices are implicitly normalized to one.[7] Equation (12) makes explicit that shadow prices have a technical meaning only if the farm operates on the production frontier. Although the discussion that follows equation (12) makes a case for the perceived shadow price of nitrogen pollution to be positive even when a farm is inefficient, the calculations require the use of data on the frontier. Acknowledging this fact, farm-specific shadow prices are calculated by projecting each farm's observed data onto the frontier along the hyperbolic path implied by the distance functions and as far as is required to reach the frontier, given the farm-specific efficiency score.

Apart from the data being projected onto the frontier, calculation of the derivatives in equation (12) requires knowledge of all the parameters of the distance function. But since output y_1 is used for imposing the almost homogeneity property, equation (13) does not contain the parameters involving this output. However, these parameters can be retrieved using the almost homogeneity constraints imposed on the translog specification of the distance function.[8]

For our estimations, we use the maximum likelihood method. This method is best equipped to deal with the assumed structure of the combined error term ($u_i + v_i$). Estimation is performed using the statistical software package STATA.

Results and Discussion

Technology Representation

Table 1 presents the parameter estimates in both hyperbolic and enhanced hyperbolic distance functions as they are expressed in equations (13) and (14).[9] The parameters associated with the first-order terms are significant in both models and have the expected sign. The monotonicity conditions are fulfilled at the approximation point (sample geometric mean).

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[6] We use heteroskedastic specification for v_{it} because the maximum likelihood estimator will be inconsistent if the error term is heteroskedastic and this is ignored.

[7] Both milk and non-milk outputs enter the empirical model in terms of revenues. Since we have data on a single year, prices are constant and the derivatives in the right-hand side of equation (12) are the same in the following way: $p_m \frac{dy_m}{db}|_{D_H=1} = \frac{d(p_m \cdot y_m)}{db}|_{D_H=1}$.

[8] These constraints are imposed in the estimable form of the distance function by imposing the almost homogeneity property. Cuesta, Lovell, and Zofío (2009) provide details on how they can be derived.

[9] We use pooled data (conventional and organic) for estimation of the production technology, since a likelihood ratio test did not reject the null hypothesis that the two distance function parameters are the same for the two groups of farms at the 1% significance level. (For similar tests, see Battese, Rao, and O'Donnell, 2004; Newman and Matthews, 2007).

Table 1. Parameter Estimates in Hyperbolic (D_H) and Enhanced Hyperbolic (D_{ENH}) Distance Functions

	D_H (equation 13)		D_{ENH} (equation 14)	
Parameters	**Estimate**	**SE**	**Estimate**	**SE**
α_0 (constant)	−0.039***	0.014	−0.020***	0.007
α_1 (land)	−0.046**	0.019	−0.045***	0.010
α_2 (labor)	−0.065***	0.020	−0.053***	0.010
α_3 (capital)	−0.133***	0.016	−0.083***	0.008
α_4 (livestock)	−0.308***	0.031	−0.191***	0.015
α_5 (materials)	−0.237***	0.023	−0.145***	0.011
α_{11}	−0.095*	0.056	−0.037	0.029
α_{22}	−0.022*	0.094	0.005	0.047
α_{33}	−0.065	0.047	−0.058**	0.024
α_{44}	−0.223	0.142	−0.122*	0.068
α_{55}	−0.544***	0.113	−0.243***	0.054
α_{12}	−0.021	0.115	−0.033	0.056
α_{13}	0.117	0.094	0.095**	0.047
α_{14}	−0.147	0.163	−0.049	0.078
α_{15}	−0.120	0.123	−0.009	0.056
α_{23}	−0.087	0.099	−0.038	0.050
α_{24}	−0.128	0.202	−0.154	0.095
α_{25}	0.042	0.153	0.014	0.072
α_{34}	0.015	0.157	0.071	0.072
α_{35}	0.281**	0.114	0.080	0.059
α_{45}	0.454**	0.181	0.393***	0.089
β_2 (non-milk output)	0.389***	0.022	0.212***	0.011
β_{22}	0.014	0.077	0.056*	0.031
γ_o (nitrogen surplus)	−0.101***	0.014	−0.001	0.008
γ_{oo}	−0.051	0.035	−0.002	0.021
δ_{12}	0.131**	0.055	0.050**	0.024
δ_{22}	0.082	0.067	0.034	0.028
δ_{32}	−0.077*	0.047	−0.054**	0.021
δ_{42}	−0.010	0.077	−0.034	0.038
δ_{52}	0.128**	0.664	0.035	0.030
ω_{1o}	0.058	0.042	0.022	0.023
ω_{2o}	0.030	0.055	0.085***	0.029
ω_{3o}	−0.072**	0.036	−0.050***	0.019
ω_{4o}	0.061	0.058	−0.024	0.031
ω_{5o}	0.087*	0.051	0.006	0.027
xi_{2o}	−0.038	0.050	0.005	0.025
Heteroskedasticity in σ_u				
ρ_0	31.315**	13.33	12.211	12.590
ρ_1 (part-time farming)	1.738***	0.367	1.645***	0.380
ρ_2 (share of agricultural output of total output)	0.018	0.022	−0.039*	0.023
ρ_3 (organic farming)	−1.731***	0.567	−1.514***	0.557
ρ_4 (zone)	−0.546**	0.248	−0.191	0.234
ρ_5 (milk yield)	−0.001***	0.0002	−0.001***	0.0002
ρ_6 (ecological payments per animal)	−0.0002	0.001	−0.000	0.001
ρ_7 (direct payments per hectare)	−0.001*	0.0003	−0.001*	0.0003
Heteroskedasticity in σ_v				
τ_0	−13.030*	6.878	−9.368	6.910
τ_1 (part-time farming)	−.386	0.296	−0.288	0.264
τ_2 (share of rented land)	−0.004	0.003	−0.002	0.003
τ_3 (share of hired work)	0.006	0.004	0.003	0.004
τ_4 (zone)	0.164	0.131	0.069	0.132
Log-Likelihood	376.28		705.63	

Notes: Single, double, and triple asterisks (*, **, ***) indicate significance at at the 10%, 5%, and 1% level, respectively.

Table 2. Hyperbolic Efficiency of Farms

	Hyperbolic Efficiency (i)	Enhanced Hyperbolic Efficiency (ii)
Mean	0.936	0.966
SD	0.062	0.038
Range	0.48–1.00	0.80–1.00
5th percentile	0.796	0.886
10th percentile	0.860	0.926
25th percentile (lower quartile)	0.923	0.961
50th percentile (median)	0.957	0.979

Farm Performance

Table 2 summarizes the estimated efficiency scores corresponding to the hyperbolic and enhanced hyperbolic measures, as defined above.

Applying the hyperbolic distance function, we find the efficiency of the farms to be 0.936, on average. Therefore, the average farm can expand its desirable outputs by 6.8% (1/0.936) and at the same time reduce its undesirable output (nitrogen surplus) by 6.4% (1-0.936), while holding inputs fixed. Besides this high mean efficiency value, we find the range of efficiency scores to be between 0.48 and 1.00, indicating the potential for improving the economic and environmental performance of the farms. For example, the farms in the lower 10th percentile could produce 16.3% more desirable outputs and simultaneously decrease nitrogen surplus by 14.0%, whereas those in the lower 5% percentile can increase their desirable outputs by 25.6% and reduce nitrogen surplus by 20.4%.

Using the enhanced hyperbolic distance function, we obtain a mean efficiency score of 0.966. Figure 1 illustrates that for most farms the efficiency scores estimated using the enhanced hyperbolic distance function (where farms can adjust inputs, desirable outputs and undesirable outputs at the same time) are higher than those estimated using the hyperbolic distance function (where inputs are held fixed at their observed levels).

Cuesta, Lovell, and Zofío (2009) also obtained higher efficiency scores from the enhanced hyperbolic distance function than from the hyperbolic distance function. The authors attribute this finding to the enhanced hyperbolic distance function representing a more comprehensive path toward the frontier by allowing for simultaneous adjustment of inputs, desirable outputs, and undesirable outputs.

As indicated in figure 1, the ranking of farms is marginally affected by the choice of efficiency measure. The Spearman correlation coefficient between efficiency estimates from hyperbolic and enhanced hyperbolic distance functions is 0.95, and Kendal's correlation coefficient is 0.82.

The results of this study confirm our hypotheses regarding the influence of farm characteristics on technical efficiency of Swiss farms.[10] We find a significant negative influence of part-time farming on farm efficiency. This might be related to the fact that farmers with higher off-farm income may be less motivated to increase efficiency on their farms. The empirical literature finds both negative (Brümmer, 2001; Goodwin and Mishra, 2004; Jan, Lips, and Dumondel, 2010) and positive influence (Huffman and Evenson, 2001; Tonsor and Featherstone, 2009) of off-farm activities on technical efficiency. We find a significant positive influence of organic farming on farm efficiency. As organic production is more labor-intensive, and sometimes related to lower yields, organic farmers may put more effort into production and use their time more efficiently. Farmers in higher mountain zones also have higher efficiency. Similar to organic farmers, farmers in higher zones have to deal with adverse production conditions (less productive land, lower livestock numbers) and may be motivated to put more effort in increasing the efficiency on their farms. According to our results,

[10] Table 1 presents results on estimated parameters for variables explaining inefficiency differences across farms.

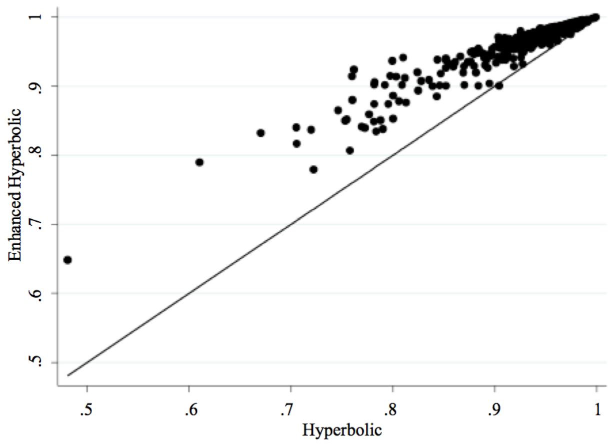

Figure 1. Efficiency Scores Estimated with Hyperbolic and Enhanced Hyperbolic Distance Functions

farmers with higher milk yields are more efficient, possibly related to the fact that farmers with higher milk yields have more productive cows, either due to breeding or a better farm management. Finally, we find a significant positive influence of direct payments on farm efficiency. The high share of direct payments might be related to a higher motivation of farmers to comply with the current regulatory environment and thus get closer to the production frontier. The empirical literature finds both positive (Hadley, 2006; Jan, Lips, and Dumondel, 2010) and negative influence (Ferjani, 2008; Lakner, 2009; Bakucs et al., 2010; Zhu and Lansink, 2010) of direct payments on technical efficiency of farms.

Beside the fact that we find significant parameter estimates, the magnitude of impact is very small for most of the variables used. This may be associated with the high efficiency scores of farms found in this study.[11]

Shadow Prices of Nitrogen Pollution

We calculate the farm-specific shadow prices of undesirable output (nitrogen surplus) with respect to both desirable outputs (expressions 9–12). Shadow prices reflect the cost of reducing undesirable output (nitrogen pollution) in terms of forgone revenue from desirable (marketable) output. Table 3 summarizes the obtained shadow prices for each output.

Table 3 indicates that, with respect to milk output, it costs 28 Swiss francs, on average, to abate 1 kg nitrogen pollution on Swiss dairy farms in the region. With respect to non-milk output, we obtain 50 Swiss francs, on average.[12] Our results imply that, on average, it would cost around 33,000 Swiss francs per farm to abate their entire nitrogen surplus.[13] The obtained high costs of pollution reduction hint at the difficulties of political implementation of effective levies on nitrogen surpluses.

We find negative shadow prices with respect to milk and non-milk output for 7% and 5% of farms, respectively. Van Ha, Kant, and Maclaren (2008) discussed the possibility of negative shadow prices. If pollution abatement is implemented in compliance with the regulations, one could expect negative shadow prices, since there is a resource-use for abatement (Van Ha, Kant, and Maclaren,

[11] The high efficiency scores found in our analysis may be related to the choice of distribution for the inefficiency term. We use the half-normal model, which assumes that most inefficiency scores are close to zero; thus, technical efficiencies are close to 1.

[12] It should be noted that the distributions of shadow prices are quite diffuse and the mean values are largely driven by extreme observations.

[13] When we multiply average shadow price with respect to milk output (28 Swiss francs) by the average kg of nitrogen surplus per farm (1,180 kg) we get around 33,000 Swiss francs per farm.

Table 3. Shadow Prices of Nitrogen Surplus (in Swiss Francs per kg of Nitrogen)

	Mean	Median	SD
Shadow prices with respect to milk output (in Swiss francs)	27.96	14.55	101.80
Shadow prices with respect to non-milk output (in Swiss francs)	49.67	31.39	75.67

Table 4. Median Value of Shadow Prices of Nitrogen Surplus (in Swiss Francs per kg of Nitrogen)

	With Respect to Milk Output (in Swiss Francs)	With Respect to Non-Milk Output (in Swiss Francs)
Organic farms (n=118)	17.4	42.5
Conventional farms (n=389)	13.6	28.4

2008). In our study, we include direct payments as a part of non-milk output. Some of these payments are obtained conditional on compliance with regulations and application standards. Thus, although reducing nitrogen surplus has to reduce physical output, it may increase one of the other outputs in the model, leading to a negative shadow price.

Our results indicate a tendency of higher shadow prices for organic farms compared to conventional farms. As shown in table 4, we find slightly higher shadow prices for organic farms than for conventional farms with respect to each output. However, the difference in shadow values between conventional and organic farms is not statistically significant.[14] This may be related to the fact that all farms in our sample are grassland-based dairy farms, exhibiting relatively small differences in terms of organic and conventional production systems.[15]

In general, organic farming regulations are more restrictive in terms of improving the environmental quality of inputs used. For example, the use of synthetic chemical fertilizers is not allowed in organic farming. Instead, organic farms apply animal manure to renew the nutrition content in soils. The pollution arising from animal manure application is lower than that from synthetic chemical fertilizers, making organic farms less harmful with regard to nitrogen pollution. Arandia and Aldanondo-Ochoa (2011) found higher shadow prices of reducing nitrogen pollution for organic farms than for conventional farms. The authors explain this finding by the fact that application of animal manure is more labor-intensive, leading to higher costs for organic farms. Moreover, more restrictive regulations for organic farms imply that these farms operate on the section of the production function where marginal returns on nitrogen are high. In other words, organic farms have already abated more nitrogen, so further abatement is more expensive at the margin (assuming that the marginal cost of abatement is increasing).

The results on shadow prices could provide an indication of the allocative efficiency of the studied farms. If farms are fully allocatively efficient, we would expect the same shadow prices with respect to each output. However, our results show that there are large discrepancies between the two shadow prices and, thus, indicate that Swiss dairy farms are not allocatively efficient. For each farm, we calculate the ratio of shadow price with respect to non-milk output to the shadow price with respect to milk output. The histogram of these ratios (see Appendix C, figure A1) shows that this ratio is above one for almost all farms, indicating allocative inefficiency of these farms.

In general, our results on shadow prices are comparable with those obtained by Huhtala and Marklund (2008) and Arandia and Aldanondo-Ochoa (2011). However, as discussed in Arandia and Aldanondo-Ochoa (2011), some prudence is needed when comparing shadow prices derived using different methodological frameworks (parametric versus non-parametric studies, treatment of pollution as input or as output, etc.).

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[14] We use a t-test for the equality of means. The difference is not statistically significant, with a p-value of 0.623.

[15] Swiss conventional dairy farms in the mountainous region use a very small quantity of mineral fertilizers and largely rely on the application of manure.

Conclusions

This study analyzed the economic and environmental performance of farms incorporating nitrogen pollution (undesirable output) into the representation of the production technology and then estimated the shadow prices that indicate the marginal abatement costs of nitrogen pollution on farms. The analysis was based on a 2010 cross-sectional sample of 507 dairy farms in the mountainous region of Switzerland.

We represented the technology of farms with a hyperbolic distance function, allowing for an asymmetric treatment of desirable and undesirable outputs. Such a representation describes an economically desired and environmentally friendly technology since it simultaneously maximizes marketable outputs and minimizes undesirable outputs. Furthermore, we also employed an enhanced hyperbolic distance function, which considers the adjustability of all inputs and outputs (both desirable and undesirable).

Two measures of farm performance were used in this study: hyperbolic efficiency (measured with a hyperbolic distance function), and enhanced hyperbolic efficiency (measured with an enhanced hyperbolic distance function). These measures provide a more comprehensive evaluation of the performance of farms, in contrast to a separate assessment of either input/output or environmental performance.

The results of both measures indicated high efficiency scores for Swiss farms in the sample. We obtained average efficiency scores of 0.936 using the hyperbolic distance function and 0.966 using the enhanced hyperbolic distance function. Nevertheless, we found the range of efficiency scores to be between 0.48 and 1.00, indicating potential for improving the performance of Swiss dairy farms.

Nitrogen pollution from agriculture is a negative externality, and its costs are external to production decisions. Modeling the technological relationship between marketable outputs and nitrogen pollution allowed for retrieval of the shadow prices (i.e., opportunity costs) of nitrogen pollution. We obtained farm-specific shadow prices of nitrogen surplus with respect to two different desirable outputs. These shadow prices were measured in Swiss francs and indicate the revenue from desirable output that has to be given up in order to reduce undesirable output (nitrogen surplus) by one unit (one kg) if the farm were on the production frontier. The mean shadow price for 1 kg nitrogen surplus with respect to milk output was 28 Swiss francs. Slightly higher shadow prices of nitrogen pollution in organic farms may reflect more restrictive regulations in organic farming.

We note some policy implications that can be derived from this analysis for the Swiss dairy farms in the mountainous region. First, the high mean values of the hyperbolic efficiency and enhanced hyperbolic efficiency suggest that most Swiss dairy farms in the mountainous region are well adapted to the current regulatory and physical environment. Second, the estimated shadow prices provide quantitative information on farmers' costs of reducing undesirable output. This information can be used to design specific policies aiming to reduce nitrogen pollution in Swiss agriculture. Third, shadow prices were found in this study to be highly variable, indicating the need for targeted policy instruments regarding nitrogen pollution in Switzerland. At the same time, the high costs of nitrogen pollution abatement per farm provide some indication that it will be politically difficult to implement an effective levy on nitrogen surplus in Switzerland. And finally, results on shadow prices suggest a rationale for rather similar policy measures in terms of nitrogen pollution for conventional and organic farms in Switzerland.

Finally, we address some limitations of our study. We estimated shadow prices on the frontier, thus not considering farm inefficiencies. This might lead to an overestimation of shadow prices, since inefficient farmers may be able to reduce pollution without any cost. Nevertheless, the obtained information on shadow prices is useful for policy makers because it provides insights on the magnitude and variability of shadow prices after eliminating farm-level inefficiencies. Another limitation of this study is that the soil-surface approach used for nitrogen balancing considers only conversation of nitrogen "spread on the soil" into harvestable crops and only partly considers other processes (e.g., conversion of feed into animal products). Regarding the economic assessment, we considered the farm as a whole. This implies that the system boundaries between environmental and economic assessment are somehow inconsistent. Moreover, for this study we did not have access to panel data and employed cross-sectional data instead. Switzerland, as well as many other countries, does not collect nutrition balances of farms on a regular basis. Nevertheless, the topic has become more relevant in recent years, and more and more countries have started collecting such data. Since 2011, the Swiss government has been implementing pilot projects collecting environmental variables of farms, including nutrient balances. To date, only several hundred farms have participated in these pilots, and the resulting samples are very heterogeneous (dairy, arable, different zones, etc.). These data are thus not suitable for constructing a sample for efficiency analysis (sample with farms facing similar production technology). After the sample size grows and more data on several years are available, further research could expand our analyses by employing panel data.

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Appendix A: Description of the Nitrogen Balance Approach

There are two main approaches for assessing the nitrogen balance of a farm: the farm-gate approach and the soil-surface approach. These approaches differ in terms of the spatial boundaries of the agricultural system investigated. Whereas a farm-gate nitrogen balance assesses the difference between the nitrogen flows entering and leaving the farm via the farm-gate, a soil-surface nitrogen balance quantifies the nitrogen flows entering the soil via the surface and leaving it via crop uptake (Oenema, Kros, and de Vries, 2003).

We choose the OECD soil-surface approach (Parris, 1998; OECD, 2001) for estimating nitrogen balances of farms because all of the necessary data for this approach are available in the Swiss FADN database (in contrast to the data necessary for the farm-gate approach). Nitrogen balance is defined as the difference between nitrogen input and output.

Nitrogen input encompasses the following elements: inorganic fertilizer, livestock manure, biological nitrogen fixation, atmospheric deposition, and seeds and planting materials (OECD, 2001). Although nitrogen losses from manure through ammonia volatilization in farm buildings (livestock housing) and during manure storage are not included in the "livestock manure" nitrogen-input element of the official version of the OECD soil-surface approach, these losses are included in the nitrogen input estimated in the present study. This constitutes the sole difference between the official original version of the OECD soil-surface approach and the approach taken in this study.

Nitrogen output comprises the following elements: arable crops, vegetables, fruits (including grapes), grass, and fodder. All nitrogen input and output elements were indirectly assessed on the basis of accountancy and/or structural variables from the Swiss FADN. As mentioned previously, this approach is validated using a subsample of farms. The validation shows that estimates from both approaches are strongly correlated ($r > 0.80$) for all nitrogen input and output elements.

Appendix B: Descriptive Statistics

Table A1. Descriptive Statistics of the Variables in the Sample (n=507)

Variables		Mean	SD	Minimum	Maximum
Inputs					
x_1	Land (hectares of farm area)	28.80	17.74	4.49	214.74
x_2	Labor (annual working units)	1.68	0.54	0.54	4.00
x_3	Capital (Swiss francs)	44,346.26	23,459.38	6,122.62	185,407.50
x_4	Livestock (standardized animal units)	25.31	11.54	2.60	98.60
x_5	Materials (Swiss francs)	91,429.36	49,298.47	27,069.00	490,950.00
Desirable outputs					
y_1	Milk output (Swiss francs)	83,192.01	45,786.51	15,358.00	347,803.00
y_2	Non-milk output (Swiss francs)	125,956.90	63,917.90	28,700.00	496,939.00
	Total farm output (Swiss francs)	209,148.90	94,858.62	60,105.00	728,107.00
Undesirable outputs					
b	Nitrogen surplus (kg)	1,179.41	762.84	63.85	5,542.90
	Nitrogen surplus (kg/ha)	53.02	26.64	4.74	240.98
Other farm characteristics					
	Age	47.00	10.00	21.00	74.00
	Share of rented land (%)	38.16	28.63	0.00	100.00
	Share of hired labor (%)	14.50	18.75	0.00	85.00
	Milk yield (kg/cow)	5,878.25	1,207.31	1,553.00	13,218.00
	Nitrogen input (kg)	3,939.92	1,955.80	567.84	14,958.80
	Nitrogen output (kg)	2,760.51	1,361.06	120.45	10,957.91
	Nitrogen (N) use efficiency: (N in output/N in input) $\times$ 100 (%)	71.00	10.00	17.00	98.00

	Shares (%)	N
Zone		
Mountain zone 2	65.9	334
Mountain zone 3	24.6	125
Mountain zone 4	9.5	48
Full-time/part time farm		
Full-time	76.3	387
Part-time	23.7	120
Farming		
Conventional	76.7	389
Organic	23.3	118
Agricultural education		
Without professional education	11.2	57
In education	0.4	2
Completed education	67.9	344
Higher education (e.g., master's certificate)	19.3	98
University of applied sciences or university degree	1.2	6

Source: Agroscope ART, Swiss FADN (year=2010, n=507 dairy farms).

Appendix C: Ratio of Shadow Values with Respect to Two Different Outputs

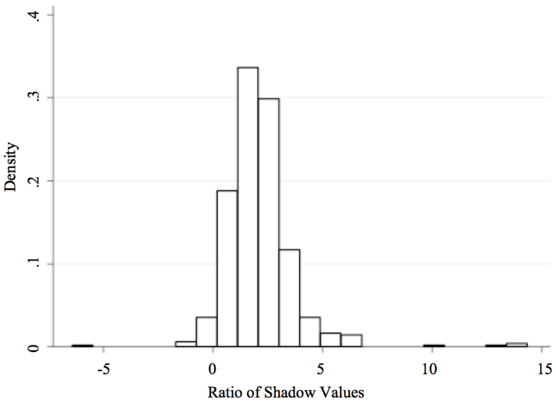

Figure A1. Ratios of Shadow Values with Respect to Non-Milk Output to the Shadow Values with Respect to Milk Output

Appendix D: Results of Additional Models When Direct Payments Are Modelled as Inputs of Production

Table A2. Results of Additional Models (Direct Payments as Inputs): Parameter Estimates

	D_H (equation 13)		D_{ENH} (equation 14)	
Parameters	**Estimate**	**SE**	**Estimate**	**SE**
α_0 (constant)	-0.061^{***}	0.019	-0.038^{***}	0.009
α_1 (land)	0.031	0.028	-0.035^{**}	0.014
α_2 (labor)	-0.04	0.025	-0.058^{***}	0.013
α_3 (capital)	-0.122^{***}	0.019	-0.077^{***}	0.010
α_4 (livestock)	-0.295^{***}	0.044	-0.250^{***}	0.021
α_5 (materials)	-0.217^{***}	0.029	-0.165^{***}	0.015
α_6 (direct payments	0.009	0.045	0.060^{**}	0.024
α_{11}	-0.072	0.085	0.021	0.046
α_{22}	0.142	0.115	0.046	0.060
α_{33}	-0.127^{**}	0.058	-0.090^{***}	0.031
α_{44}	-0.318	0.212	-0.163^{*}	0.098
α_{55}	-0.716^{***}	0.166	-0.327^{***}	0.077
α_{66}	-0.112	0.16	0.076	0.071
α_{12}	-0.048	0.145	-0.006	0.076
α_{13}	0.056	0.135	0.045	0.072
α_{14}	-0.033	0.22	0.003	0.106
α_{15}	0.042	0.192	0.168^{*}	0.090
α_{16}	0.136	0.245	-0.140	0.124
α_{23}	-0.106	0.123	-0.096	0.065
α_{24}	-0.426	0.293	-0.218	0.137
α_{25}	0.092	0.191	0.093	0.092
α_{26}	0.023	0.247	0.004	0.127
α_{34}	0.158	0.212	0.161	0.103
α_{35}	0.354^{**}	0.151	0.133^{*}	0.080
α_{36}	-0.066	0.189	-0.028	0.095
α_{45}	0.49^{*}	0.279	0.610^{***}	0.128
α_{46}	0.207	0.345	-0.039	0.159
α_{56}	0.049	0.349	-0.283^{*}	0.166
β_2 (non-milk output)	0.06^{***}	0.013	0.046^{***}	0.006

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Table A2. – continued from previous page

	D_H (equation 13)		D_{ENH} (equation 14)	
Parameters	**Estimate**	**SE**	**Estimate**	**SE**
β_{22}	0.002	0.003	0.002*	0.001
γ_o (nitrogen surplus)	−0.18***	0.017	−0.013	0.010
γ_{oo}	0.001	0.036	0.035	0.025
δ_{12}	−0.006	0.038	−0.005	0.019
δ_{22}	0.038	0.032	0.029**	0.015
δ_{32}	0.004	0.02	0.007	0.010
δ_{42}	−0.102*	0.06	−0.065**	0.028
δ_{52}	0.053	0.043	0.035*	0.021
δ_{62}	−0.012	0.055	−0.004	0.027
ω_{1o}	−0.029	0.051	−0.055*	0.033
ω_{2o}	0.045	0.062	0.062*	0.037
ω_{3o}	−0.051	0.041	−0.032	0.025
ω_{4o}	−0.008	0.08	−0.104**	0.043
ω_{5o}	0.07	0.063	−0.023	0.036
ω_{6o}	0.016	0.086	0.145***	0.052
ξ_{2o}	0.054**	0.023	0.024*	0.015
Heteroskedasticity in σ_u				
ρ_0	20.92*	11.296	3.231	11.724
ρ_1 (part-time farming)	1.072***	0.31	0.890***	0.314
ρ_2 (share of agricultural output of total output)	−0.137***	0.026	−0.128***	0.023
ρ_3 (organic farming)	−1.384***	0.457	−1.313***	0.469
ρ_4 (zone)	−0.308	0.213	0.013	0.220
ρ_5 (milk yield)	−0.001***	0.0001	−0.001***	0.000
ρ_6 (ecological payments per animal)	−0.001	0.001	−0.001	0.001
ρ_7 (direct payments per hectare)	−0.0002	0.0002	−0.0003	0.0002
Heteroskedasticity in σ_v				
τ_0	−12.487*	7.548	−13.267*	7.685
τ_1 (part-time farming)	−0.794	0.453	−0.667**	0.308
τ_2 (share of rented land)	0.002	0.003	−0.002	0.004
τ_3 (share of hired work)	0.007	0.005	0.004	0.005
τ_4 (zone)	0.156	0.144	0.150	0.147
Log-Likelihood	284.74		599.02	

Notes: Single, double, and triple asterisks (*, **, ***) indicate significance at the 10%, 5%, and 1% level, respectively.

Table A3. Results of Additional Models (Direct Payments as Inputs): Efficiency Scores

	Hyperbolic Efficiency (i)	**Enhanced Hyperbolic Efficiency (ii)**
Mean	0.907	0.948
SD	0.101	0.061
Range	0.39–1.00	0.57–1.00
5th percentile	0.676	0.809
10th percentile	0.779	0.875
25th percentile	0.888	0.938
50th percentile (median)	0.944	0.970

Table A4. Results of Additional Models (Direct Payments as Inputs): Shadow Values

	Mean	**Median**	**SD**
Shadow prices with respect to milk output (in Swiss francs)	20.65	19.68	32.37
Shadow prices with respect to non-milk output (in Swiss francs)	−2	72.98	3,296.72