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Shadow prices of greenhouse gas emissions: An application to the Czech dairy production

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Abstract: The paper presents an analysis of the shadow prices of the greenhouse gas emissions in the Czech dairy production industry. There is employed the stochastic frontier multiple output distance function with two market outputs and one non-market (undesirable) output – greenhouse gas emissions – as a representation of a negative public good. The results show that shadow prices differ significantly between producers. Moreover, the price is not stable over time. Significant differences can be seen in shadow prices for the greenhouse gas emissions among the researched group of farmers with respect to the degree of intensification. Most noticeably, the higher the intensification, the higher the shadow price. However, no evidence for a significant relationship between the greenhouse gas prices and technical efficiency was found, and not even the development of the greenhouse gas prices and technical efficiency suggested any common patterns.

Keywords: milk multiple output distance function, stochastic frontier analysis (SFA), undesirable output, valuation

From a neoclassical perspective, the agricultural production processes can be represented by a transformation function (Fried et al. 2008) that describes the transformation of many inputs into many outputs. In a standard application of the production theory, the authors use either one or more outputs and basic production factors (Brümmer et al. 2002). The outputs are usually represented by the total production of main agricultural outputs (Cechura et al. 2015). However, agricultural production is also characterized by the production of side products and non-market products or public goods. The question therefore arises, what is the price of these outputs when it is not provided by the market? The literature presents several methods detailing how to calculate or evaluate the price of the non-market or public goods including the calculation of shadow price (Färe and Grosskopf 1998).

Shadow price can be defined as an increase in the affluence of a society as a consequence of the availability of an additional unit of certain goods (Dréze and Stern 1990; Squire and Van der Tak 1995). According to Lee et al. (2014), shadow price can also be perceived as an equivalent to the price of certain goods in the case of their market realisation on a market with perfectly functioning competition; in other words, shadow price is an implicit value of the non-market output of production. Shadow price can be estimated by applying the standard tools of the production analysis that use, for example, the parametric (Stochastic Frontier Analysis – SFA) or the non-parametric techniques (Data Envelopment Analysis – DEA).

In the case of milk production, milk can be considered a desirable product that enters the market. However, milk production is also characterized by the production of several public goods, both desirable and undesirable. This paper shows how to evaluate the price of a non-market output using the production approach for the greenhouse gas emissions. These emissions are a typical example of an undesirable output (externality) that yields disutility in consumption (Shortall and Barnes 2013; Toma et al. 2013).

Shadow price assessments of this externality are based on determining the quantity of emissions produced along with one litre of milk. For such purposes, the functional unit of the energy corrected milk (ECM) or the fat and protein corrected milk (FPCM) in kg (Casey and Holden 2005) is defined as:

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FPCM (kg) = raw milk (kg) × (0.337 + 0.116 × fat content (%) + 0.06 × protein content (%)

resp.

$$ECM\ (kg) = 0.25 \times \text{mass of milk (kg)} + 12.2 \times \text{fat (kg)} + 7.7\ \text{protein (kg)} \quad (1)$$

The existing literature provides different measures of the greenhouse gas emissions. For example, the FAO (2010) provides a worldwide analysis on the average emissions per kg of FPCM at the farm gate. The highest emissions were estimated for sub-Saharan Africa, which has an average of about 7.5 kg CO_2 equivalent (eq.) per kg FPCM. The lowest values were found for the industrialized regions of the world, which have between 1 and 2 kg CO_2 eq. per kg FPCM at the farm gate. South Asia, West Asia and Northern Africa and Central and South America have intermediate levels of emissions, estimated between 3 and 5 kg CO_2 eq. per kg FPCM. Casey and Holden (2005) examined the problem of the greenhouse gas emissions produced by the dairy sector in Ireland. A life-cycle assessment methodology was used to create an objective framework for estimating CO_2 eq. emissions per unit. The authors used three main allocation approaches. Firstly, they used "no allocation", where the total greenhouse gas burden of the production system was apportioned to milk production. The total amount of greenhouse gas emissions recorded with no allocation was estimated at 1.46 kg. Second, they used a mass (physical) allocation. This approach is based on the relationship between the cow's feed energy intake and its production of milk and beef. This result was 1.45 kg CO_2 eq. per FPCM. Finally, the conventional economic allocation is based on the relationship of the amount of milk and meat, with emissions being apportioned to the milk and meat price. This approach yielded emissions of 1.3 kg. Moreover, Kiefer et al. (2015) compared two new approaches: the economic allocation with ecosystem services, and the system expansion. This provided a methodological framework from which to examine specific influences of the carbon footprint with the three allocation methods mentioned above. The paper used data from 113 dairy farms. These enterprises were located in the grassland areas of Southern Germany. The results of this research are summarized in Table 1. Kristensen et al. (2015) solved similar problems with the Danish cattle breeding development during the period ranging from 1920–2010. One of the evaluated indicators was the greenhouse gas emission. Their results showed that 2010 was the low point for emissions, with 1.20 kg CO_2 eq. per kg ECM.

Table 1. Carbon footprint results of different allocation methods in kg CO_2 equivalent per 1 kg fat and protein corrected milk (FPCM)

	Pasture-based farms	Permanent indoor housing
No allocation	1.70	1.77
Physical allocation	1.37	1.46
Conventional economic allocation	1.47	1.51
Economic allocation with ecosystem services	1.35	1.49
System expansion	0.67	0.86

Source: Kiefer et al. (2014)

The aims of the paper are to calculate the shadow price of the greenhouse gas emissions in the Czech dairy production using the production approach, as well as to present an accompanying analysis of the factors determining the price of the shadow price. In particular, the paper attempts to address the following research questions: What is the shadow price of the greenhouse gas emissions? How is this price related to the size of farm, the intensity of milk production and to the degree of specialization? Is there any relationship between the efficiency of the factor use and shadow price?

MATERIALS AND METHODS

Modelling technology with desirable and undesirable outputs

Consider a joint-production process in which a farm employs the input vector $x \in \Re_+^K$ to produce the desirable output vector $y \in \Re_+^P$ (milk, other animal products and plant products) and the undesirable output vector $b \in \Re_+^B$ (greenhouse gas), the production technology is expressed by the output possibility set

$$P(x) = \{(y, b): x\ can\ produce\ (y, b)\} \quad (2)$$

The output possibility set is assumed to be closed, convex and bounded by an isoquant defined as

$$IsoqP(x) = \{(y, b): (y, b)\} \in P(x), \lambda(x, b) \notin P(x), \lambda > 1\} \quad (3)$$

The inputs and the desirable outputs are supposed to be strongly disposable $x' \geq x$ *implies* $P(x') \supseteq P(x)$ and $y' \leq y$ imply $(y', b) \in P(x)$, *if* $(y', b) \in P(x)$. The undesirable output is supposed to be weakly disposable $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$ imply $(\theta y, \theta b) \in P(x)$ because "the productive entity has to undertake a certain amount of

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cost to reduce the undesirable outputs" (Zhou et al. 2014). Zhang and Choi (2014) added the null-jointness assumption $(y, b) \in P(x)$ *and* $b = 0$, *then* $y = 0$, which states that the undesirable outputs are not avoidable in the production process.

The output vector (y, b) must belong to the output possibility set $P(x)$, but it need not be located on its outer frontier. A radial measure of the distance from the output vector (y, b) to $IsoqP(x)$ is the Shephard's output distance function (Equation 4):

$$D_0(x, y, b) = inf\{\theta > 0: (y/\theta, b/\theta) \in P(x) \quad (4)$$

where θ is the value of the output distance function that measures the maximum degree by which (y, b) can be proportionally increased given x (Zhou et al. 2014).

In the empirical analysis, we assume that the transformation process can be well approximated by the translogarithmic function. That is, the multiple output distance in the translog functional form that incorporates the mentioned weak disposability assumption is Equation 5, where t denotes the time vector and is a proxy for capturing the effects of technological change.

Since the agricultural sector is characterized by a significant inefficiency in the input use (Cechura et al. 2017), we employ the Stochastic Frontier analysis. Introducing the inefficiency term u by defining $-\ln D_0(x, y, b, t) = u$, allowing for the stochastic noise, and after imposing the linear homogeneity in outputs, which is imposed similarly to Hadley (1998) by normalizing the outputs by one of the desirable output, the output distance function leads to the following form in Equation 6, where $u \sim i.i.d.N^+(0, \sigma_u^2)$ is a one-sided error term and $v \sim i.i.d.N(0, \sigma_v^2)$ is the symmetric error term.

Moreover, to obtain reliable results, we have to respect the significant technological heterogeneity among producers (Čechura et al. 2016) as another important feature of the agricultural sector. Heterogeneity in technology is captured using a random parameter model (Tsionas 2002). We use the extended version of the RPM specified by Alvarez et al. (2004). In particular, the technology is given by the consideration of a firm-specific factor (m_i) that enters the distance function in the same way as other inputs (Equation 7).

The model in Equation 7 cannot be estimated by the maximum likelihood since m_i is not observable. Alvarez et al. (2004) propose a maximum simulated likelihood approach, where m_i is simulated by several draws for the standard normal distribution, $m_i \sim N(0,1)$:

$$\hat{E}\left[m_i \middle| \mathbf{y}_i, \mathbf{X}_i, \boldsymbol{\delta}\right] = \frac{\frac{1}{R}\sum_{r=1}^{R} m_{i,r}\hat{f}\left(\mathbf{y}_{1i}\middle|\mathbf{y}^*_{pit}, \mathbf{x}_{it}, t, m_{i,r}; \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}\right)}{\frac{1}{R}\sum_{r=1}^{R} \hat{f}\left(\mathbf{y}_{1i}\middle|\mathbf{y}^*_{pit}, \mathbf{x}_{it}, t, m_i; \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}\right)} \quad (8)$$

where R denotes the number of repetitions and $\hat{f}$ denotes the value of the output distance function in Equation 7.

$$lnD_O(x, y, b, t) = \alpha_0 + \sum_k \beta_k lnx_k + \sum_p \alpha_p lny_p + \alpha_b lnb + \delta_t t + \frac{1}{2}\sum_k \sum_{k'} \beta_{kk'} lnx_k lnx_{k'} + + \frac{1}{2}\sum_p \sum_{p'} \alpha_{pp'} lny_p lny_{p'} + \frac{1}{2}\alpha_{bb}(lnb)^2 + \frac{1}{2}\delta_{tt}t^2 + \sum_k \sum_p \gamma_{kp} lnx_k lny_p + \sum_k \gamma_{kb} lnblnx_k + + \frac{1}{2}\sum_p \gamma_{pb} lnblny_p + \sum_k \beta_{kt} tlnx_k + \sum_p \alpha_{pt} tlny_p + \alpha_{bt} tlnb \quad (5)$$

$$-lny_1 = \alpha_0 + \sum_k \beta_k lnx_k + \sum_{p-1} \alpha_p ln\frac{y_p}{y_1} + \alpha_b ln\frac{b}{y_1} + \delta_t t + \frac{1}{2}\sum_k \sum_{k'} \beta_{kk'} lnx_k lnx_{k'} + + \frac{1}{2}\sum_{p-1}\sum_{p'-1} \alpha_{pp'} ln\frac{y_p}{y_1} ln\frac{y_{p'}}{y_1} + \frac{1}{2}\alpha_{bb}(ln\frac{b}{y_1})^2 + \frac{1}{2}\delta_{tt}t^2 + \sum_k \sum_{p-1} \gamma_{kp} lnx_k ln\frac{y_p}{y_1} + + \sum_k \gamma_{kb} ln\frac{b}{y_1} lnx_k + \frac{1}{2}\sum_{p-1} \gamma_{pb} ln\frac{b}{y_1} ln\frac{y_p}{y_1} + \sum_k \beta_{kt} tlnx_k + \sum_{p-1} \alpha_{pt} tln\frac{y_p}{y_1} + \alpha_{bt} tln\frac{b}{y_1} + +u + v \quad (6)$$

$$-lny_{1it} = \alpha_0 + \sum_{p=2}^{3} \alpha_p ln\, y^*_{pit} + \alpha_b lnb^*_{it} + \frac{1}{2}\sum_{p=2}^{3}\sum_{p'=2}^{3} \alpha_{pp'} lny^*_{pit} lny^*_{p'it} + \frac{1}{2}\alpha_{bb}(lnb^*_{it})^2 + + \sum_{k=1}^{4} \beta_k ln\, x_{kit} + \frac{1}{2}\sum_{k=1}^{4}\sum_{k'=1}^{4} \beta_{kk'} lnx_{kit} lnx_{k'it} + \frac{1}{2}\sum_{k=1}^{4}\sum_{p=2}^{3} \gamma_{kp} lnx_{kit} lny^*_{pit} + + \sum_{k=1}^{4} \gamma_{kb} lnb^*_{it} lnx_{kit} + \sum_{p=2}^{3} \gamma_{pb} lnb^*_{it} lny^*_{pit} + \delta_t t + \frac{1}{2}\delta_{tt}t^2 + \sum_{p=2}^{3} \alpha_{pt} tlny^*_{pit} + \alpha_{bt} tlnb^*_{it} + + \sum_{k}^{4} \beta_{kt} tln\, x_{kit} + \alpha_m m_i + \frac{1}{2}\alpha_{mm} m_i^2 + \delta_{tm} m_i t + \sum_{k=1}^{4} \beta_{km} m_i\, lnx_{kit} + u_{it} + v_{it}. \quad (7)$$

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The u_{it} can be estimated with the Jondrow et al. (1982) formula

$$E\left[u_{it}\left|\varepsilon_{it},m_i\right.\right]=\frac{\sigma\lambda}{\left(1+\lambda^2\right)}\left[\frac{\varphi\left(-\left(\varepsilon_{it}\left|m_i\right.\right)\lambda/\sigma\right)}{\Phi\left(-\left(\varepsilon_{it}\left|m_i\right.\right)\lambda/\sigma\right)}-\frac{\left(\varepsilon_{it}\left|m_i\right.\right)\lambda}{\sigma}\right] \quad (9)$$

where $\lambda=\frac{\sigma_u}{\sigma_v}$, $\sigma^2=\sigma_u^2+\sigma_v^2$, $\varepsilon_{it}=v_{it}+u_{it}$ and ϕ and Φ denote the density and distribution of the standard normal distribution. The software NLOGIT 5.0 was used in the application.

Shadow prices

According to Shephard (1970), there exists a duality between the output distance function (ODF) and the revenue function. Färe and Grosskopf (1998) show that "the revenue function can be derived from the output distance function by maximization with respect to outputs"

$$R(x, p) = \max_{(y,b)}\{py + rb: D_0(x, y, b)\} \leq 1 \quad (10)$$

where $p \in \Re_+^M$ is the price vector of desirable outputs and $r \in \Re_-^L$ is the shadow prices vector of undesirable outputs.

The maximization can be solved by applying the Lagrange method. The Lagrangian is defined by (11).

$$\mathcal{L}(y,\lambda) = ry + \lambda[1 - D_o(x,y)] \quad (11)$$

Let y, λ, $y(x,r)$ and $\lambda(x,r)$ be the optimal levels, then Equation 11 can be rewritten as

$$\mathcal{L}(y(x,r),\lambda(x,r)) = ry(x,r) + \lambda(x,r)[1 - D_o(x,y)] \quad (12)$$

Appling the Envelope theorem, we obtain the following equations:

$$\nabla_x R(x,r) = -\lambda(x,r)\nabla_x D_o(x,y(x,r)) \text{ and} \quad (13)$$

$$\nabla_r R(x,r) = y(x,r) \quad (14)$$

The first-order conditions (FOC) are then

$$r - \lambda\nabla_y D_o(x,y) = 0 \text{ and} \quad (15)$$

$$1 - D_o(x,y) = 0 \quad (16)$$

Equations 15 and 16 imply

$$\begin{aligned} ry(x,r) &= \lambda(x,r)\nabla_y D_o(x,y)y = \\ &= \lambda(x,r)\, D_o(x,y) = \quad \text{(using homogeineity assumption)} \\ &= \lambda(x,r) \quad \text{(using Equation 16)} \quad (17) \end{aligned}$$

That is, $R(x,r) = \lambda(x,r)$.

According to Equation 17, the optimal level of the Lagrange multiplier equals the maximum revenue for each (x,r). If

$$r(x,r) = \nabla_y D_o(x,y) \quad (18)$$

then a combination of Equation 15, 16 and 18 gives

$$r = R(x,r)r(x,y) = R(x,r)\nabla_y D_o(x,y) \quad (19)$$

Since y is the output vector maximizing income with given prices r and inputs x, vector r can be interpreted as a vector of shadow prices for outputs y with respect to the given inputs x. To estimate the shadow prices, $\nabla_y D_o(x,y)$ and $R(x,r)$ must be known; $\nabla_y D_o(x,y)$ can be derived from an estimate of the output distance function. Since the vector of shadow prices r, which determines $R(x,r)$ is unknown, the shadow prices can be computed only in relative terms

$$\frac{r_p}{r_{p'}} = \frac{\partial D_o(x,y)/\partial y_p}{\partial D_o(x,y)/\partial y_{p'}} \qquad P = 1, \ldots, P \quad (20)$$

To compute the absolute shadow prices, Färe and Grosskopf (1998) argue that one of the following assumptions must be used:

(i) a zero-profit assumption, which means that the actual (observed) costs equal the actual revenues. Then $R(x,r)$ can be substituted by the actual revenues and

$$p = R\frac{\partial D_o(x,y)}{\partial y_p} \qquad P = 1, \ldots, P \quad (21)$$

(ii) a market price assumption, which means that the shadow price of output p' equals the observed market price $\hat{r}_{m'}$. That is, $\hat{r}_{m'}$ is a reference price for the rest of shadow prices. Then

$$\hat{r}_{p'} = R(x,r)\frac{\partial D_o(x,y)}{\partial y_{p'}} \quad (22)$$

where $R(x,r)$ can be computed as $\hat{R} = \hat{r}_{p'}/\frac{\partial D_o(x,y)}{\partial y_{p'}}$ and for $p \neq p'$ we obtain the shadow price: $r_p = \hat{R}\frac{\partial D_o(x,y)}{\partial y_p}$ $P = 1, \ldots, P$. This market price approach is appropriate for specialized production, as is the case of our application.

DATA

The dataset was gathered from the Farm Accounting Data Network (FADN) database and includes all agricultural farms with non-zero cow's milk production in 2005–2010. Inputs are used as follows: x1 the total labour input, x2 land and permanent crops, x3 capital

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and x4 material and energy. Labour is represented by the total labour measured in AWU. Land is the total amount of the utilized land. Capital is the sum of the contract work and depreciation. Furthermore, the model considers the cows' milk production (y1), other animal production and crop production (y2) as the desirable outputs and the greenhouse gas emissions (y3) as the undesirable output.

The outputs (except for the greenhouse gas emissions), as well as inputs (except for labour and land) are deflated by the country price indices on each individual output and input (2005 = 100). The country price indices are taken from the EUROSTAT database.

The value of CO_2 eq. was determined based on Kiefer's (2015) study, which analysed the production of CO_2 eq. in milk production in Southern Germany. Compared to other studies, Kiefer's research best corresponds to the Czech milk production conditions. The value of CO_2 eq. was determined as the mean value of pasture-based farms (supplementary pasture feeder approach) value and the permanent indoor housing (milk yield optimizer approach) value. As Kiefer used the energy corrected milk units (ECM) in his study, the final value of CO_2 eq. per milk/kg for the developed model was adjusted accordingly. The ECM was calculated as follows (Casey and Holden 2005):

$$\text{ECM (kg)} = 0.25 \times \text{mass of milk (kg)} + 12.2 \times \text{fat (kg)} + 7.7\ \text{protein (kg)} \quad (23)$$

The values for fat and protein were adopted from Forman and Čurda (2001). Finally, the CO_2 equivalent per kg value for the developed model was determined as 1.735.

The basic characteristics of the dataset, presented in Table 2, show that the typical Czech dairy farm includes 113 ha of agricultural land and 40 workers and diversifies its production especially into the milk and crop production. The average dairy farm produces 1597 thousand kg of milk and 2056 thousand kg of the greenhouse gas emissions in CO_2 equivalent per year and sold its dairy production with an average price of 0.28 EUR per litre. The standard deviation points out that Czech dairy farms differ strongly, especially in the amount of capital and land use. On the other hand, milk prices differ only marginally. This suggests that whereas the farmers may negotiate for the input prices, they cannot efficiently affect the output price.

To sum up, the computation of shadow prices for the greenhouse gas emissions from the Czech dairy production is based on the approach of Färe and Grosskopf (1998). The Shephard's ODF is estimated with two desirable outputs (milk (y2) and other market products from plant and livestock production (y1)) and one undesirable output (greenhouse gas emissions (y3)).

To evaluate the effect of the ODF adjustment with an undesirable output, we estimate the ODF without the greenhouse gas emissions. Technical efficiency is estimated and compared with the value of TE estimated from the adjusted ODF with the undesirable output production.

RESULTS AND DISCUSSION

Table 3 provides parameter estimates of the ODF. As expected, almost all first-order parameters and the majority of second-order parameters are significant at the 1% significance level. The theoretical requirements suggest that the ODF should be non-decreasing, positively linearly homogenous and convex in outputs, as well as decreasing and quasi-convex in inputs (Coelli et al. 2005). In particular, the monotonicity requirements for outputs imply $\beta y_2 > 0$, $\beta y_3 > 0$ and $\beta y_2 + \beta y_3 < 1$; and for inputs, $\alpha x_k < 0$ for $k = 1, ..., K$. Convexity in inputs requires $\alpha_{kk} + \alpha_k^2 - \alpha_k > 0$ for $k = 1 ..., K$. Table 3 shows that these conditions are met.

Table 2. Descriptive statistics of the data set

Variable	Mean	Standard deviation	Variable	Mean	Standard deviation
Milk production (EUR)	478 403	489 572	AWU	40	40
Crop production (EUR)	550 151	657 052	Number of livestock units	245	226
Other animal production (EUR)	227 051	319 010	Land and permanent crops (ha)	113	1 003
CO_2 equivalent (kg)	2 056 341	2 095 036	Other material and energy (EUR)	534 783	611 457
Milk production (kg)	1 597 332	1 627 390	Specific material (EUR)	453 504	43 761
Milk yield (kg/cow)	6 058	1 641	Capital (EUR)	164 375	1 711 486
Milk price (EUR/l)	0.284	0.044			

Source: Own calculations

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Table 3. Parameters estimate – the output distance function (ODF) with undesirable output

Means for random parameters				Non-random parameters			
	coefficient	standard error	*p*-value		coefficient	standard error	*p*-value
Constant	–0.1678***	0.0053	0.0000	TT	–0.0008	0.0013	0.5154
T	–0.0004	0.0012	0.7266	Y2	0.5671***	0.0029	0.0000
X1	–0.2109***	0.0055	0.0000	Y3	0.3472***	0.0229	0.0000
X2	–0.1702***	0.0069	0.0000	Y2T	0.0023**	0.0011	0.0327
X3	–0.0690***	0.0042	0.0000	Y3T	0.0234**	0.0112	0.0369
X4	–0.5692***	0.0074	0.0000	Y22	0.1333***	0.0022	0.0000
Coefficients on unobservable fixed management				Y33	0.2819***	0.0884	0.0014
Constant	0.1947***	0.0024	0.0000	Y23	–0.0022	0.0156	0.8898
T	0.0048***	0.0009	0.0000	X1T	0.0076***	0.0027	0.0049
X1	–0.0545***	0.0053	0.0000	X2T	–0.0074**	0.0034	0.0307
X2	0.0438***	0.0058	0.0000	X3T	–0.0049***	0.0018	0.0054
X3	0.0064**	0.0032	0.0431	X4T	0.0011	0.0039	0.7898
X4	–0.0117	0.0076	0.1238	X11	–0.0130	0.0162	0.4226
α_{mm}	0.0396***	0.0038	0.0000	X22	–0.1250***	0.0090	0.0000
Variance parameter for v +/– u				X33	–0.0109**	0.0049	0.0253
Sigma	0.1766***	0.0025	0.0000	X44	0.0010	0.0295	0.9719
Asymmetry parameter, lambda				X12	0.1426***	0.0142	0.0000
Lambda	1.8709***	0.0997	0.0000	X13	–0.0463***	0.0072	0.0000
				X14	–0.0879***	0.0181	0.0000
				X23	–0.0095	0.0079	0.2275
				X24	0.0222	0.0165	0.1797
				X34	0.0543***	0.0095	0.0000
				Y2X1	–0.0355***	0.0049	0.0000
				Y2X2	0.0019	0.0050	0.6987
				Y2X3	–0.0105***	0.0029	0.0003
				Y2X4	0.0067	0.0060	0.2659
				Y3X1	0.0187	0.0401	0.6414
				Y3X2	–0.2052***	0.0417	0.0000
				Y3X3	0.0684**	0.0279	0.0142
				Y3X4	0.0574	0.0511	0.2606

***, **, * denotes significance at the 1%, 5%, and 10% levels respectively

Source: Own calculation

Since all variables are normalized in logarithm by their sample mean, the first-order parameters can be interpreted as the elasticity of production and as the shadow value share with respect to outputs evaluated on the sample mean. Considering the shares of outputs, the results show that the average farm diversified its production. The share of other desirable outputs is 57%. It is also obvious that the greenhouse gas emission is an important part of the milk production. The share of this undesirable output is 35%.

Comparing production elasticities, it can be concluded that the highest elasticity is for the material and energy inputs and the lowest is for capital. According to Čechura et al. (2014), this suggests that milk producers might have faced capital market imperfections. The sum of the input elasticities (1.0192) shows the presence of slightly increasing returns on scale, which indicates that the farmers operate at a slightly lower than optimal size. Finally, the parameter lambda is highly significant and higher than one. The variation in u_{it} is more pronounced than the variation in the random component v_{it}. This indicates that most of the deviation from the frontier of the input requirement set is due to technical inefficiencies rather than random shocks.

The average technical efficiency of dairy farms with respect to the greenhouse gas emission is 89.1%, with a standard deviation of 4.7%. When compared to the technical efficiency estimated from the ODF without an undesirable output (Figure 1), we can conclude that considering undesirable output does not affect

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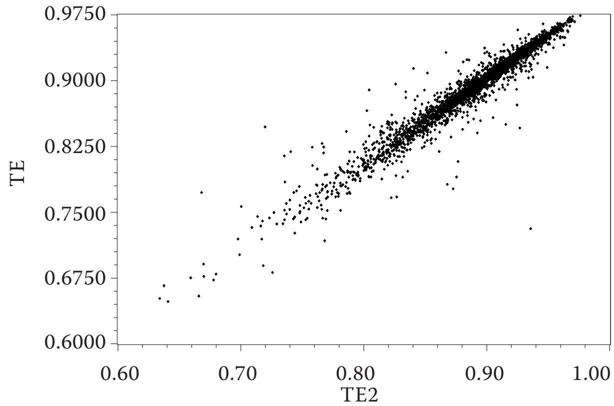

Figure 1. Relationship between technical efficiency (TE) estimated from the output distance function (ODF) without an undesirable output and from ODF with greenhouse gas

Source: Own calculations

the estimated technical efficiency (TE). The average value is 88.9% and the standard deviation is 4.8%. Differences lower that 1% between the TE with and without undesirable output presences is also observed in the research of Shortall and Barnes (2013), which is based on a DEA approach, the Scottish data and the greenhouse gas emissions in CO_2 eq.

Table 4 provides the distribution of technical efficiency in the analysed time period. The distribution is skewed to higher values, which suggests that the majority of producers highly exploit the production possibilities.

Table 4. Technical efficiency with the consideration of undesirable output into the output distance function (ODF) and the shadow price of greenhouse gas – distribution

Percentile	Technical efficiency	Shadow price of greenhouse gas
Min.	0.6481	0.0024
10^{th}	0.8284	0.0574
20^{th}	0.8557	0.0767
25^{th}	0.8661	0.0849
30^{th}	0.8753	0.0944
40^{th}	0.8891	0.1121
Med.	0.9012	0.1331
60^{th}	0.9109	0.1572
70^{th}	0.9202	0.1919
75^{th}	0.9252	0.2127
80^{th}	0.9309	0.2436
90^{th}	0.9415	0.3304
Max.	0.9740	0.5552

Source: Own calculation

Table 5. Shadow price of the greenhouse gas – development in the analysed time period

Year	Greenhouse gas price	Technical efficiency	Milk price
2005	0.1282	0.9106	0.2744
2006	0.1386	0.8992	0.2749
2007	0.1576	0.8860	0.3015
2008	0.1780	0.8457	0.3336
2009	0.2188	0.9150	0.2413
2010	0.2233	0.9044	0.2967

Source: Own calculations

We calculate the shadow price of the greenhouse gas by applying the Lagrange method and the Shephard's dual lemma. The average value of this price is 0.17 EUR per kg and the standard deviation is 0.11. Table 4 provides the distribution of the shadow price. The median is 0.13 EUR per kg, representing, according to Hadley (1998), the average loss in revenue incurred by a reduction of one kg of greenhouse gas, e.g. through the livestock feeding and genetics (Ross et al. 2014), the optimization of the lifetime of the herd, and the improvement in the manure application (Weiske et al. 2006). However, the variation in the sample is large. Moreover, Table 5 suggests that the mean value of the greenhouse gas shadow price is not stable over time.

The highest mean value was estimated in 2010 (0.22 EUR/kg). On the other hand, the lowest mean value was estimated in 2005 (0.13 EUR/kg). Overall, we can conclude that the shadow price of the greenhouse gas increased by 74% in the analysed time period.

Similar to the development of the greenhouse gas prices, the development of technical efficiency is not stable over time. However, the development of

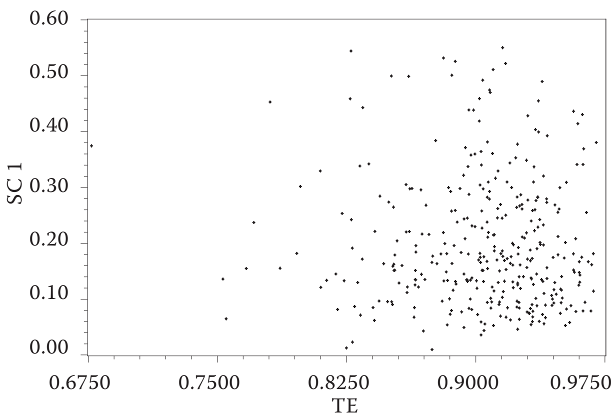

Figure 2. Relationship between technical efficiency (TE) and shadow price of greenhouse gas

Source: Own calculations

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Table 6. Shadow price of the greenhouse gas, technical efficiency and milk price – differences with respect to size

Size	Greenhouse gas price		Technical efficiency		Milk price		Share of milk production in the total production	
	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.
0–50 ha	0.3164	0.1121	0.8761	0.0690	0.2908	0.1202	0.6799	0.1413
51–100 ha	0.3338	0.1203	0.8775	0.0715	0.3042	0.1000	0.6322	0.1464
101–500 ha	0.2181	0.1360	0.8857	0.0579	0.2843	0.0490	0.5848	0.1394
>500 ha	0.1557	0.1028	0.8926	0.0443	0.2846	0.0385	0.4087	0.1268

Source: Own calculation

the greenhouse gas prices and technical efficiency do not suggest any common patterns. Furthermore, Figure 2 does not provide any significant evidence for the relationship between the greenhouse gas prices and technical efficiency. That is, our results do not confirm the result of Shortall and Barnes (2013), that a higher technical efficiency is connected with a higher environmental efficiency based on a reduction of the greenhouse gas emissions.

Our research also deals with the determinants of the greenhouse gas shadow price variation. The size of farm measured by the utilized agriculture area (UAA) was the first of our analysed determinants. Table 6 shows that the shadow price is the lowest in the large farms with the UAA higher than 500 ha. The mean value in this category was 0.16 EUR per kg. The shadow prices in this category were also the tightest around the group mean. Moreover, this group can also be characterized as the most technically efficient, in average; technical efficiency was estimated at 89% for this group. On the other hand, the highest mean value of the shadow price and also the highest variability was estimated in the group of farms with the UAA between 51–100 hectares, where the technical efficiency is also the lowest, in average (88%). This result can be connected with the specialization of dairy farms. According to the share of milk production in the total production level, large farms highly diversify their production. On the other hand, the farms with the UAA under 100 hectares can be characterized as highly specialized farms. The share of milk production of the total production is 63–68%, in average.

To confirm the result that specialized dairy farms are less technically efficient and have higher shadow prices for the greenhouse gas, we categorized farms according to their share of milk production in the total production level, and compared the mean values of the shadow prices and technical efficiency. Table 7 illustrates that significant differences in milk prices cannot be observed. The shadow price in highly specialized dairy farms, where the share of milk production in the total production is greater than 70%, is almost the same as in strongly diversified farms. The lowest value of the shadow price is within farms with the share of milk production in the total production higher than 50%.

Table 8 shows the differences in technical efficiency, the greenhouse gas price and milk prices with respect to farm intensification. Significant differences in milk prices cannot be observed. However, significant differences can be observed in the shadow prices for the greenhouse gas emissions and in technical efficiency among the analysed groups of farmers. The farms with a milk yield higher than 8000 kg are the most technically efficient farms in average, and also have the highest shadow price of the greenhouse gas.

Moreover, the higher the intensification, measured by milk yield, the higher the shadow price and the

Table 7. Shadow price of the greenhouse gas, technical efficiency and milk price – differences with respect to specialization

Milk production vs. total production	Greenhouse gas price		Technical efficiency		Milk price	
	mean	st. dev.	mean	st. dev.	mean	st. dev.
> 30%	0.1647	0.1104	0.8907	0.0479	0.2876	0.0457
> 50%	0.1628	0.1093	0.8855	0.0524	0.2947	0.0558
> 70%	0.1649	0.1117	0.8779	0.0563	0.3094	0.0950

Source: Own calculation

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Table 8. Shadow price of the greenhouse gas, technical efficiency and milk price – differences with respect to milk yield

Milk yield per year per cow	Greenhouse gas price		Technical efficiency		Milk price	
	mean	st. dev.	mean	st. dev.	mean	st. dev.
0–4000 kg	0.1336	0.1100	0.8591	0.0657	0.2842	0.0706
4001–6000 kg	0.1521	0.1083	0.8841	0.0493	0.2846	0.0418
6001–8000 kg	0.1700	0.1087	0.8980	0.0408	0.2853	0.0438
> 8000 kg	0.2014	0.1154	0.9032	0.0425	0.2864	0.0378

Source: Own calculation

higher technical efficiency. This is an important result for the policy makers to make note of. Potential policy measures focusing on the environmentally friendly technologies should take into account the greater loss of highly intensified dairy farms connected with the reduction of the greenhouse gas emissions.

CONCLUSION

This paper presents a fitted multiple output distance function with two market outputs and one non-market (undesirable) output – the greenhouse gas emissions as a negative public good. The results show that the shadow price differs significantly among producers, depending on several factors. Moreover, the mean value is not stable over time. This also holds true for technical efficiency. However, the development of the greenhouse gas price and technical efficiency do not suggest any common patterns. Furthermore, no evidence for the significant relationship between the greenhouse gas price and technical efficiency could be found. On the contrary, significant differences can be observed in the shadow prices for the greenhouse gas emissions among the analysed groups of farmers with respect to the degree of intensification in dairy production. Most notably, the higher the intensification, the higher the shadow price. Policy makers should consider the various production characteristics and production environments when discussing the price that should be paid for public goods in general. This can be supported by Berre et al. (2013), who found that the farmers are able to reduce pollution if the society accepts balancing out the farmers' opportunity costs.

The results of this paper are in line with Bokusheva and Kumbhakar (2014), who analysed other determinants influencing the shadow price of undesirable outputs in milk production. These authors focused on the nitrogen surplus, which is an example of a greenhouse gas. Based on the Färe and Grosskopf (1998) approach, and data from the Dutch dairy farms during the 2001–2009 period, these authors estimated the average shadow price of the nitrogen surplus at 12.4 EUR/1 kg. They also analysed the determinants that explained the variation of the shadow price. Based on a Tobit model, they concluded that lower values for the price of the nitrogen surplus are obtained from farms with a lower livestock density, a higher magnitude of off-farm manure and a lower investment rate. This indicates that further cuts in the nitrogen surplus due to switching to more environmentally-friendly systems are possible only at higher costs. Supposing that the aforementioned also holds for all greenhouse gases, it can be concluded that the policy measures focusing on the greenhouse gas reduction should be accompanied by subsidies covering the farmers' additional costs connected with the environmentally-friendly behaviour.

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