Environmentally integrated efficiency analysis of crop production systems in the Austrian Marchfeld region

Eine Integrative Effizienzanalyse von Pflanzenproduktionssystemen im Marchfeld

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Zusammenfassung

Im Rahmen der Studie führen wir Effizienzanalysen unterschiedlicher Bewirtschaftungssysteme in der Region Marchfeld anhand einer nichtparametrischen Directional Distance Function (DDF) Analyse und Data Envelopment Analyse (DEA) durch. Wir ermitteln eine relative Reihung der technischen Effizienz sowie der Profiteffizienz von alternativen Bewirtschaftungssystemen unter Berücksichtigung von Standortbedingungen (Klima), negativer Externalitäten (Stickstoffemissionen und Sedimenttransport), als auch positiver Externalitäten (Bodenkohlenstoffspeicherung). Die Effizienzanalysen werden mit Daten des bio-physikalischen Prozesssimulationsmodells EPIC (Environmental Policy Integrated Climate) durchgeführt. Die Ergebnisse zeigen, dass technisch effiziente und Profit effiziente Bewirtschaftungssysteme häufig minimale Bodenbearbeitung und geringere Düngungsmengen inkludieren. Ferner sind Felderbse und Zuckerrübe häufig in technisch effizienten und Profit effizienten Bewirtschaftungssystemen zu finden.

Schlagworte: alternative Bewirtschaftungssysteme, Effizienzanalyse, EPIC, Directional Distance Function Approach, Externalitäten

Summary

We apply a non-parametric Directional Distance Function (DDF) approach and Data Envelopment Analysis (DEA) techniques to evaluate technically efficient and profit efficient crop management systems for the Austrian Marchfeld region. We provide a ranking of

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technically and profit efficient crop production systems under consideration of site specific factors (climate), positive externalities (soil organic carbon stocks), and negative externalities (nitrogen emissions and soil sediment losses). Our model is based on simulation outputs from the bio-physical process model EPIC (Environmental Policy Integrated Climate). The integrated analysis reveals that field peas and sugar beets as well as minimum tillage, and lower fertilization rates are most often found in technically and profit efficient crop production systems.
Keywords: Agricultural production systems, EPIC, Directional Distance Function Approach, Externalities

1. Introduction

To support sustainable agricultural development it is important to know which crop production systems are technically and profit efficient considering positive and negative externalities of agricultural production. In this analysis we employ an environmentally integrated Directional Distance Function (DDF) approach and Data Envelopment Analysis techniques (DEA) to provide a single efficiency measure for alternative crop production systems. Thereby we account for positive agricultural externalities such as soil organic carbon stocks as well as negative externalities such as nitrate emissions and soil sediment losses, and alternative climate scenarios for the next 30 years. The respective crop production systems, which efficiencies are ranked in our analysis, are a combination of alternative crop rotations and crop residue systems as well as fertilization, irrigation, and straw management options. They are simulated with the bio-physical process model EPIC (Environmental Policy Integrated Climate) on different sites in the Austrian Marchfeld region.

The analysis focuses on the following research questions: Which crop production systems are technically and profit efficient in the Marchfeld region? Which crop management options seem to make production more beneficial compared to other options? How does the efficiency ranking change when various climate change scenarios are taken into account?

The article is structured as follows. In the next section the DDF method is presented followed by a description of the case study data. Results and conclusions are presented in the final section of this article.

2. Method

DDF is a data driven frontier analysis technique to model operational processes for performance evaluation. The traditional DEA model is a special case of the DDF employing linear programming techniques. It is used to estimate efficiencies of comparable entities, which are called decision making units (DMUs). A DMU can be any entity with the ability to convert one or multiple inputs into one or multiple outputs. DDF does not require specific functional assumptions on the production function, which is often restrictive in agricultural production analysis. Instead, it is a non-parametric method which uses linear programming models to construct a piece-wise surface frontier over the observations. The DMUs which exhibit best practice performance constitute the efficiency frontier of the group, against which the relative efficiencies of the remaining DMUs are measured to. The level of efficiency is identified by benchmarking them with DMUs lying on this frontier (cp. COELLI, et al., 2000). Thus, a DMU is rated technical efficient on the basis of available evidence if and only if the performances of other DMUs does not show that some of its inputs or outputs can be improved without worsening some of its other inputs or outputs (cp. COOPER et al., 2004). We apply a DDF approach presented by CHUNG et al. (1997) and FÄRE and GROSSKOPF (2004), which allows integrating undesirable agricultural outputs such as nitrogen emissions and soil sediment losses in the analysis.

$$\vec{D}(x^{k'}, y^{k'}, u^{k'}; g) = max\,\theta$$
$$\text{s.t.}$$
$$\sum_{k=1}^{K} x_{kn}\,\lambda_k \leq x_{k'n} \qquad n = 1, \dots, N$$
$$\sum_{k=1}^{K} y_{km}\,\lambda_k \geq y_{k'm} + \beta g_{y_m} \qquad m = 1, \dots, M \qquad (1)$$
$$\sum_{k=1}^{K} u_{kj}\,\lambda_k = u_{k'j} - \beta g_{u_j} \qquad j = 1, \dots, J$$
$$\lambda_k \geq 0, \qquad k = 1, \dots, K$$

In the model (equation system 1) there are $k = 1, \dots, K$ DMUs. Desirable outputs, $y \in \Re_+^M$ and undesirable outputs, $u \in \Re_+^K$, are producible from the input vector $x \in \Re_+^N$. A direction vector $g = (g_y, -g_u)$, with $g_y = y_k$ and $-g_u = u_{kj}$, is included, which ensures that the resulting efficiency value for each DMU is subject to the environmental constraint. The variable λ is a Kx1 vector giving the distance to the closest technically efficient DMU for each DMU. The β is a constant, which is the efficiency score for each DMU. Technical efficiency is indicated when $\beta = 0$; $\beta > 0$ indicates inefficiency and implies that the DMU can increase outputs without requiring more inputs in order to reach efficiency (FÄRE and GROSSKOPF, 2004).

3. Data description and model specification

The efficiency evaluation is based on simulation outputs from the bio-physical process model EPIC (Environmental Policy Integrated Climate; WILLIAMS, 1995; IZAURRALDE et al., 2006). EPIC simulates important bio-physical processes in agricultural land use management and thereby provides model outputs on e.g. crop yields, nitrogen emissions, soil organic carbon contents, and soil sediment losses. The simulation outputs integrate five thematic datasets: (i) land use data, (ii) topographical data, (iii) soil data, (iv) cropland management data, and (v) climate data.

For our efficiency analysis of crop production systems in the Marchfeld region, six crops which are typical for the region have been simulated within two crop rotation systems. The first crop rotation system includes corn, spring barley, sunflower and winter wheat and the second crop rotation system includes field peas, sugar beets as well as winter wheat. Both crop rotation systems have been simulated for 36 alternative crop management systems over a period of 65 years, from 1975 to 2040.

These crop management systems consist of a combination of (i) three alternative crop residue systems i.e. conventional, reduced, and minimum tillage, (ii) irrigation or rainfed management, (iii) optional straw removal, and (iv) three fertilization levels (standard fertilization according to Austrian guidelines for good agricultural production practices, high fertilization which is 20% higher than standard fertilization, and low fertilization which is 20% lower than standard fertilization). The crop rotations and crop management options constitute our crop production systems and consequently DMUs. In total, we have 1260 DMUs.

The EPIC simulations for the period 1975 to 2007 are based on historical daily weather observations in the Marchfeld. During this period, the average annual precipitation sum is 522 mm. The EPIC simulations for the period 2008 to 2040 are based on stochastic climate scenarios, which have been developed by STRAUSS et al. (2009). These climate scenarios constitute an increasing annual average temperature until 2040 and stochastic precipitation developments. For our analysis, we have selected two climate change scenarios, one with long-run average annual precipitations of 499 mm (low precipitation) and another with long-run average annual precipitations of 551 mm (high precipitation). In our efficiency analysis, we use average parameter values of the period 1975 to 2007 and refer to them as *historical period* as well as average parameter values for both climate change scenarios of the period 2008 to 2040 and refer to them as *future periods*.

To pursue our research questions we perform several variations of the efficiency models for the historical period as well as the future periods. We evaluate technical efficiency for the historical and future periods as well as profit efficiency for the historical period. The inputs to the physical models include nitrogen fertilizer in kg/ha and irrigation water in mm; desirable outputs include dry matter crop yields in t/ha, dry matter straw yields in t/ha, and topsoil organic carbon stocks in t/ha; and undesirable outputs are total nitrogen emissions in kg/ha, and soil sediment losses in t/ha.

In order to evaluate profit efficiency, the production costs including fertilizer, irrigation and straw removal, which are the input prices multiplied by the respective quantities used by the DMU as well as machinery costs per hectare. Revenues of crop and straw yields constitute the positive outputs as well as soil organic carbon stocks; negative environmental externalities of crop production are nitrogen emissions and soil sediment losses. Prices and costs are provided by BMLFUW (2009).

In all models, we assume constant returns to scale, as our main aim is to identify attributes of efficient crop production systems in relation to all feasible combinations of attributes, and not, as proposed under the variable returns to scale constraint, in relation to DMUs of similar size.

4. Results

The efficiency results of each model are categorized in five efficiency classes. The first class includes DMUs which are rated fully efficient and constitute the efficiency frontier against which the efficiency of the remaining DMUs are measured to. DMUs found in the 2nd class can increase their outputs by up to 20% compared to the most efficient rated DMUs. In the 3rd class and 4th class output increases between 20-

40% and 40-60% are feasible. In the least efficient class, DMUs can increase their output by more than 60% compared to the most efficient rated DMUs. In the following analysis, we are only interested in the attributes of crop management systems found in the highest and lowest efficiency class.

The efficiency results of the historical period 1975-2007 reveal that about 12% of all DMUs are rated technically efficient. Management systems which are found in the highest efficiency class usually include minimum tillage systems (57%) followed by conventional tillage (26%) and reduced tillage systems (17%). This is not surprising as minimum tillage results in higher levels of soil organic carbon and lower levels of nitrate emissions compared to other tillage systems in the analysis. In the least efficient class, crop management systems which include minimum tillage systems are not found at all; instead the proportion of management systems with conventional tillage is 79% and with reduced tillage 21%. In the highest efficiency class, crop management systems with low fertilizer levels are more often found (61%) compared to the standard fertilization (19%) and high fertilization rates (20%).

Concerning the crop cultivation choices, our results (cp. Figure 1) reveal that crop rotation systems which include field peas, winter wheat, and sugar beets are found in the highest efficiency class. Field peas are legumes and do not necessarily require nitrogen fertilizer as input. Field peas in combination with minimum tillage also exhibits low levels of nitrogen emissions and a relatively high level of soil organic carbon stocks, which explains their dominance in the highest efficiency class.

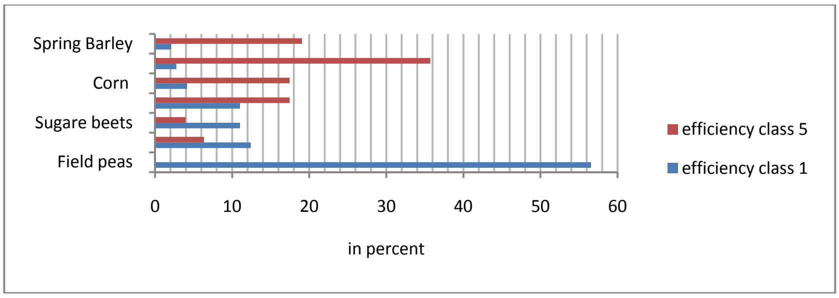

Figure 1: Percentages of crops found in the highest and lowest efficiency classes

In the lowest efficiency class, there are no crop management systems including field peas and only 3% including sugar beets. Instead systems which include sunflower and spring barley are found to a proportion of 36% and 19% in the least efficiency class, respectively. In the highest efficiency class, 25% of all crop production systems have straw harvests (systems including spring barley and winter wheat).

In the highest efficiency class, the proportion of irrigated crop management systems amounts to 51%. However, out of these irrigated crop management systems more than half (57%) have included field peas, which are annually irrigated with 30 mm. Crop production systems with annual irrigation amounts of 120 mm, such as corn and sugar beets, are only found to a proportion of 7% and 9%. Also crop production systems with 60 mm annual irrigation amount (i.e. with winter wheat, sunflower, and spring barley), are found to relatively low proportions of 27% in the highest efficiency class. In contrast, in the lowest efficiency class, crop production systems with irrigation dominate with 53%. However, within this class only crop production systems are found which have higher irrigation amounts of 60 mm (84%) and 120 mm (16%). It shall be noticed that irrigation amounts are assumed to be crop specific and constant.

Similar analyses have been performed for the future period from 2008 to 2040 for the high and low annual precipitation scenarios.

Tab.2: Summary statistics of efficiency values of historic and future period (n = 1260)

	Mean	Std. Dev.	Min	Max
historical period	0.30	0.22	0	0.78
future period (low precipitation)	0.32	0.23	0	0.85
future period (high precipitation)	0.30	0.22	0	0.81

The efficiency analysis has been separately conducted for both future periods. Mean efficiency values of future period with lower precipitation as well as standard deviation and maximum efficiency values in both future periods are higher than in the historical period. This implies an increasing inefficiency on average (cp. Table 2). However, the attributes of the management systems found in the highest efficiency class are approximately the same: crop management systems with minimum tillage and low fertilization dominate in the highest efficiency class. In the lowest efficiency class, crop management systems with conventional tillage, and high fertilizer input are found.

Also the trends for crop cultivation are similar to the historical period: field peas, followed by and sugar beets, dominates in the highest efficiency class, whereas sunflower and spring barley dominate in the lowest efficiency class. In the efficiency analyses for the future periods, approximately 20% of crops with straw removal are found in the highest efficiency class in the lower precipitation scenario, and about 17% in the higher precipitation scenario. Concerning irrigation, in the lower precipitation scenario, 57% of crop production systems feature irrigation management in the highest efficiency class; in the higher precipitation scenario, 54% of crop production systems with irrigation are found in the highest efficiency class. In both scenarios, crop management systems with comparably low amounts of irrigation are rather found in the highest efficiency class than in the lowest class.

Finally, profit efficiency is determined for the historical period. This model takes into account input costs and output prices. The properties of DMUs found in the highest profit efficiency class are similar to the properties found in the technical efficiency analysis. However, the proportion of conventional tillage systems is lower (7%) and the proportion of minimal tillage higher (66%) than in the technical efficiency analysis. As expected the proportion of production systems with low fertilizer application rates dominate in the highest efficiency class with 56%. In contrast to the technical efficiency analysis, management systems without irrigation are more often found in the highest profit efficient class (68%). Concerning the crops cultivated in the highest efficiency class, the results remain similar: field peas dominate in the highest efficiency class (62%) followed by sugar beets (19%). In the highest efficiency class, only for 10% of all crops straw removal is feasible (i.e. winter wheat and spring barley). Both proportions are lower than found in the highest efficiency class of the technical efficiency analysis. This seems intuitive since straw removal not only entails additional revenues, but also additional costs. An interesting difference shall be noted in the lowest efficiency class, where management systems with sunflower cultivation are not dominating, but merely constitute a proportion of 10%, whereas management systems with spring barley constitute 43% and systems with corn 38%.

5. Conclusion

The results of technical and profit efficiency of crop management systems show interesting similarities: crop management systems with minimum tillage systems, low fertilizer application rates and irrigation are most often rated technically and profit efficient, along with crop management systems with field peas and sugar beets. The lowest efficiency class includes management systems which can increase their output by over 60% without increasing their inputs under consideration of environmental externalities. In this class, mainly crop management systems with conventional tillage, and high fertilizer application rates, as well as sunflower and spring barley are found.
Considering climate change in the next thirty years, these patterns seem to remain, but the efficiency values decrease and an augmentation of management systems which can increase their outputs compared to technically efficient DMUs can be expected.
Performing an analysis of profit efficiency, which takes into account input costs and market prices for outputs, a similar ranking is shown. However, the proportion of management systems with straw removal, conventional tillage and irrigation decreases in the highest efficiency class, which can be explained by the additional costs. Overall, the results confirm that the attributes of technically efficient crop production systems remain the same over various climate scenarios. However, efficiencies decline, which points to the necessity to adapt crop production systems to the changing climate conditions.

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