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# Approach for determining the eco-efficiency of sugar beet cultivation in Germany

Ansatz zur Ermittlung der Öko-Effizienz im Zuckerrübenanbau in Deutschland

## Abstract

The eco-efficiency concept, originally developed as a business model, seems also appropriate to point out options for sustainable development in crop production. Thus, the study aimed to introduce a system of indicators in order to describe the current eco-efficiency of sugar beet cultivation. In addition, the relation between production intensity and yield performance of sugar beet was analyzed.

In Germany, sugar beet cultivation of 109 farms with 232 fields in 2004 was surveyed across all growing areas. In our study, the operations tillage, fertilizer application, plant protection and harvest were considered. Energy input of tillage, N fertilizer rate, standardized treatment index of pesticide use and soil tare were used to reflect production intensity and environmental impact. These indicators were related to yield performance, i.e. white sugar yield (WSY) and aggregated to an index. This index reveals the range of eco-efficiency of sugar beet production in Germany in 2004.

On the field level, energy input of tillage, N fertilizer rate, standardized treatment index, soil tare and WSY (6-15 t $ha^{-1}$) were highly variable. Therefore, eco-efficiency varied considerably, too. A positive relation was given between soil tare and WSY. However, energy input of tillage, N fertilizer rate and standardized treatment index did not correlate with WSY. It was thus proved that WSY was independent of production intensity. But the effect of the farm (including crop management, site, weather, soil and their interactions) on WSY was highly significant.

In the short run, the most effective way to increase eco-efficiency is to reduce production intensity, which is not necessarily associated with a yield decrease. In the long run, continuously increasing yield will continuously enhance eco-efficiency of sugar beet cultivation.

**Key words:** Eco-efficiency, sugar beet, farm survey, indicators, white sugar yield, energy input of tillage, N fertilizer rate, pesticide use index, soil tare, *Beta vulgaris* L.

## Zusammenfassung

Das Öko-Effizienzkonzept wurde ursprünglich als produktbezogenes Modell für Wirtschaftsunternehmen entwickelt. Es scheint aber auch geeignet, Optionen für eine nachhaltige Entwicklung in der Pflanzenproduktion aufzuzeigen. Ziel dieser Untersuchung war es daher, mit Hilfe eines Indikatorensystems die derzeitige Öko-Effizienz im Zuckerrübenanbau zu beschreiben. Darüber hinaus wurde das Verhältnis zwischen Produktionsintensität und Ertragsleistung von Zuckerrüben analysiert.

Insgesamt wurden 109 Betriebe mit 232 Schlägen aus allen Anbauregionen in Deutschland zur Gestaltung des Zuckerrübenanbaus 2004 befragt. Berücksichtigt wurden die Maßnahmen Bodenbearbeitung, Düngung, Pflanzenschutz und Ernte. Um Produktionsintensität und Umweltwirkungen abzubilden wurden der Energieaufwand für die Bodenbearbeitung, die N-Düngung, der Behandlungsindex für die Pflanzenschutzintensität und der Erdanteil verwendet. Diese Indikatoren wurden ins Ver-

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hältnis zur Ertragsleistung, d.h. zum Bereinigten Zuckerertrag, gesetzt und zu einem Index aggregiert. Der Index zeigt eine erhebliche Variation der Öko-Effizienz im Zuckerrübenanbau 2004 in Deutschland.

Auf Schlagebene variierten der Energieaufwand für Bodenbearbeitung, die Höhe der N-Düngung, der Behandlungsindex, der Erdanhang und der Bereinigte Zuckerertrag (6-15 t $ha^{-1}$) deutlich. Dadurch variierte auch die Öko-Effizienz erheblich. Zwischen Erdanhang und Bereinigtem Zuckerertrag gab es eine positive Korrelation. Dagegen zeigten Energieaufwand für Bodenbearbeitung, Höhe der N-Düngung und Behandlungsindex keinen Zusammenhang mit dem Bereinigten Zuckerertrag. Damit wurde nachgewiesen, dass die Höhe des Bereinigten Zuckerertrags nicht mit der Produktionsintensität zusammenhängt. Im Gegensatz dazu war der Einfluss des Betriebs (zusammengesetzt aus den Faktoren Anbaugestaltung, Standort, Witterung, Boden und deren Interaktionen) auf den Bereinigten Zuckerertrag hoch signifikant.

Kurzfristig lässt sich die Öko-Effizienz am wirksamsten erhöhen, in dem die Produktionsintensität reduziert wird, was nicht zwangsläufig zu Ertragsverlusten führt. Auf Dauer führen kontinuierlich steigende Erträge zu einer kontinuierlichen Erhöhung der Öko-Effizienz.

**Stichwörter:** Öko-Effizienz, Zuckerrüben, Betriebsbefragung, Indikatoren, Bereinigter Zuckerertrag, Energieaufwand Bodenbearbeitung, N-Düngung, Aufwand Pflanzenschutzmittel, Erdanhang, *Beta vulgaris* L.

## Introduction

Present strategies for a sustainable development in agriculture trace back to the Agenda 21, passed by more than 170 nations at the UN Conference on Environment and Development in Rio in 1991 (UNCED, 1992). Agenda 2000 (EC COMMISSION, 1999), the action programme of the European Commission, emphasized environmental goals for European agriculture. Common Agricultural Policy (CAP) consequently made direct payments dependent on compliance with environmental targets ('cross-compliance') (EC REGULATION 1782, 2003). Since the reform of the EU sugar regime in 2005, sugar beet belongs to the general regulations of CAP.

The eco-efficiency concept was first introduced in 1992 by the World Business Council for Sustainable Development as a business concept for a sustainable development. Eco-efficiency requests businesses to achieve more value from lower inputs of raw materials and energy and with reduced emissions (VERFAILLIE and BIDWELL, 2000). The concept was internationally adopted for numerous industrial applications (SALING et al., 2002; DE SIMONE and POPOFF, 1997).

Eco-efficiency is typically measured as product or service value divided by the environmental influence. Generally applicable indicators for product or service value as the quantity of goods or services produced or provided to customers or net sales were related to indicators for environmental influence. In our study, the inverse of this formula was used for more transparency following the WBCSD's position that the substantial information contained in both is the same (VERFAILLIE and BIDWELL, 2000).

In agriculture, the efficient use of resources is one of the major challenges towards a sustainable development of production methods. The eco-efficiency concept relates input representing environmental impact to output representing yield performance. Eco-efficiency of e.g. wheat and barley production in Australia (MCGREGOR et al., 2004), farming systems in general (WILKINS, 2007) and dairy, arable and pig farms in Flanders (MEUL et al., 2007a, b) was already analyzed.

The intensity of agricultural production can be assessed by quantifying inputs such as mechanization, fertilizer rates and pesticide use (HERZOG et al., 2006). Some studies claim that sugar beet cultivation is highly intensive (EC COMMISSION, 2003; SRU, 2004), but this evaluation is insufficiently proven. A few aspects of cultivation intensity were previously described in an expert survey (MERKES et al., 1996, 2003), but without regarding the individual farm management. Yield data are regularly collected by sugar factories in Germany (FUCHS et al., 2008). To date, agronomic measures of sugar beet cultivation and yield were not recorded and evaluated on a field level in Germany. Consequently, the aims of the present study were:

a) to analyze the relation between production intensity of sugar beet cultivation and yield performance and
b) to introduce a system of indicators in order to describe the current eco-efficiency of sugar beet cultivation in Germany.

The study was based on a survey of farms across all sugar beet growing areas in Germany. It comprised a set of indicators for the operations tillage, fertilizer application, plant protection, developed in a co-project (REINEKE and STOCKFISCH, 2008), and harvest. Indicators were used for assessing the environmental impact of sugar beet cultivation. In addition, the importance of farm management for the different operations was estimated by an analysis of covariance.

## Materials and methods

The sugar beet cultivation on 232 fields representing 109 farms throughout Germany was surveyed in 2004. For three fields per farm at maximum, information on yield and quality, and agronomic measures of sugar beet production were collected for all operations after harvest of the preceding crop in 2003 until beet harvest 2004 (STOCKFISCH et al., 2008).

*Operation-specific indicators*

Production intensity and environmental impact of sugar beet cultivation are represented by operation-specific indicators. For tillage the direct fossil energy input (0.0396

GJ $l^{-1}$ diesel) of all tillage operations was considered (HÜLSBERGEN, 2003). For indirect energy inputs the standard value of 0.012 GJ $l^{-1}$ diesel for the energy needed for the manufacturing of tractors and field machinery was taken into account (DALGAARD et al., 2001).

Fertilizer application is expressed by nitrogen (N) fertilizer rate (kg $ha^{-1}$). Many different types of organic manures were used on 35% of the fields, including manure from pigs, cows or sheep, compost, slurry and poultry manure. For organic manures, standard values of N-concentration were used and the amount of N (kg $ha^{-1}$) mineralized from organic manures and available for sugar beet during the growing period was taken into account (KOLBE, 2006; LWK, 2009). This procedure seemed accurate enough because of the broad range of N fertilizer rate for maximum white sugar yield (WSY) (MÄRLÄNDER, 1990).

Standardized treatment index (STI) was the indicator of plant protection. It is a fixed indicator for the quantification of pesticide use in agriculture in Germany (BMVEL, 2004). STI regards the number of pesticides (active ingredients plus inert ingredients) used and their actual application rate per ha in relation to (i) the registered maximum rate for application fixed by the official national authority (BVL, 2008) and (ii) the percentage of the treated area in relation to the total area (ROSSBERG et al., 2002, 2007; SATTLER et al., 2007). Reduced dosages and non-spraying of field parts lower the index value (BÜRGER et al., 2008). As a convention, the application of insecticides and fungicides in the pelleted seed was not considered by STI.

Soil tare (t $ha^{-1}$) is the soil adhering to the beet root and delivered to the sugar factory. Here, it was used as an indicator of harvest. The definition of soil tare followed RUYSSCHAERT et al. (2004), as shown in Eq. (1):

$$\text{Soil tare} = \text{mass of soil} + \text{mass of soil moisture} + \text{mass of rock fragments} \quad (1)$$

Information provided by the delivery notes of the sugar factories differed in detail, but constantly contained the parameter total tare (%). Soil tare (t $ha^{-1}$) was calculated by subtracting root yield from gross root yield and discounting 3.5% for leaves and crowns.

*Yield performance*

The yield performance of sugar beet was expressed by white sugar yield calculated according to MÄRLÄNDER et al. (2003) (Eq. 2).

$$WSY = \frac{RY \cdot (SC - SML - SFL)}{100} \quad (2)$$

WSY: White sugar yield (t $ha^{-1}$)
RY: Root yield (t $ha^{-1}$)
SC: Sugar content (%)
SML: Standard molasses loss (%)
SFL: Standard factory loss (constant at 0.6%)

Detailed information on the natural conditions and the organisation of the surveyed farms is given in Tab. 1. The farms were grouped by their mean WSY into top 25%, medium 50% and bottom 25% as usually carried out in economic farm comparisons (TRENKEL, 1999). Soil fertility score gives information about the productivity of the

**Tab. 1. Characterization of the surveyed farms (n = 109); farms grouped by white sugar yield, median for each group of farms and for all farms**

*Charakterisierung der untersuchten Betriebe (n = 109); Betriebe gruppiert nach Bereinigtem Zuckerertrag, Mediane für die einzelnen Betriebsgruppen sowie für alle Betriebe*

| | Top 25% | Medium 50% | Bottom 25% | All |
|---|---|---|---|---|
| White sugar yield (t $ha^{-1}$) [a] | 11.7 | 10.2 | 8.7 | 10.3 |
| Field size (ha) [a] | 5 | 9 | 12 | 9 |
| Annual precipitation (mm) [a] | 650 | 620 | 550 | 620 |
| Annual temperature (°C) [a] | 8.5 | 8.5 | 8.7 | 8.6 |
| Soil fertility score (max. productivity = 100) [a] (min/max) | 69 (30/90) | 68 (25/95) | 50 (27/82) | 65 (25/95) |
| Livestock rate (%) | 15 | 24 | 33 | 24 |
| Arable land (ha) [a] | 120 | 214 | 297 | 208 |
| Sugar beet growing acreage (ha) [a] | 27 | 36 | 47 | 32 |
| Percentage of sugar beet growing acreage [a] (% of arable farmland) | 19 | 19 | 11 | 16 |

[a] Median

surveyed fields in relation to maximum productivity in Germany (AD-HOC-AG BODEN, 2005).

*Eco-efficiency criteria*

Eco-efficiency criteria were calculated field-specifically for the operations tillage, fertilizer application, plant protection (n = 232 fields) and harvest (n = 224 fields due to missing data) following Eq. 3:

$$eco\text{-}efficiency = \frac{operation\text{-}specific\ indicator}{WSY} \quad (3)$$

The denominator contained the operation-specific input indicators representing production intensity and environmental impact, whereas the numerator contained WSY representing yield performance.

*Eco-efficiency index*

The total eco-efficiency of sugar beet cultivation was finally composed field-specifically from the eco-efficiency criteria for tillage, fertilizer application, plant protection and harvest. The absolute value of each single eco-efficiency criterion was normalized by setting the mean for all 224 fields of every eco-efficiency criterion to 100. The four relative values were summarized as an eco-efficiency index (EEI) and indicate the deviation in percent from the operation-specific mean. The EEI weighted the four eco-efficiency criteria by 25% each, due to a lack of a solid base to distinguish different environmental impacts of single operations (BRENTRUP et al., 2001).

*Statistical analysis*

Statistical analysis was carried out using the SAS 9.1 statistical package (SAS Institute Inc., Cary, NC, USA). A linear regression analysis was made with the SAS procedure CORR calculating Pearson's correlation coefficients. The analysis of covariance (ANCOVA) was conducted with the General Linear Model procedure of SAS using only data of 58 farms. These farms featured three surveyed sugar beet fields that were available as replicates. Energy input of tillage, N fertilizer rate and STI were supposed to have additional effects on WSY. Thus, ANCOVA was performed separately for each covariate. Degrees of freedom were reduced for the interactions between farm and covariate where identical treatments across all fields (replicates) of one farm occurred. The effect of the farm subsumed crop management, site, weather, soil and their interactions.

## Results

On the field level, WSY of sugar beet ranged from 5.8 to 15.1 t ha$^{-1}$ and energy input of tillage from 1.0 to 6.3 GJ ha$^{-1}$ (Fig. 1). Energy efficiency (of tillage) was below 0.21 GJ t$^{-1}$ WSY for the 25% most efficiently managed fields (n = 58), between 0.21 and 0.33 GJ t$^{-1}$ WSY for the medium 50% (n = 116) and above 0.33 GJ t$^{-1}$ WSY for the 25% least efficiently managed fields (n = 58). N fertilizer rate varied between 38 and 317 kg ha$^{-1}$ (Fig. 2). N fertilizer efficiency was below 9.1 kg N t$^{-1}$ WSY for the 25% most efficiently managed fields, between 9.1 and 15.9 kg

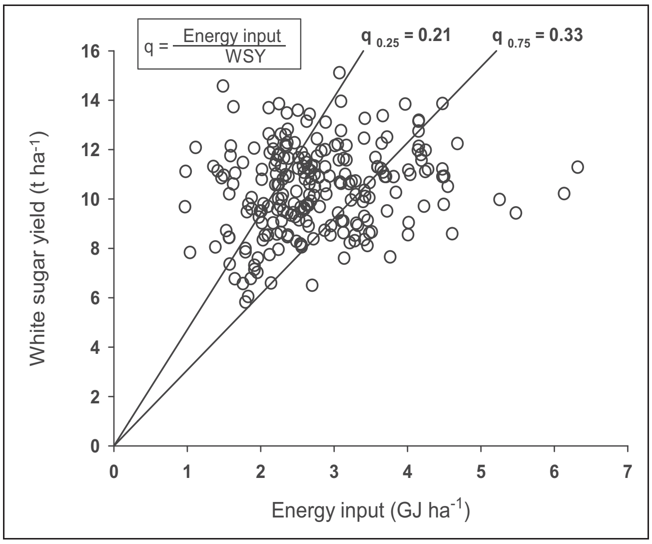


**Fig. 1.** White sugar yield (WSY) and energy input of tillage in sugar beet in Germany 2004 (n = 232 fields). Isoquants (q; GJ t$^{-1}$ WSY) of equal efficiency for energy input per WSY. 25% most efficiently managed fields ≤ $q_{0.25}$; 25% least efficiently managed fields ≥ $q_{0.75}$.
*Bereinigter Zuckerertrag (WSY) und Energieaufwand für die Bodenbearbeitung im Zuckerrübenanbau in Deutschland 2004 (n = 232 Schläge). Isoquanten (q; GJ t$^{-1}$ WSY) geben gleiche Effizienz des Energieaufwands bezogen auf den Bereinigten Zuckerertrag wieder. Schläge mit 25% höchster Effizienz ≤ q0.25; Schläge mit 25% geringster Effizienz ≥ q0.75.*

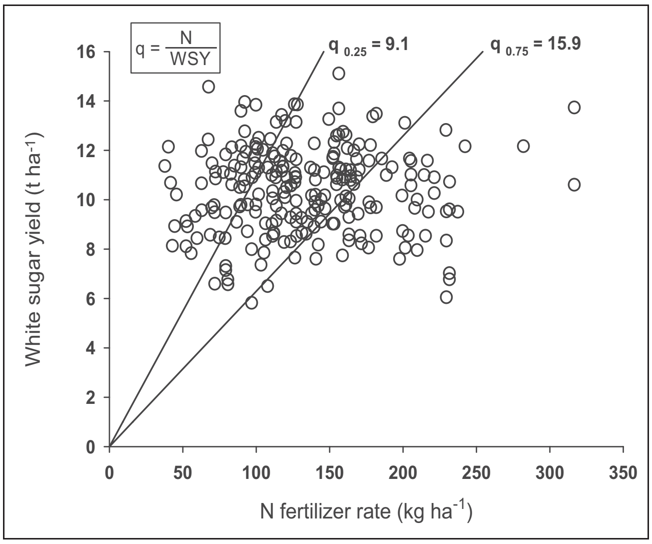


**Fig. 2.** White sugar yield (WSY) and N fertilizer rate in sugar beet in Germany 2004 (n = 232 fields). Isoquants (q; kg N t$^{-1}$ WSY) of equal efficiency for N fertilizer rate per WSY. 25% most efficiently managed fields ≤ $q_{0.25}$; 25% least efficiently managed fields ≥ $q_{0.75}$.
*Bereinigter Zuckerertrag (WSY) und Höhe der N-Düngung im Zuckerrübenanbau in Deutschland 2004 (n = 232 Schläge). Isoquanten (q; kg N t$^{-1}$ WSY) geben gleiche Effizienz der N-Düngung bezogen auf den Bereinigten Zuckerertrag wieder. Schläge mit 25% höchster Effizienz ≤ q0.25; Schläge mit 25% geringster Effizienz ≥ q0.75.*

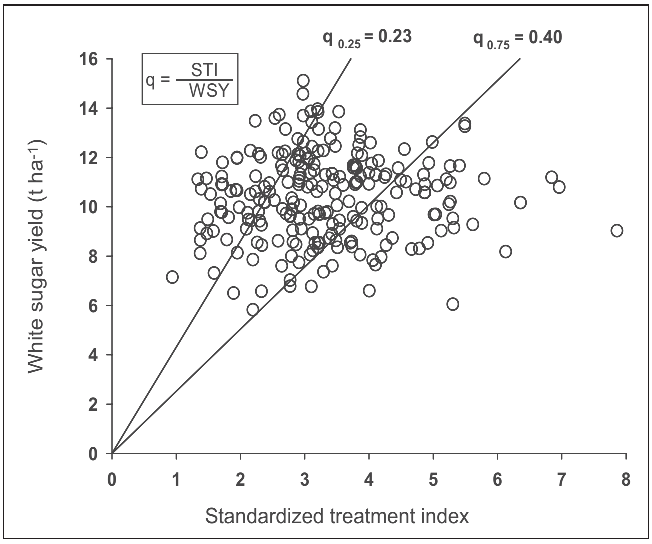


**Fig. 3.** **White sugar yield (WSY) and standardized treatment index (STI) in sugar beet in Germany 2004 (n = 232 fields). Isoquants (q; STI $t^{-1}$ WSY) of equal efficiency for STI per WSY. 25% most efficiently managed fields ≤ $q_{0.25}$; 25% least efficiently fields managed ≥ $q_{0.75}$.**
*Bereinigter Zuckerertrag (WSY) und standardisierter Behandlungsindex (STI) im Zuckerrübenanbau in Deutschland 2004 (n = 232 Schläge). Isoquanten (q; STI $t^{-1}$ WSY) geben gleiche Effizienz für den Behandlungsindex bezogen auf den Bereinigten Zuckerertrag wieder. Schläge mit 25% höchster Effizienz ≤ q0.25; Schläge mit 25% geringster Effizienz ≥ q0.75.*

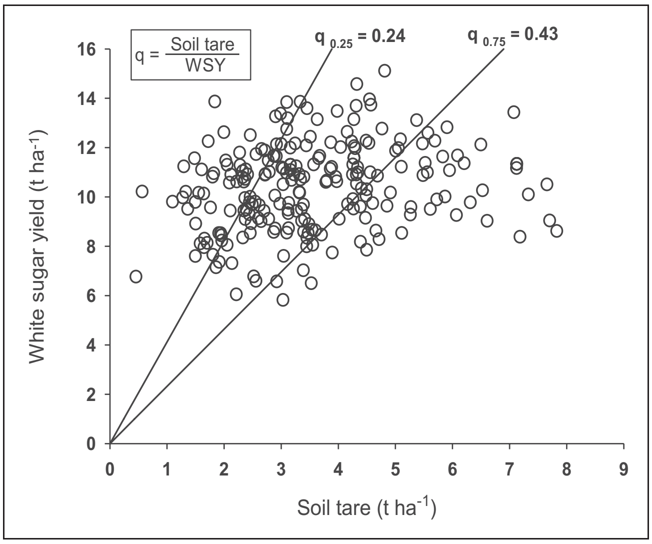


**Fig. 4.** **White sugar yield (WSY) and soil tare in sugar beet in Germany 2004 (n = 224 fields). Isoquants (q; t $t^{-1}$ WSY) of equal efficiency for soil tare per WSY. 25% most efficiently managed fields ≤ $q_{0.25}$; 25% least efficiently managed fields ≥ $q_{0.75}$.**
*Bereinigter Zuckerertrag (WSY) und Erdanhang bei Zuckerrüben in Deutschland 2004 (n = 224 Schläge). Isoquanten (q; t $t^{-1}$ WSY) geben gleiche Effizienz für den Erdanhang bezogen auf den Bereinigten Zuckerertrag wieder. Schläge mit 25% höchster Effizienz ≤ q0.25; 25% Schläge mit 25% geringster Effizienz ≥ q0.75.*

N $t^{-1}$ WSY for the medium 50% and above 15.9 kg N $t^{-1}$ WSY for the 25% least efficiently managed fields. STI varied between 0.9 and 7.9 (Fig. 3). STI per WSY as an indicator for plant protection efficiency was below 0.23 $t^{-1}$ WSY for the 25% most efficiently managed fields, between 0.23 and 0.40 $t^{-1}$ WSY for the 50% medium and above 0.40 for the 25% least efficiently managed fields. Soil tare varied between 0.5 and 7.8 t $ha^{-1}$ (Fig. 4). Soil tare efficiency was below 0.24 t $t^{-1}$ WSY for the 25% most efficiently managed fields (n = 56), between 0.24 and 0.43 t $t^{-1}$ WSY for the 50% medium (n = 112) and above 0.43 t $t^{-1}$ WSY for the 25% least efficiently managed (n = 56).

Considering all fields included in the survey, the relation between energy input of tillage and WSY (r = 0.19) was very weak (Tab. 2). N fertilizer rate and STI showed no correlation with WSY. A slight relation was given between soil tare and WSY. STI correlated slightly with energy input of tillage and N fertilizer rate.

For a subgroup of 58 farms featuring 3 fields each as replicates, the effect of the farm, composed of the effects management, site, weather, soil and their interactions, on WSY was highly significant (Tab. 3). None of the covariables energy input of tillage, N fertilizer rate and STI had a significant effect on WSY. The interactions between farm and energy input of tillage, N fertilizer rate or STI were not significant.

The total eco-efficiency index (EEI) of sugar beet cultivation representing 224 fields in Germany ranged from -371 (lowest eco-efficiency) to 198 (highest eco-efficiency) (Fig. 5). In most cases, single EEI values for at least three operations were below the operation-specific mean for the 25% least efficiently managed fields (n = 56). For the medium 50% (n = 112), there were amplitudes in both directions which compensated for each other. Typically, the 25% most eco-efficiently managed fields (n = 56) reached above average EEI values in three out of four operations.

**Tab. 2.** **Pearson's coefficients of correlation (r) for white sugar yield (WSY) and operation parameters (n = 224 or 232 fields)**
*Pearson Korrelationskoeffizienten (r) für Bereinigten Zuckerertrag (WSY) und Bewirtschaftungsmaßnahmen (n = 224 oder 232 Schläge)*

| | White sugar yield ($t\ ha^{-1}$) | Energy input of tillage ($GJ\ ha^{-1}$) | N-fertilizer rate ($kg\ ha^{-1}$) | STI |
|---|---|---|---|---|
| Energy input of tillage ($GJ\ ha^{-1}$) | 0.19** | | | |
| N-fertilizer rate ($kg\ ha^{-1}$) | 0.05 ns | -0.03 ns | | |
| Standardized treatment index (STI) | 0.05 ns | -0.15 * | 0.22*** | |
| Soil tare ($t\ ha^{-1}$) | 0.23*** | 0.02 ns | 0.05 ns | 0.03 ns |

*, **, *** Significant at p ≤ 0.05, 0.01 and 0.001; ns = not significant

**Tab. 3. Analyses of covariance for the effects of energy input of tillage, N fertilizer rate and standardized treatment index (STI) of plant protection on white sugar yield (WSY) of sugar beet (n = 58 farms); in each case regarding the effect of the farm**
*Kovarianzanalysen der Effekte von Energieaufwand für die Bodenbearbeitung, N-Düngung und standardisiertem Behandlungsindex (STI) des Pflanzenschutzes auf den Bereinigten Zuckerertrag (WSY) von Zuckerrüben (n = 58 Betriebe); jeweils unter Berücksichtigung des Faktors Betrieb*

| Effect | DF | MS | F-Value |
|---|---|---|---|
| Farm | 57 | 6.29 | 4.09*** |
| Energy input of tillage | 1 | 0.35 | 0.23 |
| Energy input of tillage x farm | 56 [a] | 1.88 | 1.23 |
| Farm | 57 | 6.29 | 3.60*** |
| N-fertilizer rate | 1 | 1.83 | 1.05 |
| N-fertilizer rate x farm | 44 [a] | 1.61 | 0.92 |
| Farm | 57 | 6.29 | 4.35*** |
| STI | 1 | 0.93 | 0.64 |
| STI x farm | 54 [a] | 1.98 | 1.37 |

*, **, *** significant at $p \leq 0.05$, 0.01 and 0.001; ns = not significant
[a] DF are reduced due to identical treatments across all fields of a farm

For the 58 farms with three surveyed sugar beet fields the coefficient of variation for the EEI was on average 16.1%. For the majority of farms, all three fields were in the same group (top or bottom 25%, medium 50% fields). However, it also occurred that the three fields split up in two or three groups (not shown).

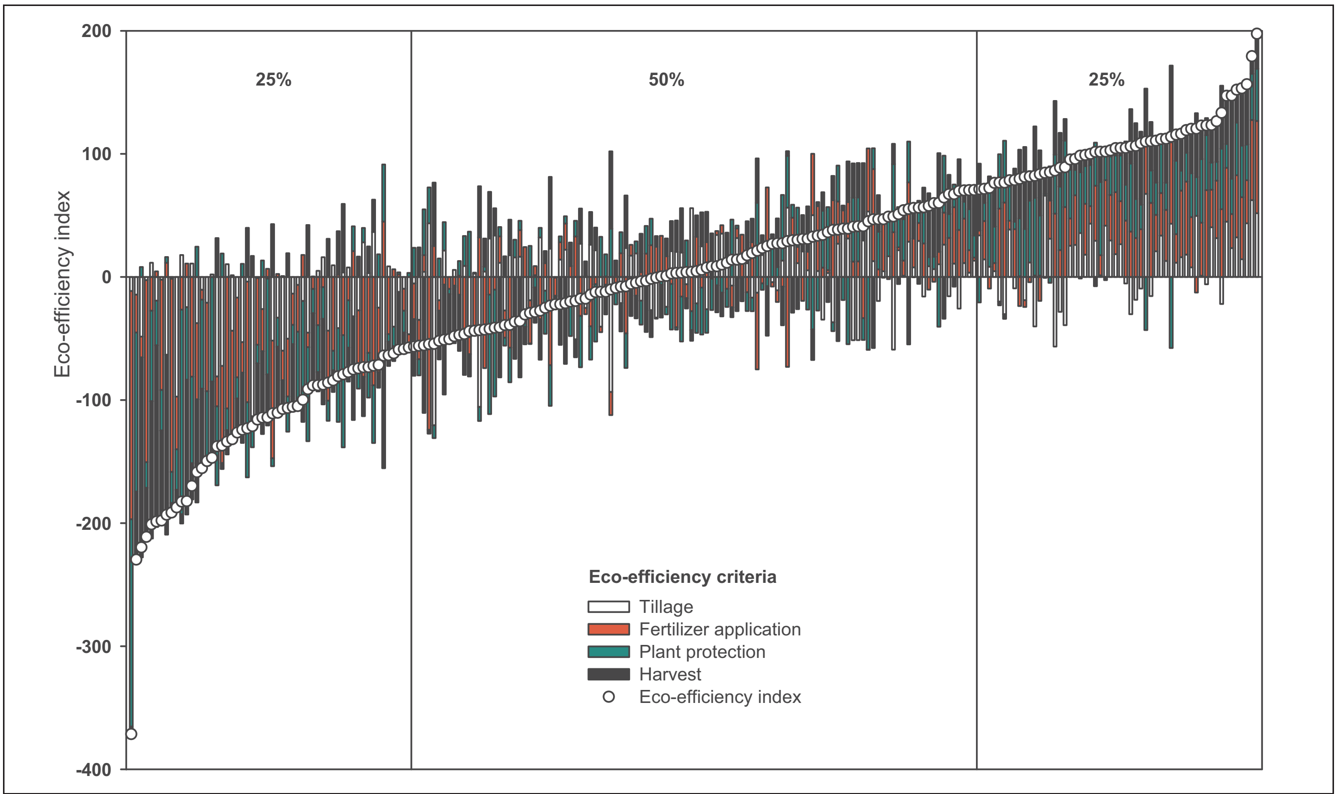


**Fig. 5. Eco-efficiency index of sugar beet cultivation (n = 224 fields) considering tillage, fertilizer application, plant protection and harvest. Values of the four eco-efficiency criteria add up to the total eco-efficiency index; eco-efficiency indices arranged by increasing order starting at the field with the lowest eco-efficiency.**
*Öko-Effizienz-Index im Zuckerrübenanbau (n = 224 Schläge) unter Berücksichtigung von Bodenbearbeitung, Düngung, Pflanzenschutz und Ernte. Die Werte der vier Öko-Effizienz-Kriterien summieren sich zum Öko-Effizienz-Index; Öko-Effizienz-Indices aufsteigend angeordnet, beginnend mit dem Schlag mit der geringsten Öko-Effizienz.*

## Discussion

A high percentage of the food consumed in Europe is produced by intensive agricultural farming systems and it is necessary to manage environmental problems of such systems by decreasing the pollution from agents such as nitrogen, pesticides and carbon dioxide (GOODLASS et al., 2003). In this context, crop production's environmental impact is often interrelated to its intensity (GELDERMANN and KOGEL, 2002). It is known that sugar beet reacts differently from other crops. A reduction of the input does not necessarily imply a diminished output, e.g. WSY of sugar beet is hardly affected by N fertilizer rate (MÄRLÄNDER et al., 2003). However, the whole set of inputs to realize a certain production level should be considered due to a possible interaction of various inputs (DE WIT, 1992).

Agricultural land use intensity can be assessed by quantifying production inputs such as mechanization, fertilizer and pesticides which are used to increase productivity. According to LYNCH (1998), efficiency is the ability of a system to convert inputs into desired outputs, or to minimize the conversion of inputs into waste. If resources are used efficiently, undesirable environmental impacts can be minimized (HERZOG et al., 2006).

Eco-efficiency has been defined in different ways. Prevalently, it means ecological optimization of whole systems while not disregarding economic factors (VON WEIZSÄCKER and SEILER-HAUSMANN, 1999).

In this study, increased eco-efficiency means the improvement of ecological performance through optimized operations by lower input as well as the improvement of the economical performance by higher white sugar yield. The calculated eco-efficiency criteria reflect differences in production intensity in relation to WSY on a field level.

*Tillage*

Consumption of fossil fuels should be sustainable because of their finiteness and climate relevant pollution by their combustion (DALGAARD et al., 2001). Tillage is generally associated with a high energy input. Besides mineral N fertilizer rate, diesel fuel consumption is the most important source of energy input (HÜLSBERGEN et al., 2001) in today’s crop production. Reduced tillage intensity enables sugar yield similar to ploughing (HOFFMANN et al., 1996; KOCH et al., 2009). MÄRLÄNDER et al. (2003) pointed out that net energy output is higher for reduced tillage than for ploughing and therefore primary energy (fuel, lubricants) is used more efficiently.

In our study, the variation of the eco-efficiency of tillage was considerably high. The results showed a weak relation between WSY and energy input of tillage ($r = 0.19$). The 50% of the fields with medium eco-efficiency ranged from 0.21 to 0.33 GJ $t^{-1}$ WSY. The large variation highlights the great differences in number and type of tillage operations. However, each decrease in frequency and depth of tillage reduces energy input thoroughly. Our results suggest that a significant reduction of the energy input of tillage is possible without any loss in WSY on a field level. According to WEGENER (2001), a yield similar to conventional tillage methods is attainable through mulch sowing with energy input reduced by almost 30%. Energy input of harvest operations is usually very high, but it does not differ significantly between fields and was consequently not involved.

*N fertilizer application*

Overuse and underuse of nitrogen fertilizers is widespread (RAMAN, 2006). Excessive N fertilizer rate must be avoided, because it increases the risk of nitrate leaching into groundwater, eutrophication of surface waters (drainage; manure runoff) (LÆGREID et al., 1999) and $N_2O$ release (BOUWMAN, 1996). The pronounced variation of N fertilizer use caused a strong variation in N balances as well (REINEKE and STOCKFISCH, 2008). Furthermore, over- or undervalued N fertilizer rates cause economic losses due to reduced yields and quality of the products (OLFS et al., 2005). MÄRLÄNDER (1990) showed that high N fertilizer rate lowered WSY of sugar beet. Although it increased root yield, it simultaneously increased standard molasses loss adversely affecting WSY. On fertile loess soils, for the majority of the surveyed fields the optimum N fertilizer rate in terms of WSY is approximately 100 kg N $ha^{-1}$ (MÄRLÄNDER et al., 2003). Compared to other crops such as winter wheat, sugar beet yield hardly responds to increasing N fertilizer rate (DELOGU et al., 1998; STICKSEL et al., 1999).

N fertilizer rates varied between 35 and 4 kg $t^{-1}$ WSY on the surveyed fields. The results showed no relation between N fertilizer rate and WSY ($r = 0.05$), hence, high WSY could be reached with low as well as with high N fertilizer rates. Thus, a fundamental reduction of N fertilizer rate is possible on the fields that were supplied above the optimum whereas a moderate increase is feasible on fields that were supplied below the optimum.

*Plant protection*

Sugar beet cultivation is inevitably linked with the occurrence of weeds, diseases and pests that require the application of pesticides. The intensity of pesticide use is indicated by the STI established by the German Federal Ministry of Food, Agriculture and Consumer Protection (BMVEL, 2004). STI only considers the quantitative effect of environmental risks associated with pesticide application (SATTLER et al., 2007). Chemical and physical properties influencing pesticide effects on the environment and the toxicity effect on different organisms (HAPEMAN et al., 2003) are not included. The need for pesticide application in conventional sugar beet cultivation is, however, undisputed as the renunciation of herbicides can lead to a total loss of revenue (SCOTT and WILCOCKSON, 1974; BRANDES, 2000).

In our study, the variation of the eco-efficiency of plant protection was very high. STI values ranged from about 0.1 to 0.9 $t^{-1}$ WSY. The single STI values resulted from a multitude of active ingredient combinations, particularly for herbicides. However, there was no relation between STI and WSY ($r = 0.05$). The isoquants clearly demonstrated that a WSY of 6 t $ha^{-1}$ and STI of about 2 caused almost the same plant protection efficiency as a WSY of 13 t $ha^{-1}$ and STI of about 5. However, the use of pesticides is thoroughly field and weather specific as are the occurrences of leaf spot diseases and weeds. In order to optimize the plant protection regime on a field level, the reduction of the pesticides' quantity, respectively the STI should not be the only aim. Moreover, it is important to enhance the efficiency of the whole system. For example, one herbicide treatment less seems possible on fields with very high STI (≥ 6), if (i) the herbicides sprayed are well adapted to existing weeds (species, number), (ii) the application time with regard to weather and plant development stage is optimum, and (iii) the best available application technique is used. Further steps towards optimizing the system include the cultivation of less susceptible cultivars (Bürger et al., 2008), e.g. to leaf spot diseases, and the use of most effective seed protection in order to minimize fungicide and insecticide application during the growing season.

*Harvest*

Soil is a key natural resource and its quality determines crop productivity (Fageria, 2002). Sugar beet harvesting causes losses of valuable topsoil and nutrients similar to losses due to wind and water erosion (Poesen et al., 2001; Ruysschaert et al., 2005). From a manufacturing point of view these soil losses are referred to as soil tare and considerable efforts have been made to clean the beets and dispose or recycle the soil (van der Poel et al., 1998). The amount of soil tare strongly depends on soil type and soil moisture content at harvest time, which is primarily affected by preceding weather conditions (Ruysschaert et al., 2004). Soil moisture is frequently high at sugar beet harvest in autumn, and harvest date is determined by the demand of the sugar factory and has to be performed during the fixed period. The differences in soil moisture content in interaction with the soil type led to a very high variation of soil tare on the surveyed fields. Soil tare was significantly correlated with WSY ($r = 0.23$), because root yield is a main component of WSY and the higher the root yield the higher the potential area for soil tare to adhere (Koch, 1996). Although the amount of soil tare can not be lowered to zero, there are still options to reduce it. Mechanical cleaning already on the sugar beet harvester lowers soil tare significantly (Vermeulen, 2002), but a compromise has to be made between optimal beet cleaning and a gentle treatment of the beets. The more intense efforts to remove soil tare are, the higher are the root injuries and the storage losses of the beet (Steensen, 2002; Kenter et al., 2006). Additionally, self-feeding cleaner loaders clean the beets mechanically on headlands before loading them on transportation units (Rigo, 2005).

*Effects of farm, energy input of tillage, N fertilizer rate, and STI on WSY*

Sugar beet fields belonging to a certain farm are usually subject to similar environmental conditions such as soil type, annual temperature and precipitation, and the farmer's crop management methods. Consequently, the subsumed farm effect on WSY was highly significant, as the results of the analysis of covariance have shown. However, energy input of tillage, N fertilizer rate and STI had no significant effect on WSY. This demonstrates that the complex variable farm dominates the effects on WSY. Results finally indicate that WSY of farms has no relation to the intensity of agronomic measures. Hanse et al. (2010) also demonstrated for more than 140 sugar beet fields in the Netherlands that there was no significant relation between intensity of production and sugar yield. The top sugar beet growers were more efficient in resource use. Our results are also in accordance with Märländer (1991) showing a high effect of weather (year) and site and a low effect of agronomic measures in field trials. Moreover, input-output combinations are site-specific as van Ittersum and Rabbinge (1997) showed for sugar beet in the Netherlands. In superior physical environments, characterized by high fertility and water-holding capacity of the soil, yield was larger whereas input level was not higher or even lower than in inferior environments. Therefore it is suggested that a substantial reduction of energy input, N fertilizer rate and STI (pesticide use) may be possible on a considerable share of the surveyed fields without taking the risk of a yield decrease.

*Eco-efficiency index*

Concentrating various intensity indicators to one index facilitates communication (Herzog et al., 2006). After normalizing, the single eco-efficiency criteria were aggregated to the eco-efficiency index (EEI) that field-specifically reflects the total eco-efficiency of sugar beet cultivation in 2004. EEI for sugar beet was established for the first time in this study. In future, EEI can be used as a reference for further studies and can disclose development trends in the efficiency of sugar beet cultivation.

On the field level, operation-specific indicators and WSY were highly variable. Thus, eco-efficiency indicators of fields showed a high variation, too. Highest increase of eco-efficiency seems possible at the 25% of the fields with the lowest eco-efficiency in 2004. However, 50% medium and 25% top may also have a potential for further increase of eco-efficiency.

An analysis of yield development of sugar beet in the recent past predicted a steady increase of sugar yield of approximately 1 t ha$^{-1}$ in a period of 10 years (Fuchs et al., 2008). This yield increase will further enhance index values continuously on fields which have already high eco-efficiency due to optimum input levels. As usual in sugar beet production, variations in WSY between years will occur on a field level. Regarding figures 1 to 4, on the short run the most effective way to increase eco-efficiency seems to reduce input levels. As our results have suggested, the reduction of the input levels on fields with a low eco-efficiency must not necessarily result in a yield decrease. In addition, reducing excessive inputs also reduces the economic risk as pointed out by Keating et al. (2010).

## Conclusion and outlook

Worldwide, Agenda 21 (UNCED, 1992) launched a process to make agricultural production systems more sustainable. Agenda 2000 (EC COMMISSION, 1999) set inter alia environmental targets for European agriculture. In this context, methods for the evaluation of sustainable development of crop production systems are required. To date, such a system is missing for the sector of sugar beet cultivation as a whole.

The relation between production intensity and yield performance of sugar beet cultivation was analyzed, based on data of a survey on 109 farms throughout Germany in 2004. WSY showed a high variation between the surveyed fields and was independent of energy input of tillage, N fertilizer rate and STI. Yield performance was thus decoupled from the environmental impact. This means, that production intensity can presumably be reduced without the risk of lower yield.

Applying this knowledge on a farm level, i.e. to avoid all agronomic measures that do not contribute to yield increase, would reduce economic and ecological risks and promote sustainable development in sugar beet cultivation. New indicator systems like the DLG Certificate "Sustainable Agriculture – Fit for the Future" are now available for implementing sustainable development on a farm level (CHRISTEN et al., 2009; DLG, 2010). First experiences have been gained from a subset of 12 farms out of the whole set of 109 farms with the REPRO-model (DEUMELANDT and CHRISTEN, 2008).

A set of practicable indicators reflecting ecological and agronomical performance was introduced in a first attempt to describe the current eco-efficiency of sugar beet cultivation. The enhancement of eco-efficiency by reducing input levels seems quite possible. In this context, it is to wonder why suboptimal, often very high production intensity occurs on the field level. Socio-economic expertise may be required for answering this question (VAN ITTERSUM and RABBINGE, 1997). Altogether, sugar beet seems to be a crop to produce food and feed stuff, bioenergy and raw material for industrial applications independent of production intensity.

On a national level, a continuous survey of the eco-efficiency criteria would allow to evaluate the development of eco-efficiency in sugar beet cultivation. The set of indicators and eco-efficiency criteria is under further development and will be completed with indicators concerning soil and water protection, climate change or biodiversity. The focus will, however, remain on sugar beet cultivation and on values that can be surveyed as simple as possible. This seems the most important requirement for recording enough data so that a survey can be representative for sugar beet cultivation throughout Germany (STOCKFISCH et al., 2008). Sugar beet grower associations and sugar companies are invited to implement the eco-efficiency concept to ensure sustainable development.

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