# Assessing the value of organic fertilizers

Michael Friedrich Tröster[a]

Michael.troester@triesdorf.de

[a] Agricultural Education Centre Triesdorf, Markgrafenstraße 12, 91746 Weidenbach, Germany

**Abbreviations:**

CAL = calcium acetate lactate extract; DSS = decision support system; $N_t$ = total nitrogen; NUE = nitrogen use efficiency

**Abstract**

Fertilizer prices have risen worldwide since the end of 2021. In this context, the value of organic fertilizers has also changed from the farmers' perspective. Hence, an open question about its value arises with an increased demand for organic fertilizers. This question must be addressed individually for each farm. Hence, a linear optimization model is applied. The model can be adapted to farm conditions and provides mineral and organic fertilizers as plant nutrition variables. The price level at which an organic fertilizer becomes competitive within the farm can be identified by parameterizing the organic fertilizer prices. This substitution value marks the maximum price a buyer could pay for a particular fertilizer. This method is repeated in the study in different scenarios. For a digestate (NPK = 5-2-5 kg per ton), substitution values between €1.70 and € 16 per ton could be determined, excluding transport and application cost. This study provides a basis for a decision support system that farmers can use to determine the value of organic fertilizers. As a positive implication, it can be expected that organic fertilizers will be used where they contribute best to value creation.

**Keywords**

Substitution value; organic fertilizer; fertilizer price; optimization; linear programming

# 1 Introduction

Organic fertilizers contribute significantly to the nutrient supply of crops. As natural compound fertilizers, they can substitute mineral fertilizers. However, from the farmers' perspective, organic fertilizers have disadvantages compared with mineral fertilizers, for example, owing to increased transport and application costs or a lower nitrogen utilization efficiency (NUE) (Lichti and Wendland, 2013). In addition, restrictions under fertilizer legislation mean that farms with a large amount of organic fertilizers must pass on considerable quantities to other farms. An example is German legislation, which currently limits nitrogen use from liquid organic fertilizers to 170 kg per hectare (Deutscher Bundestag, 2017). Hence, organic fertilizers have often been valued below their actual nutrient value and, in some cases, have even been subject to "transfer costs."

Considering the energy crisis and the war in Ukraine, fertilizer prices have multiplied. In addition, the availability of fertilizer is not guaranteed in all cases. This situation had a significant impact on the demand for organic fertilizers in the 2022 season. This case now raises the question of reassessing the value of organic fertilizers for many farms. The literature offers numerous studies on the evaluation of organic fertilizers. Often, the focus is on plant cultivation aspects, such as assessing the fertilizer effect. Delin *et al.* (2012) compared the methods for estimating the nitrogen fertilizers' effect on organic residues. Brown (2021) evaluated various organic fertilizers from livestock farming. Then, Menino *et al.* (2021) dealt with a novel approach, namely, the use of Black Soldier Fly larvae frass as an organic fertilizer. These studies are among the many studies that addressed organic fertilizers from a crop production perspective. Meanwhile, studies on the economic evaluation of organic fertilizers are less common. Wilkinson (1979) and Thuriès *et al.* (2019) used a deterministic approach to capture the monetary value of organic fertilizers. However, notably, the actual economic value of an organic fertilizer corresponds to a farm-specific substitution value. Numerous farm-specific aspects have an influence on this substitution value. Keplinger and Hauck (2006) therefore used a linear optimization model to determine the economic value of organic fertilizers. They focused on the economic valuation of organic fertilizers from livestock farming in connection with the influence of transport distance and the quantity of these fertilizers.

The present study aims to facilitate a fair economic valuation of organic fertilizers between supplying and receiving farms. Based on Keplinger and Hauck (2006), a model-based approach is chosen to determine the substitution value, but different questions are analyzed:

- Are there seasonal differences in the substitution value?
- What is the influence of fluctuating mineral fertilizer prices?
- What is the influence of the soil nutrient status of the receiving farm?
- What is the influence of the NUE of organic fertilizers?

Answering these questions, in conjunction with a reassessment of the substitution value of organic fertilizers, is particularly relevant for farmers and their advisors. Owing to the differentiated consideration of season, soil nutrient status, and NUE, under which conditions organic fertilizers achieve the highest substitution value may be determined. Optimally, this knowledge will contribute to an increase in the use efficiency of organic fertilizers at the regional level and thus have positive economic and ecological impacts.

# 2 Materials and methods

The question concerning the monetary value of organic fertilizers arises as soon as an exchange between farms takes place. Generally, the supplying farm is under pressure, for example, because internal use is impossible or uneconomical for reasons of efficiency or is limited for legal reasons. Therefore, this study assumes a consumer market for organic fertilizers and takes the perspective of the receiving farm to determine the substitution value of organic fertilizers. Thus, the results reflect the maximum price that can be paid from the buyer's perspective.

Marginal costs and marginal benefits determine the maximum price that a buyer of organic fertilizer could pay. For example, if the application of organic fertilizer leads to higher costs than the previous application of fertilizer, marginal costs arise. Moreover, if the use of organic fertilizer can reduce previous fertilizer expenditures, then marginal benefits arise. Marginal costs and marginal benefits also vary within the farm, for example, the first unit of organic fertilizer applied can be used more efficiently than the last unit before reaching a potential saturation limit. Where this potential saturation limit lies depends on the situation and is examined based on comparative scenarios[1]:

- "Base scenario"
- Variation of nitrogen fertilizer prices: "fertilizer price" scenario
- Variation of phosphorus (P) and potash (K) content in soil: "P&K supply" scenario
- Variation of NUE of organic fertilizers: "N efficiency" scenario
- Variation of the transfer window (first to fourth quarters): "Timing" scenario

These scenarios are analyzed for an exemplary receiving farm with 90 ha of arable land and 30 ha of grassland. The crop rotation for the arable land is winter wheat–winter barley–(catch crop)–silage maize.

A linear optimization model based on the following structure (modified after Andrei (2013, p.119)) is used to represent these scenarios for the exemplary farm:

$$\textit{minimize} \qquad f(x) \tag{1}$$

$$\textit{subject to:} \qquad g(x) \leq 0 \tag{2}$$

$$h(x, y) = 0 \tag{3}$$

[1] More detailed explanations of the conditions of these scenarios can be found in the description of the corresponding results in Section 3.

The monetary objective function *f* and the sample constraint functions *g* and *h* represent linear functions. The restrictions arise from the nutrient requirements derived from soil nutrient supply, crop, and crop rotation. In parallel, legal restrictions must be considered. For example, the requirements of German fertilizer legislation are applied, including an upper limit of 170 kg of nitrogen per hectare from organic fertilizers and strict limitations and deadlines for fertilizing measures after the main crop has been harvested. More detailed information on fertilizer requirements and fertilizer legislation can be found in the form of laws and directives (Deutscher Bundestag, 2009; Deutscher Bundestag, 2017; Bayerische Landesanstalt für Landwirtschaft, 2022). Another part of the model is the variable *x* that represents the use of mineral and organic fertilizers (Table 1). Mineral fertilizers are included in the model at market prices, and price assumptions are assigned to organic fertilizers. By parameterizing these price assumptions step by step, farm-specific substitution values of organic fertilizers can be determined using the model.

*Table 1: Fertilizer selection*

| | **Price[#1] 09/22 [€ $t^{-1}$]** | **Price[#1] 02/23 [€ $t^{-1}$]** | **N [kg $t^{-1}$]** | **$P_2O_5$ [kg $t^{-1}$]** | **$K_2O$ [kg $t^{-1}$]** | **S [kg $t^{-1}$]** |
|---|---|---|---|---|---|---|
| Biogas digestate[#2] | ? | ? | 5 | 2 | 5 | 0.8 |
| Calcium ammonium nitrate | 870 | 470 | 270 | | | |
| Calcium ammonium nitrate + S | 890 | 485 | 240 | | | 40 |
| Ammonium sulfate nitrate | 910 | 545 | 260 | | | 130 |
| Urea | 980 | 670 | 460 | | | |
| NP 20 20 | 930 | 720 | 200 | 200 | | |
| Diammonium phosphate | 1195 | 880 | 180 | 460 | | |
| Potash | 640 | 615 | | | 400 | 50 |

Remarks: #1 Consumer prices (net) ex wholesale depot (Southern Germany); #2 The usability of the nitrogen content of 5 kg per ton is controlled by the NUE factor. This factor is 0.36 or 0.45, depending on the scenario (based on Lichti and Wendland, 2013).

# 3 Results

This section shows the determined substitution values of the biogas digestate (Table 1, row 1) under the assumptions of the various scenarios. A quarterly differentiation is made to illustrate the seasonal influence on the substitution value of the organic fertilizer.

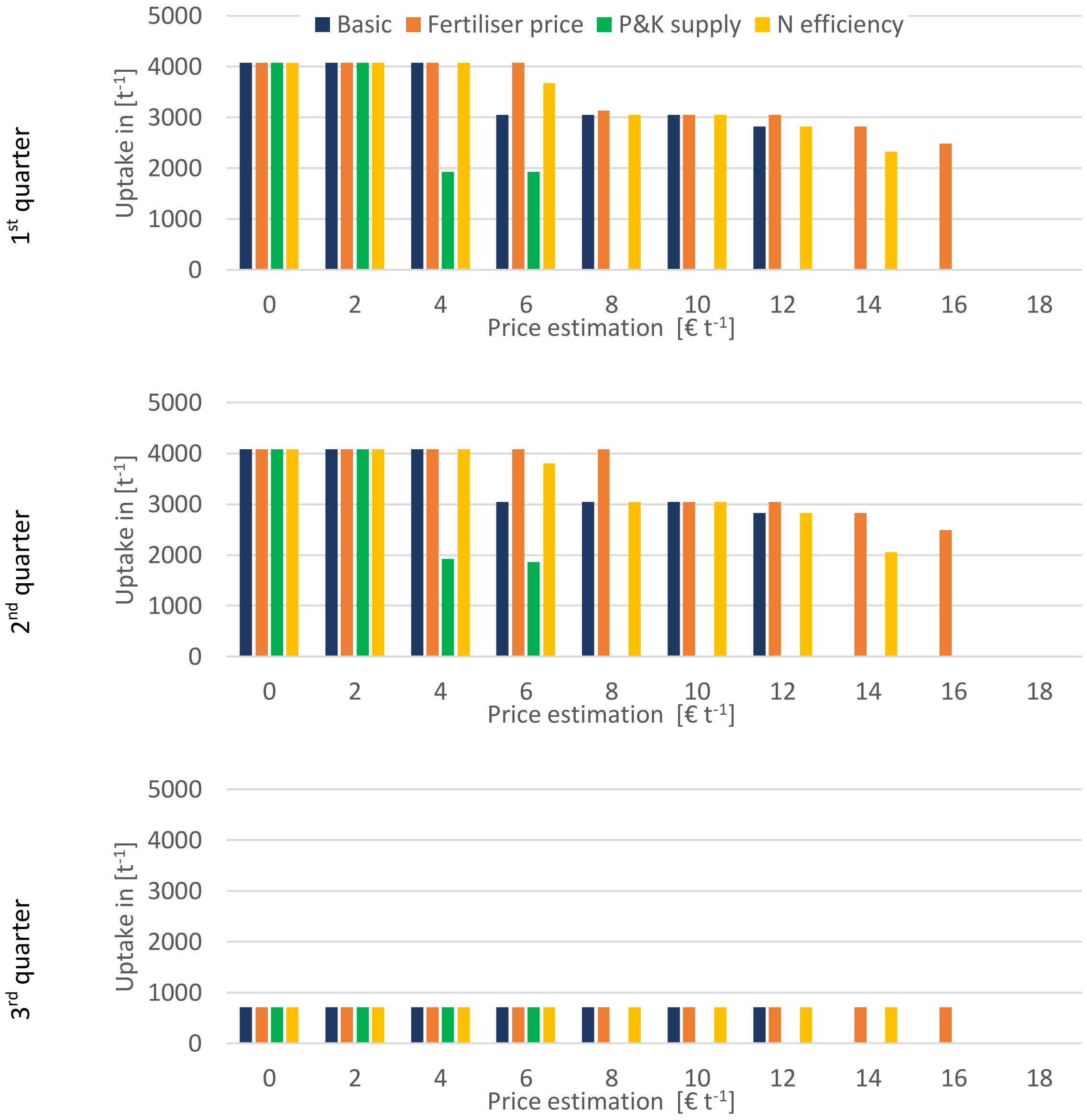


**Figure 1:** Quarterly substitution values[#1] for biogas digestate[#2] under changing scenarios[#3]

Remarks: #1 Excluding transport, storage, and spreading. #2 Sample digestate ($N_t$ = 5 kg $t^{-1}$; $P_2O_5$ = 2 kg $t^{-1}$; $K_2O$ = 5 kg $t^{-1}$; S = 0.8 kg $t^{-1}$); #3: **"Base" scenario:** fertilizer prices according to 02/2023; phosphorus supply in soil normal (CAL: 10–20 mg/100 g soil); potash supply in soil normal (CAL: 10–20 mg/100 g soil); NUE 36% of $N_t$. **Scenario "fertilizer price":** fertilizer prices according to 09/2022; otherwise, identical to the "Base" **Scenario "P&K supply":** Phosphorus supply in soil high (CAL: 21–30 mg/100 g soil); potash supply in the soil very high (CAL: >30 mg/100 g soil); otherwise, identical to the "Base" **Scenario "N efficiency":** NUE increased to 45%; otherwise, identical to "Base." Fourth quarter (not shown) largely identical to the third quarter.

### 3.1 Impact of mineral fertilizer prices—“fertilizer price” scenario

The volatile fertilizer prices clearly influence the substitution value of organic fertilizers (Table 1). Fig. 1 shows the comparison of the “Base” and “fertilizer price” scenarios. Definition of the scenarios:

- Base: fertilizer prices as of 02/2023 (Table 1); soil phosphorus supply normal (CAL: 10–20 mg/100 g soil); soil potash supply normal (CAL: 10–20 mg/100 g soil); NUE 36% of $N_t$.
- Fertilizer price: fertilizer prices according to 09/2022 (Table 1); otherwise, identical to the base scenario.

Under the conditions of the base scenario, a receiving farm could bear a maximum cost of €12 per ton of digestate in all quarters (Figure 1). However, transport, storage, and application costs reduce this value if they are to be paid by the receiving farm. The quantities that can be purchased at these maximum costs differ considerably between the quarters, as can be seen from the bar height in the diagram (Figure 1). For instance, the sample farm with 90 ha of arable land and 30 ha of grassland would take 2822 tons of digestate at a maximum cost of €12 per ton in the first quarter. In the third quarter, the quantity drops to 711 tons at this price because the use options and the efficiency are already clearly limited at this time. With increased fertilizer prices, as of September 2022 (“fertilizer price” scenario), the receiving farm could accept €16 per ton of digestate. However, the change in the uptake quantity between the quarters is comparable to the base scenario.

### 3.2 Impact of soil nutrient status—“P&K supply” scenario

In this study, the soil nutrient supply with phosphorus and potash has the greatest influence on the substitution value of the biogas digestate. Compared with the base scenario, the maximum substitution values are halved from €12 to €6 per ton. Scenario definition:

- P&K supply: Phosphorus supply in soil high (CAL: 21–30 mg/100 g soil); potash supply in soil very high (CAL: >30 mg/100 g soil); otherwise identical to the base scenario.

The difference in the substitution values of the scenarios “Base” and “P&K supply” is €6 per ton. This difference can also be interpreted as the maximum effort that is acceptable to transfer the biogas digestate to remote fields with lower nutrient content. Figure 1 also shows that higher nutrient contents of phosphorus and potash in the soil also lead to a decrease in the sensibly applicable fertilizer quantities. The “P&K supply” scenario is also the worst case scenario in this study. This scenario has the poorest overall conditions for achieving a high substitution value.

### 3.3 Impact of NUE—“N efficiency” scenario

The analyzed change in NUE has the smallest influence on the substitution value in this study. Compared with the base scenario, the quarterly substitution values increase by €2 per ton to €14 per ton. Scenario definition:

- N efficiency: NUE (related to $N_t$) increased to 45%; otherwise, identical to the base scenario.

The NUE for biogas digestate was derived from Lichti and Wendland (2013). According to this, a NUE of 45% (based on $N_t$) can only be achieved under favorable conditions and with corresponding loss-reducing technology. Against this background, the gain in substitution value of €2 per ton is also regarded as the maximum additional expenditure for loss-reducing application technology (with an improvement in NUE from 36% to 45%, based on $N_t$).

### 3.4 Average substitution value and the effects of overlays

The results explained so far show the maximum substitution values that can be achieved according to the marginal value principle. Thus, they refer to the monetary value of the first unit of biogas digestate used by a receiving farm. In practice, however, there are cases where larger quantities of organic fertilizer are exchanged between farms. Table 2 compares which average substitution value would have to be applied if a total transfer of 3000 tons of biogas digestate is involved.

**Table 2:** Substitution value[#1] according to an average value approach for 3000 tons delivery quantity

| Scenario | First quarter [€ $t^{-1}$] | Second quarter [€ $t^{-1}$] | Third quarter [€ $t^{-1}$] |
|---|---|---|---|
| Basic | 11.88 [#2] | 11.88 | 8.18 [#3] |
| Fertilizer price | 15.54 | 15.54 | 12.18 |
| P&K supply | 4.57 | 4.52 | 1.70 |
| N efficiency | 13.43 | 13.25 | 10.18 |

Remarks: #1 Substitution value excluding transport and spreading;
#2 Calculation: $€11.88 = (2822\ t\ \times €12 + 178\ t\ \times €10) \div 3000\ t$; (compare figure 1, first quarter)
#3 Calculation: $€8.18 = \left(320\ t\ \times €12 + 2680\ t\ \times (€12 - SC)\right) \div 3000\ t$; (compare figure 1, first and third quarters); *SC* = Costs for storage incl. storage and retrieval = €5 per ton.

If in the base scenario, 3000 tons are taken over by the receiving farm, then the maximum substitution value of €12 per ton cannot be kept. The quantity of 2822 tons for which this maximum substitution value is valid in the first quarter is exceeded. The maximum substitution value for the remaining 178 tons is €10 per ton. The average substitution value in this case is €11.88 per ton. Similar to this observation, the average substitution values in the remaining cases are also reduced. As only a part of the 3000 tons can be spread directly in the third quarter in all cases, additional costs for the storage, including storage and removal from storage, must be applied to the overstocked quantity. Costs of €5 per ton are used, which of course vary from farm to farm.

In the worst case, the receiving farm would therefore only be able to pay €1.70 per ton (Table 1, third quarter) if a total quantity of 3000 tons is concerned. As organic fertilization causes higher transport and application costs compared with mineral fertilization, further marginal costs are charged to the receiving farm. With farm-specific additional costs for transporting and spreading the biogas digestate of, for example, €3.00 per ton, the remaining substitution value is € −1.30 per ton. In this case, the supplying farm would have to make additional payments to the receiving farm.

# 4 Discussion and conclusion

The results of this study show that organic fertilizers have a significantly different value for receiving farms depending on the situation. In the best case (scenario “fertilizer price”; first quarter; Figure 1), a maximum substitution value of €16 per ton of biogas digestate was achieved. In the worst case (scenario “P&K supply”; third quarter; Table 2), the average substitution value is only €1.70 per ton. In both cases, these values are further reduced by additional costs for transporting and applying organic fertilizers. According to this study, the following factors contribute to the differentiation of the substitution values, starting with the strongest influence:

- Phosphorus and potash levels in the soils of the receiving farm
- Price situation on the fertilizer markets
- Quantity of organic fertilizer transferred in connection with timing (quarter)
- NUE

As the soil nutrient levels of phosphorus and potash play a major role, higher transport costs can be accepted to transfer organic fertilizers from surplus to deficient regions. This finding is not new (Nunez and McCann, 2008; Hoffmann *et al.*, 2001), but an objective economic assessment is a prerequisite for correctly mapping the transport value. The strong influence of fertilizer markets in combination with their volatility (Table 1; Lahmiri, 2017) also leads to the need for a regular reassessment of the substitution value of organic fertilizers. A model-based decision support system (DSS) is appropriate to simultaneously consider other influencing factors such as timing, transferred organic fertilizer quantity, and NUE.

When developing a DSS, the limitations of this study must be solved because, to date, only a static sample farm has been considered. Thus, all results refer to one crop rotation; a uniform NUE across all crops and quarters; and general assumptions on storage, transport, and application costs. A farm-specific DSS must be flexible in this respect. For farm-specific statements on substitution values of organic fertilizers, such a tool must contain (i) an interface to current mineral fertilizer prices and (ii) an input option for field-, crop-, and time-specific user data.

However, some limitations of this study can probably not be overcome by the described DSS. The literature showed that organic fertilization can have positive yield effects (Salam *et al.*, 2021, Du *et al.*, 2020; Zhang *et al.*, 2020; LI *et al.*, 2018; Körschens *et al.*, 2013). This case is especially true on depleted soils without long-term organic fertilization (Agbede *et al.*, 2013). Drivers of such positive yield effects are, for example, micronutrients or the general improvement of soil’s physical properties (Oikeh and Asiegbu, 1993). However, negative yield effects are also reported in connection with organic fertilization. This case is often because of soil compaction (Ishaq *et al.*, 2001) caused by the use of heavy agricultural equipment (Douglas and Crawford, 1998). Both positive and negative yield effects of organic fertilization are not considered in this study but can strongly influence the substitution value in individual cases.

When supplying farms use the approach presented in this article to determine a price for organic fertilizers, the following should be noted: A substitution value determined from the buyer's perspective is by no means a market price but the monetary upper limit that a buyer could accept. Under conditions of a buyer's market, it is expected that farms that are under pressure to sell organic fertilizer will do so below value. This case will likely reduce the market price for organic fertilizer in surplus regions. In these cases, however, the valuation approach presented here offers a good opportunity to check the transportability of organic fertilizer from surplus to deficit regions.

This study provides important insights into the monetary valuation of organic fertilizers and also forms a basis for a DSS that is yet to be developed. In addition to the pricing of organic fertilizers, such a DSS can also contribute to a more efficient regional distribution of these fertilizers. Ecological goals that are important from a social perspective can also be pursued by allocating organic fertilizers in an economically efficient manner.

**References**


Agbede, T. M., Adekiya, A. O. and Ogeh, J. S. 'Effects of organic fertilizers on yam productivity and some soil properties of a nutrient-depleted tropical Alfisol' *Archives of Agronomy and Soil Science*, Vol. 59 (2013) pp. 803–822. https://doi.org/10.1080/03650340.2012.683423.

Andrei, N. *Nonlinear Optimization Applications Using the GAMS Technology* (Boston, MA: Springer US, 2013).

Bayerische Landesanstalt für Landwirtschaft. *Leitfaden für die Düngung von Acker- und Grünland* (2022).

Brown, C. Available Nutrients and Value for Manure from Various Livestock Types. 2021. Available at: https://files.ontario.ca/omafra-available-nutrients-and-value-for-manure-from-various-livestock-types-21-077-en-2022-11-24.pdf.

DELIN, S., STENBERG, B., NYBERG, A. and BROHEDE, L. 'Potential methods for estimating nitrogen fertilizer value of organic residues' *Soil Use and Management*, Vol. 28 (2012) pp. 283–291. https://doi.org/10.1111/j.1475-2743.2012.00417.x.

Deutscher Bundestag. *Düngegesetz. DümgG* (09.01.2009).

Deutscher Bundestag. *Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen. DüV* (26.05.2017).

Douglas and Crawford 'Soil compaction effects on utilization of nitrogen from livestock slurry applied to grassland' *Grass and Forage Science*, Vol. 53 (1998) pp. 31–40. https://doi.org/10.1046/j.1365-2494.1998.00101.x.

Du, Y., Cui, B., zhang, Q., Wang, Z., Sun, J. and Niu, W. 'Effects of manure fertilizer on crop yield and soil properties in China: A meta-analysis' *CATENA*, Vol. 193 (2020) p. 104617. https://doi.org/10.1016/j.catena.2020.104617.

Hoffmann, I., Gerling, D., Kyiogwom, U. B. and Mané-Bielfeldt, A. 'Farmers' management strategies to maintain soil fertility in a remote area in northwest Nigeria' *Agriculture, Ecosystems & Environment*, Vol. 86 (2001) pp. 263–275. https://doi.org/10.1016/S0167-8809(00)00288-7.

Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M. and Lal, R. 'Subsoil compaction effects on crops in Punjab, Pakistan' *Soil and Tillage Research*, Vol. 59 (2001) pp. 57–65. https://doi.org/10.1016/S0167-1987(00)00189-6.

Keplinger, K. O. and Hauck, L. M. 'The Economics of Manure Utilization: Model and Application', Vol. 31 (2006) pp. 414–440.

Körschens, M., Albert, E., Armbruster, M., Barkusky, D., Baumecker, M., Behle-Schalk, L., Bischoff, R., Čergan, Z., Ellmer, F., Herbst, F., Hoffmann, S., Hofmann, B., Kismanyoky, T., Kubat, J., Kunzova, E., Lopez-Fando, C., Merbach, I., Merbach, W., Pardor, M. T., Rogasik, J., Rühlmann, J., Spiegel, H., Schulz, E., Tajnsek, A., Toth, Z., Wegener, H. and Zorn, W. 'Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century' *Archives of Agronomy and Soil Science*, Vol. 59 (2013) pp. 1017–1040. https://doi.org/10.1080/03650340.2012.704548.

Lahmiri, S. ‘Asymmetric and persistent responses in price volatility of fertilizers through stable and unstable periods’ *Physica A: Statistical Mechanics and its Applications*, Vol. 466 (2017) pp. 405–414. https://doi.org/10.1016/j.physa.2016.09.036.

LI, C., MA, S., SHAO, Y., MA, S. and ZHANG, L. ‘Effects of long-term organic fertilization on soil microbiologic characteristics, yield and sustainable production of winter wheat’ *Journal of Integrative Agriculture*, Vol. 17 (2018) pp. 210–219. https://doi.org/10.1016/S2095-3119(17)61740-4.

Lichti, F. and Wendland, M. Biogasgärreste. Einsatz von Gärresten aus der Biogasproduktion als Düngemittel. 2013. Available at: https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/p_31972.pdf (last accessed 18 February 2023).

Menino, R., Felizes, F., Castelo-Branco, M. A., Fareleira, P., Moreira, O., Nunes, R. and Murta, D. ‘Agricultural value of Black Soldier Fly larvae frass as organic fertilizer on ryegrass’ *Heliyon*, Vol. 7 (2021) e05855. https://doi.org/10.1016/j.heliyon.2020.e05855.

Nunez, J. T. and McCann, L. ‘Determinants of manure application by crop farmers’ *Journal of Soil and Water Conservation*, Vol. 63 (2008) pp. 312–321. https://doi.org/10.2489/jswc.63.5.312.

Oikeh, S. O. and Asiegbu, J. E. ‘Growth and yield responses of tomatoes to sources and rates of organic manures in ferralitic soils’ *Bioresource Technology*, Vol. 45 (1993) pp. 21–25. https://doi.org/10.1016/0960-8524(93)90138-2.

Salam, M. A., Sarker, M. N. I. and Sharmin, S. ‘Do organic fertilizer impact on yield and efficiency of rice farms? Empirical evidence from Bangladesh’ *Heliyon*, Vol. 7 (2021) e07731. https://doi.org/10.1016/j.heliyon.2021.e07731.

Thuriès, L. J.-M., Ganry, F., Sotamenou, J., Oliver, R., Parrot, L., Simon, S., Montange, D. and Fernandes, P. ‘Cash for trash: an agro-economic value assessment of urban organic materials used as fertilizers in Cameroon’ *Agronomy for Sustainable Development*, Vol. 39 (2019). https://doi.org/10.1007/s13593-019-0598-7.

Wilkinson, S. R. ‘Plant Nutrient and Economic Valus of Animal Manures’ *Journal of Animal Science*, Vol. 48 (1979) pp. 121–133. https://doi.org/10.2527/jas1979.481121x.

Zhang, X., Fang, Q., Zhang, T., Ma, W., Velthof, G. L., Hou, Y., Oenema, O. and Zhang, F. ‘Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: A meta-analysis’ *Global change biology*, Vol. 26 (2020) pp. 888–900. https://doi.org/10.1111/gcb.14826.