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Optimisation of fertiliser rates in crop production against energy use indicators

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ABSTRACT

Optimising mineral nitrogen (N) use in crop production is inevitable target as mineral fertilisers reflect one of the highest inputs both in terms of economy and energy. The aim of the study was to compare the relationship between the rate of N fertiliser application and different measures of energy parameters exemplary data for spring-wheat in boreal climate condition in Estonia in 2006–2010. The effect of mineral N with rates 0, 40, 80, 120 and 160 kg N ha^{-1} was studied on the background of composted cow manure and without organic fertilisers. Univalent parameters, energy gain (EG) (energy output – energy input) and energy ratio (ER) (energy output/energy input) were calculated. To aggregate parameters with different units (ER and EG) we proposed two standardisation approaches for combined indices. ER maximisation gave both organic fertilisation background optimum N norms significantly lower than EG ($p < 0.05$) optimisation. Both the new combined indices gave optimum N norms in between the rate of ER an EG. Composted cow manure background did not affect mineral N optimisation significantly. We suggest optimisation of mineral N according to bi-dimensional parameters as they capture important features of production efficiency and are more objective using as advisory tool for sustainable production systems.

1. Introduction

The most widely used energy indicators are energy gain (EG) and energy ratio (ER). The ER (ratio of energy output and input) has been previously used as an indicator of environmental effects and the sustainability of plant production (Hülsbergen et al., 2001). Maximising EG (energy output minus input) is desirable when the land is used to produce renewable energy (Deike et al., 2008) or in situations where available arable land is a limited resource (Kelm et al., 2001; Deike et al., 2008). Previous studies in optimisation of mineral fertiliser rates have mainly focused on maximising crop yield or economic profitability (William and Gordon, 1999; Aizpuruaa et al., 2010). Maximum EG is obtained at high fertilisation intensity, whereas maximum ER is achieved for much lower fertilisation intensities (Kuesters and Lammel, 1999; Biermann et al., 1999; Hülsbergen et al., 2002; Rathke and Diepenbrock, 2006). Optimising mineral fertilisers according to ER implies that more land will be needed to compensate the yield reduction caused by the relatively low input of fertilisers (Hülsbergen et al., 2002). Therefore optimising N according to EG and ER are incompatible targets.

The main goal of this study was to clarify and compare the relationship between the rate of nitrogen fertiliser application and different measures of energy use based on exemplary data for spring-wheat. Furthermore, we provided novel methodical approach to optimise N fertilisation in the context of bi-dimensional energy balance that takes into consideration both maximising net energy yield and minimising the energy input per unit output. Approaches for combining EG and ER were analysed and discussed.

2. Materials and methods

2.1. The field experiment

This study is based on a field trial running in Tartu, Estonia (58°22′ N, 26°40′ E) over several years as part of the research performed by 22 European experimental centres in the framework of the International Organic Nitrogen Long-Term Field Experiment (IOSDV) (Debreczeni and Körschens, 2003). The experiment was established on sandy loam *Stagnic Albeluvisol* (WRB). In this study data from plots without organic fertilisers and on the background of first year after-effect of 40 t ha^{-1} composted cow manure on 2006–2010 for the spring-wheat was considered. Mineral nitrogen (N) was applied at five rates – 0, 40, 80, 120, 160 kg N ha^{-1} per year. The aim was to mimic the production conditions in

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commercial farms as closely as possible and fertiliser application was identical for all plots except for high rates (120 and 160 kg N ha^{-1}) where ammonium nitrate was applied in two doses since 2009. The applied agro-technology was based on autumn ploughing. Total aboveground biomass (grain + straw) was considered as the primary outcome of interest.

2.2. Energy calculations

The idea of energy balancing originates Hülsbergen et al. (2001) and is based on a kind of process analysis where physical material flow is assessed, but only taking into account fossil energy use. The energy input (EI) was calculated as direct (diesel fuel, electricity) and indirect (seeds, mineral fertilisers, plant production agents, machinery) energy. The following energy equivalents were used in the calculations: diesel 39.6 MJ l^{-1} (Reinhardt, 1993); mineral nitrogen fertiliser as ammonium nitrate 35.3 MJ kg^{-1} N (Appl, 1997); herbicide 288 MJ kg^{-1} per active ingredient (ai), fungicide 196 MJ kg^{-1} ai, insecticide 237 MJ kg^{-1} ai (Green, 1987); seed 5.5 MJ kg^{-1} (Hülsbergen et al., 2001); tractors and machinery 108 MJ kg^{-1} (Kalk and Hülsbergen, 1996); transportation 6.03 MJ t^{-1} km^{-1} (Müller, 1989). The effect of composted cow manure was considered as first year after-effect on the subsequent crop, 30% of total input of direct effect. Manure was handled as by product of dairy cattle and only transport and application energy was considered in calculations. All energy equivalents were considered to be constant over the 5-year period. To calculate the energy output (EO), 18.72 MJ kg^{-1} grain dry matter (DM) was assumed and 18.24 MJ kg^{-1} DM for straw.

Two energy parameters were calculated in order to characterise production efficiency. To maximise total net energy per hectare the EG (EO − EI) as GJ ha^{-1} was calculated and ER (EO per one unit input) (EO/EI), GJ GJ^{-1} were calculated.

2.3. Definition of combined indices

The optimal nitrogen rates determined according to EG and ER may vary greatly. Both measures, however, may capture important features of production efficiency and therefore it is desirable to use a combined index. For aggregation of parameters with different units is necessary to standardise them initially. We considered two combined indices that are derived using different approaches for standardisation, either using a *z*-score approach by dividing mean EG and ER values by their standard error of the mean or dividing them by their maximum value, similar to the robust equivalent of the *z*-score obtained using the median absolute deviation.

2.3.1. z-Score approach

Let x_n^t denote the EG or ER value for single plot n and year t. The average across N rates $\bar{x^t}$ and the standard deviation (SD) across N rates $\bar{\sigma^t}$ for each year (t) was defined. The standardised energy measure is defined as: $I_n^t = (x_n^t - \bar{x^t})/\bar{\sigma^t}$, so that all the I_n^t have similar range of variation across fertilisation variants within a year (roughly between −2 and 2). To eliminate the year effect (weather conditions) SD over all plots for each year (t) for both organic fertiliser backgrounds was used. This method compares the energy parameter to the mean value (yearly average) relative to the variability measured in terms of standard deviations and this may be appropriate in case the mean EG and ER values approximately follow a symmetric distribution. The combined index, referred to ERG *z*-index is obtained as the sum of the two standardised measures:

$$\text{ERG } z\text{-index} = \frac{x_{\mathrm{ER}n}^t - \mathrm{mean}(x_{\mathrm{ER}n}^t)}{\mathrm{SD}_{\mathrm{ER}}^t} + \frac{x_{\mathrm{EG}n}^t - \mathrm{mean}(x_{\mathrm{EG}n}^t)}{\mathrm{SD}_{\mathrm{EG}}^t}$$

2.3.2. Relative importance of the maximum approach

The second approach we used proposed by Rossner (2009) for normalising energy parameters uses the maximum value of each year as the standardisation factors ($\max_{\mathrm{EG}}^t$ and $\max_{\mathrm{ER}}^t$). The index was referred to as ERG index and was formulated using linear aggregation. The resulting formula is:

$$\text{ERG index} = \frac{x_{\mathrm{ER}n}^t}{\max(x_{\mathrm{ER}}^t)} + \frac{x_{\mathrm{EG}n}^t}{\max(x_{\mathrm{EG}}^t)}$$

This index may be viewed as a robust version of the *z*-score index, appropriate in situations where the EG or ER values are right-skewed.

Index values were found for each single plot (from N rate 0 to 160) with maximum theoretical value 2. Both bi-dimensional indexes were calculated for each single plot (75 single values – 5 N norms, 3 replications, 5 years) and were used to optimise nitrogen fertilisation.

2.4. Nitrogen optimisation and statistical analyses

Energy yield and energy parameters were regressed on the rate of mineral N using a quadratic function ($y = a + b_1x + b_2x^2$). The rates of mineral N necessary to achieve maximum energy yield, EG, ER and derived combined indexes were estimated by putting the first derivative of the quadratic function equal to 0 and then solve the equation. The goodness of fit of the equation was indicated by the coefficient of determination.

All statistical analyses were carried out using R version 2.15.3 (R Core Team, 2013). Specifically, for the nitrogen optimisation function deltaMethod( ) in the extension package alr3 was used to obtain estimated standard errors for the optimal rates (Weisberg, 2005). Statistically significant differences between estimated optimal N norm levels were established using post hoc *t*-tests.

3. Results

The rate of N application necessary to obtain maximum energy yield (105.9 GJ ha^{-1}) on plots without manure background was 124 kg ha^{-1} (Fig. 1 and Table 1) and on the background of composted manure was slightly higher, 128 kg ha^{-1} (Table 1) giving yield increase 15 GJ ha^{-1}. The highest N norm (160 kg ha^{-1}) gave lower average energy yields (Fig. 1). EG varied between 45.6 and 95.3 GJ ha^{-1} (Fig. 1). The highest EG without manure background, was achieved with the N rate of 119 kg ha^{-1} (Table 1).

ER achieved maximum value on N rate of 52 kg ha^{-1} on background of manure and decreased thereafter. Without manure background it was 14 kg ha^{-1} lower (Table 1). The lowest ER was obtained with highest N rates (Fig. 1).

The rate of N application required to achieve maximum ER were substantially lower than that for EG ($p < 0.05$) (Table 1). Optimum rate of N without manure background to maximise ERG index was 95 kg ha^{-1}, 4 kg ha^{-1} lower on plots with manure background (Fig. 1 and Table 1). Comparing ERG index with ER and EG the optimum doses of N were in between the range of two base parameters. To maximise ER, the necessary N rate was 29 kg ha^{-1} lower and to maximise EG 24 kg ha^{-1} higher than required for maximising ERG index. On manure background the optimum N rates for maximise ERG index were 31 kg ha^{-1} higher and 39 kg ha^{-1} lower than necessary for maximising EG and ER accordingly. ERG *z*-index gave similar but slightly lower values compared to ERG index (Fig. 1 and Table 1). Optimum fertiliser amounts of bi-dimensional parameters enable to produce quite high net energy yield per hectare with relatively high energy use efficiency Background of composted cow manure did not gave statistically significant difference in optimum N norms.