Energy Efficiency of Continuous Rye, Rotational Rye and Barley in Different Fertilization Systems in a Long-Term Field Experiment

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Abstract: A goal in sustainable agriculture is to use fossil energy more efficiently in crop production. This 60-year-old experiment on a silt loam chernozem investigated effects of fertilization (unfertilized control, mineral fertilizer (NPK) and farmyard manure (FYM)) and rotation (continuous winter rye (CR), winter rye in rotation (RR), spring barley in rotation (SB) on diesel fuel consumption, total energy input (made of both direct and indirect inputs), crop yield, energy output, net-energy output, energy intensity, energy productivity and energy use efficiency. The input rates of fertilizer, herbicides and seeds were set constant during the experiment. Soil tillage was done with a moldboard plough with subsequent combined seedbed preparation and seeding. The mean calculated total energy input was highest in NPK with 11.28 GJ ha\(^{-1}\) and lowest in the unfertilized control with 5.00 GJ ha\(^{-1}\). Total energy input for FYM was intermediate with 6.30 GJ ha\(^{-1}\). With energetic consideration of NPK nutrients in FYM the total energy input increased to the level of NPK. The share of the fertilizer energy on the total energy input was 49% for NPK. Fertilization with FYM and NPK increased yield and energy output considerably, especially of CR and SB which attained about doubled values. Crop rotation also increased the yield and energy output, especially of unfertilized rye, which attained values increased by about 75%. Fertilization with FYM resulted in the highest energy efficiency as the net-energy output, the energy productivity and the energy use efficiency were higher but the energy intensity was lower compared to unfertilized controls and NPK. When the nutrients in FYM were also energetically considered, the energy efficiency parameters of FYM decreased to the level of the NPK treatment. Crop rotation increased the energy efficiency of winter rye compared to the monoculture.

Keywords: rotational cropping; continuous cropping; winter rye; spring barley; farmyard manure; mineral fertilizer; long-term experiment; Pannonian climate; diesel fuel consumption; energy efficiency

1. Introduction

The use of mineral fertilizers (nitrogen (N), phosphorus (P), potassium (K), (NPK), for plant cultivation and production stimulated both a new industry for the production of fertilizers and research in the 19th century [1]. Long-term field experiments were established, e.g., in Rothamsted (UK), Halle (Germany) and also in Groß-Enzersdorf (Austria), to assess the long-term effects of cultivation techniques like fertilization and crop rotation. Steineck and Ruckebauer [1] reported for the long-term experiment in Groß-Enzersdorf, that continuous rye cropping led to yield depressions, which could not be compensated by fertilization with NPK or farmyard manure (FYM). The fertilization
effect on grain yield was found to be greater in spring barley than in winter rye. Applying FYM has a long-term effect on physical soil properties [2], soil micro-organisms [3] and soil chemical characteristics [1,4]. Soil organic matter and arbuscular mycorrhizal colonisation increases with application of FYM compared to mineral fertilization [5].

Arable farming has become increasingly mechanized, requiring significant energy inputs at particular stages of the production cycle to achieve optimum yields. The energy efficiency of crop production is dependent on the amount of external energy inputs and the energy output [6,7]. The energy input takes place either directly as fuel or electricity to operate machinery and equipment, or indirectly for the production of fertilizers, pesticides, machinery and seeds [8]. Site specific conditions like soil and climate affect the energy efficiency, e.g., under Pannonian climate conditions, the yield and energy efficiency of winter wheat are more strongly affected by climate conditions than by soil tillage [9,10].

The fertilization strategy influences the amount of used fossil energy. In organic farming systems, where no mineral NPK is used, the total energy input is up to 65% lower than in NPK systems [11,12], as mineral fertilization consumes a lot of energy [10,13–15], especially as process energy for the fertilizer production. Therefore, low-input systems are mainly based on FYM [16] as low-input agricultural systems have a greater energy use efficiency and lower greenhouse gas emissions compared to high-input systems [17]. In mineral fertilized systems, the amount of fertilizer and the number of splits can influence yield, product quality and the environment: Higher amounts of N fertilizer result in a lower energy efficiency. Calcium ammonium nitrate is more energy efficient than pure, stabilized or soil incorporated urea and three compared to two splits decrease the N loss from the system [15,18].

Further, the design of the crop rotation affects the resource efficiency and environmental effects of an arable farming system to a large extent. The use of crops that are well adapted to site-specific conditions increases the productivity and decreases potential environmental risks, as lower amounts of fertilizers, pesticides or fuel are needed [19].

The energy efficiency of two crops (winter rye and spring barley) as affected by different fertilization systems and crop rotation (for winter rye only) was analysed for a long-term field trial which was established at the Experimental Farm Groß-Enzersdorf of the University of Natural Resources and Life Sciences, Vienna in 1906 with the focus on the investigation of the replacement capacity of NPK for FYM and the compensation of negative monoculture effects of continuous winter rye through crop rotation and organic or mineral fertilization systems [1]. The overall objective of this study was to find out the fertilization and rotation system with the highest energy efficiency. In particular, this study aimed to present and discuss the crop yield, diesel fuel consumption, total energy input, energy output, net energy output, energy intensity, energy productivity and energy use efficiency of these systems for winter rye and spring barley.

2. Materials and Methods
2.1. Experimental Site and Climatic Conditions

The experiment was established in 1906 at the Experimental Farm of the University of Natural Resources and Life Sciences Vienna (BOKU) in Groß-Enzersdorf, which is located north-east of Vienna (48°11’ N,16°33’ E; 153 m a.s.l.). The field site is located on the edge of the Marchfeld plain, which is an important crop production region in the north-western part of the Pannonian Basin. The soil is a calcaric Phaeozem from loess and alluvial fine sediments with a silty loam texture. Soil samples for site characterisation were taken in March 2017 and analysed for soil organic carbon [20], phosphorus and potassium [21] and pH CaCl₂ [22] (Table 1).
Table 1. Nutrient contents in the soil of the continuous rye and crop rotation plots.

|                        | Continuous Rye | Crop Rotation A |
|------------------------|----------------|-----------------|
|                        | Control        | NPK            | FYM |
| Soil organic carbon    |                |                |     |
| (g kg\(^{-1}\))        |                |                |     |
| 0–30 cm                | 20.5           | 23.9           | 31.6 |
|                        | 18.8\(^{a}\)   | 19.9\(^{a}\)   | 27.4\(^{b}\) |
| 30–60 cm               | 17.1           | 20.5           | 24.8 |
|                        | 20.8\(^{a}\)   | 12.3\(^{a}\)   | 21.9\(^{a}\) |
| 60–90 cm               | 7.7            | 9.4            | 17.1 |
|                        | 12.0\(^{b}\)   | 7.7\(^{a}\)    | 11.7\(^{b}\) |

| Phosphorus (P) (mg kg\(^{-1}\)) |                |                |     |
| 0–30 cm                   | 44             | 134            | 159 |
|                           | 57\(^{a}\)     | 110\(^{b}\)    | 156\(^{c}\) |
| 30–60 cm                  | 21             | 25             | 65  |
|                           | <20\(^{a}\)    | <20\(^{a}\)    | <20\(^{a}\) |
| 60–90 cm                  | <20            | <20            | <20 |

| Potassium (K) (mg kg\(^{-1}\)) |                |                |     |
| 0–30 cm                   | 80             | 405            | 778 |
|                           | 99\(^{a}\)     | 295\(^{b}\)    | 553 \(^{c}\) |
| 30–60 cm                  | 46             | 129            | 493 |
|                           | 50\(^{a}\)     | 67\(^{a}\)     | 338 \(^{b}\) |
| 60–90 cm                  | 20             | 34             | 182 |
|                           | 31             | 26             | 94  |

| pH\(_{\text{CaCl2}}\) |                |                |     |
| 0–30 cm                   | 7.6            | 7.6            | 7.5 |
|                           | 7.7\(^{b}\)    | 7.6\(^{b}\)    | 7.5 \(^{a}\) |
| 30–60 cm                  | 7.7            | 7.7            | 7.7 |
|                           | 7.7\(^{a}\)    | 7.8\(^{a}\)    | 7.7 \(^{a}\) |
| 60–90 cm                  | 7.9            | 7.9            | 7.8 |
|                           | 7.8            | 8.0            | 7.6 |

A Mean value of the three plots in the crop rotation. Significant differences between fertilization treatments in each layer are shown with different minor letters (p < 0.05). NPK = mineral fertilizer; FYM = farmyard manure.

Compared to the unfertilized control, FYM had, after 103 years of different fertilization, a higher soil organic carbon content at 0–30 cm, a higher phosphorus and potassium content at 0–60 cm and a lower pH in 0–30 cm. The effects of long-term fertilization were higher for FYM than for NPK. Both did not to affect the contents at 60–90 cm.

The climate in the Marchfeld plain is Pannonian, characterised by hot, dry summers and cold winters with little snow. The long-term mean (1960–2019) of the annual temperature is 10.2 °C and of the mean annual precipitation is 537 mm (Table 2).

Table 2. Mean monthly precipitation and temperature at the experimental station Groß-Enzersdorf, 1960–2019.

| Month | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | I–XII |
|-------|---|----|-----|----|---|----|-----|------|----|----|-----|------|-------|
| °C    | −0.3 | 1.4 | 5.3 | 10.4 | 15.0 | 18.4 | 20.4 | 20.0 | 15.4 | 10.3 | 5.0 | 1.0 | 10.2 |
| mm    | 25.1 | 26.5 | 33.4 | 38.2 | 59.2 | 67.7 | 66.5 | 59.3 | 53.8 | 37.3 | 38.6 | 31.0 | 536.6 |

2.2. Experimental Design and Management

The long-term field experiment was started to test the possibility of replacing FYM by easily soluble NPK, and whether different fertilization systems can compensate for crop rotation deficits from continuous cropping of winter rye [1]. Data on the experiment before the 1960s, however, are rare or missing. Therefore, the yield data from 1960 to 2019 were used for this study. The field trial comprises an area of 4000 m\(^2\), which is divided into four long plots of 1000 m\(^2\), each with three equal sub-plots (20 m × 13 m) used for the different fertilization levels, and split into two parts for either monoculture or crop rotation (Figure 1).
Two factors were tested in the long-term field experiment. (1) Cropping system (continuous winter rye (CR) cropping versus a three-field crop rotation of winter rye (RR)-spring barley (SB)-bare-fallow). (2) Fertilization: unfertilized control, mineral fertilizer (NPK) of nitrogen (N), phosphorus (P) and potassium (K) with 117 kg N ha\(^{-1}\), 100 kg P\(_2\)O\(_5\) ha\(^{-1}\) (triple superphosphate, 45% P\(_2\)O\(_5\)), 222 kg ha\(^{-1}\) and 150 kg K\(_2\)O ha\(^{-1}\) (potassium chloride, 60% K\(_2\)O, 250 kg ha\(^{-1}\)) and farmyard manure (FYM from a cattle farm; 20 t fresh weight ha\(^{-1}\), 110–125 kg N ha\(^{-1}\), 90–110 kg P\(_2\)O\(_5\) ha\(^{-1}\), 140–160 kg K\(_2\)O ha\(^{-1}\)). Fertilization of P\(_2\)O\(_5\), K\(_2\)O and FYM was performed in autumn before ploughing. Mineral N fertilization was done in two equal splits in mid-March and mid-April.

Sowing was generally performed for winter rye (Austrian variety “Tschermaks vere-delter Marchfelder”) in mid-October and for spring barley (varieties until 1975: Eura II, Probstdorfer Adora, varieties from 1975 till 2019: Apex, Atem, Viva, Prosa, Evelina) in March at a row-distance of 12.5 cm. Plants were sprayed against broadleaf weeds in one pass-over in mid-April in all plots. Harvest was generally performed at maturity in July. Seed rate was for winter rye at 100 kg ha\(^{-1}\) and for spring barley at 160 kg ha\(^{-1}\).

The bare-fallow was mechanically weed controlled with shallow cultivation (5–8 cm).

### 2.3. Diesel Fuel Consumption

Diesel fuel consumption for the tillage processes (stubble cultivation and ploughing) as well as seeding was measured on a nearby field with similar soil conditions [23,24]. Shallow cultivation (working depth: 5–8 cm) was carried out with a wing sweep cultivator (seven tines on two bars with a tine distance of 84 cm and line distance of 42 cm), where three rotary hoes for crumbling and a wedge ring roller for crumbling and depth adjustment were mounted behind the bars of cultivator. Ploughing (working depth: 25–30 cm) was done with a four-furrow reversible mouldboard plough with a technical working width of 1.7 m. Seeding was carried out with a pneumatic seed drill, which was equipped with a short disc harrow for seedbed preparation, a combined chassis and packer unit for re-compacting the soil before seeding with 24 double disc coulters in offset. Working width of the wing sweep cultivator and pneumatic universal seed drill was 3.0 m.

For other processes (spreading of fertilizer, spraying of herbicide, harvest, transport), fuel consumptions were obtained from the Austrian Association for Agricultural Engineering and Landscape Development (ÖKL) [25]. Fuel consumption for harvesting, straw baling and transport was calculated for the mean crop yield of each treatment from 1960–2019. For the transportation of the harvested grain and straw, the diesel fuel consumption

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**Figure 1.** Design of the long-term field experiment in Groß-Enzersdorf (in 2017). FYM = farmyard manure; NPK = mineral fertilizer, Unfertilized = unfertilized control; white sub-plots: bare-fallow, winter rye and spring barley in crop rotation; grey sub-plots: continuous cropping of winter rye.
was calculated with the specific diesel fuel consumption coefficient of 0.09 liters diesel fuel per ton and kilometre according to ÖKL [25]. A distance of 5 km for transportation of the harvested grain and straw with tractor and trailer was assumed. The consumption of lubrication oil consumption was set at 2% of fuel consumption [26]. The fuel consumption for herbicide and fertilizer application were set constant for the years 1960–2019.

2.4. Energy Efficiency Indicators and Energy Equivalents

The energy analysis applied in this study compared the energy efficiency indicators for winter rye and spring barley in different fertilization systems. The energy efficiencies (Table 3) were calculated according to Hülsbergen et al. [6] and Yuan et al. [27] and were modified for grain and straw yield. This method corresponds to the process analysis, where human labor and solar energy input is not considered in the energy balances of agricultural production systems [6].

| Table 3. Definition of energy efficiency indicators. |
|-----------------------------------------------|
| **Energy input (E)**                           |
| Direct energy input (E_d)                     |
| Indirect energy input (E_i)                   |
| Total energy input (E)                        |
| **Energy output (E_O)**                       |
| E_OGRAIN = grain yield × gross energy in grain |
| E_OSTRAW = straw yield × gross energy in straw |
| E_OAGB = E_OGRAIN + E_OSTRAW                  |
| **Net-energy output (N_E)**                   |
| N_E = E_O – E                                 |
| **Energy intensity (E_I)**                    |
| E_IGRAIN = E/grain yield                       |
| E_IAGB = E/AGB                                |
| Grain allocated EI (E_IGRAIN)                 |
| E_IGRAIN = E/AGB × HI C/100                   |
| Straw allocated EI (E_ISTRAW)                 |
| E_ISTRAW = E/AGB × (1 – HI)/100                |
| **Energy productivity (E_P)**                 |
| E_PGRAIN = grain yield/E                      |
| E_PA GB = AGB yield/E                         |
| **Energy use efficiency (E_U_E)**             |
| E_U_EAGB = E_OAGB/E                           |

|  | Definition | Unit |
|---|------------|------|
| E_d = diesel fuel and lubricant oil | GJ ha⁻¹ |
| E_i = seeds + fertilizer + herbicide + machines | GJ ha⁻¹ |
| E = E_d + E_i | GJ ha⁻¹ |
| E_OGRAIN | GJ ha⁻¹ |
| E_OSTRAW | GJ ha⁻¹ |
| E_OAGB | GJ ha⁻¹ |
| N_E = E_O – E | GJ ha⁻¹ |
| E_IGRAIN = E/grain yield | MJ kg⁻¹ |
| E_IAGB = E/AGB | MJ kg⁻¹ |
| E_IGRAIN = E/AGB × HI C/100 | MJ kg⁻¹ |
| E_ISTRAW = E/AGB × (1 – HI)/100 | MJ kg⁻¹ |
| E_PGRAIN | kg GJ⁻¹ |
| E_PA GB = AGB yield/E | kg GJ⁻¹ |
| E_U_EAGB = E_OAGB/E | GJ GJ⁻¹ |

A, B, C, D: Energy input for processing, storage and sale of seed, NUTR, harvest index, AGB, respectively.

The yields of grain, straw and the above-ground biomass (AGB = grain yield plus straw yield) are given with 14% moisture content. The straw yield was calculated with the mean harvest index (HI = grain yield/AGB × 100) of the years between from 2011 to 2019. Each year the straw was completely removed from the plots after baling. The gross energy in the grain and the straw of both winter rye and spring barley was set to 18.4 MJ kg⁻¹ dry matter [6], which is the same as the gross energy content for feeding.

The direct and indirect energy input were calculated by multiplying the amounts of inputs of diesel fuel, lubricant oil, seeds, fertilizer and herbicide by the corresponding energy equivalents (Table 4).

A calculation for the energy equivalent of the embedded energy in farm machinery was presented by Biedermann [28] for cereal production in different fertilizations systems based on a 100 ha cereals area under Austrian conditions. The mass of the machinery was converted into cumulative energy demand according to the VDI-guideline 4600 [29] using the energy-coefficients from Scholz [30]. It was then divided by the estimated technical and economic life (10,000 h for the tractor, 3000 h for the combine harvester, 2000–3000 ha for the implements), to allow the calculation of the area-specific energy demand.
Table 4. Energy equivalents used in this study.

|                               | Unit          | Energy Equivalent | References |
|-------------------------------|---------------|-------------------|------------|
| **Direct energy use**         |               |                   |            |
| Diesel fuel                   | MJ L$^{-1}$   | 39.6              | [6,31]     |
| Lubricant oil                 | MJ L$^{-1}$   | 39.0              | [31]       |
| **Indirect energy use**       |               |                   |            |
| Mineral fertilizer (NPK)      |               |                   |            |
| Calcium ammonium nitrate (27% N) | MJ kg$^{-1}$ N | 32.2              | [7,32]     |
| Triple super phosphate (45% P$_2$O$_5$) | MJ kg$^{-1}$ P$_2$O$_5$ | 9.1              | [33]       |
| Potassium chloride (60% K$_2$O) | MJ kg$^{-1}$ K$_2$O | 5.4              | [33]       |
| **Herbicide**                 |               |                   |            |
| Herbicide for broadleaf weed control | MJ kg$^{-1}$ | 259               | [34]       |
| **Seeds**                     |               |                   |            |
| Winter rye, spring barley     | MJ kg$^{-1}$  | 5.5               | [6]        |
| **Machinery**                 |               |                   |            |
| Unfertilized                  | GJ ha$^{-1}$  | 1.58              | [28]       |
| NPK                           | GJ ha$^{-1}$  | 1.64              | [28]       |
| FYM                           | GJ ha$^{-1}$  | 1.80              | [28]       |

FYM can be considered as waste or a valuable fertilizer in crop production with different consequences in the calculation of energy efficiency [6]. Consequently, in our study, the nutrients of FYM were either not considered energetically (FYM) or energetically considered (FYM$_{NUTR}$). The substitution approach was used for the energetic consideration of nutrients of FYM [6]. The energy contents of N, P and K in FYM were energetically evaluated based on energy contents of mineral fertilizers including these nutrients. In our study we used for N the fertilizer calcium ammonium nitrate (27% N), for P the fertilizer triple super phosphate (45% P$_2$O$_5$) and for K the fertilizer potassium chloride (60% K$_2$O). It was assumed that 100% of the nutrients were plant available in the long-run.

The dataset of RR was built from the yield of each year, which allowed the comparison to CR.

2.5. Statistical Analysis

All analyses were conducted using IPM® and SPSS® Statistics 21. The requirements for analysis of variance (ANOVA) were tested with the Levene test for homogeneity of variances and the Shapiro-Wilk test for normal distribution of residuals. One-way ANOVA tests were carried out for crop yield and energy efficiency indicators to detect fertilization effects. Year was considered as replication. Multiple comparisons to separate means were carried out with the Student-Newman-Keuls procedure ($p < 0.05$). The experiment is 20 years older than the introduction of randomized experiments in 1926, which was the start of the modern statistical designing of agricultural experiments [35]. Therefore, no true replications are available, which limits the possibilities of statistical evaluation [36].

3. Results

3.1. Total Fuel Consumption

A high share of the area-based diesel fuel consumption is required for ploughing and harvesting. The consumption was highest with FYM and lowest in the unfertilized control over all crops (Table 5). The higher fuel consumption of FYM and NPK compared to unfertilized was mainly due to spreading of fertilizer, and slightly due to higher fuel consumption for harvest. Spreading of FYM required more diesel fuel than for NPK. RR required more diesel fuel than CR; the consumption of SB lay in between.
Table 5. Diesel fuel consumption (L ha\(^{-1}\)) for continuous winter rye, winter rye in rotation and spring barley in rotation.

| Operations          | Unfertilized | NPK | FYM |
|---------------------|--------------|-----|-----|
|                     | CR \(^A\)    | RR \(^B\) | SB \(^C\) | CR | RR | SB | CR | RR | SB |
| Shallow cultivation | 5.7          |      |      | 9.0 \(^D\) | 17.0 \(^E\) |
| Ploughing           | 18.8         |      |      |     |     |     |     |     |     |
| Seeding             | 6.6          |      |      |     |     |     |     |     |     |
| Spreading of fertilizer | 0.0      | 9.0 \(^D\) |     |     |     | 9.5 |     |     |     |
| Spraying of herbicide \(^B\) | 2.0 |      |     |     |     |     |     |     |     |
| Harvesting          | 20.0         | 22.0 | 22.0 | 10.3 | 11.9 | 11.3 |     |     |     |
| Straw baling        | 5.1          | 8.3  | 3.3  | 9.5  | 12.3 | 9.6  | 10.3 | 11.9 | 11.3 |
| Transport (grain, straw; 5 km) | 2.2 | 3.7  | 1.7  | 4.3  | 5.3  | 4.5  | 4.3  | 5.0  | 5.1  |
| Total               | 60.4         | 65.1 | 58.1 | 77.9 | 81.7 | 78.2 | 86.7 | 89.0 | 88.5 |

\(^A\) Continuous rye, \(^B\) Rye in rotation, \(^C\) Spring barley in rotation, \(^D\) Two applications of N, one application of PK, \(^E\) Loading, transport and spreading of FYM, \(^F\) One application of herbicide.

3.2. Total Energy Input

The total energy input was higher with NPK and lowest in unfertilized (Table 6) with a mean over all crops of 11.27 GJ ha\(^{-1}\) for NPK and 4.99 GJ ha\(^{-1}\) for unfertilized.

Table 6. Direct and indirect energy input (GJ ha\(^{-1}\), mean over years 1960–2019) for continuous winter rye, winter rye in rotation and spring barley in rotation.

| Direct Energy        | Unfertilized | NPK | FYM (FYM\(^{NUTR}\)) |
|----------------------|--------------|-----|----------------------|
| Diesel fuel, lubricant | 2.44         | 2.63 | 2.35                 |
|                      | 3.15         | 3.30 | 3.16                 |
|                      | 3.50         | 3.59 | 3.57                 |

Indirect energy

| Seeds             | 0.55 | 0.88 | 0.55 | 0.88 | 0.55 | 0.88 |
|-------------------|------|------|------|------|------|------|
| Fertilizer        |      |      |      |      |      |      |
| N                 | 0.00 |      | 3.77 |      | 0.00 (3.77) |      |
| P\(_2\)O\(_5\)     | 0.00 |      | 0.91 |      | 0.00 (0.91) |      |
| K\(_2\)O           | 0.00 |      | 0.81 |      | 0.00 (0.81) |      |
| Herbicide         | 0.28 |      | 0.28 |      | 0.28 |      |
| Machinery         | 1.58 |      | 1.64 |      | 1.80 |      |
| Total             | 4.85 | 5.04 | 5.09 | 11.11 | 11.26 | 11.45 | 6.13 (11.62) \(^D\) | 6.22 (11.71) | 6.53 (12.02) |

\(^A\) Continuous winter rye, \(^B\) Winter rye in rotation, \(^C\) Spring barley in rotation, \(^D\) In brackets with energetic consideration of the mineral nutrients in FYM.

The total energy input of FYM was intermediate between Unfertilized and NPK with a mean over all crops of 6.29 GJ ha\(^{-1}\) (without consideration of nutrients) or for FYM\(^{NUTR}\) with 9.63 GJ ha\(^{-1}\) (with consideration of nutrients). SB required a slightly higher total energy input than RR and CR, due to the higher indirect energy input with seeds.

The ratio of direct energy to indirect energy (in %) for the fertilization treatments (means over all crops) was unfertilized 50:50, NPK 44:56 and FYM\(^{NUTR}\): 37:63. The share of fertilizer energy on the total energy for NPK was 49%. The diesel fuel and lubricant consumption for tillage, seeding, spraying, spreading, harvest and transport was the second highest energy consumer. The share of the indirect energy input of the machinery on the total energy input was as follows: Unfertilized 32%, NPK 15%, FYM 29% and FYM\(^{NUTR}\) 19%. The energy input allocated to the seeds was: 14% for Unfertilized, 6% for NPK, 11% for FYM and 7% for FYM\(^{NUTR}\). The lowest energy input proportion was for herbicides with about 6% for Unfertilized, 2% for NPK, 4% for FYM and 3% for FYM\(^{NUTR}\).
3.3. Crop Yield and Energy Output

The grain yield among winter rye treatments was lowest for unfertilized CR and highest for RR fertilized with NPK (Table 7). The grain yield increase with fertilization compared to the unfertilized controls for CR was +123% (NPK) or +83% (FYM), and for RR +38% (NPK) or +26% (FYM). The straw yield increased by +98% (NPK) and +89% (FYM) for CR and +45% (NPK) and 42% (FYM) for RR. In the case of CR, the grain yield increase was higher for NPK than for FYM, whereas for RR there was no difference between NPK and FYM.

Table 7. Crop yield and energy efficiency indicators for continuous winter rye, winter rye in rotation and spring barley in rotation (mean over years 1960–2019).

| Crop Yield A | Harvest Index (%) | Energy Output | Energy Efficiency | Energy Use Efficiency |
|--------------|-------------------|---------------|-------------------|----------------------|
|              | Grain Straw       | Net Energy Output | Energy Intensity | Energy Productivity |
|              | (kg ha⁻¹)        | (GJ ha⁻¹) | (GJ ha⁻¹) | Grain B | AGB C | Grain D | Straw D |
|              |                   |                |                | (MJ kg⁻¹) | (MJ kg⁻¹) | (MJ kg⁻¹) | (MJ kg⁻¹) |
| Continuous  |                   |                |                |            |            |            |            |
| winter rye  |                   |                |                |            |            |            |            |
| Unfertilized| 3504 a            | 34.3           | 106.1 a        | 3.60 b     | 0.74 b     | 0.37 b     | 0.15 b     |
| NPK         | 6931 b            | 111.9 b        | 173.9 b        | 3.39 b     | 0.74 b     | 0.32 b     | 0.15 b     |
| FYM         | 6007 b            | 110.6 b        | 170.3 b        | 1.59 b     | 0.74 b     | 0.32 b     | 0.15 b     |
| Winter rye  |                   |                |                |            |            |            |            |
| in rotation |                   |                |                |            |            |            |            |
| NPK         | 3927 b            | 130.5 b        | 295.5 b        | 1.59 b     | 0.74 b     | 0.32 b     | 0.15 b     |
| FYM         | 3588 b            | 127.7 b        | 173.9 b        | 1.59 b     | 0.74 b     | 0.32 b     | 0.15 b     |
| Spring      |                   |                |                |            |            |            |            |
| barley      |                   |                |                |            |            |            |            |
| Unfertilized| 1725 a            | 35.6           | 88.9 b         | 3.73 c     | 0.73 c     | 0.37 c     | 0.15 c     |
| NPK         | 5630 a            | 115.9 b        | 184.7 a        | 3.73 c     | 0.73 c     | 0.37 c     | 0.15 c     |
| FYM         | 5457 a            | 156.2 b        | 295.5 b        | 1.59 b     | 0.74 b     | 0.32 b     | 0.15 b     |

Significant differences (p < 0.05; Student-Newman-Keuls test) are indicated with different letters. A 14% moisture content. B Total energy input is allocated to the grain. C Total energy input is allocated to the AGB. D Total energy input is allocated to grain or straw by using harvest index. E In brackets with energetic consideration of the mineral nutrients in FYM. AGB = above-ground biomass.

The grain yield of SB increased with fertilization by +134% (NPK) and +145% (FYM), with no significant differences between fertilizer types. The straw yield of SB was by +106% (CR), +43% (RR) or +156% (SB). The harvest index of SB was generally higher than that of winter rye.

The harvest index of winter rye did not differ between fertilization treatments or crop rotations. Also the harvest index of SB was not affected by fertilization. The harvest index (HI) of SB was generally higher than that of winter rye.

The results for energy output of grain and straw showed the same relative differences between treatment for the yields of grain and straw. The energy output of the AGB increased compared to the unfertilized controls with NPK by +106% (CR), +43% (RR) or +156% (SB) and with FYM by +87% (CR), +37% (RR) and +156% (SB).

Crop rotation increased the grain yield, and thereby the energy output of grain, of winter rye (RR compared to CR) by +76% in the unfertilized control, by +9% with NPK and by +22% with FYM. The straw yield, and thereby the energy output of straw, of winter rye was advanced with rotation by +60% in Unfertilized, by +14% with NPK and by +22% with FYM (Table 8). Consequently, the total energy output of the AGB was increased by +64% in unfertilized control, by +14% with NPK and by +20% with FYM for RR compared to CR.
Table 8. Differences between RR and CR (mean over years 1960–2019).

|                       | Unfertilized | NPK       | FYM       | (FYM\text{NUTR} \text{E}) |
|-----------------------|--------------|-----------|-----------|-----------------------------|
| **Crop yield** \text{A} |              |           |           |                             |
| Grain (kg ha\text{−1}) | +1223        | +309      | +633      |                             |
| Straw (kg ha\text{−1}) | +2076        | +949      | +1410     |                             |
| Harvest index (%)      | +2.2         | −1.6      | +0.3      |                             |
| **Energy output**      |              |           |           |                             |
| Grain (GJ ha\text{−1}) | +19.8        | +5.0      | +10.2     |                             |
| Straw (GJ ha\text{−1}) | +33.2        | +18.6     | +21.1     |                             |
| AGB (GJ ha\text{−1})  | +53.0        | +23.6     | +31.3     |                             |
| **Net-energy output**  |              |           |           |                             |
| AGB (GJ ha\text{−1})  | +53.0        | +20.0     | +32.8 (+31.2) |                             |
| **Energy intensity**   |              |           |           |                             |
| Grain \text{B} (MJ kg\text{−1}) | −1.55       | −0.24    | −0.51 (-0.98) |                             |
| AGB \text{C} (MJ kg\text{−1}) | −0.45       | −0.12    | −0.16 (-0.29) |                             |
| Grain \text{D} (MJ kg\text{−1}) | −0.13       | −0.06    | −0.05 (-0.08) |                             |
| Straw \text{D} (MJ kg\text{−1}) | −0.32       | −0.06    | −0.11 (-0.21) |                             |
| **Energy productivity** |              |           |           |                             |
| Grain (kg GJ\text{−1}) | +231         | +23      | +94 (+52) |                             |
| AGB (kg GJ\text{−1})  | +749         | +117     | +288 (+159) |                             |
| **Energy use efficiency** |            |           |           |                             |
| EUE\text{AGB} (GJ GJ\text{−1}) | +9.9         | +3.2     | +4.9 (+2.5) |                             |

\text{A} 14\% moisture content, \text{B} Total energy input is allocated to the grain, \text{C} Total energy input is allocated to the AGB, \text{D} Total energy input is allocated to grain or straw by using harvest index, \text{E} In brackets with energetically consideration of the mineral nutrients in FYM. NPK = mineral fertilizer, FYM = farmyard manure, AGB = above-ground biomass.

3.4. Energy Efficiency

The net-energy output was for CR, RR and SB lowest with Unfertilized (Table 7). Compared to Unfertilized it was higher for CR +112\% (NPK), +95\% (FYM), +90\% (FYM\text{NUTR}), for RR +40\% (NPK), +40\% (FYM), +36\% (FYM\text{NUTR}) and for SB +168\% (NPK), 178\% (FYM), 174\% (FYM\text{NUTR}). For all three crops, net-energy output did not differ significantly between NPK and FYM. Taking the nutrients in the FYM into consideration (FYM\text{NUTR}), the net-energy output decreased in all three crops by 2\% compared to FYM (not significant). Crop rotation increased the net-energy output of the AGB of winter rye (RR compared to CR) by +71\% in Unfertilized, by +13\% with NPK, by +22\% with FYM and with FYM\text{NUTR} (Table 8).

The energy intensity was either considered for the production of grain or AGB when the total energy input was allocated to the grain or AGB, or for grain or straw when the total energy input was allocated to grain or straw by using the harvest index. All parameters for CR were lower with FYM compared to Unfertilized, NPK and FYM\text{NUTR}. For RR, they were ranked with FYM with Unfertilized lower than with FYM\text{NUTR} and NPK. For SB, they were ranked as follows: FYM < FYM\text{NUTR}/NPK < Unfertilized (Table 7). Crop rotation decreased the energy intensity of the grain yield or AGB of winter rye (RR compared to CR), when all energy was allocated to the particular dry matter, by −43\% or −39\% in Unfertilized, by −7\% or −10\% with NPK, by −21\% or −22\% with FYM and by −22\% or −21\% with FYM\text{NUTR} (Table 8).

The energy productivity for grain and AGB production was, for all three crops, highest for FYM (except for Unfertilized and FYM in RR). For CR, there was no difference between Unfertilized and NPK. Considering the nutrients energetically (FYM\text{NUTR}), the energy productivity decreased to the level of Unfertilized and NPK. In RR, the energy productivity for grain production of NPK was lower than that of FYM and of Unfertilized and that for AGB production was ranked as follows: FYM > Unfertilized > NPK. In SB, for grain production and for AGB production it was higher with FYM than with NPK and Unfertilized. Considering the nutrients energetically (FYM\text{NUTR}), the energy productivity decreased for CR and SB to the level of Unfertilized and NPK, and for RR to the level
of NPK, but stayed lower compared to Unfertilized. Crop rotation increased the energy productivity for grain or AGB of winter rye (RR compared to CR) by +69% or +81% in Unfertilized, by +7% or +12% with NPK, by +20% or +19% with FYM and FYM_{NUTR} (Table 8).

The energy use efficiency (EO_{AGB}/EI) for CR and RR was highest with FYM and lowest with NPK, whereas the unfertilized control was intermediate. In SB, it was higher with FYM than with NPK and Unfertilized. Considering the nutrients energetically (FYM_{NUTR}), energy use efficiency decreased to the level of NPK (CR, RR) or NPK and Unfertilized (SB). Crop rotation increased the energy use efficiency of winter rye (RR compared to CR) by +60% in Unfertilized, by 23% with NPK, by +20% with FYM and by +19% with FYM_{NUTR} (Table 8).

4. Discussion

4.1. Total Fuel Consumption

Intensification in plant production is often linked with higher area-based fuel consumption. In this study, nitrogen fertilizer was applied in two passes and the phosphorus and potassium fertilizer in one pass. Therefore, an additional fuel consumption of 9 L ha\(^{-1}\) was required for NPK fertilization in comparison to Unfertilized. The highest fuel consumption for the FYM treatment was caused by the manipulation (loading, transportation, spreading) of the 20 t ha\(^{-1}\) fresh weight of FYM. A higher fuel consumption for FYM systems than in mineral fertilized systems was also found by Hülsbergen [6]. This fact is often the reason for the higher fuel consumption for fertilization in organic farming systems than in conventional farms [16]. On the other hand, FYM fertilization increased the soil organic carbon (Table 2), which has positive effects on fuel consumption during tillage. A Canadian long-term study [37] showed a lower fuel consumption for ploughing in FYM treatments than in NPK treatments due to lower soil resistance.

Application of mineral N in three doses, instead of two doses or one dose, in winter wheat, increased the fuel consumption, direct energy input and the nitrogen efficiency [18], whereas the values of energy efficiency indicators were not clearly affected [15].

4.2. Total Energy Input

Our long-term experiment was carried out under rainfed conditions without irrigation. Such systems have a much lower energy input in comparison to irrigated cropping systems [38]. The total energy input in our study was mainly determined by the fertilization system. The input was for the unfertilized control and FYM as well as FYM_{NUTR} below 10 GJ ha\(^{-1}\) and thereby represents a low-input system [16,38], whereas NPK is a high-input system. The high share of energy through mineral fertilization (49%) in this study is characteristic for conventional cropping systems [10,12,15,39].

Through the energetic consideration of the mineral nutrients in FYM_{NUTR}, the total energy input increased by about 54%. This approach is suitable if FYM is imported from a livestock farm to an arable farm. Depending on the distance of arable field and livestock farm, an additional fuel consumption for the transport of the voluminous and heavy-weight FYM would increase the total fuel consumption and total energy input. The energetic non-consideration of the nutrients of FYM is justified if FYM is a nutrient carrier in the nutrient cycle of a mixed farm (livestock farming is linked with cropping). In contrast, for specialised arable farms, where organic and mineral fertilizers are brought into the farm system, the nutrient of organic manure should be energetically considered in energy analyses. This resulted in our study in similar energy inputs as for NPK-fertilized cropping systems.

4.3. Crop Yield and Energy Output

Long-term experiments show rotation and fertilization effects more clearly in grain yield. Energy output is the most important parameter, which is mainly determined by grain and straw yield level.
In the Pannonian region with its semi-arid climate conditions, water is the limiting factor for plant growth and mainly responsible for yield variability of agricultural crops [40].

The yearly application of FYM increased the soil organic carbon for all FYM-treated plots (Table 2), and the mean aggregate size in the seedbed [2], which had positive effects on crop yield and energy output. Neugschwandtner et al. [4] also found significant effects of fertilization on pH, total organic carbon and plant available phosphorus and potassium in the soil of our experimental plots. In the upper soil layer (0–30 cm), the differentiation of fertilization treatments was larger than in the following two 30 cm soil layers [4]. Whereas, the fertilization showed clear effects on the soil nutrient content, there was a lower soil nutrient content for the upper soil layer (0–30 cm) in the fertilized continuous rye plots then in the fertilized continuous rye plots (Table 2).

The differences between RR and CR were much higher for Unfertilized than for NPK and FYM (Table 8). This indicated that the compensation through fertilization with NPK or FYM was smaller than for the unfertilized treatment. This result was also found by Steineck and Ruckenbauer [1] for the years 1960–1975 in the same experiment.

Higher crop yields after preceding crops than in continuous cropping (monoculture) were also reported by [41]. In our study, we supposed that the nitrogen and water accumulation in the bare-fallow influenced the crop yield of RR positively. The positive bare-fallow effect on the following crop is also observed in dry-land cropping systems.

4.4. Energy Efficiency

Energy input and energy output were combined to calculate the efficiency parameters [6] net-energy output, energy intensity and energy use efficiency. These parameters were mainly determined by the higher energy output in comparison to the lower energy input values as already shown by Arvidsson [7]. Eventually crop yield is a main determinant of energy efficiency.

In our study, a clear differentiation of fertilizer treatments and rotations was visible for the energy efficiency indicators. FYM application was more energy-efficient than NPK for CR, RR and SB. The higher efficiency of energy use in organically fertilized cropping systems was also found in studies by Moitzi et al. [12], Sartori et al. [39] and Pimentel et al. [42].

Including the energetic consideration of the mineral nutrients in FYM, the energy efficiency parameters for FYM$_{NUTR}$ were intermediate between NPK and FYM. It should be noted that the energy efficiency of manure-fertilized crops on an arable farm without its own livestock production is similar to NPK-fertilized crops because of the energetic consideration of the nutrients and the higher fuel consumption for spreading (see Section 4.1). In this case an improvement can mainly be achieved with low energy consuming transport of solid and liquid manure across small distances between manure storage and the field.

Besides crop rotation and fertilization, the tillage system also affects the energy efficiency of crops in semi-arid regions. In a long-term tillage experiment close to the present experiment, winter wheat produced in a ploughless system with shallow soil loosening showed the highest net-energy output and energy use efficiency with the lowest energy intensity [10].

5. Conclusions

The aim of this study was to analyse the energy efficiency of CR, RR and SB in a long-term fertilization and rotation experiment under Pannonian climate conditions. Based on the results of the investigations, the following conclusions were drawn.

- FYM-manured cropping systems required more diesel fuel than an NPK-fertilized cropping system. This higher direct energy input was compensated by the lower indirect energy input if the nutrient of the FYM was not energetically considered.
- Cultivation of CR without fertilization reduced the yields considerably. The yield depression due to monoculture could not be compensated by fertilization.
• The fertilization effects for SB were higher than those for winter rye.
• RR produced higher yields and was more energy efficient than CR. From the point of energy efficiency, winter rye and spring barley fertilized with FYM were more energy efficient than with NPK fertilization.
• Taking the nutrients of FYM energetically into consideration reduced the energy efficiency of FYM considerably.
• Crop rotation results in a higher energy efficiency than monoculture.
• Energy optimization of crop management includes crop rotation and FYM fertilization.

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