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Crop sequence effects on energy efficiency and land demand in a long-term fertilisation trial

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Abstract: The effect of crop sequences (CR – continuous winter rye; CropR – three-field crop rotation of winter rye-spring barley-bare fallow) and fertilisation systems (unfertilised control, mineral fertiliser (NPK), farmyard manure (FYM)) on crop yield, energy efficiency indicators and land demand were analysed in a long-term experiment under Pannonian climate conditions. Due to lower fuel consumption in the bare fallow, the total fuel consumption for CropR was 27% lower than in CR. It was for NPK and FYM fertilisation by 29% and 42% higher than in the control. Although the energy output was lower in CropR than CR, the energy use efficiency for grain production increased by 35% and for above-ground biomass production by 20%. Overall crop sequences, the NPK treatment had higher crop yields, energy outputs and net-energy output with a lower energy use efficiency than the unfertilised control. CropR increased the land demand just by 20% in comparison to CR, although one-third of the land was not used for crop production. The land demand could be decreased with fertilisation by 50% (NPK) or 48% (FYM). A bare fallow year in the crop rotation decreased the crop yield, energy input and increased the energy use efficiency and land demand.

Keywords: cropping systems; energy analysis; land use efficiency; mineral fertilisation; Pannonian basin

Energy-efficient arable crop production can be realised with a large energy output combined with low energy input (Moitzi et al. 2019). The energy use efficiency (energy output/energy input) is a most important indicator for the evaluation of the economic and ecologic performance of the cropping system (Hülsbergen et al. 2001, Jacobs et al. 2016). Energy output and energy input are determined by the kind of crop species as well as by production site characteristics like climate, soil properties, the socio-economic situation of the farm, cultivation system and agricultural legislation. Management (e.g. fertilisation, mechanisation and cropping system) and crop rotation are major determinants of energy efficiency in crop production (Zając et al. 2013, Klimek-Kopyra et al. 2017). Nitrogen fertilisation and diesel fuel are the most energy-intensive inputs (Hoeppner et al. 2005, Jacobs et al. 2016, Moitzi et al. 2019). Long-term field experiments have been established to assess the long-term effects of management (fertilisation and crop rotation) on soil and agronomic parameters. Steineck and Ruckenbauer (1976) reported for the long-term experiment in Groß-Enzersdorf (Austria), which has been established in 1906, that continuous rye cropping led to yield depressions, which cannot be compensated by fertilisation with mineral fertiliser (NPK) or farmyard manure (FYM). In this long-term experiment in Groß-Enzerdorf (Austria), winter rye grown in a three-field crop rotation of winter rye-spring barley-bare fallow was more energy-efficient than rye in continuous cropping, and the fertilisation effects on grain yield and energy efficiency were found to be larger in spring barley than in winter rye (Moitzi

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et al. 2021). In this study, the crops winter rye and spring barely of the three-field crop rotation were considered in the energy efficiency analysis and not the bare fallow. Fallow is a resting period of agricultural land in which the field is not cropped and dormant species are allowed to re-establish by natural succession after cropping with positive effects on plant and soil microbial diversity (Castro et al. 2016). The weeds emerging on fallow plots must be controlled through shallow soil cultivation. Besides the weeding effect, also soil water is conserved as the capillary rise to the topsoil is broken. Thereby soil water and nitrogen can accumulate for the subsequent crop (Zeleke 2017). But in a crop rotation with a bare fallow cropping season, less area is available for crop production compared to continuous or rotational cropping. In a previous study (Moitzi et al. 2021), we reported that crop rotation resulted compared to continuous cropping in a higher winter rye yield especially in the unfertilised control but also when NPK or FYM was applied. Also, spring barley reacted positively to NPK or FYM. But in that study, the assessment was focused on the individual crops, i.e. the bare fallow was not taken into consideration for assessing energy efficiency indicators. As there is a lack of knowledge of the energetic efficiency of crop rotations, especially for those including a bare fallow, we analysed in this study the effect of different crop sequences (winter rye-spring barley-bare fallow rotation and continuous winter rye) and fertilisation systems (unfertilised, mineral fertilisation and farmyard manure) as observed in a long-term field trial. In particular, this study aimed to analyse the fuel consumption, energy input (direct and indirect), energy output (grain, straw), net-energy output, energy use efficiency and land demand.

MATERIAL AND METHODS

Experimental site and climatic data. The long-term experiment was established in 1906 at the Experimental Farm of the University of Natural Resources and Life Sciences Vienna (BOKU) in Groß-Enzersdorf. It is located in the Marchfeld plain, north-east of Vienna (48°11'N, 16°33'E; 153 m a.s.l.), which is an important plant production region in the north-western part of the Pannonian Basin. The soil is a silty loam from loess and alluvial fine sediments, classified as Calcaric Chernozem.

The long-term average temperature is at 10.2 °C and the long-term mean precipitation is at 536.6 mm. Monthly climate data and soil properties data are shown in Moitzi et al. (2021).

Experimental design and management. The field experiment, which has been established in 1 906 without replications, covers an area of 4 000 m^2 and is divided into four long plots of 1 000 m^2, each with three sub-plots (20 m × 13 m each) used for the different fertilisation levels, and split into two parts for either continuous cropping or crop rotation. Two factors are tested in the long-term field experiment: (1) Cropping sequence (continuous winter rye (CR) cropping *versus* a three-field crop rotation (CropR) of winter rye-spring barley-bare fallow); (2) fertilisation system: unfertilised control, mineral fertiliser (NPK) of nitrogen (N), phosphorus (P) and potassium (K) with 117 kg N/ha (calcium ammonium nitrate, 27% N), 44 kg P/ha (triple superphosphate, 20% P) and 125 kg K/ha (potassium chloride, 50% K) or cattle farmyard manure (FYM 20 t fresh weight/ha, 110–125 kg N/ha, 40–48 kg P/ha, 116–133 kg K/ha). The fertilisation was done on plots with crops every year. The bare fallow was not fertilised at all. The fertilisation of minerals P, K and FYM was done in autumn before ploughing, mineral N fertiliser was applied in two equal splits in mid-March and mid-April.

Sowing was performed for winter rye (Austrian cv. Tschermaks veredelter Marchfelder) in mid-October and for spring barley (cultivars until 1975: Eura II, Probstdorfer Adora, cultivars from 1975 till 2019: Apex, Atem, Viva, Prosa, Evelina) in March at a row-distance of 12.5 cm. The seed rate was for winter rye at 100 kg/ha and for spring barley at 160 kg/ha. Cultivated plants were sprayed against broadleaf weeds in one pass-over in mid-April in all plots. Harvest was generally performed at maturity in July. The bare fallow was mechanically weed controlled three times per year with shallow cultivation (5–8 cm). As crop yield data before the 1960s are rare or missing, the yield data from 1960 to 2019 (60 years) were used for this study.

Energy efficiency and land demand analysis. The energy analysis applied in this study compared the energy input (direct and indirect), energy efficiency indicators (energy output, net energy output and energy use efficiency) for CR and CropR in different fertilisation systems. The energy efficiency indicators were calculated according to Hülsbergen et al. (2001). The energy output of grain and straw and total above-ground biomass (AGB) of winter rye and spring barley was calculated by multiplying

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the dry crop yields with the gross energy content of 18.4 MJ/kg dry matter. The gross energy content of grain and straw was calculated from the crude nutrient content and gross energy factors according to the DLG (1997). Each year the straw has been completely removed from the plots after baling. The diesel fuel consumption for stubble cultivation, ploughing as well as seeding was measured on a nearby field with similar soil conditions. For other processes (spreading of fertiliser, spraying of herbicide, harvest, transport), the fuel consumptions were obtained from the Austrian Association for Agricultural Engineering and Landscape Development (ÖKL 2019). 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 was calculated with the specific diesel fuel consumption coefficient of 0.09 L diesel fuel per ton and kilometre according to ÖKL (2019). A distance of 5 km for transportation of the harvested grain and straw with tractor and trailer was assumed. The consumption of lubrication oil was set at 2% of fuel consumption (KTBL 2015). The fuel consumption for herbicide and fertiliser application was set constant for the years 1960–2019. The direct and indirect energy inputs were calculated by multiplying the amounts of inputs of diesel fuel, lubricant oil, seeds, fertiliser and herbicide by the corresponding energy equivalents. The amounts of the used production facilities were multiplied with the energy equivalents (EQ): For diesel fuel, an EQ of 39.6 MJ/L and for lubricant, an EQ of 39.0 MJ/L were assumed (Sørensen et al. 2014). An EQ of 32.2 MJ/kg was set for calcium ammonium nitrate according to Jenssen and Kongshaug (2003). EQ for triple superphosphate and potassium chloride was set with 4.0 MJ/kg P and 4.5 MJ/kg K (Brentrup and Küsters 2008). Herbicide for broadleaf weeds was set at 259 MJ/kg (Saling and Kölsch 2008). The EQ for the seed of winter rye and spring barley was set with 5.5 MJ/kg according to Hülsbergen et al. (2001). The determination of the EQ of the embedded energy in farm machinery was presented by Biedermann (2009) for cereal production in different fertilisation systems based on a 100 ha cereals area under Austrian conditions: unfertilised: 1.58 GJ/ha, NPK: 1.64 GJ/ha, FYM: 1.80 GJ/ha. For CropR, the energy input (direct and indirect) and energy output were calculated for winter rye plus spring barley and then divided by three (including thereby also the area for the bare fallow), whereas the indirect machinery energy was considered once in the CropR. This assumption fits to the real situation on an arable farm, where the same machinery is used for processing all fields. Net-energy output was calculated as the difference between the energy output AGB and total energy input (direct and indirect). Energy use efficiency was calculated for grain and AGB production as the quotient of energy output and total energy input. The land demand was calculated as the reciprocal of the net-energy output in m^2/GJ (Jacobs et al. 2016).

Statistical analysis. All analyses were conducted using IBM® SPSS® Statistics 21 (New York, USA). The requirements for analysis of variance (ANOVA) were tested with the Levene test for homogeneity of variances and with the Shapiro-Wilk test for normal distribution of residuals. The two-way ANOVA tests were carried out for crop yields, energy efficiency indicators and land demand to detect crop sequence effects and fertilisation effects. The year was considered as replication. Multiple comparisons to separate means of fertilisation were carried out with the Student-Newman-Keuls procedure ($P < 0.05$). Separating means of crop sequence × fertilisation interactions was done with the least significant differences (*LSD*, $P < 0.05$). The dataset of CropR was built for each year, which allowed the comparison to CR. The experiment is 20 years older than the introduction of randomised experiments in 1926, which was the start of the modern statistical design of agricultural experiments (Verdooren 2020). Therefore, no true replications are available which is limiting the possibilities of statistical evaluation (Schmidt et al. 2000).

RESULTS

Fuel consumption and energy input. The area-specific total diesel fuel consumption shown in Table 1 was in CropR about 27% lower than in CR, which is mainly explained by the low fuel consumption in bare fallow (threefold shallow cultivation). With NPK and FYM fertilisation, the fuel consumption increased by 29% and 42%. This increase is caused by the additional fuel consumption by spreading fertiliser and the crop yield depending on field processes harvest, straw baling and transport. The total energy input (Table 2) for CropR was about 37% lower than in CR overall fertilisation systems (unfertilised, NPK, FYM). Overall crop sequences, the total energy input was in NPK by 133% and in FYM by 26% higher than in unfertilised. The ratio of direct energy to indirect

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Table 1. Diesel fuel consumption (L/ha, mean over years 1960–2019) for continuous rye (CR) and crop rotation (CropR) as affected by fertilisation

	CR			CropR		
	unfertilised	NPK	FYM	unfertilised	NPK	FYM
Cultivation (5–8 cm, tine cultivator)	5.7	5.7	5.7	7.6	7.6	7.6
Ploughing (25–30 cm, mouldboard plough)	18.8	18.8	18.8	12.5	12.5	12.5
Seeding (seed drill with disc harrow)	6.6	6.6	6.6	4.4	4.4	4.4
Fertiliser spreading	–	9.0	17.0	–	6.0	11.3
Herbicide spraying	2.0	2.0	2.0	1.3	1.3	1.3
Harvesting (combine)	20.0	22.0	22.0	13.3	14.6	14.6
Straw baling	5.1	9.5	10.3	3.9	7.3	7.7
Transport (grain, straw; 5 km)	2.2	4.3	4.3	1.8	3.3	3.4
Total	60.4	77.9	86.7	44.8	57.0	62.8

NPK – mineral fertiliser; FYM – farmyard manure

energy (in %) were for CR: 50:50 in the unfertilised treatment, 28:72 in the NPK treatment and 57:43 in the FYM treatment. For CropR, the ratios were 60:40 (unfertilised), 32:68 (NPK) and 57:43 (FYM). The reduction in total energy input in CropR was primarily due to energetic consideration of the bare fallow year, where just a low amount of energy is consumed for shallow cultivation. The total energy inputs were for all treatments except CR in NPK below 10 GJ/ha, which characterises according to Lin et al. (2017) a low-input system. The energetic consideration of bare fallow in CropR lowered also the total energy input for NPK under 10 GJ/ha, which indicates that a bare fallow period in the rotation contributes to a low-input system.

Crop yield, energy efficiency and land demand. Crop yield and energy efficiency indicators were significantly affected by crop sequence and fertilisation (Tables 3 and 4). Mean values of crop yields and energy efficiency indicators were (means over the two crop sequences and the three fertilisation levels): grain yield: 2 495 kg/ha, straw yield: 4 768 kg/ha, energy output grain: 40.3 GJ/ha, energy output straw: 77.0 GJ/ha, energy output AGB: 117.2 GJ/ha, net-energy output: 111.2 GJ/ha, energy use efficiency for grain production: 7.3 GJ/GJ, energy use efficiency for AGB production: 20.7 GJ/GJ and land demand: 114.1 m^2/GJ. Overall fertilisation systems, CropR showed lower values than CR for the crop yield (–17.3% with grain, –32.1% with straw), crop energy output (–17.3%

Table 2. Energy input (GJ/ha, mean over years 1960–2019) for continuous rye (CR) and crop rotation (CropR) as affected by fertilisation

	CR			CropR		
	unfertilised	NPK	FYM	unfertilised	NPK	FYM
Direct energy						
Diesel fuel, lubricant	2.44	3.15	3.50	1.81	2.31	2.54
Indirect energy						
Seeds	0.55	0.55	0.55	0.48	0.48	0.48
N fertiliser	–	3.77	–	–	2.51	–
P fertiliser	–	0.91	–	–	0.61	–
K fertiliser	–	0.81	–	–	0.54	–
Herbicide	0.28	0.28	0.28	0.19	0.19	0.19
Machinery	1.58	1.64	1.80	0.53	0.55	0.60
Total	4.85	11.11	6.13	3.01	7.19	3.81

NPK – mineral fertiliser; FYM – farmyard manure

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Table 3. ANOVA results for crop yield and energy efficiency indicators as affected by crop sequence (CS) × fertilisation (F)

	Unit	ANOVA		
		CS	F	CS × F
Grain yield	(kg/ha)	***	***	***
Straw yield	(kg/ha)	***	***	**
Energy output grain	(GJ/ha)	***	***	***
Energy output straw	(GJ/ha)	***	***	**
Energy output AGB	(GJ/ha)	***	***	**
Net-energy output AGB	(GJ/ha)	***	***	**
Energy use efficiency for grain production	(GJ/GJ)	***	***	***
Energy use efficiency for AGB production	(GJ/GJ)	***	***	ns
Land demand	(m^2/GJ)	***	***	ns

**P < 0.01; ***P < 0.001; ns – not significant; AGB – above-ground biomass

with grain, –32.1% with straw), energy output AGB (–27.3%), and for net-energy output AGB (–26.8%).

Whereas, CropR had higher values than CR for the energy use efficiency for grain production (+35.5%), energy use efficiency for AGB production (+21.4%), and for land demand (+20.2%).

NPK and FYM fertilisation resulted overall crop sequences in higher grain and straw yields, energy outputs of grain, straw and AGB and a higher net-energy output of AGB with a lower energy use efficiency for grain and AGB production and a lower land demand compared to unfertilised. The increase or decrease was for NPK or FYM as follows: grain yield and grain energy output: +99.5% or +76.9%, straw yield and straw energy output: +90.3% or 83.0%, energy output AGB: +93.4% or 80.8%, net-energy output: +91.3% or 84.0%, energy use efficiency for grain production: –16.2% or +39.3%, energy use efficiency for AGB production: –22.3% or +41.6%, and land demand: –50.4% or –48.1%. Significant crop sequence × fertilisation interactions were observed for grain and straw yields, energy outputs of grain, straw and AGB, the net-energy output of AGB and energy use efficiency for grain production, indicating that crop sequence and fertilisation affected yields and energy efficiency indicators not independently. The reason for these significant interactions was that the grain and straw yields, energy outputs of grain, straw and AGB and the net-energy output of AGB ranked in CR as follows: NPK > FYM > unfertilised, whereas NPK and FYM did not differ in CropR with both having higher values than the unfertilised control. Consequently, the differences between CR and CropR were lowest in the unfertilised control. The grain yield in the unfertilised control was 6.4% higher in CR than in CropR. In the NPK treatment and FYM treatment, the grain yield increase between CR and CropR was much higher: +34.4% and +13.6%. The energy output of AGB was consequently also in CR higher than in CropR: +26.1% (unfertilised), +46.1% (NPK) and +35.5% (FYM). The energy use efficiency for grain production and AGB production ranked as follows: FYM > unfertilised > NPK. It was in CropR compared to CR higher in the unfertilised control by 50.0%, in the NPK treatment by 13.2% and in the FYM treatment by 41.0%.

DISCUSSION

Energy efficiency indicators are mainly influenced by crop yield and the intensity of the external inputs (e.g. fuel and fertiliser). The design of crop rotation under specific soil and climate conditions has a high impact on crop yields and energy yields (Li et al. 2002, Hoeppner et al. 2005). Pre-crops are strongly influencing yields, as shown for winter wheat under Pannonian climate conditions (Neugschwandtner et al. 2015). Christen and Sieling (1995) showed higher crop yields in crop rotation compared to continuous cropping. Also in the present study, the grain and straw yields of winter rye were higher in crop rotation after bare fallow than in continuous winter rye, which indicates that nitrogen and water accumulation in the bare fallow affected the subsequent crop yield of winter rye positively (Moitzi et al. 2021). Also, effects of the crop rotation on plant health might be important. Replacing bare fallow with cover crops might increase retention of post-harvest surplus in-

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Table 4. Crop yield and energy efficiency indicators as affected by crop sequence × fertilisation (mean over years 1960–2019)

		Unfertilised	NPK	FYM	Mean
Grain yield[1] (kg/ha)	CR	1 619^{Ba}	3 618^{Bc}	2 955^{Bb}	2 731^{B}
	CropR	1 522^{Aa}	2 652^{Ab}	2 602^{Ab}	2 259^{A}
	mean	1 571^{a}	3 135^{c}	2 779^{b}	
Straw yield[1] (kg/ha)	CR	3 504^{Ba}	6 931^{Bc}	6 607^{Bb}	5 681^{B}
	CropR	2 541^{Aa}	4 571^{Ab}	4 456^{Ab}	3 856^{A}
	mean	3 023^{a}	5 751^{b}	5 532^{b}	
Energy output grain (GJ/ha)	CR	26.1^{Ba}	58.4^{Bc}	47.7^{Bb}	44.1^{B}
	CropR	24.6^{Aa}	42.8^{Ab}	42.0^{Ab}	36.5^{A}
	mean	25.4^{a}	50.6^{c}	44.9^{b}	
Energy output straw (GJ/ha)	CR	56.6^{Ba}	111.9^{Bc}	106.6^{Bb}	91.7^{B}
	CropR	41.0^{Aa}	73.8^{Ab}	71.9^{Ab}	62.2^{A}
	mean	48.8^{a}	92.9^{b}	89.3^{b}	
Energy output AGB (GJ/ha)	CR	82.7^{Ba}	170.3^{Bc}	154.3^{Bb}	135.8^{B}
	CropR	65.6^{Aa}	116.6^{Ab}	113.9^{Ab}	98.7^{A}
	mean	74.2^{a}	143.5^{b}	134.1^{b}	
Net-energy output AGB (GJ/ha)	CR	77.8^{Ba}	159.2^{Bc}	148.2^{Bb}	128.4^{B}
	CropR	62.6^{Aa}	109.4^{Ab}	110.1^{Ab}	94.0^{A}
	mean	70.2^{a}	134.3^{b}	129.2^{b}	
Energy use efficiency for grain production (GJ/GJ)	CR	5.4^{Aa}	5.3^{Aa}	7.8^{Ab}	6.2^{A}
	CropR	8.1^{Bb}	6.0^{Ba}	11.0^{Bc}	8.4^{B}
	mean	6.8^{b}	5.7^{a}	9.4^{c}	
Energy use efficiency for AGB production (GJ/GJ)	CR	17.1	13.9	25.2	18.7^{A}
	CropR	21.8	16.3	29.9	22.7^{B}
	mean	19.5^{b}	15.1^{a}	27.6^{c}	
Land demand (m^2/GJ)	CR	160.7	70.7	79.9	103.8^{A}
	CropR	179.0	97.9	96.4	124.4^{B}
	mean	169.8^{b}	84.3^{a}	88.2^{a}	

[1]14% moisture content; Significant differences of means are separated for cropping systems by capital letters and for fertilisation systems by lower case letters; NPK – mineral fertiliser; FYM – farmyard manure; AGB – above-ground biomass; CR – continuous rye; CropR – crop rotation;

organic N and reduce nitrate leaching (Dinnes et al. 2002) and increased N uptake but not the crop yield of the subsequent crop (Gabriel and Quemada 2011). But the energy input for seeding and management of the cover crop will be higher than in a bare fallow. The climate conditions are responsible for energy efficiency which is closely associated with crop yield and energy yield. With increasing rainfall in the growing season under semi-arid climate conditions, the crop yield of winter wheat rises (Neugschwandtner et al. 2015) and also energy output and energy efficiency (Hernanz et al. 2014). The winter rye yield was lower in CR than in CropR on all fertilisation levels, especially in the unfertilised control, whereas these differences became smaller with NPK and FYM (cf. Moitzi et al. 2021). Consequently, higher energy inputs are boosting crop yields and energy outputs stronger, if negative effects of less effective crop cultivation techniques like continued cropping can be offset by them. Energy use efficiency for grain and AGB production increased when lower energy inputs were used, i.e. by applying FYM instead of NPK or applying no fertiliser at all. This increase in energy use efficiency was higher for CropR than CR. Consequently, the higher yields and energy output with CropR could more than offset the additional energy input for the cultivation of the bare fallow which yielded no energy output at all. A significantly higher energy use efficiency in crop rotation than in continuous cropping was also found by Li et al. (2002), wherein seven analysed crop rotations the energy use efficiency was 23% higher than in continuous wheat cropping. Crop rotation had also a stronger effect on energy efficiency than the tillage method, as shown for rotations including corn and soybean (Rathke et al. 2007). The productivity of crop cultivation is of special concern for the trade-off between input intensity and land demand. A certain crop yield or crop energy output can be produced with a high amount of input with lower land demand or with low input on more land. With NPK and FYM, the land demand for producing one GJ net-energy output can be reduced to half compared to the control. Folberth et al. (2020) have shown on a global level that optimising fertiliser inputs is one keystone for maintaining present crop production while biodiversity would hardly profit from a maximum land-sparing approach. In our study, crop rotation resulted just in a by 20% higher land demand than continuous cropping, although 33% of the land was not used for production and even additional input for the cultivation of the bare fallow was needed. The design of crop rotation is a key factor for sustainable cropping with high energy efficiency.

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