Field Crops Research 326 (2025) 109866

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Rotation, tillage and irrigation influence agronomic and environmental performance of maize-based bioenergy systems in a dynamic long-term experiment in NE Germany

Genís Simon-Miquel [a,*], John Kirkegaard [b], Moritz Reckling [a,c]

[a] Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg 15374, Germany
[b] CSIRO Agriculture and Food, GPO Box 1700, Canberra, ACT 2601, Australia
[c] Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Sweden

ARTICLE INFO

Keywords:
Bioenergetic cropping systems
Diversification
Legumes
N use efficiency
Soil organic C
Trade-offs
Yield benchmarking

ABSTRACT

Context and objectives: Cropland use for biogas production has sparked debate due to its competition with food production and potential environmental trade-offs derived from maize-based systems. Furthermore, climate change influenced cropping conditions, generating the need to adapt productive and sustainable systems. This work aimed to optimise crop production and sustainability in the face of these challenges by exploring alternatives to existing crop sequence, tillage and irrigation strategies.
Methodology: Within a long-term field experiment conducted in Müncheberg (NE Germany), specific cropping systems were assessed from 2008 to 2015, with two alternative crop sequences (continuous maize vs. 4-year crop rotation), tillage practices (plough/no-till), and irrigation (irrigated/rainfed). Productivity indicators, water and N use efficiency, and soil fertility indicators were evaluated at the cropping system level.
Results and discussion: Continuous maize systems achieved the highest energy and methane yield levels, while the diverse crop rotation achieved the highest protein yields. Irrigation showed variable yield increases (8–125 %) at rainfall levels < 400 mm pa. The tillage reduction showed a trend to lower yield but higher soil C in the later experimental years. Overall, the systems with the highest productivity also showed high levels of resource use efficiency.
Conclusions: We observed a trade-off between productivity and sustainability when diversifying continuous maize systems. Higher productivity came with evidence of soil quality decline over time. A maize and perennial legume forage-based system coupled with a target water supply for maize of 400 mm pa and the adoption of strategic tillage could maintain high productivity and sustainability in the long term.

1. Introduction

During the first decade of the XXI century, Germany promoted the expansion of biogas production as part of a national energy transition. Biogas was produced from animal slurry, waste products and crops, incentivising the cultivation and use of maize (*Zea mays* L.) and other energy crops (Thrän et al., 2020). In essence, the objective of energy crops is to maximise biomass production. In this socioeconomic situation, maize became an important crop for farmers and was grown at high intensity including fields with continuous maize production to maximise biomass productivity (Jänicke et al., 2022). Germany's proportion of arable land devoted to silage and grain maize was 21 % in 2023 (2.5 Mill ha) (Destatis, 2024). Similarly, worldwide land use for maize production increased to 205 Mill ha in 2023 (FAO, 2024). Approximately, a third of the German maize acreage was used for biogas production (FNR, 2020). Click or tap here to enter text. In recent years, the use of cropland for biogas production has been under debate for its direct competition with the production of food (Jordan et al., 2023) and potential negative environmental impacts including nutrient losses, impacts on biodiversity, and altered weed communities (von Redwitz and Gerowitt, 2018).

In contrast to simplified systems, diverse crop rotations including legumes can provide a range of benefits and services fundamental for long-term sustainability, such as N fixation, control of biotic factors or improved soil quality (Bennett et al., 2012; Peoples et al., 2009; Rizzo et al., 2022). However, significant attention has been paid to individual energy crop performance (Schittenhelm et al., 2011; Strauss et al.,

* Corresponding author.
E-mail address: genis.simon-miquel@zalf.de (G. Simon-Miquel).

https://doi.org/10.1016/j.fcr.2025.109866
Received 10 January 2025; Received in revised form 21 February 2025; Accepted 15 March 2025
Available online 22 March 2025

2019), while productivity at the cropping system level has received less attention. Such an evaluation requires the use of effective indicators to allow a fair and holistic comparison (Costa et al., 2021; Simon-Miquel et al., 2023). In the context of biogas-oriented systems, specific methane yields for each crop can be used as a standard measure (Herrmann et al., 2016a). Accounting for the tensions regarding cropland use for biogas production, the output of such cropping systems can also be used as forage for livestock. In such cases, the crop gross energy and protein productivity can also be used as productivity indicators (Costa et al., 2021).

Besides the agronomic and socioeconomic factors fostering cropping system diversification, climate change increased mean air temperatures in central European areas and changed precipitation patterns. This situation increased potential evapotranspiration and crop water demands (European Environment Agency, 2024). In northeastern Germany, spring droughts are increasingly affecting spring cropping (Schmitt et al., 2022). While irrigation can alleviate these issues, the agronomic and economic outcome depends on the inclusion of high-value crops and future water availability (von Czettritz et al., 2023) which is unlikely. In traditionally semi-arid areas of the world, reduced tillage or no tillage techniques have been adopted as a water-saving strategy (Cornish et al., 2020; Lampurlanes et al., 2016). In addition, no-tillage adoption can lead to other advantages such as reduced fuel and labour demand and reduced soil erosion risks (Kotir et al., 2022; Llewellyn et al., 2012). However, tillage reduction in temperate areas (such as Germany) has lower adoption and has been less studied, with variable yield responses that are dependent on the crop species (Fiorini et al., 2020; Gruber et al., 2012; Krauss et al., 2022).

Given this scenario, alternatives are needed to maintain productive and sustainable cropping systems (Olesen et al., 2011; Springmann et al., 2018) that can improve upon the existing baseline (maize-based) systems (Hufnagel et al., 2020) in terms of both production and sustainability. In addition, it is important to understand the factors that may limit current productivity in the baseline systems such as the supply of water (Passioura and Angus, 2010), nitrogen (N) (Lassaletta et al., 2014) and radiation (Sadras and Dreccer, 2015). For water availability, boundary functions have been previously used worldwide in various major crops such as wheat, sunflower and maize (Sadras, 2020), allowing yield potential benchmarking based on water supply (Miti et al., 2024). In the case of N use, one of the simplest, yet meaningful metrics is the NUE indicator proposed by the EU Nitrogen Expert Panel (2015). The N Input-Output ratio allows categorisation of the cropping systems into three areas: those with either (i) increased risk of N pollution (low NUE), (ii) targeted NUE and (iii) increased risk of soil mining (high NUE, Outputs > Inputs). From a sustainability perspective, cropping systems must also be designed to maintain soil fertility in the longer term, and in that regard, the changes in soil organic matter provide a comprehensive indicator for several soil functions such as nutrient supply through mineralisation, water holding capacity and soil structure (Lefèvre et al., 2017). As well, soil organic N content, plant available P and K and pH are paramount for ensuring long-term soil fertility.

Long-term field experiments provide a framework to evaluate alternative cropping sequences and management alternatives over long periods (Johnston and Poulton, 2018). This allows robust conclusions on the relative productivity and sustainability of different management options (Cusser et al., 2020) that can be monitored over time. However, for utility, it is also desirable that the long-term experiments represent practices that can be adopted on farms, and that these can evolve to retain relevance in the longer term.

The objectives of this work were to (i) investigate cropping system productivity under alternative crop sequences, tillage intensity and irrigation, (ii) quantify the factors limiting yield in the different systems, and (iii) evaluate the impact of the different cropping systems on soil fertility (soil organic C and N, plant-available P and K, pH). The research was carried out in the framework of a dynamic long-term experiment in NE Germany. Our hypotheses were (i) that crop diversification and reduced tillage can reach similar productivity levels as continuous maize and intensive tillage while having a positive effect on soil fertility, and (ii) that water availability will be the main abiotic factor limiting crop productivity.

2. Materials and methods

2.1. Experimental site and design

In 1999, a field experiment was established at the Leibniz Centre for Agricultural Landscape Research (ZALF) in NE Germany (52º30'57'' N, 14º07'21'' E, 63 masl). The soil particle size distribution was 80 % sand, 15 % silt and 5 % clay in the 0–60 cm layer. The soil had a field capacity volumetric water content of 14.6 % and a permanent wilting point content of 3.7 % in the 0–60 cm layer. At the beginning of the experiment, soil organic C concentration in the 0–30 and 30–60 cm was 5.4 and 1.8 g kg^{-1}, respectively. The soil pH was 6.3 and 6.5 in the 0–30 and 30–60 cm layers, respectively. The experimental area has a score of 25–32 points within the German soil quality rating, which has a range from 7 (very low fertility), < 20 (marginal and difficult to crop) up to 100 (most fertile). Maintaining fertility is therefore a challenge for the farming systems of the area. The region has a central European climate with an annual mean air temperature of 9.4 °C, precipitation of 567 mm and potential evapotranspiration of 716 mm. On average, winter, spring, summer and autumn months receive 110, 144, 166 and 121 mm, respectively (Figure S1).

The initial study (established in 1999) focused on the effects of irrigation (with or without) and tillage (mouldboard ploughing and no-tillage) with crop rotation adapted to each tillage strategy. After 7 years of studying the effect of tillage and irrigation on these two adapted rotations, and due to the growing interest in energy crops for biogas plants (Thrän et al., 2020), the crop sequences in the experiment were transitioned towards biomass production. Plots were re-arranged to accommodate crop sequence as an additional factor, giving a total of three study factors with two levels each (Huynh et al., 2019). The tillage and irrigation treatments were maintained in the same areas as established in 1999. The tillage treatments consisted of mouldboard ploughing (hereafter, MP) or a strict no-till system (hereafter, NT). The irrigation treatments consisted of a rainfed (hereafter, Rfed) and irrigated (hereafter, Irri) treatment. The crop rotation treatments consisted of either a continuous maize system (hereafter, MM) or a four-year crop rotation (hereafter, CR) including winter rye (*Secale cereale* (L.)M.Bieb) and sorghum (*Sorghum bicolor* (L.) Moench) double cropping system (year 1), winter triticale (× *Triticosecale*) (year 2), alfalfa (*Medicago sativa* L.)-clover (*Trifolium pratense* L.)-grass (*Lolium perenne* L.) mixture (ACG, year 3) and maize (year 4) (Fig. 1). The main goal of the treatments was to compare the biogas production potential, along with protein and energy, and assess the system's sustainability through resource use efficiency (water and N) and soil organic C evolution. The experiment ran for 8 years, covering two entire rotation cycles for the CR system (2008–2015) and the plot size was 37.5 x 21 m. As for the experimental design, crop rotation and tillage factors were arranged as a standard split-plot design with crop rotation in the main plots, yellow and green areas in Figure S2. Irrigation was a split-block arrangement (randomised in perpendicular strips) over crop rotation and tillage factors (Federer and King, 2008), as shown by the blue areas in Figure S2. The field experiment had three replications.

2.2. Cropping systems management and data collection

The MM system consisted of a winter rye cover crop followed by the maize (cv. Atletico) planting in late April-early May (22^{nd} April – 2^{nd} May) (Fig. 1, top). The only pesticides used were herbicides and were always applied as a post-emergence herbicide at the BBCH 12–13. The N fertilisation was applied according to soil mineral N content before

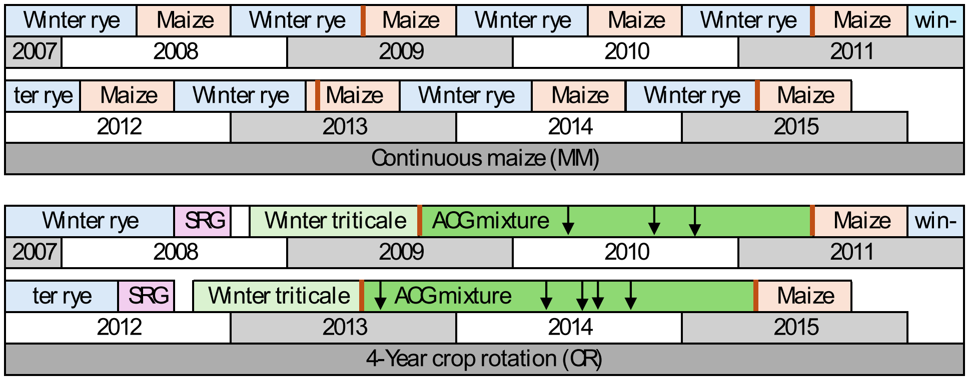

Fig. 1. Conceptual diagram of the crop sequences tested in the Long-term field experiment in Müncheberg in the 2008–2015 period. Winter rye in the MM system is a cover crop; SRG: sorghum; ACG mixture: alfalfa-red clover-grass mixture; Black arrows indicate ACG mixture cut; brown bars in 2009, 2011, 2013 and 2015 indicate soil organic C measurements.

fertilisation (Table 1). In 2012–2015, an extra 30 kg ha^{-1} of N was added to the irrigated treatments to acknowledge the higher-yielding potential of the irrigated crops (Table 1). Maize harvest was between the 23rd of August and the 18th of September. The rye cover crop was sown in early October and no pesticides nor N fertilisation were applied. In the case of MP treatment, mouldboard ploughing was conducted before each crop was sown e.g. twice a year for double cropping and followed by a cultivator pass. Except for maize, sowing was conducted with a commercial seeder (Amazon 302®) equipped with a rotary cultivator and harrow. Maize was sown with a Becker® aeromat precision seeder. In the case of the NT treatment, the rye cover crop was terminated with a glyphosate application before maize sowing. After the maize harvest, the crop residues were chopped using a mulcher. Sowing was performed with a no-till seeder (John Deere 750 A®). In the case of maize, the same machine as in the MP treatments was used.

In the CR treatment, year 1 consisted of a winter rye and sorghum double cropping system, year 2 was a winter triticale followed by an alfalfa-red clover-grass mixture sown in July, year 3 included the multiple cuts of the ACG mixture and Year 4 included maize (Fig. 1, bottom). In the MP treatments, tillage (same operations as in the MM) was conducted before the sowing of each crop. In the NT treatments, glyphosate applications and mulcher passes were carried out as seedbed preparation. Although no cover crops were included in the CR, the combination of winter, summer and perennial crops ensured year-round green cover. Crop protection was based on post-emergence herbicides applied according to specific needs. Similarly to the previous MM system, N fertilisation was based on crop needs and soil mineral N content before the application (Table 1). Maize and sorghum in the irrigated treatments received a 30 kg N ha^{-1} increase in fertilisation to acknowledge the higher yield potential (Table 1).

Table 1
N fertiliser rates (kg N ha^{-1}) applied to different treatments across the experimental years (MM: continuous maize; CR: 4-Years crop rotation). WR+S: winter rye + sorghum; WT: winter triticale; ACG: alfalfa-red clover-grass mixture. Within each crop rotation (MM or CR) and irrigation (Rainfed or irrigated) combination, there were no differences between ploughed (MP) and no-tillage (NT) plots.

Years	MM			CR		
	Crop	Rainfed	Irrigated	Crop	Rainfed	Irrigated
2008	Maize	227	227	WR+S	249	279
2009	Maize	196	196	WT	139	139
2010	Maize	198	198	ACG	220	220
2011	Maize	208	238	M	127	157
2012	Maize	207	237	WR+S	260	290
2013	Maize	188	218	WT	130	130
2014	Maize	181	211	ACG	260	260
2015	Maize	168	198	M	118	148
Average		**197**	**215**		**188**	**203**

Irrigation in the Irri treatments was determined by the WEB-BEREST model that calculates the irrigation water based on the crop demand using the coefficient of actual to potential evapotranspiration (Mirschel et al., 2020). The dates, applied irrigation amounts, precipitation, temperature, radiation and potential evapotranspiration were calculated according to Wendling et al. (1991) are provided in the data set by Reckling and Rosner (2024), with annual irrigation rates varying from 44 to 400 mm depending on the year. The Rfed treatments did not receive any irrigation throughout the eight experimental years. In March 2013, lime was applied to the entire field experiment at a rate of 2 t ha^{-1}. The cited dataset also includes all dates and input rates for all the operations conducted during the experimental period.

Crop biomass was sampled when the crops were harvested. For the winter rye, winter triticale, sorghum and maize only one sampling date was necessary. In the case of ACG, biomass was sampled several times per year with the harvest dates (3 in 2010 and 5 in 2013–2014) (Fig. 1). In all the cases, the biomass was sampled using a plot harvester for forage crops and the area harvested was 18 m^2. A sub-sample was used to determine the dry matter content (all data reported as oven-dry biomass). The samples were ground and N (Kjeldahl), P and K (atomic absorption spectrometry) concentrations were analysed. The total nutrient amount removed with the harvest was calculated by multiplying the nutrient concentration by the biomass yield. Soil samples (0–30 and 30–60 cm) for water content were taken at pre-sowing and post-harvest. On average, 3–5 samples were taken per plot and merged for analysis. Soil samples were taken with a semiautomatic soil sampler (i.e., a rod with a rectangular cross-sectional area of 20 ×15 mm) at depths of 0–15, 15–30, and 30–60 cm. Sampling dates were adapted to each cropping system (MM and CR).

2.3. Productivity indicators

The different cropping systems were designed principally for whole-crop biomass production. In this context, two outcomes can be defined, animal feed or biogas production. For the former, the nutritional value of the produce is important, especially gross energy and protein. For the latter, the biogas yield productivity is the output to be maximised. Consequently, these three productivity indicators were considered in the present study. Gross energy productivity was calculated using Eq. 1

$$EY\ \left(GJ\ ha^{-1}\right) = BmY\ \left(t\ ha^{-1}\right)\ x\ GEC\ \left(GJ\ t^{-1}\right) \tag{1}$$

where EY is the energy yield, BmY is the annual biomass yield and GEC is the specific gross energy content of each crop (Table 2). In the ACG mixture, an average value from alfalfa, clover and grass was used. Protein yields were calculated using Eq. 2.

Table 2
Gross energy content (GEC), ash content and specific methane yield (SMY) used for the calculation of cropping systems productivity. Values for GEC and ashes content were extracted from Feedipedia (2024) and SMY from Herrmann et al. (2016a). ACG: alfalfa-clover-grass mixture.

Crop	GEC (GJ t^{-1} dm)	Ash (in g 100 g^{-1})	SMY (L_N kg $^{-1}_{ODM}$)
Maize	18.2	7.0	350
Rye	17.8	10.7	325
Sorghum	18.1	8.7	314
Triticale	17.7	8.9	345
ACG	18.1	10.4	304

$$PY\ (kg\ ha^{-1}) = BmY\ (t\ ha^{-1})\ x\ BmNCont.\ (g\ 100\ g^{-1})\ x\ 6.25 \quad (2)$$

Where PY is the protein yield, BmY is the annual biomass yield and *BmNCont.* is the biomass N content. The 6.25 is the standard conversion factor from N to protein in plant tissues, despite recent discussions to account for crop-specific values (Mariotti et al., 2008). For methane yields, it was assumed that all product was fermented into silage before being processed in the biogas plant. Specific methane yields were obtained from Herrmann et al. (2016a), who analysed 43 crop species across Germany and determined their specific methane yields. The study was also selected because the analyses were performed using the same methods as in large-scale anaerobic digestion, thus increasing the comparability with farm-scale results. Methane yields were calculated using Eq. 3

$$MY\ (L_N\ ha^{-1}) = BmY\ (kg\ ha^{-1})\ x\ SMY(L_N\ kg_{ODM}^{-1})\ x\ (1 - Ash\ (g\ 100\ g^{-1})) \quad \text{Eq. 3}$$

Where MY is the Methane yield, BmY is the annual biomass yield, SMY is the specific methane yield of each crop in litres of methane per Kg of organic dry matter, and (1-Ash) is the correction from dry matter to organic dry matter. The SMY and Ash content for each crop are reported in Table 2.

2.4. Resource use efficiency and productivity benchmarks

Two approaches were used to evaluate cropping system water use efficiency over the experimental period. The first focused on the continuous maize under ploughed conditions (MM-MP), both rainfed and irrigated. The objective was to benchmark maize biomass yield according to the water available to the crop and define a minimum amount of water required to reach the maximum yields. Therefore, a regression was conducted between water use and crop biomass yield. The water use was calculated according to Eq. 4.

$$WU\ (mm) = Ppt\ +\ \Delta SWC\ +\ (Irrig) \quad (4)$$

Where WU is water use, Ppt is the precipitation received between maize sowing and harvest, ΔSWC is the difference in soil water content between sowing and harvest, and Irri is the irrigation water applied in the Irrigated treatments. To benchmark the yields achieved within a broader context, we added the boundary function for maize water use efficiency defined by Grassini et al. (2009). This boundary was defined using a simulation approach with 859 cases across the US Corn Belt. The same authors used the boundary function against empirical data from several locations worldwide ($n = 263$), reporting satisfactory applicability across environments.

The second approach involved the calculation of the Input-water use efficiency (I-WUE) of all systems and experimental years. The main aim was to understand the effects of irrigation and tillage in the MM and CR systems, as both factors are inherently linked to water use. Eq. 5 was used to calculate I-WUE.

$$I - WUE\ (kg\ ha^{-1}\ mm^{-1}) = \frac{BmY\ (kg\ ha^{-1})}{Ppt\ (mm) + (Irrig\ (mm))} \quad (5)$$

Where I-WUE is Input-Water use efficiency, BmY is the annual biomass yield, Ppt is the precipitation received between sowing and harvest, and Irri is the irrigation water applied in the Irrigated treatments. In this instance, ΔSWC was not included in the calculations as the CR systems included overwinter crops. During winter, the precipitation accumulated is approximately 98 mm greater than the potential evapotranspiration, suggesting a high deep percolation risk. Therefore, including the ΔSWC might have led to an overestimation of the water used by the crop.

In the case of N use efficiency (NUE), a standardised procedure published by the EU Nitrogen Expert Panel (2015) was used. Such a method allows standardisation and comparability of the results between cropping systems within the same experiment and other published studies. As recommended, NUE was calculated at the cropping system level, following Eq. 6. Doing so also allowed for smoothing the crop rotation effects in terms of N supply and uptake across years, giving a more meaningful overview of the different cropping systems.

$$NUE\ (\%) = \frac{Noutput\ (kg\ ha^{-1})}{Ninput\ (kg\ ha^{-1})} x100 \quad (6)$$

Where NUE is the N use efficiency, N output is the amount of N exported from the system through harvest. In this case, N output equals above-ground N uptake as the whole plant is harvested and removed from the field. The N input is the amount of N provided to the system over the cropping period including mineral N fertilizers (Table 1) and biological N fixation in the ACG mixture phases. This experiment did not include organic fertilizers or animal grazing.

Biological N fixation was not measured in this field experiment. However, the N balance (N fertilizer minus N uptake) in the ACG mixture was −210 and −309 kg ha^{-1} in 2010 and 2014, respectively. Such results suggest that biological N fixation had a key role as a N input source. Therefore, an estimation is used to account for the biological N input of the alfalfa and clover. The estimations are based on Carlsson and Huss-Danell (2003), who summarised several studies investigating N fixation in red clover and alfalfa across a gradient of environments from 42ºN to 67ºN. They focused on studies using the isotope dilution and N difference methods (Unkovich et al., 2008). Also, they considered whether the legumes were grown as sole crops or mixtures. Eqs. 7 and 8 were presented for N fixation estimation of red clover and alfalfa grown in legume/grass mixtures and have been used in the present study to estimate biological N fixation.

$$Ndfa_{clover}(kg\ ha^{-1}) = 0.026\ x\ DM\ +\ 7.4\ R^2 = 0.91 \quad \text{Eq. 7}$$

$$Ndfa_{alfalfa}\ (kg\ ha^{-1}) = 0.021\ x\ DM + 16.9\ R^2 = 0.91 \quad \text{Eq. 8}$$

Where $Ndfa_{clover}$ and $Ndfa_{alfalfa}$ are the amount of N biologically fixed in red clover and alfalfa and DM is the amount of dry matter biomass produced from each crop. It was assumed that alfalfa and red clover represented, on average, 60 % (30 % for each species) of the total biomass yield (monitoring justifies these assumptions but also showed that the proportions can vary between years and individual cuts within years). The coefficient of determination (R^2) was reported by the authors of the equations (Carlsson and Huss-Danell, 2003).

2.5. Effects on soil organic C and N and plant-available P and K

Soil samples for soil organic C (SOC), total organic N (TON), plant-available P and K and pH were taken every two years, in 2009, 2011, 2013 and 2015 (Fig. 1, brown marks). For each plot, 3–4 samples for each depth were taken and bulked for analysis. Given the absence of soil carbonates in the soil, SOC was measured with the dry combustion method (DIN ISO 10694). As well, total soil N was measured using dry combustion (DIN ISO 13878). The plant-available P and K were measured using atomic absorption spectroscopy. The soil pH was extracted in KCl. The SOC, TON and plant-available P and K were used as indicators of the effects of the system on soil quality and nutrient balances over time.

2.6. Statistical analyses

All statistical analyses were performed with JMP Pro 16. Analyses of variance (ANOVA) were performed for the different variables. The statistical design can be described as follows: Crop rotation and tillage factors are set up in a standard split-plot design and irrigation as a split-block arrangement over crop rotation and tillage (Federer and King, 2008, see section 5.4 and Figure S2). Following the recommendation in the cited book, the ANOVA consists of six error terms that acknowledge the different precision for each factor and interaction (Table S1). Such a model was used for the analysis of the three productivity indicators (gross energy, protein and methane) and water use efficiency. The means separation test HSD Tukey was performed for significant interactions and/or single factors. Year-independent analyses were preferred to avoid confounding significant effects due to the climatic effect. The interannual variability was tackled in the water-limited yield benchmarking regressions, where causes for significant yield variation are evaluated. The NUE was calculated at the cropping systems level and plotted against the NUE reference values diagram designed by the EU Nitrogen Expert Panel (2015). Finally, SOC, TON and plant-available P and K concentrations were subjected to an ANOVA with tillage, irrigation, crop rotation and year as fixed factors (Table S1). The study factors were arranged in the same way as in the productivity indicators. The Year effect was included as a split-plot in the elementary plots, as recommended by Gomez and Gomez (1984). The inclusion of Year in this case was to study the changes in the selected variables over time as a response to the treatment factors applied. Finally, key indicators for the categories of productivity (energy, protein and methane yields), resource use efficiency (NUE and I-WUE) and soil quality (SOC concentration and pH) were plotted in a spider chart to gain a holistic overview of the performance of the systems across indicators. Each variable (except NUE) was normalised to the highest impact result (Sevenster et al., 2024). In the case of NUE, we report the closeness to the target value of 90 % set by the EU Nitrogen Expert Panel (2015).

3. Results

3.1. Climatic conditions during the experimental period

During the experimental period, annual precipitation ranged from 468 to 763 mm representing a difference of −104 and 221 mm with the long-term average. The driest year was in 2015, with the major differences found in the April-August period. In the wettest year (2010), precipitation was highest in July-November, with a 92 % increase (on average) compared with the long-term average. Mean air temperature and potential evapotranspiration did not present significant variations from the long-term average.

3.2. Cropping systems productivity

The three productivity indicators showed a similar pattern of factor significance and only a few significant interactions were evident (Table S2). Consequently, single effects across years are reported to capture the main sources of variability and robust data trends. The energy yield was, on average, 16 % greater in the MM system than in CR (Fig. 2A) with 333 and 281 GJ ha^{-1} yr^{-1}, on average. Within the CR, winter triticale (2009 and 2013) performed poorly (on average, 173 GJ ha^{-1} yr^{-1}) compared to maize. Winter rye/sorghum double cropping system and the ACG mixture showed more competitive energy yields compared to maize (2008, 2010, 2012 and 2014), with an average energy yield of 306 GJ ha^{-1} yr^{-1}. Finally, maize in the CR showed no

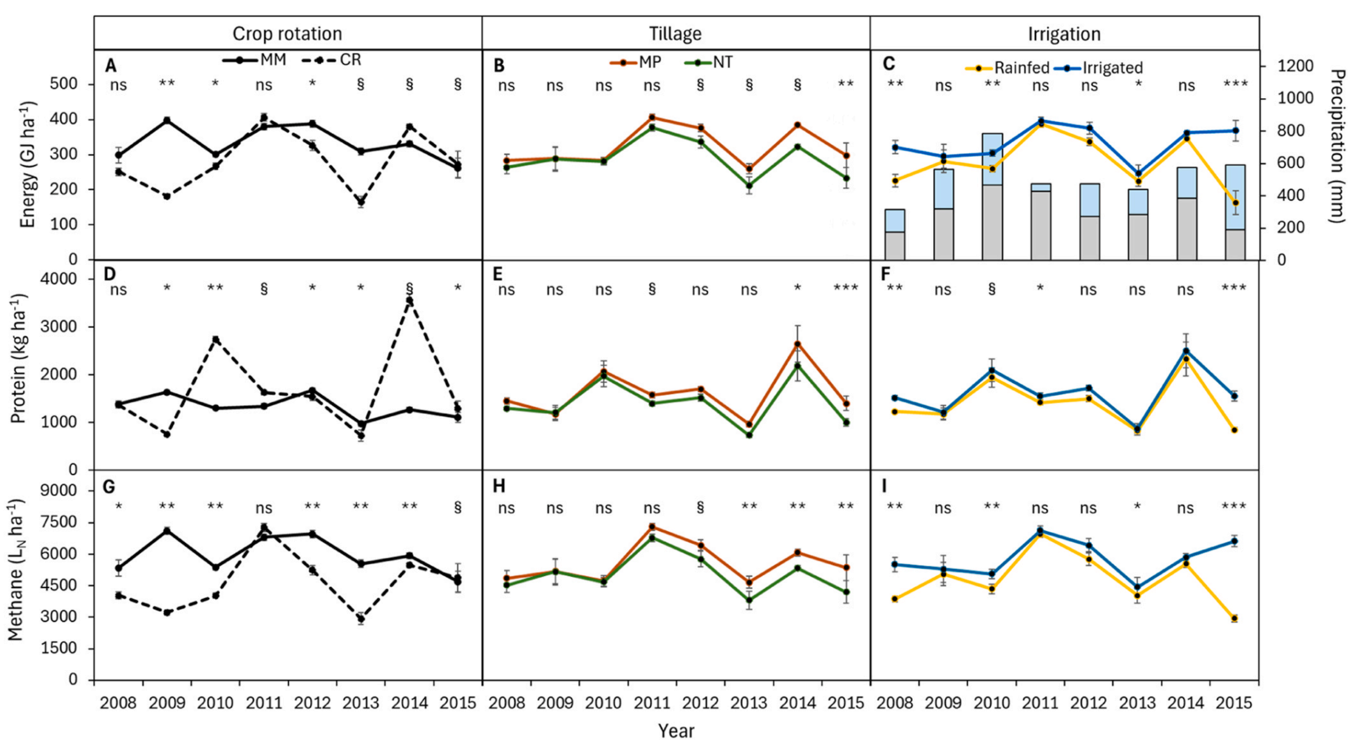

Fig. 2. *Energy (GJ ha^{-1}, A, B, C), protein (kg ha^{-1} D, E, F) and methane (L_N ha^{-1}*G, H, I) productivity affected by the single factors of Crop rotation (MM: continuous maize; CR: 4-Year crop rotation, A, D, G), Tillage (MP: mouldboard ploughing; NT: no-till, B, E, H) and Irrigation (Rainfed, Irrigated; C, F, and I) across the eight experimental years. Within each year, ns: not significant, §p < 0.1, *p < 0.05, * *p < 0.01, * **p < 0.001. In sub-figure C, maize in-crop precipitation (grey bars) and irrigation (blue bars) were added as an interannual variability indicator.

differences compared with the MM system, suggesting a negligible pre-crop effect of 5 % on maize performance (Fig. 2A). In the case of protein, the CR showed similar or higher protein yields than the MM system (Fig. 2D), with an average increase of 27 % across years (1338 and 1706 kg protein ha^{-1} yr^{-1}, respectively). Only winter triticale in 2009 showed significantly lower protein yield than the MM (-54 % compared to CR). The ACG mixture produced the most protein (2744 and 3545 kg ha^{-1} in 2010 and 2014, respectively). The methane yield showed a similar pattern as the energy yield, with the difference between the MM and CR significant in 6 out of 8 years (Fig. 2G). Only in 2011 and 2015 (maize phase in the CR), were methane yields similar between the two crop sequences (5746 and 6079 L_N ha^{-1} yr^{-1} in the MM and CR, respectively).

Tillage had a similar effect on the three productivity indicators, and no differences were observed in response to tillage during the first half of the experimental period (Fig. 2B, E and H). From 2011 onwards, the difference between treatments emerged with higher yields in the MP treatments. The yield reduction in the NT plots was 20 % on average across indicators and the years from 2012 to 2015 with absolute differences of 53 GJ ha^{-1} yr^{-1}, 318 kg protein ha^{-1} yr^{-1} and 853 L_N ha^{-1} yr^{-1}. The irrigation treatment also had consistent effects across indicators (Fig. 2C, F and I), and systems were most responsive in the driest years (2008 and 2015). In these instances, yield increases ranged from 42 % to 125 %. In the other wetter years, the smaller yield increases averaged 8 %.

3.3. Water and N use efficiency

Continuous maize under MB and rainfed conditions was considered the baseline system, representing the standard management practices for the region. The selection and presentation of maize was also chosen to acknowledge the interannual crop variability across the same species. As described in Section 3.1, precipitation showed the most variability across the experimental years. In order to capture the effect of water availability on the different systems, water use (in crop precipitation + soil water content variation) was evaluated for its effect on maize yield (Table S3). Under rainfed and MP conditions, maize yield increased linearly with increasing water availability (Fig. 3). To further test the effect of water availability, the same regression was performed adding the irrigated MB-MM data to the analysis. The second-degree regression showed a trend towards limited yield increase after 400 mm of water use, suggesting that further yield increases are likely limited by other factors (Fig. 3). Data from 2010 fell significantly below the expected yields given the water availability. Metadata confirmed a severe *Ostrinia nubilalis* attack, thus the data was excluded from the regressions.

Input-water use efficiency was mainly affected by the Irrigation x Crop rotation interaction (in 5 out of 8 experimental years) and the tillage single effect in the four latter experimental years (Table S2). The Irrigation x Crop rotation interaction showed a consistent pattern across years with three differentiated levels. In all significant cases, rainfed MM showed the highest WUE (55 kg biomass ha^{-1} mm^{-1}), followed by the irrigated MM (Fig. 4) with 37 kg biomass ha^{-1} mm^{-1}. The CR systems showed a lower WUE (on average, 23 kg biomass ha^{-1} mm^{-1}) compared to MM and no differences between rainfed and irrigated treatments were evident. Overall, the lowest I-WUE were recorded in 2010 and 2014 (ACG phases, 16 kg biomass ha^{-1} mm^{-1}) and the highest in 2011 for the CR and 2012 for the MM. In 2008, the interaction effect was not significant. However, there was a significant crop rotation effect (Fig. 4, capital letters). The tillage effect was significant in the 2012–2015 period (Table S2), with MP treatments showing a higher I-WUE than NT treatments (from 34.9 to 41.7 kg biomass ha^{-1} mm^{-1}, respectively). The effect was a result of the yield increases described in Fig. 2B, E and H.

As the EU Nitrogen Expert Panel (2015) recommends, NUE is reported at the cropping system level. For the case of arable cropping systems, they recommend NUE ranges between 50 % and 90 %, to ensure that there is neither an N accumulation in soils (low NUEs) nor an increased risk of soil mining (NUE > 100 %). Overall, cropping systems NUE values ranged from 92 % to 114 % across systems, with no differences across irrigation and crop rotation systems (Table 3). The MP systems presented a slight increase in NUE due to the higher yield in the later years and the unchanged N input in such systems. In all the cases, the NUE was above 90 %, the maximum value recommended to avoid soil nutrient mining over time (Table 3).

As for the N Input-Output levels, MM showed lower values and, overall, lower variability in the N Outputs (Fig. 5, circles). Within these, irrigated systems showed slightly higher values due to the increased N fertilisation in the 2012–2015 period. The CR systems were located in the N input range of 255–285 kg ha^{-1} yr^{-1}, presenting a higher N output variability due to the different crop species in this system (Fig. 5, squares). Similar to the MM, the irrigated systems were at the higher end of the N input and Outputs, especially under the MB system. In the CR systems, the N input from biological N fixation was estimated using biomass productivity and Eqs. 7 and 8. These estimations yielded an average N fixation of 253 and 341 kg N ha^{-1} in 2010 and 2014, respectively. Minimal differences were observed between irrigation and tillage treatments. The higher values in 2014 are explained by the higher biomass accumulated in that year.

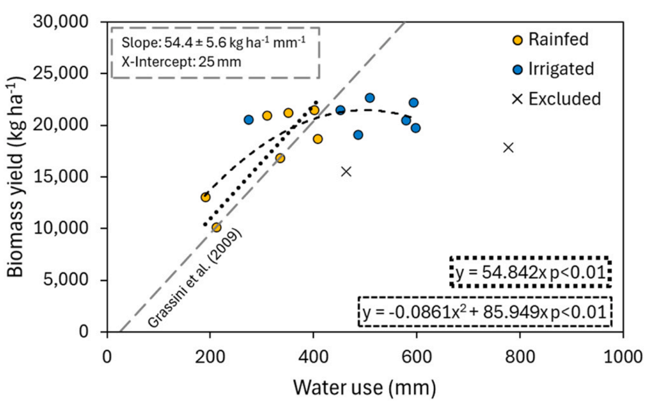

Fig. 3. Regression between water use (in crop precipitation + soil water content variation) and maize biomass yield for the rainfed, MP and MM conditions (Yellow circles and dotted line) and for the rainfed + irrigated, MP and MM conditions (blue circles and dashed line). The two values for 2010 (X) were excluded from the regression analysis, see text for further information. The grey dashed line is the boundary function for WUE in maize defined by Grassini et al. (2009).

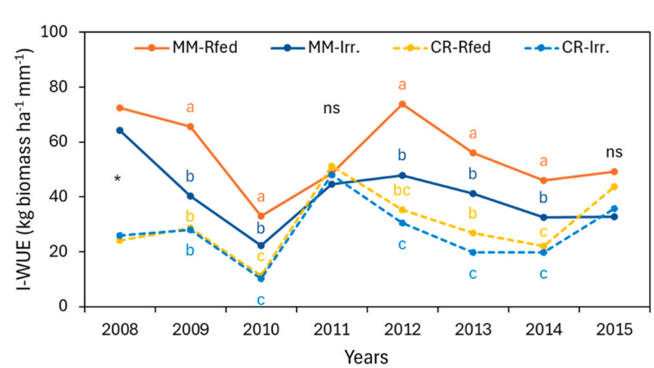

Fig. 4. Input-water use efficiency depending on the crop rotation x irrigation interaction across the experimental years (MM-Rfed: continuous maize - Rainfed; MM-Irri: Continuous maize – Irrigated; CR-Rfed: crop rotation - Rainfed; CR-Irr.: crop rotation - irrigated). Within each year, levels not connected by the same letter are statistically different at $p < 0.05$. * indicate significant differences between CR and MM found in 2008. ns: not significant.

Table 3
N use efficiency indicator for the eight cropping systems tested *(MM: continuous maize; CR: crop rotation; Rfed: Rainfed; Irri.: irrigated;* MP: mouldboard ploughing; NT: no-till). Values refer to the average of the 8-year experimental period.

System			NUE (%)
Crop rotation	Irrigation	Tillage	
MM	Rfed	MP	104 %
		NT	95 %
	Irri	MP	114 %
		NT	104 %
CR	Rfed	MP	105 %
		NT	92 %
	Irri	MP	112 %
		NT	95 %

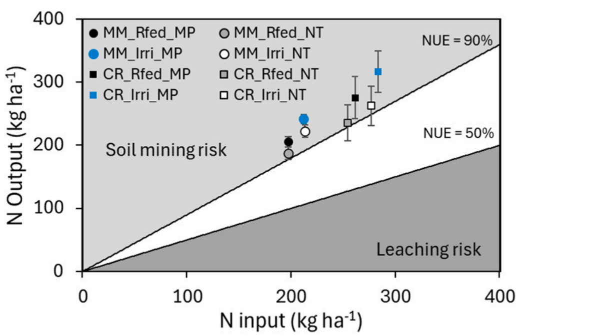

Fig. 5. Conceptual diagram of the NUE indicator; a two-dimensional N_{input}-N_{output} diagram. Adapted from EU Nitrogen Expert Panel (2015). The diagram depicts the NUE target area for arable cropping systems (between 50 % and 90 %) recommended by the authors of the NUE report. The circle and square series represent the annualised NUE values (N input vs. N output) for the eight cropping systems tested in the field experiment (MM: continuous maize; CR: crop rotation; Rfed: Rainfed; Irr.: irrigated; MP: mouldboard ploughing; NT: no-till). Error bars refer to standard error of the N_{output}.

3.4. Soil organic C and N, and plant-available P and K

Soil organic C and N concentrations were mostly affected by the Year x Crop rotation interaction across all depths. Tillage also reduced SOC and TON concentrations in the upper layers (0–15 and 15–30 cm) (Table S4). The SOC showed a trend towards greater concentrations in the CR systems over the experimental period, especially in the upper layers (Fig. 6 A and B). In the 30–60 cm layer, no difference was observed between systems but a declining trend from 2009 was evident with values going from 2.7 to 1.8 g kg^{-1} (Fig. 6 C). The TON concentrations followed a similar pattern to SOC, with greater and increasing concentrations in the CR than in the MM (Fig. 6 D and E). Similar to organic C, no differences were observed between systems and across years in the 30–60 cm layer (Fig. 6 F). For both variables, the tillage main effect showed more N and C in the surface layer (0−15) compared to the 15–30 cm layer (data not shown). The 30–60 cm layer had no differences between the tillage systems (Table S4).

The Year x Crop rotation interaction affected the P concentrations in the 0–15 cm layer and the K concentrations in all layers (Table S4). In the case of P, the means separation test highlighted a stronger declining effect across years than differences between systems (Fig. 7A), with average P concentrations declining from 133 to 95 mg kg^{-1} over the experimental period. In the deeper layers, there were no differences across years or between crop rotations (Fig. 7B and C). In the case of K, CR generally had lower values than MM (except in 0–15 cm in 2011) (Fig. 7D, E and F). Across layers, K concentration tended to decrease over time, which was clearer in the 30–60 cm layer (Fig. 7 D, E and F). The pH was also affected by the Year x Crop rotation interaction in the three depth layers. However, the means separation test only showed a significant pH decline over the experimental period, from 6.3 to 5.3 in the 0–15 cm layer and from 6.3 to 5.8 in the 15–30 cm (averages across systems). In the 30–60 cm layer, the pH remained constant at 6.3 across years and systems.

3.5. Cropping systems performance across indicators

The different cropping systems in the field experiment have been evaluated from the perspectives of productivity, resource use efficiency, and soil quality. In order to gain a general understanding of the systems' performance, Fig. 8 presents key variables normalised to the highest result and averaged across the experimental period. Overall, the systems with the highest productivity also showed a high level of resource use efficiency, with minimal impacts on the soil quality parameters during the course of the experiment but with declining trends (Fig. 8). In terms of productivity (energy, protein and methane), irrigation increased yields compared to the rainfed counterparts (Fig. 8, solid vs. dashed lines). The MM systems achieved the highest yield levels in energy and methane, while the CR outperformed the MM in terms of protein. The I-WUE was greater in the MM systems, especially the rainfed system. In the case of NUE, the CR-NT-Rfed, CR-NT-Irri and MM-NT-Rfed presented the closest values to the target proposed by the EU Nitrogen Expert panel (2015). On the other hand, the ploughed and irrigated systems (both under MM and CR) were the furthest from the mentioned target (Fig. 8). Soil quality parameters (SOC and pH in 2015) showed a lower variability compared to the other indicators. In the case of SOC, CR-NT exhibited the highest SOC concentration in 2015, while no clear differences were observed for pH across cropping systems. However, an overall reduction in the soil pH was observed over the experimental period.

4. Discussion

The present study explored the productivity and sustainability of alternative biogas production systems compared to the baseline system of continuous rainfed maize in a ploughed system. As the systems are based on whole plant harvest and intensive biomass (and nutrient) export, reductions in soil quality in the mid- to long-term are a risk. In addition, a changing climate, declining soil quality and increased input costs will mean water and N-use efficiency may become increasingly important along with high productivity. Our study considered the impacts of diverse rotation, irrigation and reduced tillage on systems performance and the balance between productivity and sustainability.

4.1. Cropping systems productivity

The MM system showed the highest gross energy and methane yields, especially compared to winter triticale (2009 and 2013). These results are consistent with Strauss et al. (2019) who reported an average biomass yield decrease of 8.1 t ha^{-1} in Triticale compared to maize across 8 locations in Germany. The ACG mixture showed the most competitive results compared to maize in terms of gross energy and protein, but lower methane productivity (Herrmann et al., 2016b; Strauss et al., 2019). The legume components of the mixture allowed an increase in protein productivity, partly facilitated by the biological N fixation in these species (Simon-Miquel et al., 2023). Such results indicate that maize and ACG mix-based cropping systems could be a way forward to deliver high productivity (across all indicators) while reducing the dependence on external inputs. Furthermore, extending the ACG mixture to a second year could also reduce costs (crop already established) and increase N fixation. The winter rye + sorghum double cropping (2008 and 2012) showed intermediate results between winter triticale and maize across indicators. Such results contrast with Schittenhelm et al. (2011), who reported a 15 % increased biomass productivity in double cropping systems across Germany and under irrigated conditions. This finding also suggests that the increase in cropping

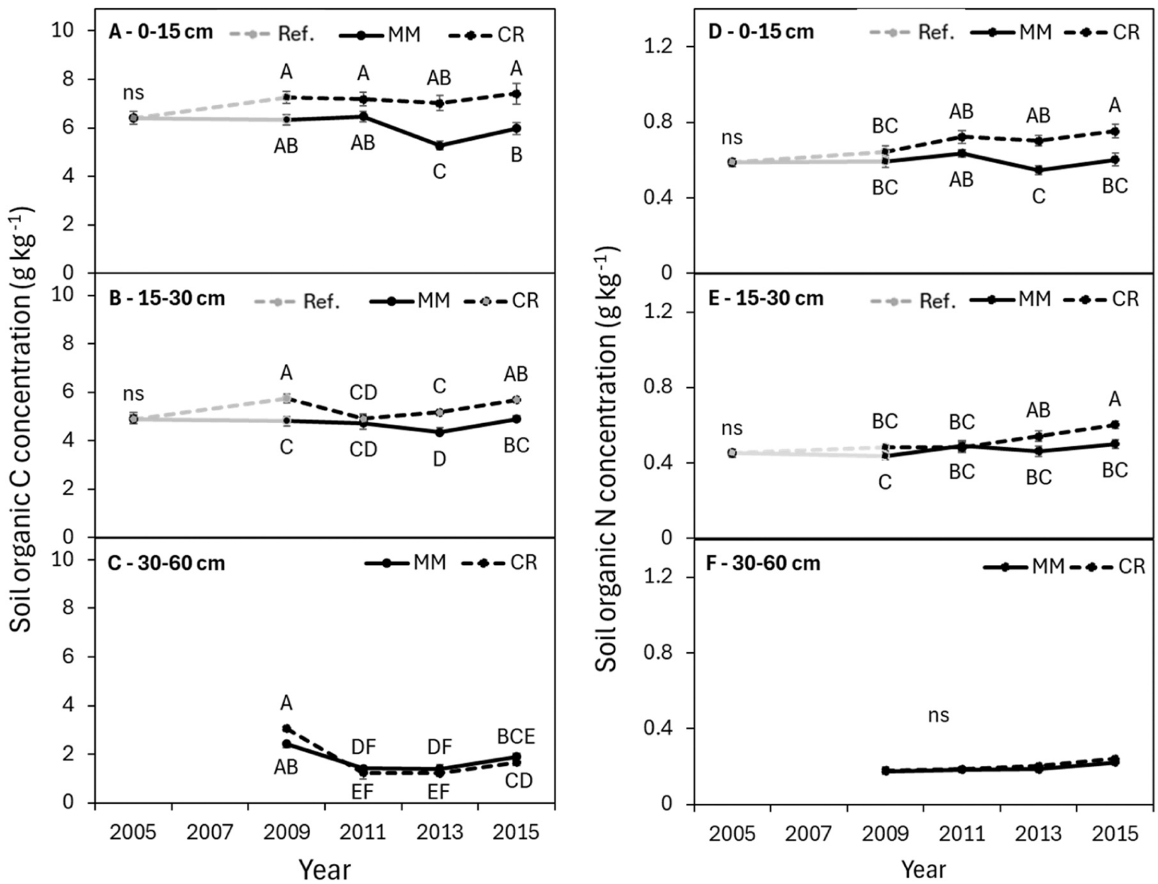

Fig. 6. Soil organic C concentration (A, B, C) and soil organic N concentration (D, E, F) affected by the year x Crop rotation interaction (Ref.: reference values before experimental phase; MM: continuous maize; CR: crop rotation) across three depth layers. Within each subfigure, levels not connected by the same letter are statistically different at $p < 0.05$. ns: not significant. For the 0–15 and 15–30 layers, the data from 2005 was added as a reference point before the start of the experimental period.

intensity will likely increase labour demand and costs (Kotir et al., 2022), thus reducing profitability.

No-tillage consistently reduced productivity indicators in the later experimental years. The experimental metadata suggested that a higher weed pressure in the NT systems may have contributed to the yield decrease. Adapting the weed control strategies to the tillage treatments would be the next step to close the yield gap between ploughed and no-till systems (Nichols et al., 2015). From a broader time perspective, Cusser et al. (2020) reported that no-till yield responses might take up to 19 years to be significant. However, the authors reported positive economic returns after just 13 years (effect of reduced costs). A similar situation (albeit for grain maize) was reported in a location in the same state by Verch et al. (2009). Although the authors reported lower maize yields under NT, they observed greater profitability than MP. In such situations, the adoption of strategic tillage, targeted at controlling specific weeds, would contribute to a reduction in fuel and labour demand that could ultimately reduce cropping systems C footprint (Kirkegaard et al., 2014) and economic costs. In contrast to more arid areas, such as the Mediterranean or Australia, no-till did not lead to better soil water storage to impact yields (Lampurlanés et al., 2016; Page et al., 2019) in central European systems.

Irrigation increased yield by 4–111 % (average across indicators), with significant increases only observed in the years with the lowest in-crop precipitation. Such results suggest low average returns on irrigation investments during the experimental period (von Czettritz et al., 2023). On the other side of the spectrum, no yield increases in maize were observed when the water availability exceeded 400 mm (precipitation + irrigation + soil water), suggesting that further irrigation would lead to inefficient water use. Nonetheless, water availability may decrease and potential evapotranspiration in the area may increase due to climate change, thus increasing the water deficit and the need for irrigation systems to maintain productivity (Iglesias and Garrote, 2015), especially during critical crop phases such as flowering. It is worth noting, that irrigation could not offset the lower productivity of the CR system compared to MM which remained higher in both irrigated and rainfed systems.

While still a third of German maize production is devoted to biogas production, the end of the subsidies for biogas and land competition for food production (Jordan et al., 2023) has reduced the demand for bioenergetic cropping systems. In that context, there is an opportunity to explore other crop sequences to keep improving the cropping system's productivity and profitability. Such alternatives could include traditional grain crops (small-grain cereals, oilseed rape (*Brassica napus* L.), etc.) and food-grade crops (e.g. soybean or chickpea).

4.2. Yield benchmarking and abiotic limiting factors

To provide a context to the productivity performance, we benchmarked observed yields against theoretical yield limits for different abiotic factors. Farmers and researchers have used such approaches worldwide to estimate attainable yields for the major staple crops (Sadras, 2020). In the case of water, we used a boundary function (Miti et al., 2024) for maize biomass productivity, the most productive crop in the experiment. Under rainfed conditions, we observed a linear yield increase with increasing water availability which was within the range of the boundary function reported by Grassini et al. (2009) for the US

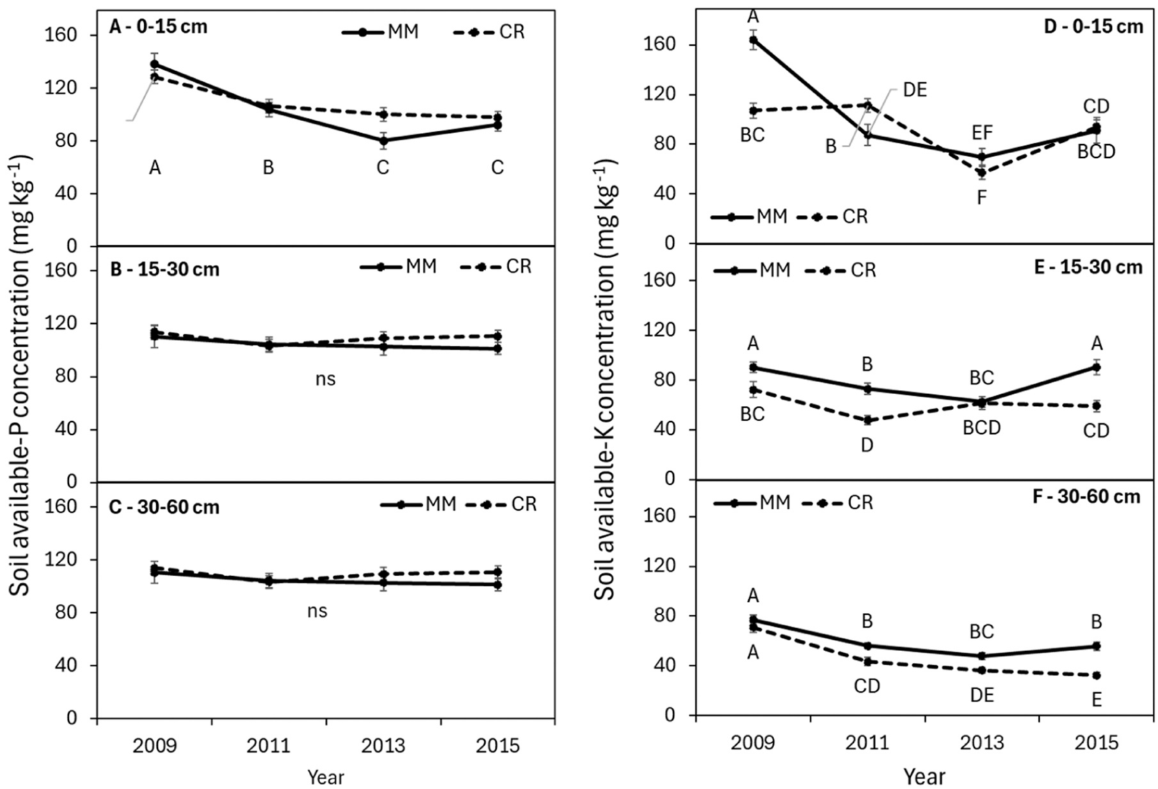

Fig. 7. Plant-available P concentration (A, B, C) and plant-available K concentration (D, E, D) affected by the year x crop rotation interaction (MM: continuous maize; CR: crop rotation) across three depth layers. Within each subfigure, levels not connected by the same letter are statistically different at $p < 0.05$. ns: not significant. In sub-Figure A, the letters only indicate differences between years.

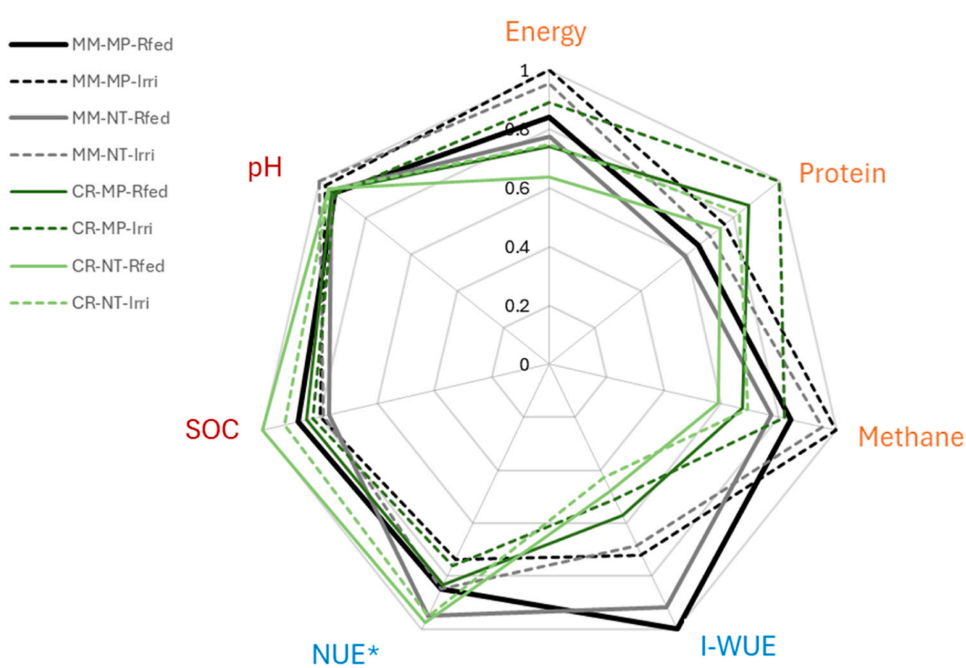

Fig. 8. Overview of seven selected indicators for the 8 cropping systems assessed in the field experiment in the 2008–2015 period. The indicators can be categorised into productivity (orange), resource use efficiency (blue) and soil quality (dark red). *In the case of NUE, the normalisation represents the closeness to the target of 90 % NUE rather than the maximum values achieved. (MM: continuous maize; CR: crop rotation; MP: mouldboard ploughing; NT: no-till; Rfed: Rainfed; Irr.: irrigated).

Corn Belt and other locations worldwide. This indicates that water will be the main limiting factor for further yield increases when the water supply is less than 400 mm. When water limitation was overcome by irrigation, the yield response flattened above 400 mm (Fig. 3), suggesting other factors limit yield when water is abundant (Shatar and Mcbratney, 2004).

Indeed, temperature and radiation (especially in the critical period of yield determination) strongly determine the potential yield of any crop in a given location. In the case of maize, and the experimental location, average cropping season radiation (2437 MJ m^{-2}) would set a potential aboveground biomass yield of 22 t ha^{-1}, according to Grassini et al. (2009). Using the same author's function for temperature (average maximum temperature before flowering) would set the yield potential at 24 t ha^{-1}. While these values can illustrate that there is room for improvement in the present results (across systems and years, maize yield was 18.4 t ha^{-1}), two considerations must be taken into account. First, only the WUE boundary function was tested with multiple datasets outside the USA Corn Belt. Second, climate change might likely increase temperatures (European Environment Agency, 2024), but decrease radiation due to the dimming effect (Stanhill and Cohen, 2001), thus impacting crop production potential (Hatfield et al., 2011).

Nutrient availability, particularly N, plays a major role in crop productivity. On average, the cropping system NUE was 102 %, indicating that N output was similar to or slightly greater than N input (namely, fertiliser and biological N fixation). This supports the idea of N being the main limiting factor, provided the water supply is sufficient, and poses the question of whether a higher N input would lead to greater productivity, especially if focussed on wetter seasons. For example, according to German nutrient regulation (DüV, 2017), the N demand for silage maize is 4.7 kg N t^{-1} of fresh matter (35 % DM). Therefore, the maize yields obtained in the wettest years (2011 and 2014), and under rainfed conditions, would have required 278 and 237 kg N ha^{-1} (average across systems). In both cases, N fertilisation was 56–71 kg ha^{-1} below these values, to comply with the EU fertilisation regulations and avoid N losses (European Commission, 2019). Following the idea of the previous section, a larger share of legumes in the system (especially perennial legumes) would help to increase N input sustainably, although matching N availability to N demand with legume residues may be more challenging than with strategic supplemental fertiliser applications when N losses are less likely.

4.3. Soil fertility evolution

Our results showed a different trend regarding SOC and TON between CR and MM systems. Generally, the MM system had a reduced SOC and TON compared to CR. While MM produced more aboveground biomass, most of it was exported with the harvest. Instead, the CR system might have led to two key factors for SOC accumulation in the soil. Firstly, a diverse C input through the belowground systems of different crops (McDaniel et al., 2014; Ruf et al., 2018). Secondly, an overall higher N input due to the biological N fixation in the ACG mixture phase, which is essential for SOC stabilisation (Van Groenigen et al., 2017). Furthermore, the ACG mixture was kept until the maize planting (ca. 5–6 months after the last harvest, Fig. 1), thus increasing the potential amount of N fixed. The lack of SOC increases in the irrigated systems, despite higher productivity than the rainfed, also supports this theory. In other environments, increases in SOC have been reported with productivity increases, and thus C input to the soil (Pareja-Sánchez et al., 2020) but a lack of stabilising nutrients (N-P-S) has been shown to limit the sequestration of residue C even when it is plentiful (Kirkby et al., 2016).

Finally, plant-available P and K, and soil pH, were not significantly affected by the experimental treatments, but in all three cases, a declining trend over time was observed. A likely explanation comes from the change in production orientation between the previous crop rotation (including more grain crops) and the biomass removal studied in this work (whole crop harvest). These systems entail a greater export of nutrients, thus increasing the risk of soil depletion and declining pH, thus impacting soil fertility (Lefèvre et al., 2017). Soil acidification warrants frequent soil monitoring and adequate liming to maintain nutrient availability. This highlights the risk of biomass-oriented cropping systems in terms of soil fertility over time. Indeed, several authors have reported similar soil fertility declines in biogas-oriented cropping systems (Anderson-Teixeira et al., 2013; Blanco-Canqui, 2010; Don et al., 2012).

5. Conclusions

This study aimed to maximise cropping system productivity while maintaining soil fertility for biogas and forage-oriented agricultural systems. We observed a trade-off between productivity and sustainability when diversifying continuous maize systems. The higher productivity came with evidence of soil quality decline over time, though relatively minor. Within the crop rotation tested, the ACG mixture was the most competitive alternative to maize. Water availability was the main yield-limiting factor when less than 400 mm were available to the crop over the season. Further yield increases could be achieved by targeted increases in N input (especially biological N fixation) that could also contribute to fostering SOC accumulation. No-tillage had increasingly negative effects on productivity in the later years. Therefore, from a practical perspective, a maize and ACG mixture-based system could maintain high productivity while minimising soil quality decline. Furthermore, strategic tillage adoption could be a sustainable way to reduce labour and greenhouse gas emissions while maintaining yields. In future research, changes in the socioeconomic conditions should be accounted for. For instance, given the reduction in biogas subsidies in recent years, crop sequences could be adapted to keep the most productive biogas phases but include other crops that could increase profitability (e.g. grain crops, food-grade crops, etc.) sustainably.

CRediT authorship contribution statement

Simon-Miquel Genís: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Kirkegaard John:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Reckling Moritz:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was funded by the German Federal Ministry of Education and Research (BMBF) through the EJP ClimateCropping project (grant 31B1374).

The authors of this manuscript thank Gunhild Rosner, Kotaiba Salama, Christoph Moeller and Kathleen Karges for collecting and handling the data, and the team of the research station Müncheberg for the set-up and maintenance of the experimental fields. The authors also appreciate the financial and scientific support from Sonoko Bellingrath-Kimura.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109866.

Data availability

Data will be made available on request.

References

Anderson-Teixeira, K.J., Masters, M.D., Black, C.K., Zeri, M., Hussain, M.Z., Bernacchi, C.J., DeLucia, E.H., 2013. Altered belowground carbon cycling following land-use change to perennial bioenergy crops. Ecosystems 16, 508–520. https://doi.org/10.1007/s10021-012-9628-x.

Bennett, A.J., Bending, G.D., Chandler, D., Hilton, S., Mills, P., 2012. Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. Biol. Rev. 87, 52–71. https://doi.org/10.1111/j.1469-185X.2011.00184.x.

Blanco-Canqui, H., 2010. Energy crops and their implications on soil and environment. Agron. J. 102, 403–419. https://doi.org/10.2134/agronj2009.0333.

Carlsson, G., Huss-Danell, K., 2003. Nitrogen fixation in perennial forage legumes in the field. Plant Soil 253, 353–372.

Cornish, P.S., Tullberg, J.N., Lemerle, D., Flower, K., 2020. No-till farming systems in Australia. No- Farming Syst. Sustain. Agric.: Chall. Oppor. 511–531. https://doi.org/10.1007/978-3-030-46409-7_29.

Costa, M.P., Reckling, M., Chadwick, D., Rees, R.M., Saget, S., Williams, M., Styles, D., 2021. Legume-modified rotations deliver nutrition with lower environmental impact. Front Sustain Food Syst. 5, 113. https://doi.org/10.3389/FSUFS.2021.656005/BIBTEX.

Cusser, S., Bahlai, C., Swinton, S.M., Robertson, G.P., Haddad, N.M., 2020. Long-term research avoids spurious and misleading trends in sustainability attributes of no-till. Glob. Chang Biol. 26, 3715–3725. https://doi.org/10.1111/gcb.15080.

Destatis, 2024. ⟨https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/Tabellen/ackerland-hauptnutzungsarten-kulturarten.html⟩ [WWW Document].

Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M.S., Drewer, J., Flessa, H., Freibauer, A., Hyvönen, N., Jones, M.B., Lanigan, G.J., Mander, Ü., Monti, A., Djomo, S.N., Valentine, J., Walter, K., Zegada-Lizarazu, W., Zenone, T., 2012. Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. GCB Bioenergy 4, 372–391. https://doi.org/10.1111/j.1757-1707.2011.01116.x.

DüV, 2017. Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordnung - DüV). ⟨https://www.gesetze-im-internet.de/d_v_2017/⟩.

EU Nitrogen Expert Panel, 2015. Nitrogen Use Effic. (NUE): Indic. Util. Nitrogen Agric. Food Syst., Wagening. Univ.

European Commission, 2019. The European Green Deal. Introd. Knowl. Manag. Commun. 106–117. https://doi.org/10.4324/9780080495781-12.

European Environment Agency, 2024. European Climate Risk Assessment. Executive summary. Copenhagen.

FAO, 2024. Faostat. Crops [WWW Document]. URL ⟨http://www.fao.org/faostat/en/#data/QC⟩ (accessed 11.13.24).

Federer, W.T., King, F., 2008. Variations on split plot and split block experiment designs. Am. Stat. https://doi.org/10.1198/tas.2008.s109.

Feedipedia, 2024. ⟨www.feedipedia.com⟩ [WWW Document].

Fiorini, A., Boselli, R., Maris, S.C., Santelli, S., Ardenti, F., Capra, F., Tabaglio, V., 2020. May conservation tillage enhance soil C and N accumulation without decreasing yield in intensive irrigated croplands? Results from an eight-year maize monoculture. Agric. Ecosyst. Environ. 296, 106926. https://doi.org/10.1016/J.AGEE.2020.106926.

FNR, 2020. Bioenergy in Germany: Facts and Figures 2020. Gülzow-Prüzen, Germany: Fachagentur Nachwachsende Rohstoffe e. V. (FNR).

Gomez, K.A., Gomez, A.A., 1984. Statistical procedures for agricultural research, Second. ed. John Wiley & Sons.

Grassini, P., Yang, H., Cassman, K.G., 2009. Limits to maize productivity in Western Corn-Belt: a simulation analysis for fully irrigated and rainfed conditions. Agric. Meteor. 149, 1254–1265. https://doi.org/10.1016/j.agrformet.2009.02.012.

Gruber, S., Pekrun, C., Möhring, J., Claupein, W., Gruber, S., Pekrun, C., Möhring, J., Claupein, W., 2012. Long-term yield and weed response to conservation and stubble tillage in SW Germany. STilR 121, 49–56. https://doi.org/10.1016/J.STILL.2012.01.015.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M., Wolfe, D., 2011. Climate Impacts on Agriculture: Implications for Crop Production. Agron. J. 103, 351–370. https://doi.org/10.2134/agronj2010.0303.

Herrmann, C., Idler, C., Heiermann, M., 2016b. Biogas crops grown in energy crop rotations: Linking chemical composition and methane production characteristics. Bioresour. Technol. 206, 23–35. https://doi.org/10.1016/j.biortech.2016.01.058.

Herrmann, C., Idler, C., Heiermann, M., 2016a. Biogas crops grown in energy crop rotations: Linking chemical composition and methane production characteristics. Bioresour. Technol. 206, 23–35. https://doi.org/10.1016/j.biortech.2016.01.058.

Hufnagel, J., Reckling, M., Ewert, F., 2020. Diverse approaches to crop diversification in agricultural research. A review. Agron. Sustain Dev. https://doi.org/10.1007/s13593-020-00617-4.

Huynh, H.T., Hufnagel, J., Wurbs, A., Bellingrath-Kimura, S.D., 2019. Influences of soil tillage, irrigation and crop rotation on maize biomass yield in a 9-year field study in Müncheberg, Germany. Field Crops Res 241. https://doi.org/10.1016/j.fcr.2019.107565.

Iglesias, A., Garrote, L., 2015. Adaptation strategies for agricultural water management under climate change in Europe. Agric. Water Manag. https://doi.org/10.1016/j.agwat.2015.03.014.

Jänicke, C., Goddard, A., Stein, S., Steinmann, H.-H., Lakes, T., Nendel, C., Müller, D., 2022. Field-level land-use data reveal heterogeneous crop sequences with distinct regional differences in Germany. Eur. J. Agron. 141, 126632. https://doi.org/10.1016/j.eja.2022.126632.

Johnston, A.E., Poulton, P.R., 2018. The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. Eur. J. Soil Sci. 69, 113–125. https://doi.org/10.1111/EJSS.12521.

Jordan, M., Meisel, K., Dotzauer, M., Schröder, J., Cyffka, K.F., Dögnitz, N., Schmid, C., Lenz, V., Naumann, K., Daniel-Gromke, J., de Paiva, G.C., Schindler, H., Aliabadi, D. E., Szarka, N., Thrän, D., 2023. The controversial role of energy crops in the future German energy system: the trade offs of a phase-out and allocation priorities of the remaining biomass residues. Energy Rep. 10, 3848–3858. https://doi.org/10.1016/j.egyr.2023.10.055.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Conyers, M., Kirkegaard, J.A., 2016. Inorganic nutrients increase humification efficiency and c-sequestration in an annually cropped soil. PLoS One 11, e0153698. https://doi.org/10.1371/journal.pone.0153698.

Kirkegaard, J.A., Conyers, M.K., Hunt, J.R., Kirkby, C.A., Watt, M., Rebetzke, G.J., 2014. Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. Agric. Ecosyst. Environ. 187, 133–145. https://doi.org/10.1016/j.agee.2013.08.011.

Kotir, J.H., Bell, L.W., Kirkegaard, J.A., Whish, J., Aikins, K.A., 2022. Labour demand – the forgotten input influencing the execution and adoptability of alternative cropping systems in Eastern Australia. Agric. Syst. 203. https://doi.org/10.1016/j.agsy.2022.103516.

Krauss, M., Wiesmeier, M., Don, A., Cuperus, F., Gattinger, A., Gruber, S., Haagsma, W. K., Peigné, J., Palazzoli, M.C., Schulz, F., van der Heijden, M.G.A., Vincent-Caboud, L., Wittwer, R.A., Zikeli, S., Steffens, M., 2022. Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. Soil Tillage Res 216. https://doi.org/10.1016/j.still.2021.105262.

Lampurlanes, J., Plaza-Bonilla, D., Alvaro-Fuentes, J., Cantero-Martinez, C., 2016. Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crops Res 189, 59–67. https://doi.org/10.1016/j.fcr.2016.02.010.

Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., Cantero-Martínez, C., 2016. Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crops Res 189, 59–67. https://doi.org/10.1016/j.fcr.2016.02.010.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9. https://doi.org/10.1088/1748-9326/9/10/105011.

Lefèvre, C., Fatma, R., Viridiana, A., Liesl, W., 2017. Soil organic Carbon: the hidden potential. FAO, Roma. Rome.

Llewellyn, R.S., D'Emden, F.H., Kuehne, G., 2012. Extensive use of no-tillage in grain growing regions of Australia. Field Crops Res 132, 204–212. https://doi.org/10.1016/J.FCR.2012.03.013.

Mariotti, F., Tomé, D., Mirand, P.P., 2008. Converting nitrogen into protein - beyond 6.25 and Jones' factors. Crit. Rev. Food Sci. Nutr. 48, 177–184. https://doi.org/10.1080/10408390701279749.

McDaniel, M.D., Tiemann, L.K., Grandy, A.S., 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24, 560–570. https://doi.org/10.1890/13-0616.1.

Mirschel, W., Wieland, R., Luzi, K., Groth, K., 2020. Model-Based Estimation of Irrigation Water Demand for Different Agricultural Crops Under Climate Change, Presented for the Federal State of Brandenburg, Germany. In: Mirschel, Wilfried, Terleev, V.V., W. K.-O. (Eds.), Landscape Modelling and Decision Support. Springer International Publishing, Cham, pp. 311–327. https://doi.org/10.1007/978-3-030-37421-1_16.

Miti, C., Milne, A.E., Giller, K.E., Lark, R.M., 2024. The concepts and quantification of yield gap using boundary lines. A review. Field Crops Res. https://doi.org/10.1016/j.fcr.2024.109365.

Nichols, V., Verhulst, N., Cox, R., Govaerts, B., 2015. Weed dynamics and conservation agriculture principles: a review. Field Crops Res 183, 56–68. https://doi.org/10.1016/J.FCR.2015.07.012.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34, 96–112. https://doi.org/10.1016/J.EJA.2010.11.003.

Page, K.L., Dang, Y.P., Dalal, R.C., Reeves, S., Thomas, G., Wang, W., Thompson, J.P., 2019. Changes in soil water storage with no-tillage and crop residue retention on a Vertisol: impact on productivity and profitability over a 50 year period. Soil Tillage Res 194. https://doi.org/10.1016/j.still.2019.104319.

Pareja-Sánchez, E., Cantero-Martínez, C., Álvaro-Fuentes, J., Plaza-Bonilla, D., 2020. Soil organic carbon sequestration when converting a rainfed cropping system to irrigated corn under different tillage systems and N fertilizer rates. Soil Sci. Soc. Am. J. 84, 1219–1232. https://doi.org/10.1002/saj2.20116.

Passioura, J.B., Angus, J.F., 2010. Improving Productivity of Crops in Water-Limited Environments. Advances in Agronomy, 1st ed. Elsevier Inc. https://doi.org/10.1016/S0065-2113(10)06002-5.

Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard-Nielsen, H., Jensen, E.S., 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48, 1–17. https://doi.org/10.1007/BF03179980.

Reckling, M., Rosner, G., 2024. Long-term experiment on soil tillage, rotation and irrigation (V4), Dataset. BonaRes Repos. https://doi.org/10.4228/zalf-xga4-xw15.

Rizzo, G., Monzon, J.P., Tenorio, F.A., Howard, R., Cassman, K.G., Grassini, P., 2022. Climate and agronomy, not genetics, underpin recent maize yield gains in favorable environments. Proc. Natl. Acad. Sci. USA 119. https://doi.org/10.1073/pnas.2113629119.

Ruf, T., Makselon, J., Udelhoven, T., Emmerling, C., 2018. Soil quality indicator response to land-use change from annual to perennial bioenergy cropping systems in Germany. GCB Bioenergy 10, 444–459. https://doi.org/10.1111/gcbb.12513.

Sadras, V., Dreccer, M.F., 2015. Adaptation of wheat, barley, canola, field pea and chickpea to the thermal environments of Australia. Crop Pasture Sci. 66, 1137–1150. https://doi.org/10.1071/CP15129.

Sadras, V.O., 2020. On water-use efficiency, boundary functions, and yield gaps: French and Schultz insight and legacy. Crop Sci. 60, 2187–2191. https://doi.org/10.1002/csc2.20188.

Schittenhelm, S., Reus, D., Kruse, S., Hufnagel, J., 2011. Assessment of productivity and profitability of sole and double-cropping for agricultural biomass production Bewertung der Produktivität und Wirtschaftlichkeit von Hauptfruchtanbau und Zweifruchtnutzung für die landwirtschaftliche Biomasseproduktion. J. F. ÜR. KULTURPFLANZEN.

Schmitt, J., Offermann, F., Söder, M., Frühauf, C., Finger, R., 2022. Extreme weather events cause significant crop yield losses at the farm level in German agriculture. Food Policy 112, 102359. https://doi.org/10.1016/j.foodpol.2022.102359.

Sevenster, M., Kirkegaard, J.A., Lilley, J.M., 2024. Rethinking environmental sustainability in rainfed cropping systems. Sustain Prod. Consum 50, 128–138. https://doi.org/10.1016/j.spc.2024.07.028.

Shatar, T.M., Mcbratney, A.B., 2004. Boundary-line analysis of field-scale yield response to soil properties. J. Agric. Sci. 142, 553–560. https://doi.org/10.1017/S0021859604004642.

Simon-Miquel, G., Reckling, M., Lampurlanés, J., Plaza-Bonilla, D., 2023. A win-win situation – increasing protein production and reducing synthetic N fertilizer use by integrating soybean into irrigated Mediterranean cropping systems. Eur. J. Agron. 146. https://doi.org/10.1016/j.eja.2023.126817.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.

Stanhill, G., Cohen, S., 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric. Meteor. 107, 255–278. https://doi.org/10.1016/S0168-1923(00)00241-0.

Strauss, C., Herrmann, C., Weiser, C., Kornatz, P., Heiermann, M., Aurbacher, J., Müller, J., Vetter, A., 2019. Can Energy Cropping for Biogas Production Diversify Crop Rotations? Findings from a Multi-Site Experiment in Germany. Bioenergy Res 12, 123–136. https://doi.org/10.1007/s12155-019-9960-5.

Thrän, D., Schaubach, K., Majer, S., Horschig, T., 2020. Governance of sustainability in the German biogas sector - adaptive management of the renewable energy act between agriculture and the energy sector. Energy Sustain Soc. https://doi.org/10.1186/s13705-019-0227-y.

Unkovich, M., Herridge, D., Peoples, M., Cadisch, G., Boddey, B., Giller, K., Alves, B., Chalk, P., 2008. Measuring plant-associated nitrogen fixation in agricultural systems. Measuring plant-associated nitrogen fxation in agricultural systems, 1st ed. Australian Centre for International Agricultural Research (ACIAR), Canberra. https://doi.org/10.1071/AR9940119.

Van Groenigen, J.W., Van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S., Van Groenigen, K.J., 2017. Sequestering soil organic carbon: a nitrogen dilemma. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.7b01427.

Verch, G., Kächele, H., Höltl, K., Richter, C., Fuchs, C., 2009. Comparing the profitability of tillage methods in Northeast Germany-A field trial from 2002 to 2005. Soil Tillage Res. https://doi.org/10.1016/j.still.2008.12.012.

von Czettritz, H.J., Hosseini-Yekani, S.A., Schuler, J., Kersebaum, K.C., Zander, P., 2023. Adapting cropping patterns to climate change: risk management effectiveness of diversification and irrigation in Brandenburg (Germany). Agric. (Switz.) 13. https://doi.org/10.3390/agriculture13091740.

von Redwitz, C., Gerowitt, B., 2018. Maize-dominated crop sequences in northern Germany: reaction of the weed species communities. Appl. Veg. Sci. 21, 431–441. https://doi.org/10.1111/avsc.12384.

Wendling, U., Schellin, H.-G., Thomä, M., 1991. Bereitstellung von täglichen informationen zum wasserhaushalt des bodens für die zwecke der agrarmeteorologischen beratung. Z. F. üR. Meteorol. 41, 468–475.