European Journal of Agronomy 177 (2026) 128097

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Model-based assessment of organic fertilization as alternative to mineral P under future climate change

Gihan Mohammed [a], Nina Siebers [a], Ines Merbach [b], Michael Herbst [a,*]

[a] Institute of Bio, and Geosciences – Agrosphere (IBG-3), Forschungszentrum Jülich, Jülich D-52425, Germany
[b] Bad Lauchstädt Experimental Station, Helmholtz Centre for Environmental Research – UFZ, Leipzig-Halle, Hallesche Str. 44, Bad Lauchstädt D-06246, Germany

ARTICLE INFO

Keywords:
Organic fertilization
P dynamics
Crop yield
Sustainability
Climate change

ABSTRACT

Sustainable agriculture depends on reliable phosphorus (P) supplies, yet global reserves of mineral P fertilizers are finite. Here, we explored whether organic fertilization could serve as a viable substitute for mineral P while sustaining crop yields and soil P under changing climate conditions. Using the calibrated and validated AgroC model with decades of field data from the Bad Lauchstädt long-term experiment site in Germany (with a four-crop rotation of sugar beet, spring barley, potato, and winter wheat), we simulated crop performance and soil P dynamics from 2019 to 2100 under the RCP4.5 and RCP8.5 climate scenarios. The analysis compared five fertilization strategies: mineral fertilization (MIN), two farmyard manure rates (FYM_20 and FYM_30), and two optimized manure regimes (FYM_37 and FYM_37 +N). Results showed that fertilization strategy had a far greater influence on soil P and yields than the projected climate scenarios. Low manure inputs (FYM_20) led to steady P depletion and yield loss, whereas FYM_30 and FYM_37 reduced winter wheat yield losses to 45% and 30% below MIN levels, respectively, while achieving comparable or superior yields for barley, potato, and sugar beet. Winter wheat required modest mineral N supplementation (~15 kg N ha^{-1}) in FYM_37 +N to achieve optimal yields, while potato, barley, and sugar beet performed well under manure-only management. Warmer conditions under RCP8.5 increased P depletion by 10–15% relative to RCP4.5, but this effect remained minor compared with fertilization management. Notably, higher manure application rates were linked to lower cumulative P leaching. Among treatments, FYM_37_N performed best, with total P losses only 1.5–2% higher than those of MIN (3.77–4.82 kg P ha^{-1} for MIN under RCP4.5 and RCP8.5). Our results suggest that optimized organic fertilization can effectively replace mineral P inputs, maintain crop yields, and enhance resilience in long-term cropping systems under climate change.

1. Introduction

Sustainable agricultural production relies on the continuous and sufficient availability of essential nutrients, particularly phosphorus (P), which is a key element for plant growth and development (Mohammed et al., 2016., Bechtaoui et al., 2021; McDowell et al., 2024). However, the global availability of mineral P fertilizers is increasingly constrained by the uneven distribution and limited accessibility of phosphate rock reserves. A few countries control most of these reserves, which makes agriculture in many regions dependent on imported raw materials and vulnerable to market and political instability (Cordell et al., 2009; Van Vuuren et al., 2010). This raises concerns about long-term food security and highlights the urgent need to explore alternative fertilization strategies (Gilbert, 2009). In addition, mineral fertilizations can acidify soils, accelerate the dissolution of soil inorganic carbon (SIC) and contribute to CO_2 emissions (Liu et al., 2023).

Over recent decades, agricultural P management has moved away from the sole goal of maximizing yields and now places greater emphasis on using resources efficiently and reducing nutrient losses. The idea of legacy P, which refers to the P that has built up in soils through many years of fertilization, shows both the potential and the problem of modern nutrient management. These accumulated reserves can continue to support crop growth for some time, but they also increase the risk of P leaching and long-term pollution of water bodies (Gocke et al., 2021; Taube et al., 2015). However, the potential of legacy P to reduce the need for mineral fertilizers is still insufficiently characterized (Sattari, 2014; Menezes-Blackburn et al., 2018). Organic amendments can promote the mobilization and bioavailability of legacy P through microbial

---

* Corresponding author.
E-mail address: m.herbst@fz-juelich.de (M. Herbst).

https://doi.org/10.1016/j.eja.2026.128097
Received 11 November 2025; Received in revised form 26 January 2026; Accepted 19 March 2026

activity, production of organic acids, and enzymatic mineralization (Richardson et al., 2011; Helfenstein et al., 2024). Therefore, understanding how organic fertilization influences the utilization of legacy P is critical for designing sustainable management strategies that reduce reliance on mineral fertilizer inputs P. Moreover, P dynamics in the soil are complex, shaped by soil physicochemical properties, microbial activity, and interactions with other nutrients. A major limitation of conventional mineral fertilization is that a substantial portion of the applied P is unavailable to plants due to fixation by soil minerals or stabilization in organic matter (Eriksson et al., 2016; Mohammed et al., 2017). This inefficiency may provoke excessive fertilizers application, which in turn contributes to environmental risks such as eutrophication, soil degradation, and water pollution from runoff and leaching (Elser and Bennett, 2011).To address these challenges, organic amendments have gained increasing attention as a viable and sustainable alternative to mineral P fertilizers (Nobile et al., 2022; Sun et al., 2022; Thomas et al., 2019; Zhao et al., 2024). Organic fertilizer provides a slow-release source of P that can enhance nutrient use efficiency, reduce fixation losses, and help sustain soil fertility over time. Beyond nutrient supply, organic fertilization improves soil health by increasing organic matter content, microbial diversity, reducing inorganic C dissolution, and enhancing soil structure, which are crucial for maintaining long-term agricultural productivity (Gao et al., 2023; Kebalo et al., 2024; Liu et al., 2023; Wen et al., 2020). In addition, organic matter application supports soil aggregation and promotes the formation of organo-mineral associations that stabilize both C and P, thereby improving nutrient retention and resilience under changing climatic conditions (Frossard et al., 2002; Hu et al., 2022). Organic fertilizer contributes to organic and inorganic forms of P that are gradually mineralized, supporting a more balanced nutrient supply and improving soil biological activity and structure. It also buffers soil pH, enhances C sequestration, and sustains microbial processes that drive P cycling and soil fertility (Bünemann et al., 2004; Frossard et al., 2016). Consequently, manure has strong potential to support sustainable crop production while reducing dependency on mineral fertilizers (Lu et al., 2021).

However, most studies so far have been conducted under historical or current climatic conditions, whereas future changes in temperature, precipitation, and atmospheric CO₂ are expected to affect soil P cycling and crop P demand (Alewell et al., 2020; Wang et al., 2021). Warmer conditions can accelerate organic matter decomposition and P mineralization, while altered rainfall regimes can potentially influence P leaching, runoff, and plant uptake. Therefore, quantifying how organic manure application interacts with these climatic factors is essential for evaluating the long-term sustainability of manure-based P management under future climate.

Modeling represents a valuable tool to understand the interaction between agricultural practices and P dynamics in the atmosphere-soil-crop system and to predict the potential environmental impacts such as P leaching after fertilizer application. Nevertheless, only few modeling studies have explicitly examined the combined effects of long-term organic manure application and future climate variability on soil P transformations and crop productivity (Žydelis et al., 2021; Wang et al., 2022). Addressing this gap is essential for understanding the resilience of P cycling processes and for developing adaptive management strategies under changing environmental conditions. This study builds upon previous studies (Herbst et al., 2025; Mohammed et al., 2024), where a new process-based P sub-model was introduced, parametrized, and evaluated within the AgroC model to predict the response of the crop yield to soil P dynamics under various fertilizer management practices under field conditions. The present work aims to investigate the impact of long-term manure application on crop yield and available soil P under future climate conditions. Our hypothesis is that manure can act as an effective alternative to mineral P fertilizers by sustaining crop productivity and maintaining adequate soil P availability while reducing the environmental risks associated with synthetic fertilization. Ultimately, the findings are expected to offer theoretical and practical insights into the potential of manure as a sustainable fertilization strategy for balancing agricultural productivity with environmental protection.

2. Materials and methods

2.1. Field site

The Bad Lauchstädt long-term field fertilizer experiment in Germany (51°23 N, 11°52E), initiated in 1902, provides extensive data on the effects of fertilization over more than a century. The experimental field covers 4 ha, divided into eight strips measuring 200 × 25.5–28.5 m. Mean annual temperature is 10.1 °C and mean annual precipitation is 489 mm (1996–2018). The soil is classified as a Haplic Chernozem with a silt loam texture, containing on average 21% clay, 68% silt, and 11% sand in the plough layer (Altermann et al., 2005; Siebers et al., 2023). A four-crop rotation has been maintained, consisting of sugar beet (*Beta vulgaris*), spring barley (*Hordeum vulgare*), potato (*Solanum tuberosum*), and winter wheat (*Triticum aestivum*). Aboveground crop residues were consistently removed, leaving only roots in the soil; nevertheless, approximately 10% of biomass residues were assumed to remain due to unavoidable field losses. The experiment included 18 fertilization treatments (Table SI-1 in Supporting Information SI), among them farmyard manure (FYM) applied at 20 Mg FM ha^{-1} (FYM_20, official treatment ID: 12) and 30 Mg FM ha^{-1} (FYM_30, official treatment ID: 6), as well as full mineral NPK fertilization (MIN, official treatment ID: 13). FYM was applied only in years with sugar beet or potato cultivation (once every two years), whereas mineral fertilizer was applied annually based on crop demand. Application rates and chemical compositions of both, FYM and mineral fertilizers, is summarized in Mohammed et al. (2024).

2.2. Modeling approach with AgroC

AgroC is a one-dimensional mechanistic model developed through the integration of the SOILCO2/RothC model for soil carbon turnover, with the SUCROS model for crop growth. It simulates biogeochemical interactions between the atmosphere, crop, and soil environmental conditions (Herbst et al., 2025, 2008). The model describes the carbon cycle and associated processes, including crop growth, soil water, heat, solute and CO_2 flux, as well as the cycling of major soil nutrients. The upper atmospheric boundary condition is defined by daily climatic records such as air temperature, radiation, precipitation, and wind speed. CO_2 concentration effects on plant physiology and water use efficiency are modelled using the Farquhar approach (Collatz et al., 1991; Farquhar et al., 1980).

AgroC was extended with a P sub-model which simulates the transformation processes of organic and inorganic P in the soil–crop system using a pool concept. The development of this sub-model is described in detail by Herbst et al. (2025), while its validation based on two decades of historical data from Bad Lauchstädt, is reported by Mohammed et al. (2024).

In brief, the sub model includes three inorganic P pools alongside three organic P pools. The inorganic pools are stable (P_{stab}), active (P_{act}), and labile (P_{lab}). The organic pools are distributed among four soil organic pools: decomposable plant material (DPM), resistant plant material (RPM), and humified organic matter (HUM). Fertilizer-derived P is incorporated into the labile inorganic pool, which is in rapid equilibrium with the active inorganic pool. Phosphorus uptake is simulated similarly to nitrogen (N) uptake, but with assuming a constant P concentration across plant organs, with diffusion as the primary uptake mechanism. Decomposition of fresh and resistant organic matter may lead to either net immobilization of labile P or net mineralization of organic P, depending on system conditions.

When net immobilization occurs, immobilization will be reduced if sufficient mineral labile P pool to supply the immobilization demand is not available. In such cases, immobilization is reduced by adjusting the turnover rates proportionally to the supply/demand ratio. These adjusted rates are also applied in the organic C and N sub-models. Consequently, P limitations during the mineralization of one or both plant material pools can also slow down the decomposition of their corresponding C and N pools. In this study, and consistent with the findings of Mohammed et al. (2024), a link was established between the plant-available P fraction (P_{av}) in soil and the integrated P sub-model pools within the top 30 cm of the soil profile (kg P/ha). This relationship is expressed as:

$$P_{av} = P_{lab} + P_{act} + 0.05.P_{stab} \tag{1}$$

The P fraction determined by the Calcium Acetate Lactate (CAL) extraction method is widely recognized as a reliable indicator of plant-available P in German soils (Gocke et al., 2021). Accordingly, in this study, the simulated plant-available P fraction in soil was directly related to the soil P fraction extracted by the Calcium Acetate Lactate method (Schüller, 1969).

2.3. AgroC initialization and parametrization

In Mohammed et al. (2024), AgroC was evaluated at the Bad Lauchstädt experimental site using long-term historical data (1996–2018) that included various fertilization treatments on field soils under crop rotation of sugar beet, spring barley, potato, and winter cereals. In the present study, simulations were extended from 2019 to 2100 under future climate scenarios, maintaining the crop rotation system. The soil hydraulic parameters, together with those governing crop growth and the turnover of C, N, and P, were those derived from the previous evaluation using historical data (Mohammed et al., 2024). Initial conditions for the soil organic C, N, and P pools were set to the values obtained at the end of the historical simulations. Details of the crop management parameters and the climatic inputs used in AgroC for the different future scenarios are described below.

2.3.1. Crop management parameters

Accumulated effective temperature sums for each crop, used as inputs to the AgroC model, were derived from historical time series data reported in Mohammed et al. (2024) and are summarized in Table 1. These sums were computed by subtracting a base temperature of 0 °C from the daily average air temperature for each day within the crop's growing period, summing only positive values to obtain seasonal totals, and averaging these totals to obtain representative values per crop.

For simulations under future climate scenarios, sowing dates were selected within specified planting windows (Table 1) based on predefined climatic criteria. Specifically, during the three days preceding sowing, temperature thresholds had to be met, and precipitation on the sowing day was required to be below 1 mm. Thresholds were defined at a maximum of 5 °C for potatoes, 4 °C for sugar beets, and a minimum of 5 °C for winter cereals. If no appropriate sowing date was identified under these criteria, thresholds were incrementally relaxed until suitable conditions were met.

Harvest dates were determined by the time required to accumulate the crop-specific effective temperature sum. Additionally, the selected harvest date had to exhibit daily precipitation below 0.5 mm d^{-1}; if unmet, the date with minimal precipitation within a ± 3-day window of the calculated harvest day was chosen.

Table 1
Summary of datasets used for determining crop sowing and harvest timing.

Crop	n	Sowing window	Accumulated effective temperature sum*
Winter wheat	6	October 1st – December 31st	2377 (2233 – 2525)
Spring barely	5	February 26th – March 31st	1863 (1740 – 1979)
Potatoes	5	March 29th – April 30th	2303 (2060 – 2499)
Sugar beets	5	March 15th – April 30th	2860 (2733 – 2976)

n: number of time series used in calculations
*: Mean values are underlined while maximum and minimum values are given in brackets

2.3.2. Climate change projections

Meteorologic input parameters required by the AgroC model were obtained from future climate projections provided by the H2020 eLTER infrastructure project (eeLTER, 2020). These projections consist of pre-processed regional climate scenarios derived from ensembles of Regional Climate Models (RCMs) dynamically downscaling Global Climate Models (GCMs) under IPCC Representative Concentration Pathways (RCPs). These RCPs are commonly used scenarios for modeling future atmospheric greenhouse gas concentrations (Moss et al., 2010; IPCC, 2014).

Two RCPs scenarios were considered: RCP4.5 representing moderate emission reductions and mid-century stabilization, and RCP8.5 representing continued high emissions. These scenarios capture divergent climate impacts, particularly in late-century temperature, precipitation extremes, and ecosystem effects.

For each RCP, daily meteorological data (2019–2100) for 12 RCM-GCM combinations at the Bad Lauchstädt site were extracted (Table SI-2). Daily datasets from each climate model combination were used as simulation inputs. Considering multiple models helps reduce uncertainties in climate projections and provides more reliable outcomes than using a single model. These datasets included minimum, maximum air temperature, solar radiation, precipitation, air pressure, wind speed, and air humidity with a horizontal resolution of ~12 km. No further bias correction was applied, as RCM–GCM data typically show larger systematic biases in precipitation than in temperature or radiation (Berg et al., 2012; Maraun. 2016). Since P cycling in this study is primarily driven by P pools and management factors rather than daily precipitation amounts, additional correction was deemed unnecessary. Sub-daily rainfall extremes are addressed separately in the study limitations section. The ensemble approach across 12 RCM–GCM combinations further mitigates residual climate input uncertainties. Atmospheric CO_2 concentration time series, which is input to the AgroC model, were taken from the RCP database. Daily evapotranspiration was estimated using the FAO Penman–Monteith equation (Zotarelli et al., 2024), while relative humidity was derived from specific humidity based on the recommended FAO formula.

2.4. Fertilization approaches: Baseline practices and scenario development

To assess the performance of organic fertilization under projected climate change conditions, five fertilization treatments were defined. Three historical practices included conventional full mineral fertilization (NPK) as the benchmark (MIN), and two organic fertilizer applications at 20 Mg fresh matter ha^{-1} (FYM_20) and 30 Mg FM ha^{-1} (FYM_30).

To provide a more balanced and P-efficient alternative, a virtual treatment was defined: FYM application at 37 Mg FM ha^{-1} (FYM_37), corresponding to the crop P demand. This application rate was derived from crop nutrient requirements reported in Mohammed et al. (2024) by dividing the crop P demand (reported as 22.8 kg P ha^{-1} per year, equivalent to 52.2 kg P_2O_5 ha^{-1}) by the P concentration in the farmyard manure (4.74 kg P_2O_5 Mg^{-1} FM). The resulting application rate was then doubled to account for the fertilizer being applied once every two years (only in years with sugar beet and potato cultivation).

Evidence from crop yields in 12 historical treatments at the same study site indicated that N is generally the most limiting nutrient for cereals, while sugar beet is more sensitive to P omission, and potato responds to the omission of either nutrient. Based on this, another virtual treatment was designed: FYM_37 +N. This approach uses the P-based manure rate but also adds a small dose of mineral N specifically for cereals. Since farmyard manure already provides some N (Albano et al., 2023; Thomas et al., 2019), only 20% of the usual mineral N rate was added (15 kg N ha^{-1} instead of the standard 80 kg N ha^{-1}).

2.5. Statistical analysis

Linear regression analysis conducted in Python 3.8.16 was used to assess relationships between annual growing period lengths (LGP) under both RCP scenarios. Additionally, Spearman correlations and simple linear regressions were calculated between LGP and mean crop yields (aggregated across fertilizer treatments) for each crop-RCP combination. Similarly, Pearson correlations and simple linear regressions were applied to examine correlations between organic C/P ratio and available phosphorus under both RCP scenarios. The coefficient of determination (R^2) was used to quantify the overall linear fit, while Pearson and Spearman ρ values captured potential nonlinear associations. Statistical significance was evaluated at $p < 0.005$ and < 0.001. To evaluate the effects of fertilization strategy, climate scenario, and their interaction on available soil P (P_{av}), a two-way analysis of variance (ANOVA) was performed in R (v.4.5.2). Fertilization and climate scenario were treated as fixed factors, and annual mean simulation data were used as replicates. The relative contribution of each factor to the total variance was derived from the ANOVA sum of squares. Residuals were examined for normality and homogeneity of variance to confirm that the assumptions underlying ANOVA were satisfied.

3. Results

3.1. Predicted changes in meteorological conditions

The atmospheric CO_2 concentration under RCP4.5 increases gradually until around 2075, after which it stabilizes, reaching approximately 538 ppm by the end of century. In contrast, under RCP8.5, CO_2 levels continue to rise rapidly throughout the century, reaching about 936 ppm by the end of century (Fig. 1a). For mean annual air temperature, the median projections (50th percentiles) for the near-future period (2019–2050) are almost identical for both scenarios, with an average of 9.9 °C. Differences between RCP4.5 and RCP8.5 only start to appear towards the end of this period, becoming more pronounced in remote future (2051–2099). Over this later period, mean annual temperatures are expected to rise to 10.6 °C under RCP4.5 and 11.8 °C under RCP8.5, which corresponds to increases of 0.7 °C and 1.9 °C, respectively, compared to the near-future average (Fig. 1b).

Over the simulation period (2019–2100), the accumulated precipitation reached 55085 mm under RCP4.5 and 56514 mm under RCP8.5, representing an increase of about 3%. However, trends in total annual

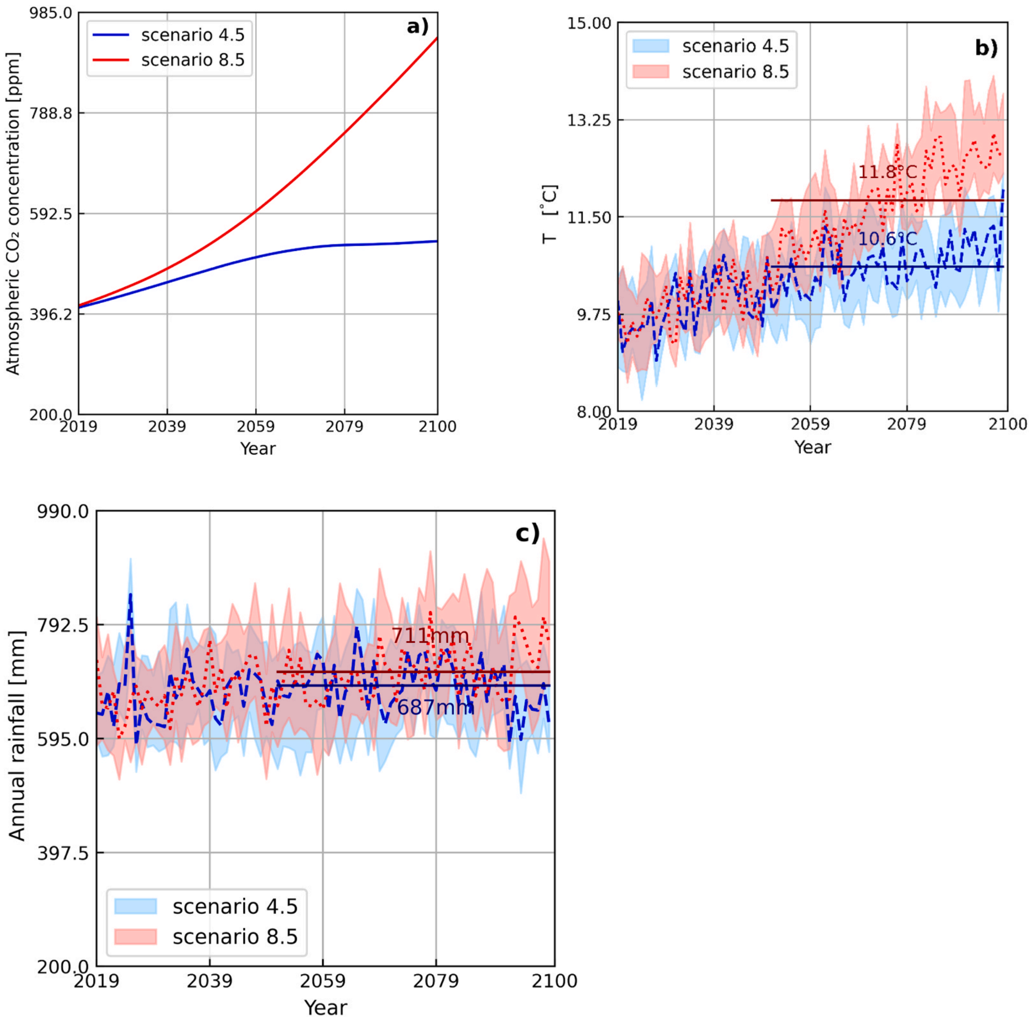

Fig. 1. Projected evolution of (a) atmospheric CO_2, (b) mean annual temperature, and (c) rainfall from 2019 to2099, based on 12 RCM-GCM combinations for scenarios RCP4.5 and RCP8.5 for the study area. Shaded areas indicate the 95% confidence intervals (CI) of the simulated values. Solid lines correspond to the mean values of the 50% CI calculated over the given periods.

precipitation are less evident. The 50th percentiles of mean precipitation during the near future averages 670 mm under RCP4.5 and 677 mm under RCP8.5, increasing moderately in remote future to 687 mm and 711 mm, respectively (Fig. 1c). These differences between the RCP4.5 and RCP8.5 precipitation projections are not statistically significant ($p > 0.05$), and this may be attributed largely to the large year-to-year variability in precipitation.

3.2. Climate change impact on crop growing season length

The annual length of the growing period (LGP), defined as the time from crop emergence to harvest, was systematically calculated for each of the four crops under both RCPs scenarios for the period 2019–2099 (Fig. 2). A linear regression was then fitted to describe the relationship between LGPs across the two scenarios: $\text{LGP}_{\text{RCP8.5}} = 0.896\ \text{LGP}_{\text{RCP4.5}} + 11.841$ (R^2=0.88, $p < 0.001$)

This relationship indicates that beyond a threshold LGP of approximately 114 days, LGP under the high-emission RCP8.5 scenario is on average reduced by about 10.4% compared to RCP4.5 conditions. This pattern was consistently observed in most simulated years derived from 12 RCM-GCM combinations (765 out of 949 data points), corresponding to all years cultivated with winter wheat, barley, and sugar beets. However, for years cultivated with potato, only 30% of the years (73 out of 240 data points) followed this pattern.

Spearman correlations between annual climate-derived LGP and mean crop yields (aggregated across fertilizer treatments) revealed significant positive associations for barley, potato, and sugar beets ($\rho = 0.19$–0.42, $p < 0.005$, see Table SI-3). Potato showed the strongest relationships ($\rho = 0.337$–0.374, $R^2 = 0.211$–0.324), while winter wheat showed no significant LGP-yield relationship ($\rho = -0.074$–0.030, $p > 0.25$).

The relationships between emergence and harvest dates under the two RCPs revealed systematic shifts toward earlier development under RCP8.5 (results not shown):

Emergence dates: $y = 0.997\ x - 0.542$ (R^2=0.99, $p < 0.001$)

Harvest dates: $y = 0.746\ x + 54.59$ (R^2=0.58, $p < 0.001$)

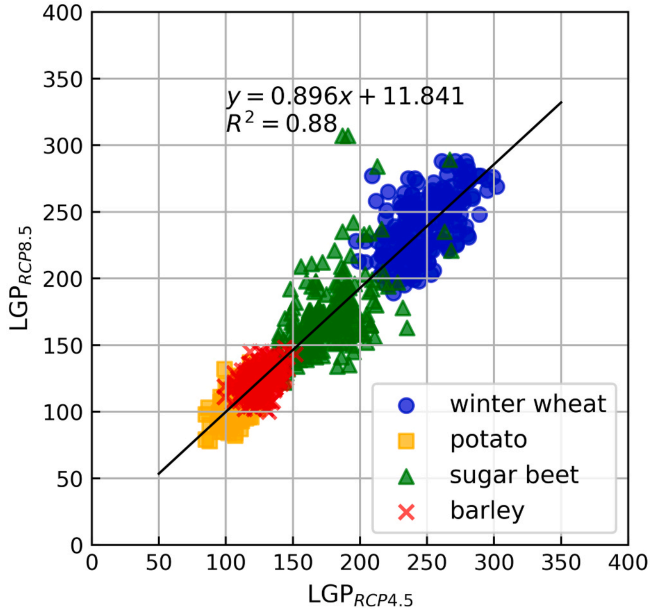

Fig. 2. Scatter plot of Length Growing Period (LGP) under RCP4.5 and RCP8.5 scenarios for four crops: winter wheat (blue circles), potato (orange squares), sugar beets (green triangles), and barley (red crosses). The black line shows the overall linear regression fit.

where x and y represent the order of emergence or harvest days in a growing year under RCP4.5 and RCP8.5, respectively.

3.3. Crop yield responses to various treatments under climate change scenarios

For winter wheat, yields were lowest for the FYM_20 treatment, decreasing by about 65% compared to MIN in both climate scenarios (Fig. 3). Applying more manure (FYM_30 and FYM_37) helped reduce the yield declines but yields remained approximately 45% and 30% lower than MIN, respectively. Adding mineral N to the highest manure rate (FYM_37 +N) generates yields close to those found for the MIN treatment, with a median value just 1% lower than MIN. This suggests that enhanced N availability stimulates winter wheat growth. However, under the warmer RCP8.5 scenario, yields with FYM_37 +N were still about 6% lower than MIN, indicating sensitivity of wheat to elevated temperatures, which likely accelerate plant maturation and shorten the grain-filling period, as discussed in Section 3.2.

Similar results to those found for winter wheat yields with low farmyard manure application rates (FYM_20 and FYM_30) were also observed for barley. However, unlike winter wheat, barley yields under FYM_37 without any mineral N addition were comparable to those obtained for the MIN treatment, with median values only 4% and 2% lower under RCP4.5 and RCP8.5, respectively. Yields with FYM_37 +N were slightly higher than FYM_37, but the difference was not significant

In contrast, sugar beet and potato yield under conventional treatment (FYM_30) showed similar patterns to those found in our previous long-term field trials in Bad Lauchstädt (Mohammed et al., 2024). Sugar beet yields were about 5% and 2% higher, and potato yields were roughly 26% and 24% higher than those with mineral fertilization under RCP4.5 and RCP8.5, respectively. Applying more manure (FYM_37) further increased yields significantly, roughly 16% and 50% higher than MIN for sugar beet and potato, respectively, under both climate scenarios. Further, results show just small differences in median crop yields between the RCP 4.5 and RCP 8.5 scenarios. These ranged from 0.4% to 5.6% (see Table SI-4), with RCP 8.5 sometimes giving slightly lower or more variable yields mostly in cereals.

3.4. Available soil P dynamics among treatments and scenarios

Using Eq. (1), the temporal evolution of soil available P (P_{av}) within the top 30 cm of soil under two climate scenarios (RCP4.5 and RCP8.5) are shown in Fig. 4(a, b). In general, manure-based treatments maintained higher P_{av} than soils treated with mineral fertilizer (MIN), except for the FYM_20 treatment, which declined below the mineral fertilizer levels after 2071. Soil available P increased proportionally to the amount of manure applied, with FYM_37 and FYM_37 +N showing the highest P_{av} throughout the simulation. Under the RCP4.5 scenario, the MIN treatment showed a 15.8% increase in P_{av} from 291.5 in 2019 (50% Interval Confidence IC) by the end of the historical period) to 337.5 kg P ha^{-1} by the end of the century, while manure treatments experienced declines ranging roughly from –22.7% (FYM_20, FYM_37) to –24.5% (FYM_37 +N) and –28.1% (FYM_30). Under RCP8.5, mineral fertilization increased less, about 9.7%. Manure treatments showed larger decreases, between –26.0% (FYM_20 and FYM_37), –27.0% (FYM_37 +N), and –31.0% (FYM_30). This corresponds to approximately 10–15% stronger P depletion under the warmer RCP8.5 scenario compared to RCP4.5 for manure-based treatments.

Statistical analysis, two-way ANOVA and Figure SI-1, showed a highly significant effect of fertilization strategy on P_{av}, explaining ∼ 92% of the total variance ($p < 0.001$). While climate scenario explained only 0.04% of the variance ($p = 0.04$). The interaction between fertilization strategy and climate scenario was not significant ($p = 0.998$), indicating that the effect of fertilization on soil P was consistent across both RCP4.5 and RCP8.5 scenarios.

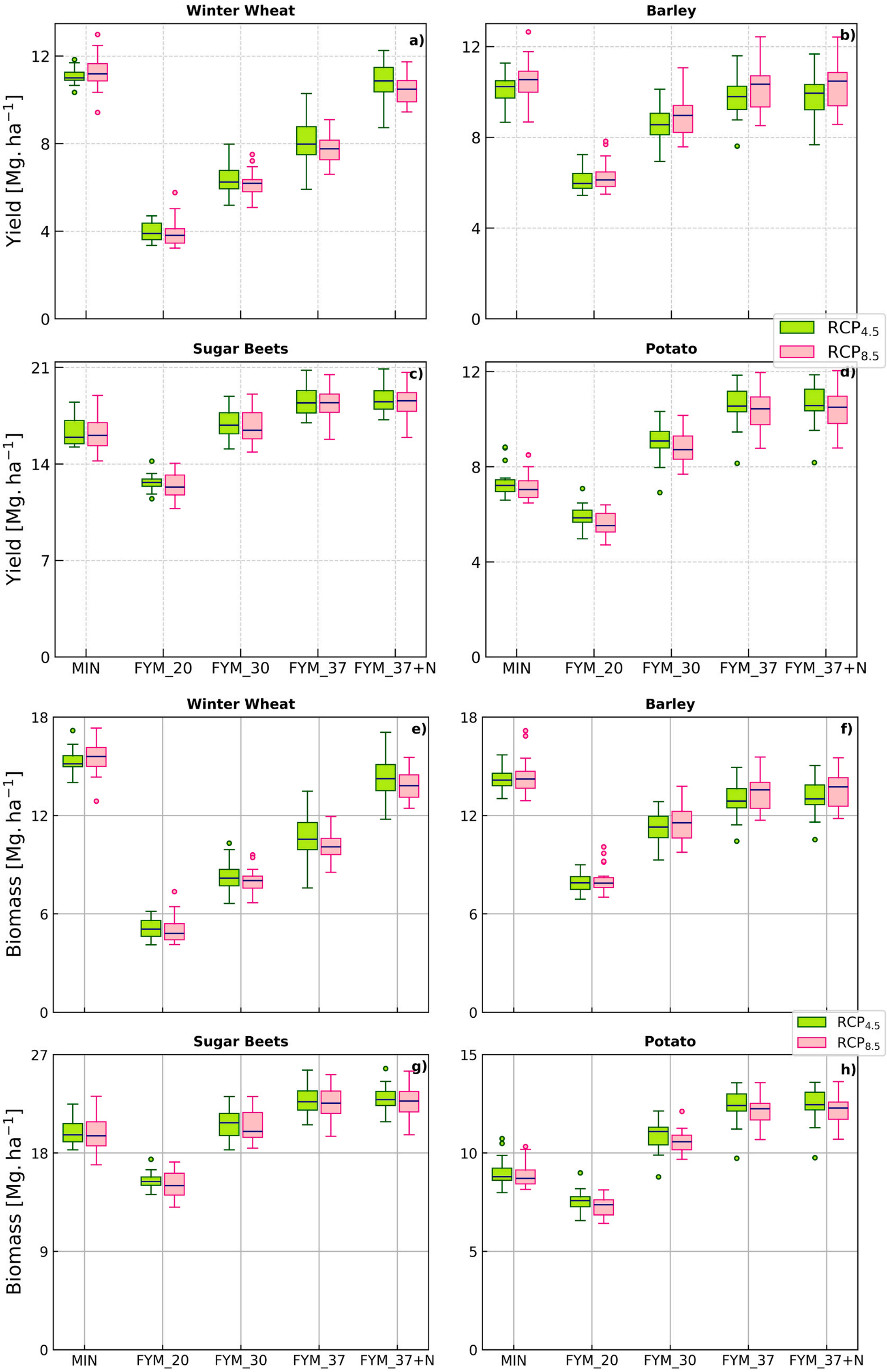

Fig. 3. Comparison of crop yields (panels a-d) and biomass (panels e-f) for winter wheat, barley, sugar beet, and potato across different treatments under the RCP4.5 (light green) and RCP8.5 (light violet) climate scenarios. Circles represent outliers, and the black lines indicate median values.

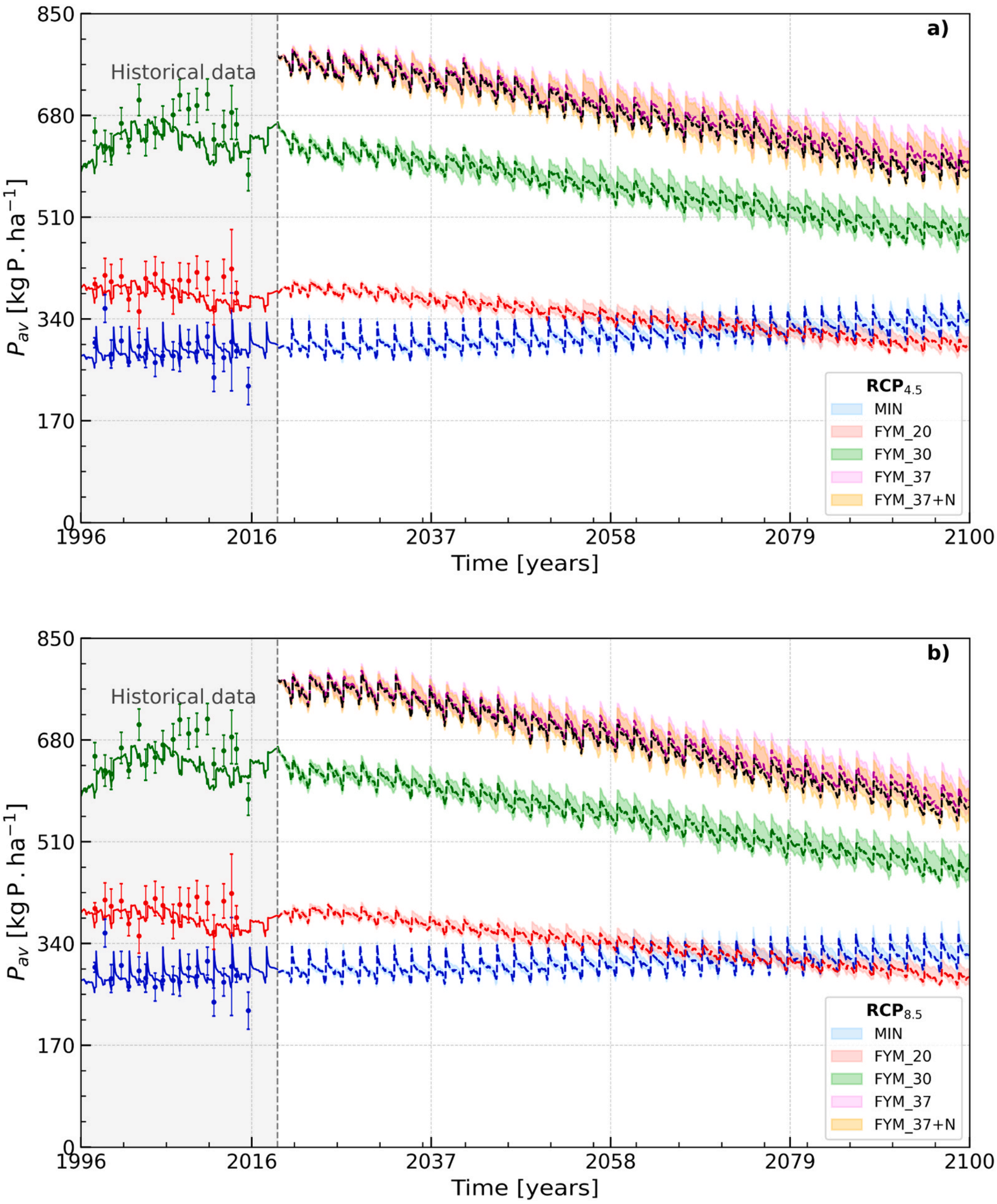

Fig. 4. Soil available phosphorus (kg P ha^{-1}) in the topsoil under mineral fertilizer and various manure treatments across two climate scenarios: (a) RCP4.5 and (b) RCP8.5. Observed and simulated historical data from 1996 to 2018, adapted from Mohammed et al. (2024), are included for comparison. Shaded areas indicate the 95% confidence intervals of the simulated values, while the solid opaque lines indicate the median (50%) estimates.

3.5. *Soil organic P dynamics among treatments and scenarios*

The model simulations showed a steady increase in P_{org} stocks (calculated as the sum of the three organic pools in the P sub-model) across all treatments and both scenarios over the simulation period (Fig. 5a, b). The relative accumulation of organic P was generally higher under RCP4.5 than under RCP8.5.

With mineral fertilization alone, soil organic P almost doubled by the end of century, rising by 102% under RCP4.5 and by 91% under RCP8.5. In contrast, farmyard manure (FYM) applications produced much larger increases in organic P stocks, with higher application rates leading to progressively greater accumulation. For example, FYM_30 and FYM_37 treatments accumulated between 579 and 672 kg P ha^{-1} under RCP4.5 and between 551 and 640 kg P ha^{-1} under RCP8.5. The addition of N in the FYM_37 +N treatment further enhanced organic P accumulation, yielding the highest stocks (769 kg P ha^{-1} under RCP4.5 and 740 kg P ha^{-1} under RCP8.5), corresponding to relative increases of 87% and 80%, respectively.

3.6. *Soil organic C across treatments*

Changes in organic topsoil C ($C_{organic}$), calculated as the sum of all RothC model pools, indicate a continuous decline in organic soil C stocks across all fertilization treatments and climate scenarios (Fig. 6a, b). The largest decrease occurred in the mineral treatment (MIN), with a decrease of about 22.4 and 26.2% under RCP4.5 and RCP8.5 respectively. Farmyard manure treatments reduced soil C loss, with higher manure application rates leading to smaller relative decreases. Reductions in total organic C under FYM_20 and FYM_30 ranged from –23.1% to –26.6% and –20.9% to –24.8% under RCP4.5 and RCP8.5, respectively. The FYM_37 and FYM_37 +N treatments showed the strongest C retention, with declines of only –17.4% to –22.4% under the

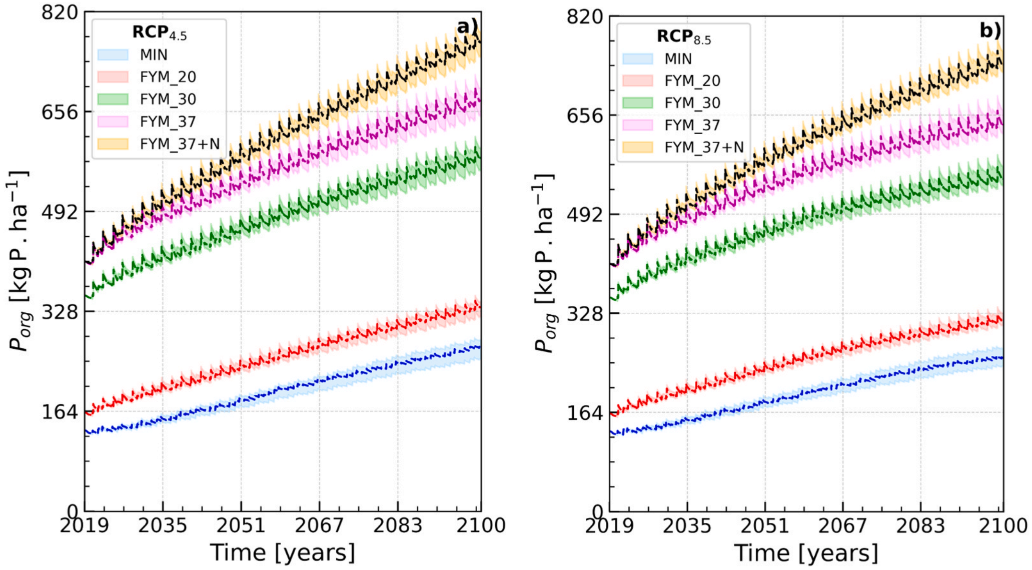

Fig. 5. Soil organic phosphorus (kg P ha^{-1}) in the topsoil under mineral fertilizer and various manure treatments across two climate scenarios: (a) RCP4.5 and (b) RCP8.5. Shaded areas indicate the 95% confidence intervals of the simulated values, while the solid opaque lines indicate the median (50%) estimates.

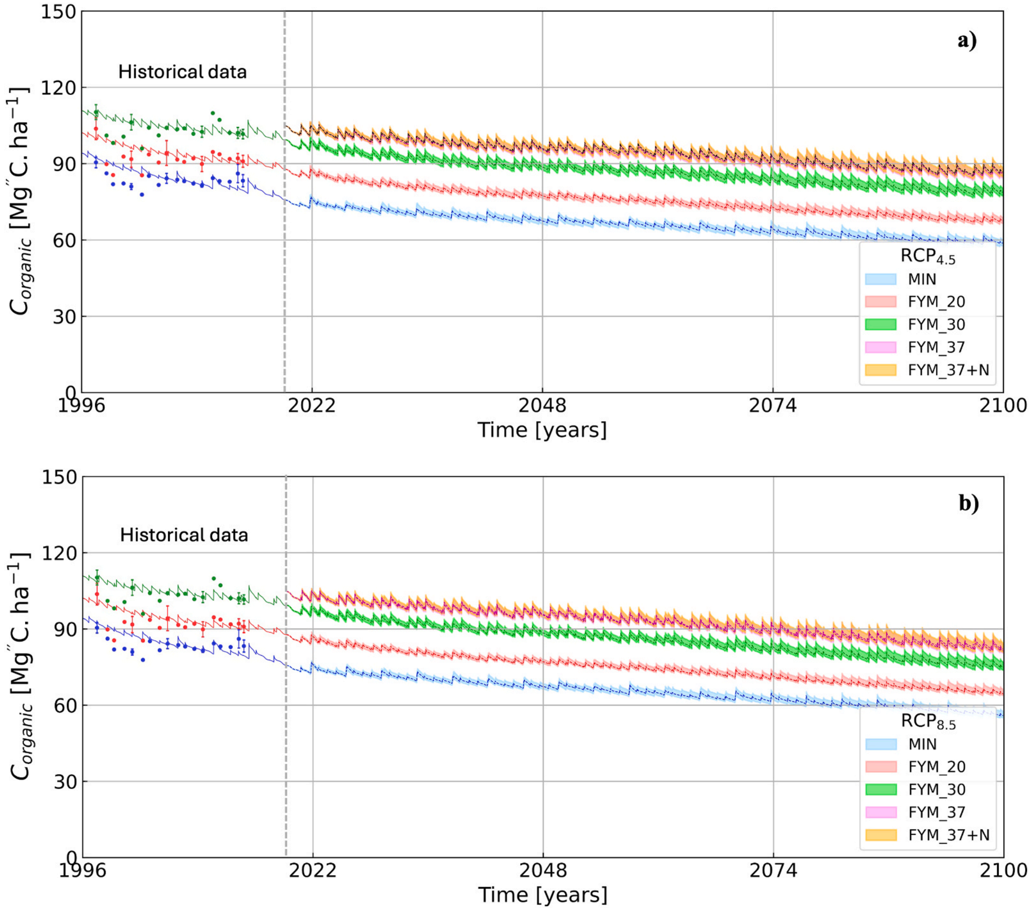

Fig. 6. Dynamics of total soil organic carbon (Mg C ha^{-1}) in the topsoil under mineral fertilizer and various manure treatments across two climate scenarios: (a) RCP4.5 and (b) RCP8.5. Observed and simulated historical data are from 1996 to 2018. Shaded areas indicate the 95% confidence intervals of the simulated values, while the solid opaque lines indicate the median (50%) estimates.

two climate scenarios respectively.

To further interpret these C dynamics, changes in the organic topsoil C/P stoichiometric ratios provide additional insight (Fig. 7, panels a and b). The organic C/P ratios declined steadily across all treatments, with the strongest reductions observed for the MIN treatment, reaching approximately 62% of the initial C/P values under both RCPs scenarios.

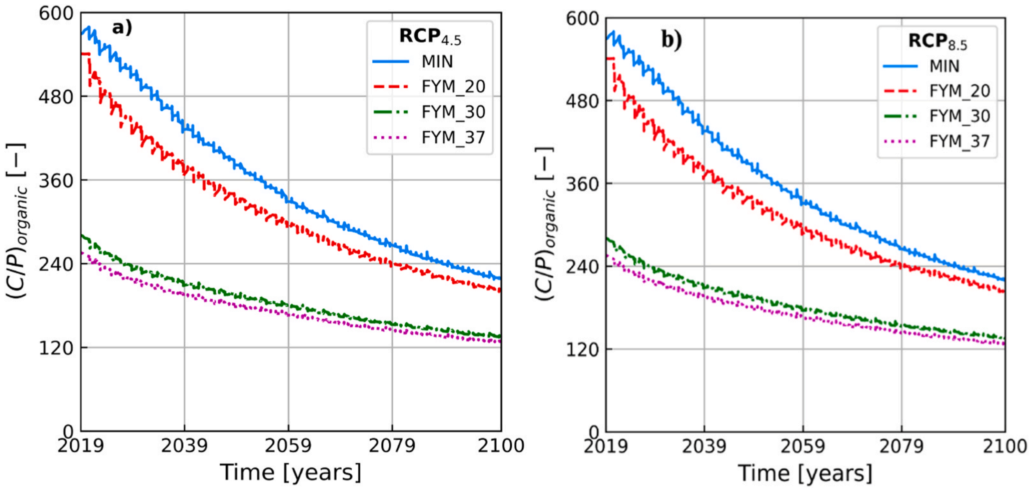

Fig. 7. Decline in organic C/P ratios under the RCP4.5 (a) and RCP8.5(b) scenarios.

Higher Farmyard manure application rates (FYM_30, FYM_37) maintained elevated stoichiometric ratios for longer, which was consistent with improved organic carbon retention. Finally, correlations between organic soil C/P ratios and available P revealed strong positive associations for manure-based treatments under both RCP scenarios ($r = 0.83–0.94$, $p < 0.001$, $R^2 = 0.69–0.89$, Table SI-5). In contrast, mineral fertilizer treatments showed moderate negative correlations ($r = –0.58$ to $–0.72$, $R^2 = 0.33–0.52$).

3.7. *P balance*

The MIN treatment consistently led to soil P accumulation under both scenarios, with increases of 455 and 474 kg P ha^{-1} under RCP4.5 and RCP8.5, respectively, reflecting continuous P inputs exceeding crop removal and leaching losses (Table 2). While this accumulation supports sustained yields, it raises concerns about long-term soil P accumulation. In contrast, all organic (FYM) treatments showed soil P depletion by the end of the century, with absolute losses ordered as FYM_37 < FYM_30 < FYM_20 < FYM_37 +N. The biggest P depletion was observed for the FYM_37 +N treatment, which contains P levels comparable to FYM_37. This is likely a consequence of the stimulation of crop growth and P uptake by the supplied mineral N, as shown in Section 3.3, thereby accelerating soil P depletion compared to manure application alone. Although the P balance was more positive (by 1–9%) for FYM treatments under the warmer RCP8.5 scenario compared to RCP4.5, differences were minor.

3.8. *Risk of P leaching*

The simulation results show differences in P leaching between the mineral fertilizer and organic treatments, as well as between the two RCPs scenarios (Fig. 8a and b). Among all treatments, the MIN treatment consistently yielded the lowest accumulated P leaching, with end-of-century values of 3.77 kg P ha^{-1} and 4.82 kg P ha^{-1} under RCP4.5 and RCP8.5, respectively. Interestingly, greater manure application rates were associated with lower cumulative P leaching. The treatments followed the order FYM_20 > FYM_30 > FYM_37 > FYM_37_N, with leaching ranging from 3.84 to 4.45 kg P ha^{-1} for RCP4.5 and 4.90–5.59 to kg P ha^{-1} for RCP8.5. Among the manure treatments FYM_37_N showed the best performance, with total accumulated losses only about 1.5–2% higher than those of the MIN treatment under both RCPs scenarios.

4. Discussion

4.1. *Implications of LGP changes for crop productivity*

The reduction in crop growth duration under RCP8.5 reflects accelerated phenological development driven by stronger climatic forcing. These emergence and harvest shifts confirm systematically earlier development under RCP8.5, supporting the observed LGP shortening of ~10.4%. While LGP-yield correlations were statistically significant for barley, potato, and sugar beet (Table SI-3), their moderate strength ($\rho = 0.19–0.42$, $R^2 = 0.06–0.32$) indicates that phenological shifts contribute to productivity changes, but other climatic drivers such as water stress

Table 2
Summary of 50 CI simulated P balance, P removal, and P gain/ loss under the RCPs scenarios.

Phosphorus balance	RCP4.5					RCP8.5				
	MIN	FYM_20	FYM_30	FYM_37	FYM_37 +N	MIN	FYM_20	FYM_30	FYM_37	FYM_37 +N
Initial total P [in kg P.ha^{-1}]	6030	6673	9107	10657	10657	6030	6673	9107	10657	10657
Inputs of P by mineral and organic amendments [in kg P ha^{-1}]										
Mineral	2460	–	–	–	–	2460	–	–	–	–
Organic	–	738	1107	1366	1366	–	738	1107	1366	1366
Outputs of P [in kg P.ha^{-1}]										
Removal P*	1999	1306	1867	2170	2328	1979	1301	1830	2110	2290
Leached P	3.8	4.5	4.2	4.0	3.8	4.8	5.6	5.3	5.1	4.9
Phosphorus balance (∑inputs - ∑outputs) [in kg P.ha^{-1}]	455	-573	-765	-809	-965	474	570	-728	-749	-929
Phosphorus gain (+) or Phosphorus loss (-) [in %] **	7.6	-8.6	-8.4	-7.6	-9.1	7.8	-8.5	-8.0	-7.0	-8.7

** The P loss (-) / gain (+) is calculated as the difference in the P mass in the soil at the end of the simulation to initial total P

[*] P removal corresponds to the total P uptaken by crops minus the P returned to the soil from decomposing crop residues left behind.

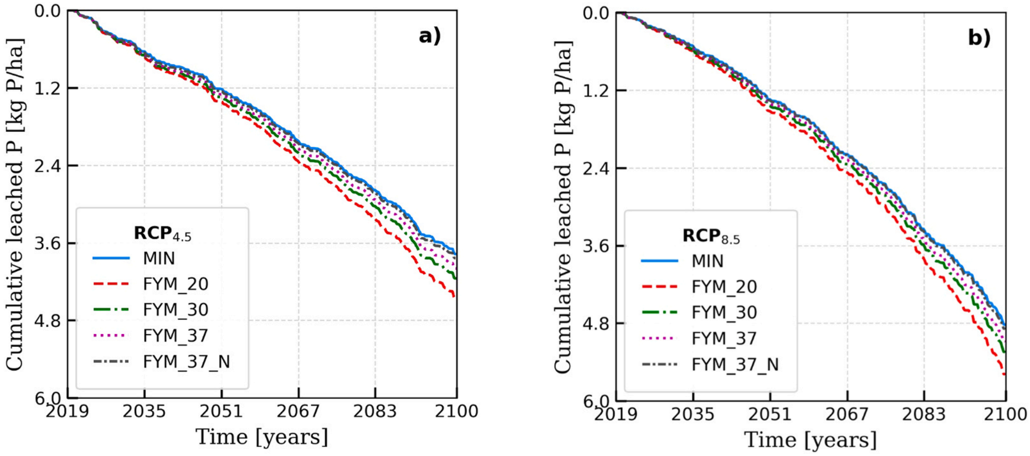

Fig. 8. 50% confidence intervals (CI) of accumulated phosphorus leaching at 110 cm soil depth under mineral fertilizer and various manure treatments across two climate scenarios: (a) RCP4.5 and (b) RCP8.5.

or heat, and phosphorus fertilization effects dominate yield variance. Potato exhibited the strongest LGP sensitivity, while winter wheat showed no relationship, likely reflecting the winter growth capacity and a certain insensitivity towards the emergence date. These findings align with Žydelis et al. (2021), who reported similar shifts in maize phenology across Northern Europe under comparable scenarios.

4.2. Manure-based fertilization enhances P dynamics under future climate scenarios

High application rates of farmyard manure, particularly FYM_37 and FYM_37 +N, resulted in the highest levels of soil P_{av} and were most effective in sustaining crop yields while minimizing environmental risks (Fig. 3 and 8). Organic matter releases P gradually through mineralization, thereby providing a sustained source of available P. This process reduces dependence on limited mineral P fertilizers while minimizing nutrient leaching risks from excess N or P inputs.

The lower P_{av} found in the MIN treatment can be attributed to the fixation of added mineral P in the soil through adsorption, rendering it less available to plants. In contrast, the highest P_{av} values occurred in the FYM_30 and FYM_37 treatments, consistent with findings, reported by Chen et al. (2023), Johnston and Steen (2002), and Zhang et al. (2023). Notably, the higher manure rates used in our study (FYM_37 vs. typical 20–25 Mg FM ha^{-1}) in combination with a four-crop rotation sustained P_{av} levels more effectively than the lower-rate, monoculture management systems described in those studies. However, the FYM_20 rate produced outcomes similar to those studies, where manure application alone was insufficient to maintain soil P_{av} at levels comparable to mineral fertilization. This suggest that adequate manure rates are crucial to sustaining soil P, whereas lower rates such as FYM_20 are inadequate (Fig. 4).

Low manure rates (FYM_20) provide insufficient nutrients for optimal crop growth, resulting in greater soil P depletion than mineral fertilization. Conversely, higher manure rates (FYM_30 and FYM_37) supply adequate nutrients for crops such as potato, sugar beet, and barley, which respond strongly to organic P inputs due to their greater nutrient uptake demand and shallower root systems. The addition of mineral N in the FYM_37 +N treatment was essential for winter wheat, whose higher biomass production and longer growth duration demand a more balanced N–P supply. These crop-specific responses explain the varying P dynamics and yield stability among treatments, highlighting that crop type modulates the effectiveness of fertilization managements. Even at higher manure rates, P_{av} declined gradually over time due to increased crop uptake, accelerated mineralization, and immobilization at elevated temperatures. In contrast, the MIN treatment maintained or slightly increased P_{av} due to regular mineral P inputs and contributions from crop residues.

The effects of climatic scenarios on soil P availability were minor compared with the large contrasts among fertilization managements. Across all treatments, P depletion was approximately 10–15% greater under the warmer RCP8.5 scenario than under RCP4.5. This difference can be attributed to two contrasting processes. On one hand, higher CO_2 concentrations under RCP8.5 stimulated crop growth (Fig. 3), increasing soil organic inputs and accelerating P mineralization from organic matter (Goll et al.,2012; Hu et al.,2022, Olander and Vitousek, 2000; Zhu et al.,2016). On the other hand, the warmer scenario enhanced P leaching, leading to reduced P availability. This simulated response aligns with experimental findings from Gong et al. (2025), Guo et al. (2024), and Vitousek et al. (2010), as well as studies reporting that warming decreases labile P and increases nutrient limitation through stronger P fixation (Hou et al., 2020; Hu et al., 2022; Tian et al., 2023). Together, these processes explain the greater P depletion simulated under RCP8.5, particularly after 2075. Importantly, two-way ANOVA supported these simulation findings, showing that fertilization strategy accounted for approximately 92% of the total variance in soil P availability. Moreover, the absence of a significant interaction between fertilization managements and climatic scenarios indicates that fertilization effects on soil P remain robust under future climate conditions.

Further evidence for treatment specific C-P relationships strengthen this interpretation. Strong positive correlations were found between organic soil C/P ratios and available P across manure-based treatments, indicating that that higher organic C/P ratios promote P mineralization from organic matter under both RCP4.5 and RCP8.5 scenarios (see Table SI-5). Linear regression showed consistent increases of 0.32–1.77 kg P ha^{-1} per C/P unit. These increases suggest that P immobilization is reduced under high organic C/P conditions, where lower microbial carbon demand leaves more P in plant-available forms. In contrast, under mineral fertilization, C/P ratios correlated negatively with P_{av}, with regression slopes from –0.08 to –0.013 kg P ha^{-1} per C/P unit. Higher C/P ratios likely enhanced P sorption to mineral surfaces, reducing plant-available P. The opposing trends, enhanced P release under manure versus greater P fixation under mineral fertilization, highlight the fertilizer-specific C–P interactions as the dominant control on long-term P dynamics. Hence, fertilization management exerts a far stronger influence on soil P cycling than projected climate change.

4.3. Soil organic P accumulation under manure and mineral fertilizations

Simulations indicate that soil organic P under mineral fertilization (MIN) nearly doubled at the end of simulation period (Fig. 5). This trend likely reflects the combined effects of regular addition of mineral fertilization and increasing atmospheric CO_2 concentrations, which stimulate plant biomass production (Fig. 3, panels e-f), root exudation, and litter deposition. These processes enhance the transfer of organic matter from plants to soil, thereby promoting organic P accumulation. Such model outputs are consistent with experimental observations showing that elevated CO_2 levels enhance productivity and belowground C inputs (Ainsworth and Long, 2021; Hopkins et al., 2014; Idso et al., 1987).

In contrast, organic treatments (FYM) resulted in markedly greater increases in soil organic P stocks, with higher application rates leading to proportionally larger accumulations. This outcome arises from the regular addition of organic matter that directly contributes to the buildup of organic P pools. Notably, the accumulation of organic P was more pronounced under RCP4.5 than under RCP8.5, suggesting that accelerated decomposition and P mineralization under warmer conditions (RCP8.5) limit long-term organic P retention. These findings agree with prior studies showing that increased temperature enhances microbial activity, accelerates organic matter breakdown, and facilitates P release from organic forms (Alkharabsheh et al., 2021; Spohn and Kuzyakov, 2013; Whalen and Chang, 2001).

Thus, farmyard manure application, especially when combined with mineral N inputs, appears to enhance the retention of soil organic P relative to mineral fertilization alone. Since organic P pools serves as a renewable reservoir that can be gradually mineralized by soil microbes and support plant P uptake when inorganic P availability declines (Jahan et al., 2025; Turner et al., 2003; Withers et al., 2015), this management strategy plays a crucial role in maintaining long-term soil fertility. However, its effectiveness may be reduced under high-emission scenarios where elevated temperatures accelerate mineralization losses.

Greater soil C losses observed under mineral fertilization (MIN) compared to organic-based treatments can partly be explained by differences in P sources. Manure provides both organic and inorganic P (Pagliari and Laboski, 2012), while mineral fertilizers supply only inorganic P.

Furthermore, the absence of P and N limitations led to a continuous decline in soil organic carbon $C_{organic}$ (Fig. 6). However, the rate of this decline varied between treatments. The organic C/P ratios decreased sharply in the MIN and FYM_20 treatments (approximately 62% in both, see Fig. 7), indicating intensified carbon mineralization and a greater loss of soil carbon stocks. In contrast, treatments receiving higher organic inputs (FYM_30 and FYM_37) showed more stable organic C/P ratios, with smaller decreases over the same period (approximately 50% for both). This relative stability suggests improved soil carbon retention, enhanced soil quality, and a reduced risk of P leaching.

4.4. *Sustained crop yields*

Simulation results indicate that potato, sugar beet, and barley yield under organic treatments (FYM_30 and FYM_37) were comparable to those obtained with conventional mineral fertilization (MIN). In contrast, the lower manure rate treatment (FYM_20) was insufficient to sustain productivity (Fig. 3, panels a-d). Winter wheat exhibited a distinct response, achieving optimal yields only under the FYM_37 +N treatment, where mineral N inputs were reduced by approximately 80%. This finding aligns with earlier studies showing that partial substitution of mineral fertilizers with 10–20% organic amendments can maintain wheat yields effectively (Bo et al., 2025; He et al., 2024; Li et al., 2022). Note that commercial mineral fertilizers usually contain N, P, and K. Thus, omitting or reducing mineral N supplementation would also impact P and K inputs from these fertilizers. These nutrient interactions need further analysis but are outside the scope of this study. With this fertilization management, reducing mineral N fertilizer inputs for winter wheat does not compromise yield performance. These observations are in line with Li et al. (2022) who reported that reducing mineral N application in cropping systems receiving sufficient organic manure maintains winter wheat yield, due to improved soil structure, nutrient retention, and microbial activity. Furthermore, this management strategy reduces environmental risks, such as nitrate leaching, supporting both economic sustainability and soil health. Interestingly, barley yields under FYM_37 without any mineral N supplementation remained comparable to those under MIN fertilization. This can be attributed to the fact that barley generally has a much shorter growing season (see Fig. 2) and lower N demands compared to winter wheat (Slafer and Savin, 2023), making it less responsive to extra nitrogen supplementation.

This capacity of farmyard manure amendments to sustain crop yields can be attributed to their balanced nutrient composition, which enhances soil fertility, organic matter content, and structure. Moreover, these inputs stimulate microbial diversity and activity, thereby improving nutrient cycling and uptake efficiency in both wheat and other crops (Kan et al., 2024; Li et al., 2023).

Yields under the RCP4.5 climate scenario were generally slightly higher than those under RCP8.5 (Fig. 3), particularly for winter wheat, whereas barley showed minimal differences. Under RCP4.5, winter wheat yields with FYM_37 +N were comparable to those achieved under the MIN treatment. However, under RCP8.5, yields declined, suggesting that an additional mineral N input, more than the 20% supplementation tested, may be required to sustain wheat productivity under more severe climatic stress. These results are consistent with previous experimental findings showing that increased temperatures and evapotranspiration reduce wheat yields and that combining organic and mineral fertilization helps stabilize productivity under such stress conditions (Duan et al., 2014; Fang et al., 2025; Gai et al., 2018; Mathur et al., 2011; Peng et al., 2017; Zhao et al., 2017).

While winter wheat may thus require limited mineral N supplementation under high-emission conditions, crops such as barley, potato, and sugar beet sustained or even improved yields solely through optimized organic fertilization. These findings emphasize that fertilization strategy remains the primary factor governing crop productivity despite the stresses imposed by changing climate conditions. However, under high-emission scenarios, more frequent extreme weather events could further influence the relationship between climate and fertilization management. Heavy rainfall, for example, may increase P losses through leaching, particularly in treatments receiving high manure inputs. In contrast, periods of drought or heat stress could slow microbial activity and delay P mineralization, reducing nutrient availability during critical crop growth stages.

Although farmyard manure–based treatments maintained or improved yields, a steady decline in soil P content was observed across these treatments toward the end of the century (Table 2). This indicates that manure application rates should be periodically adjusted to match evolving soil conditions to simultaneously satisfy crop nutrient requirements and sustain sufficient soil P reserves. However, given that projected losses correspond to only 8–9% of total soil P over roughly 80 years, severe P limitation is unlikely. Nonetheless, monitoring long-term soil P dynamics remains critical to prevent potential nutrient stress and ensure sustainable productivity.

4.5. *Reducing P leaching through manure application under climate change*

The observed decrease in P leaching with increasing manure application rates (Fig. 8) is likely linked to the organic matter contained in farmyard manure, which enhances the capacity of soil to retain water and nutrients (Alkharabsheh et al., 2021; Holthusen et al., 2012), consequently increasing P retention. This leads to a decline in the proportion of soluble and mobile P fractions that are most susceptible to leaching. In addition, repeated manure applications introduce organic P forms that mineralize gradually, lowering the immediate availability of highly soluble inorganic P compared with synthetic mineral fertilizers. This slower release pattern contributes to a reduced risk of P leaching. Consequently, our findings suggest that when applied appropriately, organic amendments fulfill a dual role: enhancing soil fertility and health and reducing P losses via leaching (Table 2), which aligns with the findings of previous studies (Alkharabsheh et al., 2021; Whalen and Chang, 2001).

Across all treatments, P leaching risks were low but greater by an average of 24.4–29% under RCP8.5 compared with RCP4.5, reflecting the effect of future warming and altered precipitation patterns on P transport dynamics. This observation is consistent with the findings of Ockenden et al. (2017) that attributed elevated leaching potential under RCP8.5 to more frequent extreme rainfall events expected in that scenario.

4.6. Study limitations

Several limitations should be considered when trying to generalize the results of this study, especially when applying them to other geographical areas. First, AgroC was calibrated for Bad Lauchstädt's Haplic Chernozem (silt loam soil), so yield and P dynamics may not transfer to other soils or regions due to site-specific parameterization of mineral P cycling and crop demand. The mineral P cycling as implemented in AgroC is highly sensitive to the P sorption parameter and the stable to active mineral P pool ratio. Herbst et al. (2025) point out the need for site-specific, probably even depth-specific calibration, of these parameters, which clearly limits the transferability as mentioned above.

Further, all simulations were performed with daily time steps because both, the Bad Lauchstädt calibration data and climate projections, were daily. If day-to-day conditions remained stable over coming decades, the simulation results could be considered reliable. However, this assumption might not fully hold. Several studies have shown that the frequency and intensity of rainfall events are likely to change substantially in the coming decades delivering monthly totals in hours, separated by longer dry periods (e.g., Berghuijs et al., 2017; Wu et al., 2024). This means that the scenarios probably underestimate the P leaching and crop water stress from these patterns, even if yearly rainfall totals do not change much. Hourly rainfall projections would be needed to simulate this properly, but it was not available for our site. Finally, although 12 RCM-GCM combinations provide robust RCP4.5 and RCP8.5 coverage, AgroC itself has built-in uncertainties, so multi-model comparisons would help verify these results.

As sensitivity specific to the scenarios presented in this study arises from the relevance of the dynamics of soil organic matter cycling, which releases a substantial fraction of the plant available P for the organic P fertilization scenarios. Any model structural or parameter error in the organic matter cycling of AgroC would directly affect the predicted P availability. Even though the organic carbon cycling was positively evaluated for the 21-years calibration period (Fig. 6), uncertainty remains with respect to the prediction of the organic P cycling over an 81-years scenario period. Further uncertainty arises with respect to the effect of nitrogen limitation and the effect of elevated CO_2 concentrations on crop growth. Despite the direction of the response being simulated correctly, the magnitude of crop growth in response to changes in atmospheric CO_2 and nitrogen limitation is uncertain.

5. Conclusions

Using the AgroC model, previously calibrated and validated against long-term field data from the Bad Lauchstädt site, this study evaluated the effects of sustained manure application on crop yields and soil P availability under two future climate scenarios (RCP4.5 and RCP8.5) projected from locally downscaled GCM data for the next 80 years.

The simulations showed that long-term soil P dynamics and crop productivity are governed more by fertilization strategy than by projected climate change. Higher manure application rates (FYM_30 and FYM_37) consistently sustained yields and reduced P leaching compared with mineral fertilization. While the warmer RCP8.5 scenario led to slightly higher P depletion and leaching, these changes were minor compared with the differences caused by fertilization management.

For crops with high N demand, such as winter wheat, moderate mineral N supplementation (as in the FYM_37 +N treatment) was needed to maintain yields. In contrast, crops with lower N requirements such as barley, potato, and sugar beet maintained comparable productivity under organic-only fertilization based on P crop demands. These findings confirm that well-managed organic fertilization strategies are effective across different crops and transferable to agricultural systems under standard N management, reinforcing their relevance for varied agronomic boundary conditions. The results support the conclusion that manure can serve as a viable and sustainable alternative to mineral P fertilizers. Looking ahead, combining adaptive fertilization strategies like variable-rate manure application adjusted for real-time soil P status, guided by advanced decision-support tools, such as crop models and digital twin systems linking observed and simulated plant-available P pools, offers a powerful approach to balancing high productivity with long-term soil health and environmental protection under future climate change.

CRediT authorship contribution statement

Ines Merbach: Writing – review & editing, Resources, Data curation. **Michael Herbst:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Nina Siebers:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Gihan Mohammed:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gihan Mohammed reports financial support was provided by Forschungszentrum Jülich Institute of Bio- and Geosciences Agrosphere 3. Gihan Mohammed reports a relationship with Forschungszentrum Jülich Institute of Bio- and Geosciences Agrosphere 3 that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was funded by the German Federal Ministry of Education and Research (BMBF) as part of the BonaRes project InnoSoilPhos [funding reference 031B1061D]. We would like to explicitly thank all technicians and other assisting staff members of Experimental Station Bad Lauchstädt (Helmholtz Centre for Environmental Research, Germany) who have been running the experimental sites for decades. Moreover, we thank the BonaRes Data Center for the financial support to prepare a part of the data.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128097.

Data Availability

Data will be made available on request.

References

Ainsworth, E.A., Long, S.P., 2021. 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? Glob. Change Biol. 27 (1). https://doi.org/10.1111/gcb.15375.

Albano, X., Whitmore, A.P., Sakrabani, R., Thomas, C.L., Sizmur, T., Ritz, K., Harris, J., Pawlett, M., Watts, C., Haefele, S.M., 2023. Effect of Different Organic Amendments on Actual and Achievable Yields in a Cereal-Based Cropping System. J. Soil Sci. Plant Nutr. 23 (2). https://doi.org/10.1007/s42729-023-01167-w.

Alewell, C., Ringeval, B., Ballabio, C., Robinson, A.D., Panagos, P., Borelli, P., 2020. Global phosphorus shortage will be aggravated by soil erosion. Nat. Commun. 11, 4546. https://doi.org/10.1038/s41467-020-18326-7.

Alkharabsheh, H.M., Seleiman, M.F., Battaglia, M.L., Shami, A., Jalal, R.S., Alhammad, B. A., Almutairi, K.F., Al-Saif, A.M., 2021. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: a review. Agronomy 11 (5). https://doi.org/10.3390/agronomy11050993.

Altermann, M., Rinklebe, J., Merbach, I., Körschens, M., Langer, U., Hofmann, B., 2005. Chernozem - soil of the year 2005. J. Plant Nutr. Soil Sci. 168 (6), 725–740. https://doi.org/10.1002/jpln.200521814.

Bechtaoui, N., Rabiu, M.K., Raklami, A., Oufdou, K., Hafidi, M., Jemo, M., 2021. Phosphate-Dependent Regulation of Growth and Stresses Management in Plants. Front. Plant Sci. 12. https://doi.org/10.3389/fpls.2021.679916.

Berg, P., Feldmann, H., Panitz, H.J., 2012. Bias correction of high resolution regional climate model data. J. Hydrol. 448, 80–92. https://doi.org/10.1016/j.jhydrol.2012.04.026.

Berghuijs, W.R., Aalbers, E.E., Larsen, J.R., Trancoso, R., Woods, R.A., 2017. Recent changes in extreme floods across multiple continents. Environ. Res. Lett. 12 (11), 114035. https://doi.org/10.1088/1748-9326/aa8847.

Bo, P., He, Q., Lan, Y., Li, J., Liu, H., Li, X., Wang, H., 2025. Reducing mineral fertilizer can improve the soil quality and increase the wheat yield and nutrient utilization efficiency: the fertilizing effect of organic–inorganic compound fertilizers. Agric. (Switz.) 15 (12). https://doi.org/10.3390/agriculture15121294.

Bünemann, E.K., Smithson, P.C., Jama, B., Frossard, E., Oberson, A., 2004. Maize productivity and nutrient dynamics in maize–fallow rotations in western Kenya. Plant Soil 264, 195–208. https://doi.org/10.1023/B:PLSO.0000047749.43017.fd.

Chen, S., Gao, J., Chen, H., Zhang, Z., Huang, J., Lv, L., Tan, J., Jiang, X., 2023. The role of long-term mineral and manure fertilization on P species accumulation and phosphate-solubilizing microorganisms in paddy red soils. SOIL 9 (1). https://doi.org/10.5194/soil-9-101-2023.

Collatz, G.J., Ball, T., Grivet, C., Berry, J.A., 1991. Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer. Agric. For. Meteorol. 54, 107–136. https://doi.org/10.1016/0168-1923(91)90002-8.

Cordell, D., Drangert, J.O., White, S., 2009. The story of phosphorus: Global food security and food for thought. Glob. Environ. Change 19 (2), 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009.

Duan, Y., Xu, M., Gao, S., Yang, X., Huang, S., Liu, H., Wang, B., 2014. Nitrogen use efficiency in a wheat-corn cropping system from 15 years of manure and fertilizer applications. Field Crops Res. 157. https://doi.org/10.1016/j.fcr.2013.12.012.

Elser, J., Bennett, E., 2011. Phosphorus cycle: A broken biogeochemical cycle. Nature 478 (7367). https://doi.org/10.1038/478029a.

eLTER. 2020. ⟨http://www.lter-europe.net/elter⟩ (2020), Accessed 1 Nov 2020. Eurostat, 2020. Crop production in EU standard humidity. Available at. ⟨https://ec.europa.eu/eurostat/databrowser/view/APRO_CPSH1_custom_58016/default/table?lang=en⟩.

Eriksson, A.K., Hillier, S., Hesterberg, D., Klysubun, W., Ulén, B., Gustafsson, J.P., 2016. Evolution of phosphorus speciation with depth in an agricultural soil profile. Geoderma 280, 29–37. https://doi.org/10.1016/j.geoderma.2016.06.004.

Fang, Y., Tang, J., Zhang, S., Zhang, N., Luo, X., Hu, D., Xu, W., 2025. Manure in combination with optimal topdressing with nitrogen fertiliser improved growth, grain yields and the efficiencies of water and nitrogen use in winter wheat in the Xinjiang Oasis drylands. PeerJ 13. https://doi.org/10.7717/peerj.19543.

Farquhar, G.D., von Caemmerer, S., Berry, J.A., 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C3 species. Planta 149, 78–90. https://doi.org/10.1007/BF00386231.

Frossard, E., Skrabal, P., Sinaj, S., Bangerter, F., Traore, O., 2002. Forms and exchangeability of inorganic phosphate in composted solid organic wastes. Nutr. Cycl. Agroecosystems 62, 103–113. https://doi.org/10.1023/A:1015596526088.

Frossard, E., Bünemann, E., Gunst, L., Oberson, A., Schärer, M., Tamburini, F., 2016. Fate of fertilizer P in soils – The organic pathway. Phosphorus in Agriculture: 100% Zero. Springer, pp. 41–61. https://doi.org/10.1007/978-94-017-7612-7_4.

Gai, X., Liu, H., Liu, J., Zhai, L., Yang, B., Wu, S., Ren, T., Lei, Q., Wang, H., 2018. Long-term benefits of combining chemical fertilizer and manure applications on crop yields and soil carbon and nitrogen stocks in North China Plain. Agric. Water Manag. 208. https://doi.org/10.1016/j.agwat.2018.07.002.

Gao, P., Zhang, T., Lei, X. yu, Cui, X. wei, Lu, Y. xiong, Fan, P. fei, Long, S. ping, Huang, J., Gao, J. sheng, Zhang, Z. hua, Zhang, H. min, 2023. Improvement of soil fertility and rice yield after long-term application of cow manure combined with inorganic fertilizers. J. Integr. Agric. 22 (7). https://doi.org/10.1016/j.jia.2023.02.037.

Gilbert, N., 2009. The disappearing nutrient. Nature 461 (7265). https://doi.org/10.1038/461716a.

Gocke, M.I., Don, A., Heidkamp, A., Schneider, F., Amelung, W., 2021. The phosphorus status of German cropland—An inventory of top- and subsoils. J. Plant Nutr. Soil Sci. 184 (1), 51–64. https://doi.org/10.1002/jpln.202000127.

Goll, D.S., Brovkin, V., Parida, B.R., Reick, C.H., Kattge, J., Reich, P.B., Van Bodegom, P. M., Niinemets, Ü., 2012. Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling. Biogeosciences 9 (9). https://doi.org/10.5194/bg-9-3547-2012.

Gong, H., Xiang, Y., Jin, M., Chen, C., 2025. Global patterns and drivers of phosphorus fraction variability in cropland soils. Resour. Conserv. Recycl. 223. https://doi.org/10.1016/j.resconrec.2025.108498.

Guo, L., Xiong, S., Mills, B.J.W., Isson, T., Yang, S., Cui, J., Wang, Y., Jiang, L., Xu, Z., Cai, C., Deng, Y., Wei, G., Zhao, M., 2024. Acceleration of phosphorus weathering under warm climates. Sci. Adv. 10, 7773. https://doi.org/10.3334/ORn.

He, H., Peng, M., Hou, Z., Li, J., 2024. Organic substitution contrasting direct fertilizer reduction increases wheat productivity, soil quality, microbial diversity and network complexity. Environ. Technol. Innov. 36. https://doi.org/10.1016/j.eti.2024.103784.

Helfenstein, J., Ringeval, B., Tamburini, F., Mulder, V.L., Goll, D.S., He, X., et al., 2024. Understanding soil phosphorus cycling for sustainable development: a review. One Earth 2024 7, 1727–1740. https://doi.org/10.1016/j.oneear.2024.07.020.

Herbst, M., Hellebrand, H.J., Bauer, J., Huisman, J.A., Šimůnek, J., Weihermüller, L., Graf, A., Vanderborght, J., Vereecken, H., 2008. Multiyear heterotrophic soil respiration: Evaluation of a coupled CO2 transport and carbon turnover model. Ecol. Model. 214 (2–4), 271–283. https://doi.org/10.1016/j.ecolmodel.2008.02.007.

Herbst, M., Mohammed, G., Eichler-Löbermann, B., Amelung, W., Vanderborght, J., Siebers, N., 2025. Linking Measurable Phosphorus Pools With Simulations of Soil P Dynamics: Results for the Long-Term Experiment 'Rostock. Eur. J. Soil Sci. 76 (4). https://doi.org/10.1111/ejss.70160.

Holthusen, D., Jänicke, M., Peth, S., Horn, R., 2012. Physical properties of a Luvisol for different long-term fertilization treatments: I. Mesoscale capacity and intensity parameters. J. Plant Nutr. Soil Sci. 175 (1), 4–13. https://doi.org/10.1002/jpln.201100075.

Hopkins, F.M., Filley, T.R., Gleixner, G., Lange, M., Top, S.M., Trumbore, S.E., 2014. Increased belowground carbon inputs and warming promote loss of soil organic carbon through complementary microbial responses. Soil Biol. Biochem. 76. https://doi.org/10.1016/j.soilbio.2014.04.028.

Hou, E., Luo, Y., Kuang, Y., Chen, C., Lu, X., Jiang, L., Luo, X., Wen, D., 2020. Global meta-analysis shows pervasive phosphorus limitation of aboveground plant production in natural terrestrial ecosystems. Nat. Commun. 11 (1). https://doi.org/10.1038/s41467-020-14492-w.

Hu, W., Tan, J., Shi, X., Lock, T.R., Kallenbach, R.L., Yuan, Z., 2022. Nutrient addition and warming alter the soil phosphorus cycle in grasslands: a global meta-analysis. J. Soils Sediment. 22 (10). https://doi.org/10.1007/s11368-022-03276-y.

Hu, Y., Jarosch, K.A., Kavka, M., Eichler-Löbermann, B., 2022. Fate of P from organic and inorganic fertilizers assessed by complementary approaches. Nutr. Cycl. Agroecosystems 124 (2), 189–209. https://doi.org/10.1007/s10705-022-10237-x.

Idso, S.B., Kimball, B.A., Anderson, M.G., Mauney, J.R., 1987. Effects of atmospheric CO2 enrichment on plant growth: the interactive role of air temperature. Agric. Ecosyst. Environ. 20 (1). https://doi.org/10.1016/0167-8809(87)90023-5.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. ⟨https://www.ipcc.ch/report/ar5/syr/⟩.

Jahan, N., Mahmud, U., Khan, Md.Z., 2025. Sustainable plant-soil phosphorus management in agricultural systems: challenges, environmental impacts and innovative solutions. Discov. Soil 2 (1). https://doi.org/10.1007/s44378-025-00039-2.

Johnston, A.E., Steen, I., 2002. Understanding phosphorus and its use in agriculture. European Fertilizer Manufacturers Association, Brussels, Belgium.

Kan, Z.R., Xu, Y., Virk, A.L., Liu, M., Pei, X., Li, Y., Yang, H., Chen, C., 2024. Organic fertilizer substitution benefits microbial richness and wheat yield under warming. Sci. Total Environ. 945, 174007.

Li, G., Niu, W., Ma, L., Du, Y., Zhang, Q., Sun, J., Siddique, K.H.M., 2023. Legacy effects of wheat season organic fertilizer addition on microbial co-occurrence networks, soil function, and yield of the subsequent maize season in a wheat-maize rotation system. J. Environ. Manag. 347. https://doi.org/10.1016/j.jenvman.2023.119160.

Kebalo, L.F., Garnier, P., Gonod, L.V., Houot, S., 2024. Using bio-based fertilizer derived from peri-urban wastes affects soil properties and lettuce yield and quality. Scientia Horticulturae 324, 112599. https://doi.org/10.1016/j.scienta.2023.112599.

Li, X., Li, B., Chen, L., Liang, J., Huang, R., Tang, X., Zhang, X., Wang, C., 2022. Partial substitution of chemical fertilizer with organic fertilizer over seven years increases yields and restores soil bacterial community diversity in wheat–rice rotation. Eur. J. Agron. 133. https://doi.org/10.1016/j.eja.2021.126445.

Liu, E., Zhou, J., Yang, X., Jin, T., Zhao, B., Li, L., Wen, Y., Soldatova, E., Zamanian, K., Gopalakrishnan, S., Mei, X., Kuzyakov, Y., 2023. Long-term organic fertilizer-induced carbonate neoformation increases carbon sequestration in soil. Environ. Chem. Lett. 21 (2), 663–671. https://doi.org/10.1007/s10311-023-01568-4.

Lu, Y., Gao, Y., Nie, J., Liao, Y., Zhu, Q., 2021. Substituting chemical P fertilizer with organic manure: effects on double-rice yield, phosphorus use efficiency and balance in subtropical China. Sci. Rep. 11 (1). https://doi.org/10.1038/s41598-021-87851-2.

Maraun, D., 2016. Bias Correcting Climate Change Simulations - a Critical Review. Curr. Clim. Change Rep. 2 (4), 211–220. https://doi.org/10.1007/s40641-016-0050-x.

Mathur, S., Jajoo, A., Mehta, P., Bharti, S., 2011. Analysis of elevated temperature-induced inhibition of photosystem II using chlorophyll a fluorescence induction kinetics in wheat leaves (Triticum aestivum). Plant Biol. 13 (1). https://doi.org/10.1111/j.1438-8677.2009.00319.x.

McDowell, R.W., Pletnyakov, P., Haygarth, P.M., 2024. Phosphorus applications adjusted to optimal crop yields can help sustain global phosphorus reserves. Nat. Food 5 (4). https://doi.org/10.1038/s43016-024-00952-9.

Menezes-Blackburn, D., Giles, C., Darch, T., George, T.S., Blackwell, M., Stutter, M., Shand, C., Lumsdon, D., Cooper, P., Wendler, R., Brown, L., Almeida, D.S., Wearing, C., Zhang, H., Haygarth, P.M., 2018. Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: a review, 2018 Plant Soil 427 (1), 5–16. https://doi.org/10.1007/s11104-017-3362-2.

Mohammed, G., Trolard, F., Bourrie, G., Gillon, M., Tronc, D., Charron, F., 2016. A long-term data sequence (1960-2013) to analyse the sustainability of hay quality in irrigated permanent grassland under climate change. Am. J. Agric. For. 4 (6), 140–151. https://doi.org/10.11648/j.ajaf.20160406.11.

Mohammed, G., Trolard, F., Gillon, M., Cognard-Plancq, A.L., Chanzy, A., Bourrié, G., 2017. Combination of a crop model and a geochemical model as a new approach to evaluate the sustainability of an intensive agriculture system. Sci. Total Environ. 595. https://doi.org/10.1016/j.scitotenv.2017.03.146.

Mohammed, G., Siebers, N., Merbach, I., Seidel, S.J., Herbst, M., 2024. Simulation of soil phosphorus dynamics and crop yield for organic and mineral fertilization treatments at two long-term field sites. Sci. Total Environ. 957. https://doi.org/10.1016/j.scitotenv.2024.177517.

Moss, Edmonds, R., Hibbard, J., k, et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756. https://doi.org/10.1038/nature08823.

Nobile, C., Lebrun, M., Védère, C., Honvault, N., Aubertin, M.L., Faucon, M.P., Girardin, C., Houot, S., Kervroëdan, L., Dulaurent, A.M., Rumpel, C., Houben, D., 2022. Biochar and compost addition increases soil organic carbon content and substitutes P and K fertilizer in three French cropping systems. Agron. Sustain. Dev. 42 (6). https://doi.org/10.1007/s13593-022-00848-7.

Ockenden, M.C., Hollaway, M.J., Beven, K.J., Collins, A.L., Evans, R., Falloon, P.D., Forber, K.J., Hiscock, K.M., Kahana, R., MacLeod, C.J.A., Tych, W., Villamizar, M.L., Wearing, C., Withers, P.J.A., Zhou, J.G., Barker, P.A., Burke, S., Freer, J.E., Johnes, P.J., Haygarth, P.M., 2017. Major agricultural changes required to mitigate phosphorus losses under climate change. Nat. Commun. 8 (1). https://doi.org/10.1038/s41467-017-00232-0.

Olander, L.P., Vitousek, P.M., 2000. Regulation of soil phosphatase and chitinase activity by N and P availability. Biogeochemistry 49 (2). https://doi.org/10.1023/A:1006316117817.

Pagliari, P.H., Laboski, C.A.M., 2012. Investigation of the Inorganic and Organic Phosphorus Forms in Animal Manure. J. Environ. Qual. 41 (3). https://doi.org/10.2134/jeq2011.0451.

Peng, Z., Liu, Y., Li, Y., Abawi, Y., Wang, Y., Men, M., An-Vo, D.A., 2017. Responses of nitrogen utilization and apparent nitrogen loss to different control measures in the wheat and maize rotation system. Front. Plant Sci. 8 (FEBRUARY). https://doi.org/10.3389/fpls.2017.00160.

Richardson, A.E., Lynch, J.P., Ryan, P.R., Delhaize, E., Smith, F.A., Smith, S.E., Harvey, P.R., Ryan, M.H., Veneklaas, E.J., Lambers, H., et al., 2011. Plant and microbial strategies to improve the phosphorus efficiency of agriculture. Plant Soil 349, 121–156. https://doi.org/10.1007/s11104-011-0950-4.

Sattari, S.Z., 2014. The legacy of phosphorus: agriculture and future food security. Ph.D. diss. Wageningen Univ, Wageningen, the Netherlands.

Schüller, H., 1969. Die CAL-Methode, eine neue Methode zur Bestimmung des pflenzenverfügbaren Phosphates in Böden. Z. Pflanzenernähr. Bodenkd. 123, 48–63. https://doi.org/10.1002/jpln.19691230106.

Siebers, N., Kruse, J., Jia, Y., Lennartz, B., Koch, S., 2023. Loss of subsurface particulate and truly dissolved phosphorus during various flow conditions along a tile drain–ditch–brook continuum. Sci. Total Environ. 866 (February), 161439. https://doi.org/10.1016/j.scitotenv.2023.161439.

Slafer, G.A., Savin, R., 2023. Comparative performance of barley and wheat across a wide range of yielding conditions. Does barley outyield wheat consistently in low-yielding conditions? European Journal of Agronomy 143, 126689. https://doi.org/10.1016/j.eja.2022.126689.

Spohn, M., Kuzyakov, Y., 2013. Phosphorus mineralization can be driven by microbial need for carbon. Soil Biol. Biochem. 61. https://doi.org/10.1016/j.soilbio.2013.02.013.

Sun, R., Niu, J., Luo, B., Wang, X., Li, W., Zhang, W., Wang, F., Zhang, C., Ye, X., 2022. Substitution of manure for mineral P fertilizers increases P availability by enhancing microbial potential for organic P mineralization in greenhouse soil. Front. Bioeng. Biotechnol. 10. https://doi.org/10.3389/fbioe.2022.1078626.

Taube, F., Appel, T., Ebertseder, T., Müller, T., Olfs, H.W., Nätscher, L., Schweitzer, K., Steffens, D., Wiesler, F., & Zorn, W. (2015). Phosphordüngung nach Bodenuntersuchung – Anpassung der Richtwerte für die Gehaltsklassen ist geboten und notwendig. Positionspapier des Verbandes Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten e.V. (VDLUFA).

Thomas, C.L., Acquah, G.E., Whitmore, A.P., McGrath, S.P., Haefele, S.M., 2019. The effect of different organic fertilizers on yield and soil and crop nutrient concentrations. Agronomy 9 (12). https://doi.org/10.3390/agronomy9120776.

Tian, Y., Shi, C., Malo, C.U., Kwatcho Kengdo, S., Heinzle, J., Inselsbacher, E., Ottner, F., Borken, W., Michel, K., Schindlbacher, A., Wanek, W., 2023. Long-term soil warming decreases microbial phosphorus utilization by increasing abiotic phosphorus sorption and phosphorus losses. Nat. Commun. 14 (1). https://doi.org/10.1038/s41467-023-36527-8.

Turner, B.L., Cade-Menun, B.J., Westermann, D.T., 2003. Organic Phosphorus Composition and Potential Bioavailability in Semi-Arid Arable Soils of the Western United States. Soil Sci. Soc. Am. J. 67 (4). https://doi.org/10.2136/sssaj2003.1168.

Van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W., 2010. Phosphorus demand for the 1970-2100 period: A scenario analysis of resource depletion. Glob. Environ. Change 20 (3). https://doi.org/10.1016/j.gloenvcha.2010.04.004.

Vitousek, P.M., Porder, S., Houlton, B.Z., Chadwick, O.A., 2010. Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen-phosphorus interactions. Ecol. Appl. 20 (1). https://doi.org/10.1890/08-0127.1.

Wang, Y., Bauke, S.L., von Sperber, C., et al., 2021. Soil phosphorus cycling is modified by carbon and nitrogen fertilization in a long-term field experiment. J. Plant Nutr. Soil Sci. 184, 282–293. https://doi.org/10.1002/jpln.202000261.

Wang, Y.P., Goll, D.S., Balkanski, Y., et al., 2022. Toward a Global Model for Soil Inorganic Phosphorus Dynamics. Glob. Biogeochem. Cycles 36 (4), e2021GB007061. https://doi.org/10.1029/2021GB007061.

Wen, Y.C., Li, H.Y., Lin, Z.A., Zhao, B.Q., Sun, Z.Bin, Yuan, L., Xu, J.K., Li, Y.Q., 2020. Long-term fertilization alters soil properties and fungal community composition in fluvo-aquic soil of the North China Plain. Sci. Rep. 10 (1). https://doi.org/10.1038/s41598-020-64227-6.

Whalen, J.K., Chang, C., 2001. Phosphorus Accumulation in Cultivated Soils from Long-Term Annual Applications of Cattle Feedlot Manure. J. Environ. Qual. 30 (1). https://doi.org/10.2134/jeq2001.301229x.

Withers, P.J.A., van Dijk, K.C., Neset, T.S.S., Nesme, T., Oenema, O., Rubæk, G.H., Schoumans, O.F., Smit, B., Pellerin, S., 2015. Stewardship to tackle global phosphorus inefficiency: the case of Europe. Ambio 44 (2). https://doi.org/10.1007/s13280-014-0614-8.

Wu, Y., Yin, X., Zhou, G., et al., 2024. Rising rainfall intensity induces spatially divergent hydrological changes within a large river basin. Nat. Commun. 15 (1), 823. https://doi.org/10.1038/s41467-023-44562-8.

Zhang, J., Wen, J., Zhang, T., Zhang, Y., Peng, Z., Tang, C., Wang, Y., Su, S., Zhang, N., Zeng, X., 2023. Effects of five–year inorganic and organic fertilization on soil phosphorus availability and phosphorus resupply for plant P uptake during maize growth. Agric. (Switz.) 13 (4). https://doi.org/10.3390/agriculture13040858.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D.B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.L., Elliott, J., Ewert, F., Janssens, I.A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Asseng, S., 2017. Temperature increase reduces global yields of major crops in four independent estimates. Proc. Natl. Acad. Sci. USA 114 (35). https://doi.org/10.1073/pnas.1701762114.

Zhao, N., Ma, J., Wu, L., Li, X., Xu, H., Zhang, J., Wang, X., Wang, Y., Bai, L., Wang, Z., 2024. Effect of organic manure on crop yield, soil properties, and economic benefit in wheat-maize-sunflower rotation system, Hetao Irrigation District. Plants 13 (16). https://doi.org/10.3390/plants13162250.

Zhu, Q., Riley, W.J., Tang, J., Koven, C.D., 2016. Multiple soil nutrient competition between plants, microbes, and mineral surfaces: Model development, parameterization, and example applications in several tropical forests. Biogeosciences 13 (1). https://doi.org/10.5194/bg-13-341-2016.

Zotarelli, L., Dukes, M.D., Romero, C.C., Migliaccio, K.W., Morgan, K.T., 2024. Step by Step calculation of the penman-monteith evapotranspiration (FAO-56 Method). EDIS 2010 (2). https://doi.org/10.32473/edis-ae459-2010.

Žydelis, R., Weihermüller, L., Herbst, M., 2021. Future climate change will accelerate maize phenological development and increase yield in the Nemoral climate. Sci. Total Environ. 784. https://doi.org/10.1016/j.scitotenv.2021.147175.