

Article

Can Long-Term Experiments Predict Real Field N and P Balance and System Sustainability? Results from Maize, Winter Wheat, and Soybean Trials Using Mineral and Organic Fertilisers

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Abstract: Agri-environmental indicators such as nutrient balance may play a key role in soil and water quality monitoring, although short-term experiments might be unable to capture the sustainability of cropping systems. Therefore, the objectives of this study are: (i) to evaluate the reliability of long-term experimental N and P balance estimates to predict real field (RF) (i.e., short-term transitory) conditions; and (ii) to compare the sustainability of short- and long-term experiments. The LTE-based predictions showed that crops are generally over-fertilised in RF conditions, particularly maize. Nutrient balance predictions based on the LTE data tended to be more optimistic than those observed under RF conditions, which are often characterised by lower outputs; in particular, 13, 44, and 47% lower yields were observed for winter wheat, maize, and soybean, respectively, under organic management. The graphical evaluation of N and P use efficiency demonstrated the benefit of adopting crop rotation practices and the risk of nutrient loss when liquid organic fertiliser was applied on a long-term basis. In conclusion, LTE predictions may depend upon specific RF conditions, representing potential N and P use efficiencies that, in RF, may be reduced by crop yield-limiting factors and the specific implemented crop sequence.

Keywords: nitrogen use efficiency; phosphorus use efficiency; real field condition; nitrogen balance; phosphorus balance; long-term experiment



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1. Introduction

The consumption of mineral fertiliser in Europe by agriculture amounts to almost 10.2 and 1.1 million tonnes for nitrogen (N) and phosphorus (P), respectively [1]. The nitrogenous fertilisers are produced from natural gas while the phosphorus ones are extracted from rock phosphate; both synthesis processes partially come from limited, non-renewable resources; therefore, efficient fertiliser usage is required to reach the sustainable development goals (SDGs) [2]. Moreover, European agriculture contributes to water N and P loading in the range of 30–80% and 20–70%, respectively [3]. Since the early 2000s, protecting the environment against agriculture-derived pollution has received increasing levels of attention (e.g., Water Framework Directive 2000/60/CE). The use of agri-environmental indicators may thus play a key role in both water quality monitoring and the development of policies focused on more sustainable agriculture. European Commission communications, such as COM (2000)20 and COM(2001)144, identified 35 indicators, among which there are gross N and P balances [4,5]. Bassanino et al. [6] proved how these indicators might allow a quick assessment of the agronomic management techniques sustainability in the Po valley. In the same area, Longo et al. [7], coupling DayCent simulation and the GIS platform, showed how the site-specific indices application might be a suitable tool for agri-environmental measures evaluation. The Eurostat database shows that across the EU, the output-to-input ratio of nutrients is often below 1, suggesting that more effort

should be put towards increasing the nutrient use efficiency of cropping systems. Indeed, in the 2012–2014 period, only 66 and 64% of N and P inputs, respectively, were taken up by crops in the 27 EU member states [8]. Globally, more than half of applied N and P is lost in the environment [9,10]. For these reasons, N application should meet crop demand maximising, at the same time, crop productivity and environmental sustainability [11]. Schröder et al. [12] showed that the P use efficiency (PUE) could be increased by optimising the different management techniques.

In this context, the 2015 EU Nitrogen Expert Panel drew attention to the Nitrogen Use Efficiency (NUE) concept and proposed an easily visualisable method for system sustainability evaluation based on minimum productivity levels, the range of NUE, and the maximum surplus thresholds [13]. Quemada et al. [14] applied this approach on the evaluation of 1240 farms NUE and concluded that it is an effective tool to assess farming systems performances. To test the sustainability of cropping systems, short-term cropping experiments are often undertaken; however, their results may be impaired by their short-term nature [7,15]. Indeed, the effects of previous practices, such as the carry-over effect from previous fertilisations, may influence short-term observations. Moreover, some cropping practices (e.g., no-tillage, organic amendments) may require medium- to long-term timescales to reach equilibrium and, in turn, show their potentialities [16,17]. In contrast, long-term experiments (LTEs) are characterised by stabilised conditions and may be useful for disentangling the sustainability of different agronomic management types [18]. Unfortunately, LTEs are not always available or do not cover the entire range of agronomic management.

Within this framework, the objectives of this study are as follows: (i) to evaluate the reliability of LTE estimates of the N and P balance to predict real field (RF) (i.e., short-term transitory) conditions; and (ii) to compare the system sustainability of short- and long-term experiments. Our hypotheses are that LTE outcomes may be applicable for predicting RF conditions irrespective of nutrient type and that short-term experiments may have similar sustainability as the LTEs.

2. Materials and Methods

2.1. Experimental Design

Outcomes from a long-term crop rotation experiment which has been ongoing since 1962 [19] were compared with RF (i.e., short-term transitory) conditions where organic farming (ORG) (organic fertiliser, mechanical weed control, no use of chemical pesticide) and conventional agriculture (CONV) (mineral fertiliser, use of pesticide according to crop requirement) were tested [20]. The LTE and RF experiments were both conducted at the “Lucio Toniolo” Padova University experimental farm and were subjected to similar tillage operations (autumn ploughing and spring seedbed preparation through harrowing). The organic fertilisers (farmyard manure and slurry) applied at both LTE and RF originated from the experimental farm livestock (cattle). The pedo-climatic conditions were similar, as both experiments were located in the Po Valley and had loamy Fluvi-Calcaric Cambisol soil with a sub-humid climate and a yearly average temperature of 13.5 °C, rainfall of 850 mm, and reference evapotranspiration of 995 mm. The considered data belonged to the 1989–2015 (LTE) and 1997–2015 (RF) periods, where the LTE represented stabilised conditions and the RF period represented transitory conditions.

The LTE had a split-plot design with 288 plots (7.8 m × 6 m each) with three replicates, where the main splitting factor allowed for high- and low-input cropping system intensifications to be compared [19]. The LTE encompassed three main groups of treatments (A, B, and C), as follows. (A) A crop rotation experiment that involved a factorial combination of four crop rotations (1, 2, 4, and 6 yr), three inorganic fertiliser rates (0–0–0, 70–70–90, and 140–140–180 kg ha⁻¹ for N, P₂O₅, and K₂O, respectively), and two types of organic inputs (previous crop residue incorporation + 40 t ha⁻¹ cattle slurry, or crop residue incorporation alone). The 6-year rotation was maize (*Zea mays* L.)–sugar beet (*Beta vulgaris* L.)–maize–wheat (*Triticum aestivum* L.)–alfalfa (*Medicago sativa* L.)–alfalfa,

and in this rotation, only residue incorporation without slurry was replaced by farmyard manure (from cattle) and previous crop residue removal. The 4-year rotation was sugar beet–soybean (*Glycine max* (L.) Merr.)–wheat–maize. The 2-year rotation was maize–wheat. The 1-year rotations were maize and wheat monocultures. (B) The silage maize monoculture and meadow experiments considered three inorganic fertiliser rates (the same reported above for the crop rotations) coupled with applications of 40 t ha⁻¹ slurry. (C) The high-input maize monoculture experiment involved eight treatments with maize as the main crop, for a total of 24 plots comparing fertilisation with only organic fertiliser (60 t ha⁻¹ farmyard manure; 120 t ha⁻¹ slurry), only inorganic fertiliser (300–150–420 for N, P₂O₅, and K₂O, respectively), mixed inputs (30 t ha⁻¹ farmyard manure + 150–75–210 for N, P₂O₅, and K₂O, respectively; 60 t ha⁻¹ slurry + 150–75–210 for N, P₂O₅, and K₂O, respectively), and no fertiliser. For further details on N and P input, see Appendix A Table A1, while K nutrient was not considered in this study. More details about the LTE experimental design can be found in Dal Ferro et al. [21] (“Long-term crop rotation experiment”) and Berti et al. [22] (“The long-term rotation experiment”).

The RF conditions involved the selection of observations according to regional standard farming practices under either CONV or ORG management. The fields were located on the University’s experimental farm without the application of a classical experimental design scheme. CONV management included maize, wheat, soybean, and sugar beet as the main crops; however, a strict succession was not followed, and the fields were fertilised with mineral fertilisers. ORG management followed a 3-year maize–winter wheat–soybean rotation and only used farmyard manure as a fertiliser. In contrast to what has been reported for LTEs, RF nutrient inputs varied yearly according to the crop requirements. For further details on N and P input, see Appendix A Table A2, while K nutrient was not considered in this study. The RF observations belonged to an 18-year time span, and they therefore covered a wide range of meteorological conditions. More details on the ORG and CONV management in RF conditions can be found in Dal Ferro et al. [21].

2.2. N and P Balance Calculations and Statistics

At the end of each cropping season for both RF and LTE, the fresh yield of each treatment was weighed and dried in a 65 °C oven until it reached a constant weight, and the dry weight was then determined. The N and P content in agricultural products used for further elaborations was calculated using the harvest indices (please see Appendix A Table A3). Similarly, the N and P applied via organic fertilisers were calculated with consideration of the average content (Appendix A Table A4). The amount of N entering the soil via biological N fixation was calculated for soybean and alfalfa in the LTE according to Anglade et al. [23], as suggested by the Tier 2 approach of the EU Nitrogen Expert Panel [13].

The NUE and phosphorus use efficiency (PUE) were calculated as an output-to-input ratio where a value < 1 reflected nutrient loss and/or soil enrichment and a value > 1 reflected soil nutrient mining.

Data from the LTE were then interpolated with a hyperbolic model according to the third model of Vos [24], as follows:

$$\frac{\text{Output}}{\text{Input}} = \text{Max} \left(1 - \frac{a \times \text{Input}}{1 + \frac{a \times \text{Input}}{b}} \right) \quad (1)$$

where *Max*, *a*, and *b* are regression parameters. The goodness of fit was evaluated through the residual means square error (RMSE). The balancing points, defined as points where the output-to-input ratio was equal to 1, were extrapolated from the fitted models. Afterwards, the abilities of the previously defined models to predict the RF conditions were evaluated using RMSE. Finally, the LTE-derived hyperbolic model was compared with RF observations. The nutrient balance was calculated for both LTE and RF, but only for comparable crops (wheat, maize, and soybean) (See Appendix A Tables A1 and A2).

2.3. System Sustainability

The system sustainability was evaluated by applying NUE and PUE graphical representations, as suggested by the EU Nitrogen Expert Panel. In the two-dimensional input versus output graph, the sustainability area was drawn according to the desired minimum productivity, use efficiency (UE) = 0.50, desired maximum surplus, and UE = 0.90 lines (Figure 1). The desired minimum productivity lines represent the lower limit for acceptable crop production, while the UE = 0.50 and UE = 0.90 lines represent the lower and upper boundary efficiencies to minimise nutrient loss into the environment and soil mining, respectively. Finally, the desired maximum surplus line delimits the maximum acceptable difference between the input and output. For further details, please see Appendix A Table A5 and the EU Nitrogen Expert Panel report [13]. At first, sustainability was evaluated for all available treatments of the LTE. In the second step, only the LTE crops which were comparable to the RF crops (wheat, maize, and soybean) were extracted from the LTE dataset.

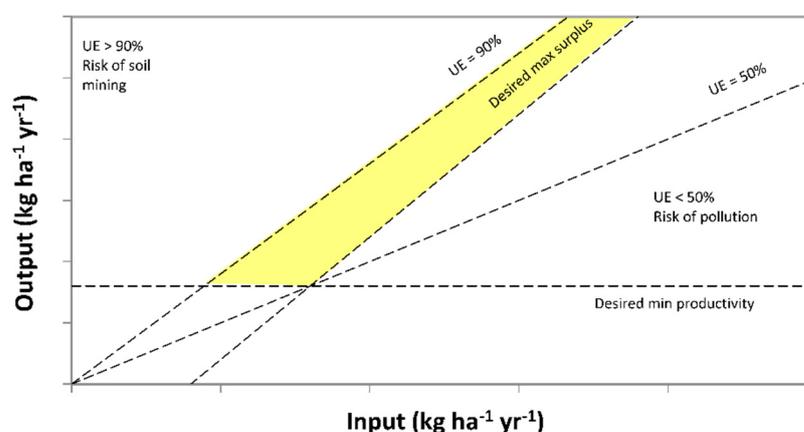


Figure 1. Graphical presentation of nutrient use efficiency (UE) using the results of the input vs. output diagram. The lines corresponding to nutrient UE = 0.90, desired maximum surplus, UE = 0.50, and desired minimum productivity create the “sustainability area” (in light yellow). The adopted graph is similar to what was reported by EU Nitrogen Expert Panel [13] for N.

3. Results

3.1. NUE and PUE for the Long-Term Experiment

The LTE NUE and PUE estimates were derived from the 1989–2015 period, in which winter wheat, maize, and soybean in different cropping systems were evaluated. During this period, the NUE for winter wheat ranged from 0.4 to 2.1, and higher values were associated with crop residues and farmyard manure and lower values were associated with slurry + mineral fertiliser applications (Figure 2a). Similarly, maize NUE was in the 0.3–1.9 range with values >1 for residue incorporation and <1 for organic fertilisation (Figure 2b). The hyperbolic model was a good fit for the LTE data, having an RMSE of 0.216 and 0.148 for winter wheat and maize, respectively (Appendix A Table A6). Following the interpolations, the balancing points, where the NUE equalled 1, were reached when 108 kgN ha⁻¹ (winter wheat) and 128 kgN ha⁻¹ (maize) were applied.

The PUE was always ≤1 independent of the studied crop, with values close to 1 for manure in winter wheat and maize and for residue incorporation in soybean (Figure 2c–e). PUE values were lower when slurry + mineral fertiliser was applied for all studied crops. Data interpolation with the hyperbolic model resulted in good performances with RMSE ≤ 0.3 (Appendix A Table A6). The balancing points were reached in the LTE when 19, 26, and 28 kgP ha⁻¹ were applied to winter wheat, maize, and soybean, respectively.

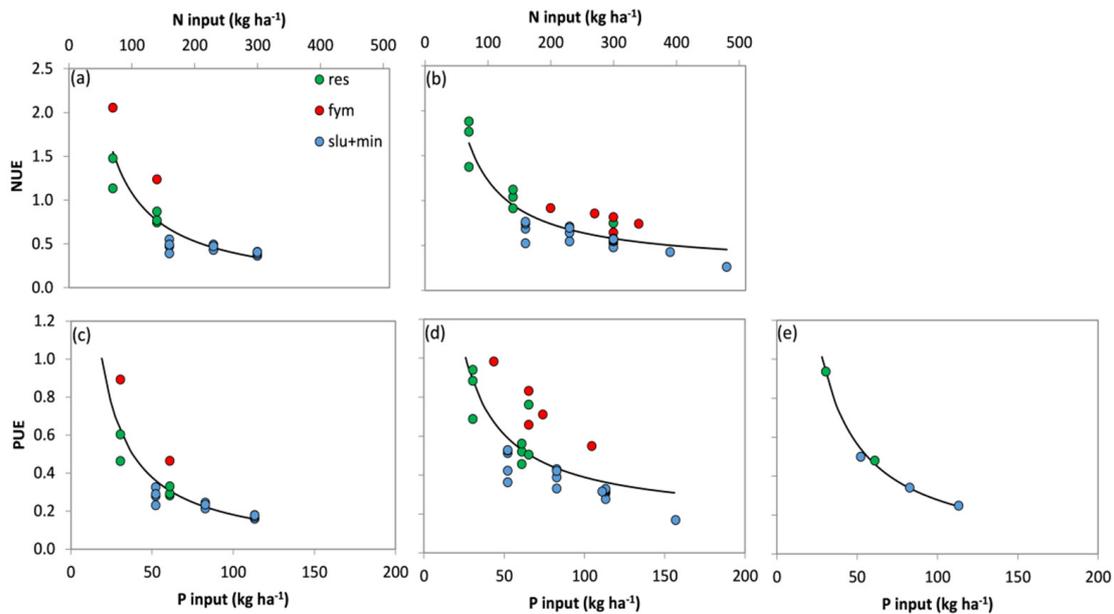


Figure 2. Relationship between nitrogen (a,b) and phosphorus (c–e) fertilisation levels and the average output-to-input ratio (i.e., NUE and PUE) for winter wheat (a,c), maize (b,d), and soybean (e) during the long-term experiments. The black line represents the interpolated hyperbolic model, and the points represent LTE observations, clustered according to the different agronomic inputs, i.e., res: crop residues incorporation in green, fym: farmyard manure in red, and slu+min: slurry + mineral fertiliser application in blue.

3.2. NUE and PUE in Real Field Conditions

Compared to the above-mentioned balancing points obtained from the LTE interpolation, the N supply in the RF conditions tended to be higher than the critical values in 69 and 92% of the observations for winter wheat and maize, respectively (Figure 3). The P supply also tended to be higher for the same crops in approximately half of the RF observations, while soybean generally resulted in a lower P supply (Figure 3).

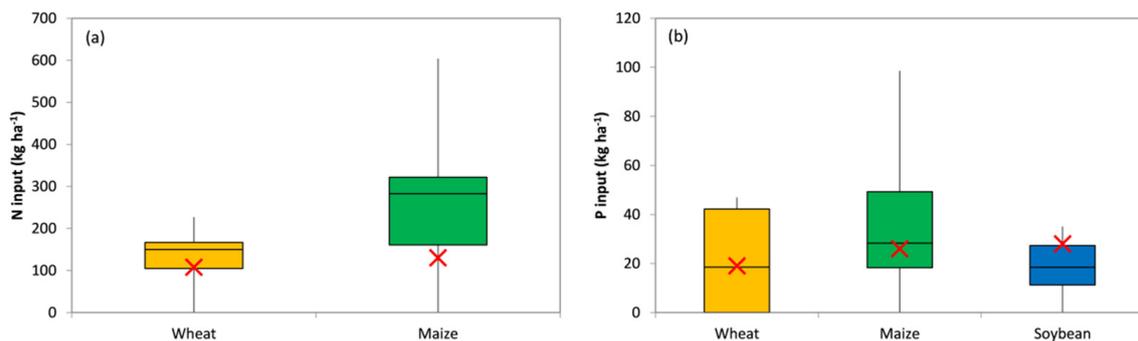


Figure 3. Nitrogen (a) and phosphorus (b) supplies under real-field conditions for the studied crops irrespective of agronomic management. N = 28, 35, and 28 for wheat, maize, and soybean, respectively. The balancing points (i.e., output-to-input ratio equal to 1) are estimated from the LTE interpolations and identified using red x symbols.

Comparing the LTE-derived hyperbolic models with the RF observations, higher performances for N were observed in winter wheat than in maize (Figure 4). In the latter crop, ORG management was overestimated by the model (Figure 4b). A similar trend was also observed for P in maize and soybean. It is noteworthy that the organic system, for both maize and soybean, showed a wide range of responses with a relatively narrow spread of P input levels (Figure 4d,e). For further details, please see Appendix A Table A7.

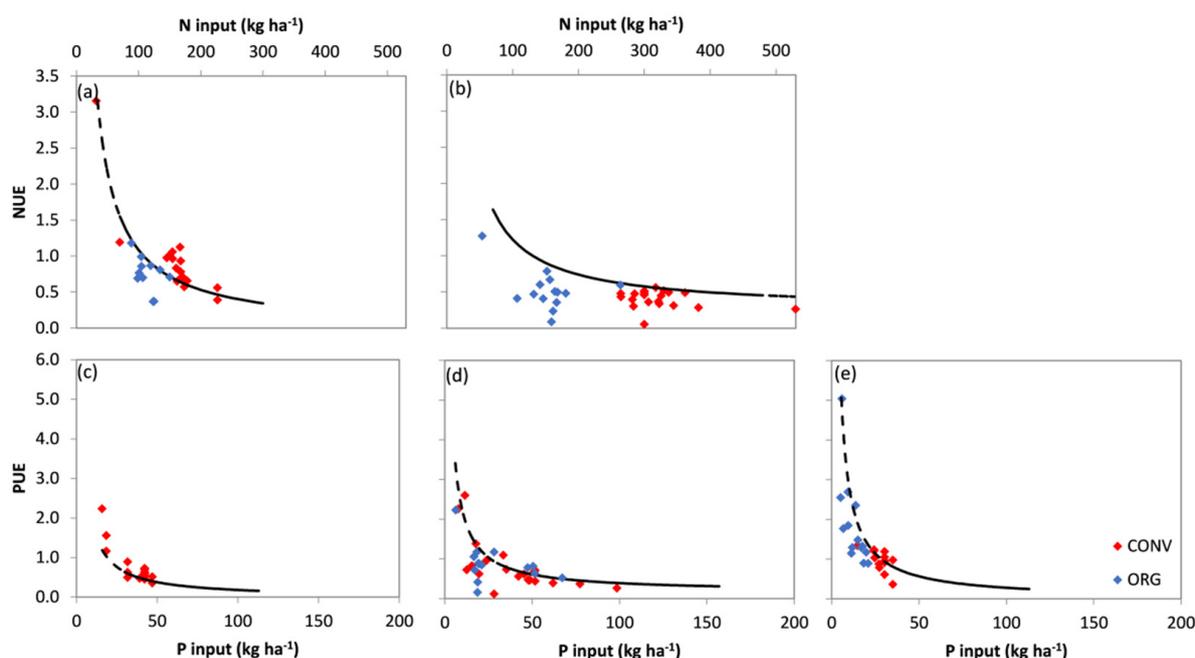


Figure 4. Relationship between nitrogen (a,b) and phosphorus (c–e) fertilisation levels and the output-to-input ratio for winter wheat (a,c), maize (b,d), and soybean (e). The black line represents the interpolated hyperbolic model from the long-term experiment (LTE), and the points represent RF observations clustered for different agronomic practices, i.e., conv: conventional agriculture (red points) and org: organic agriculture (blue points). The LTE-based model was dotted outside the LTE original range.

3.3. LTE System Sustainability

System sustainability for the LTE was evaluated with a graphical representation of the NUE and PUE, as suggested by the EU Nitrogen Expert Panel. Considering all treatments and crops available during the LTE, a general trend of increasing output was observed at each rotation complexity increment, from the monoculture that occupied the lowest part of the graph to the 6-year crop rotation that occupied the highest part of the graph (Figure 5a). The only exception was the permanent meadow that had an observed output similar to that of the 6-year crop rotation. The residue incorporation fell in the soil mining zone for N input $< 100 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in the monoculture, 2-year, and 4-year crop rotations, while the same cropping systems resulted in the risk of a pollution zone with the addition of slurry and N inputs $> 100 \text{ kg ha}^{-1} \text{ yr}^{-1}$. Only the $140\text{--}180 \text{ kg N ha}^{-1}$ (empty shape in the graph) fertilisation doses for residue incorporation and $160\text{--}196 \text{ kg N ha}^{-1}$ (filled shape in the graph) for residue + slurry incorporation fell into the sustainability area (Figure 5a).

A different dynamic was observed for P, as residues with added slurry always fell in the surplus or risk of pollution zone. Residues without added slurry fell into the sustainability area only for the maize monoculture, 2-year, and 4-year crop rotations, at an input level of 31 kgP ha^{-1} (Figure 5b).

For the LTE crops that were comparable to the RF conditions (i.e., winter wheat, maize, and soybean), a different pattern was visible between N and P (Figure 6). There was a risk of N soil mining when residues alone were incorporated, while the addition of slurry resulted in an NUE close to 0.50. In winter wheat, the N sustainability area was only marginally reached, while in maize, it was reached when residue + slurry was incorporated at a low fertilisation dose. However, the same treatment (residue + slurry) resulted in a $\text{PUE} < 0.50$, with poorer efficiency for winter wheat than maize. The P sustainability area was only reached when 31 kgP ha^{-1} was applied to maize and wheat. Soybean, which was only included in the 4-year rotation, had a $\text{PUE} < 0.50$ when slurry was added to the crop residue, while residues alone fell into the sustainability area only when the P input was 31 kg ha^{-1} . Irrespective of the nutrient type, crops involved in high-complexity rotations

(e.g., 4 and 6 yr) more frequently fell into the sustainability area, especially if the nutrient inputs were only crop residues (Figure 6).

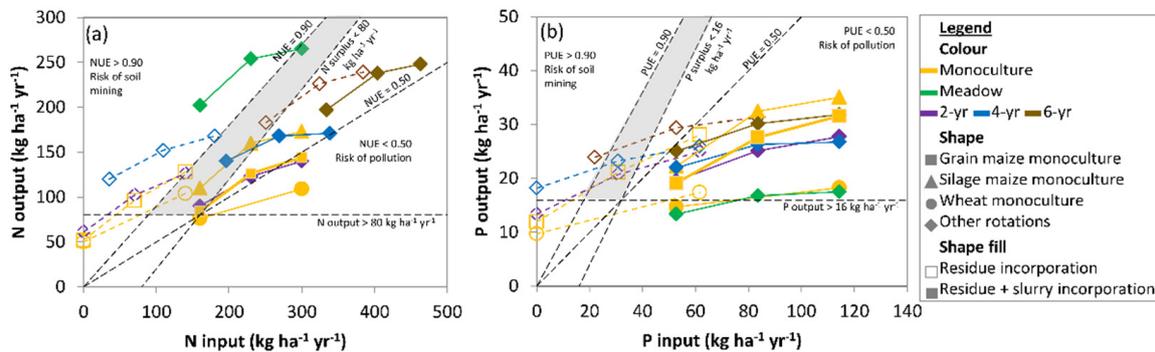


Figure 5. Graphical presentation of the nitrogen (a) and phosphorus (b) use efficiency (UE) in the long-term experiment. Observations are clustered according to crop rotation using colour (monoculture, meadow, 2, 4, and 6 yr), type of harvested product using shape (e.g., grain or silage maize), and residue management using fill (residue incorporation and residue + slurry incorporation). The lines corresponding to nutrient UE = 0.90, desired maximum surplus, UE = 0.50, and desired minimum productivity create the “sustainability area” (in light grey).

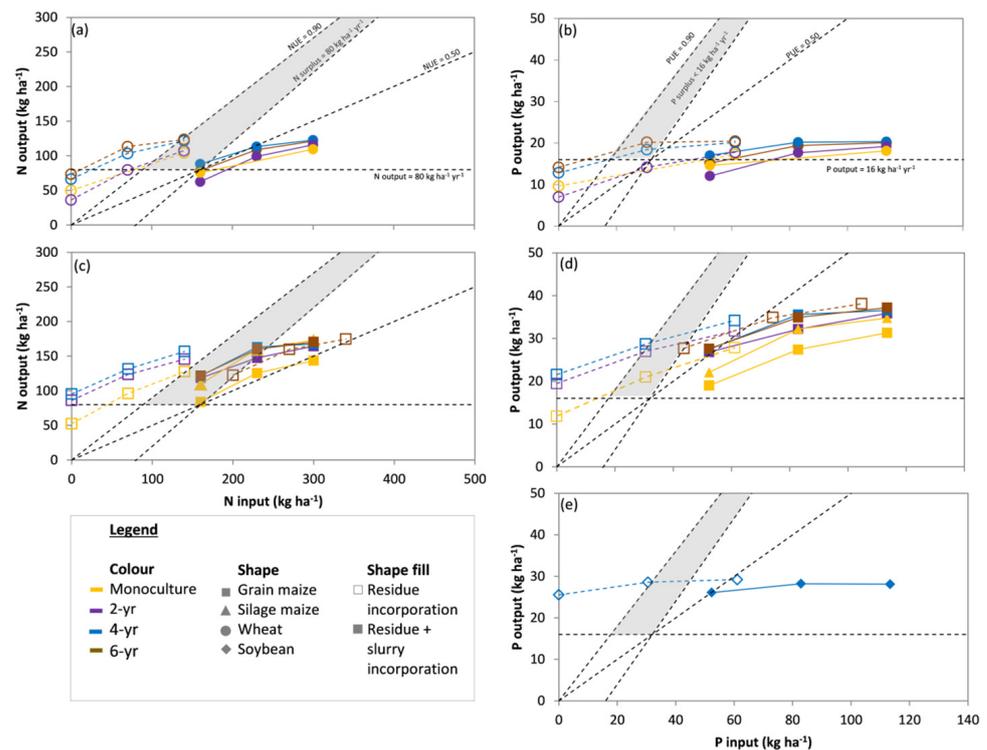


Figure 6. Graphical presentation of the nitrogen (a,c) and phosphorus (b,d,e) use efficiency (UE) in the long-term experiment winter wheat (a,b), maize (c,d) and soybean (e), identified according to crop rotations using colour (monoculture, 2, 4, and 6 yr) and characterised by different residue managements using fill (residue incorporation and residue + slurry incorporation). The lines corresponding to nutrient UE = 0.90, desired maximum surplus, UE = 0.50, and desired minimum productivity create the “sustainability area” (in light grey).

3.4. System Sustainability in the RF Condition

The RF sustainability graphical evaluation showed a different NUE pattern according to the interactions between agronomic management, crop type, and the considered nutrients (Figure 7). For winter wheat, both organic and conventional systems partially fall

into the sustainability area for 33 and 41% of their observations, respectively. In maize, the organic system resulted in sustainable NUE for 31% of the observations and was associated with low output, while the conventional agriculture system occupied the risk of pollution zone with an NUE around 0.50.

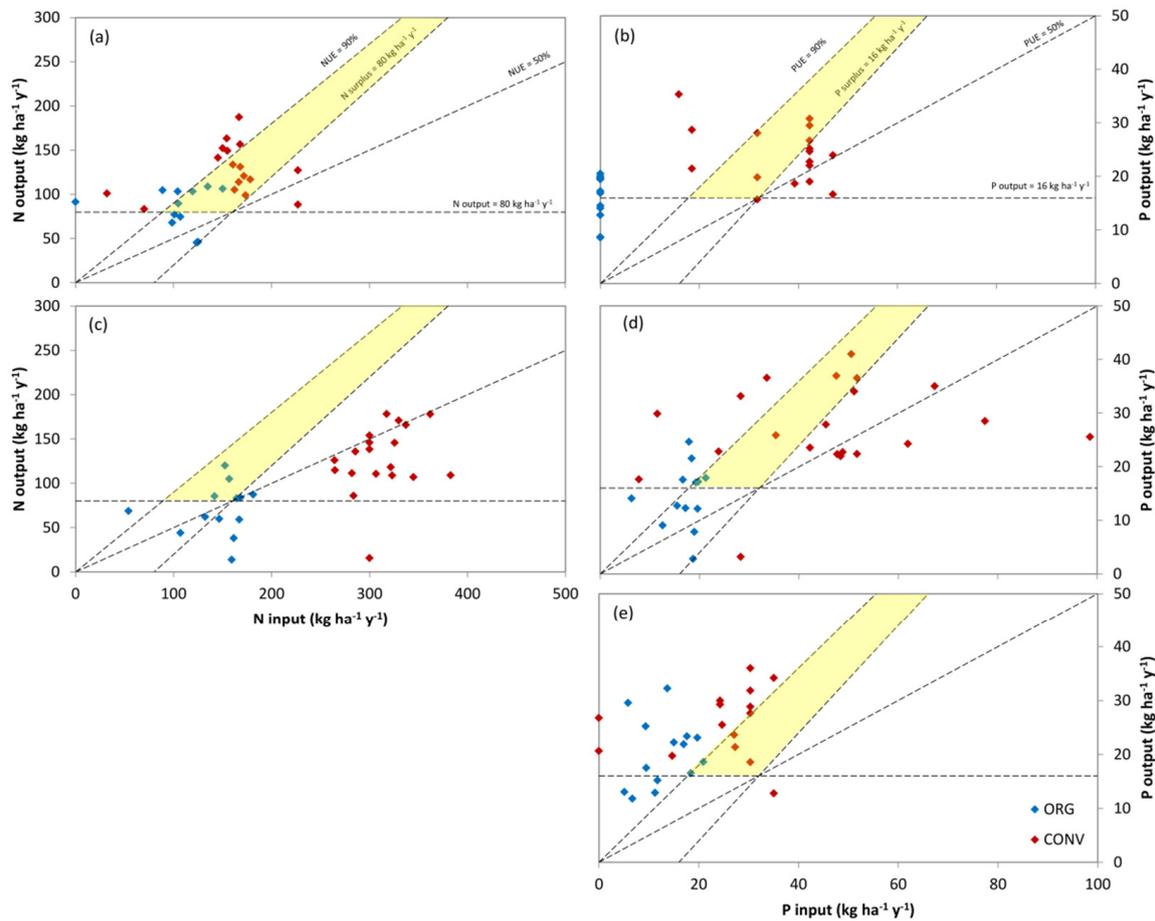


Figure 7. Graphical representation of nitrogen (a,c) and phosphorus (b,d,e) use efficiency under RF conditions for winter wheat (a,b), maize (c,d), and soybean (e). The lines corresponding to nutrient use efficiency (UE) = 0.90, desired maximum surplus, UE = 0.50, and desired minimum productivity delineate the “sustainability” area (in light yellow). Observations are clustered according to organic (blue points) or conventional (red points) agriculture management.

The PUE evaluation revealed that only a few observations fell into the sustainability area, with higher frequencies for winter wheat and maize (31% on average) than for soybean (17%). It is noteworthy that (i) the organic system resulted in a P output that was below the desirable minimum (i.e., $16 \text{ kg ha}^{-1} \text{ yr}^{-1}$) in more than half of the maize observations, and (ii) soybean occupied the left part of the graph (Figure 7e), which is associated with the soil mining area.

4. Discussion

4.1. Real Field vs. Long-Term Experiment Fertilisation Efficiency

The RF observations (i.e., short-term transitory) showed that the main cereals grown in the Po Valley, specifically winter wheat and maize, are generally over-fertilised with N with respect to the balancing points (i.e., $\text{NUE} = 1$) calculated based on the LTE data. This confirms a previous report by Bassanino et al. [6], who showed that maize was the most frequently over-fertilised crop in the same area. Nevertheless, it should be noted that the balancing points are derived from the LTE interpolation and do not represent the optimal level of crop fertilisation.

In contrast, the RF average P fertilisation levels were close to the balancing point (PUE = 1) but frequently had a negative gross balance. Despite P usually being immobile at the natural pH of the Veneto region's silty soils (pH around 7.8), a negative balance does not guarantee the absence of P losses into the environment, as dissolved or particulate P may still be present in leached or run-off water [12].

The N and P balance based on the LTE predictions closely fit the RF observations for wheat; however, for maize and soybean, there was a tendency for the balance to be overestimated, especially in fields under ORG management. These discrepancies may be due to sub-optimal weed control in RF ORG systems, but they may also be related to the different techniques for organic amendment applications in the LTEs versus RFs. Indeed, in classical LTE experiments, fertilisers are in most cases applied at a fixed rate every year; thus, the efficiency of organic nutrients depends on their direct effect in the year of distribution and on the carry-over effect of the preceding fertilisations. In RF, the apparent efficiency is affected by the specific distribution history and on the crop sequences, which may mask the residual effects of organic fertilisation. Therefore, LTEs can give relevant information on different agronomic practice potentialities, stressing once again the importance of maintaining the existing European LTEs [25].

4.2. System Sustainability

The LTE sustainability evaluation suggested that sustainability may be reached depending on the nutrient input level, independent of the crop rotation type. Nevertheless, at increased rotation complexities, a higher output, namely, crop production, was consistently found. The positive effect of rotations on crop yield and its stability over time has previously been reported by Berzsenyi et al. [26] and was further confirmed in this study. Indeed, the wheat and maize yields were higher when the crops were included in the 6-year crop rotation, and they progressively decreased when the crops were included in the 4- and 2-year rotations, with the smallest yields in the monocultures.

Cropping system sustainability was first determined by the type of agronomic input (e.g., crop residue incorporation or residue + slurry incorporation). Crop residue incorporation often fell in the soil mining area of the UE graphs, which highlighted the importance of combining residue with organic fertiliser [27]. However, soil mining may only represent a real risk in the long term (e.g., 3–5 years). Soil mining may be a good practice in the short term (e.g., within one cropping season) in highly fertile soils or when soil fertility will be restored: for instance, when organic fertilisation is planned for the next cropping season [14]. Organic fertilisation was associated with higher surpluses compared to mineral fertilisation, which in contrast, showed a higher nutrient efficiency. A lower nutrient efficiency in organic fertiliser is well documented in the literature, although a nutrient surplus should not directly result in pollution of water bodies because the nutrients are partially stored as soil organic matter, potentially increasing C storage and, in turn, soil fertility [14,28–30]. These findings warn about the use of the output-to-input ratio, as it may work properly for mineral fertilisers but not for organic fertilisers.

The PUE often fell in the soil mining area of the graphs, particularly when organic fertilisers were involved. The organic fertiliser application dose is generally determined based on its N content in order to comply with both the crop need and regulation limits (e.g., the Nitrates Directive). Additionally, the P-to-N ratio is greater in organic fertilisers than what is actually needed by crops; thus, over-fertilisation of P is often observed when organic fertilisers are used alone [31]. For organic systems, this structural imbalance of P can be a concern for pollution risks in the long term and, in general, for the sustainable use of limited resources, such as P. Furthermore, despite the fact that the organic system frequently fell in the sustainability area of the graph (Figure 7), it is still characterised by low production yields, often below the minimum desirable limit. These findings confirm those of previous studies where both medium-term simulations [7] and long-term experiments [15] consistently found that European and Chinese organic agricultural systems were producing low yields.

4.3. Methodological Limitations

The results of this study, as they relate to other research, are best discussed by highlighting some of the following methodological details that may have impaired them. First, biological N fixation was not considered in the permanent meadow. Indeed, the LTE permanent meadow included N-fixing species, but their abundance and, in turn, their contribution to biological N fixation were difficult to estimate with an acceptable degree of accuracy. Therefore, the LTE meadow N input may have been underestimated; its real graphical representation may be slightly more to the right on Figure 5 and may thus fall, in some cases, in the sustainability area. Similarly, the uncertainty of biological N fixation might have affected the LTE N input in the crop rotations, which included legumes (e.g., soybean and alfalfa in the 4-year and 6-year crop rotations, respectively). Third, the fertilisation efficiency was evaluated by using the NUE and PUE graphical evaluations, where specific limits (e.g., $\text{NUE} < 0.90$, $\text{surplus} < 80 \text{ kgN ha}^{-1} \text{ yr}^{-1}$) designated the sustainability area. It is worth noting that these N limits are not yet well established and that different thresholds may lead to different conclusions. Finally, to the best of our knowledge, this is the first published attempt to investigate the PUE with the same graphical evaluation as the NUE; thus, further research is needed to confirm or disprove the applicability of this method.

5. Conclusions

Our hypothesis has been partially confirmed as the LTE predictions may depend upon specific RF conditions, representing potential NUEs and PUEs that may be reduced in RF by factors that limit crop yields and by the implemented crop sequence. Indeed, the P output-to-input ratio was found to be greater under RF than under LTE conditions, with the greatest discrepancy being at low fertilisation levels, possibly associated with the carry-over effect of previous fertilisations (so-called legacy P). Therefore, opposite conclusions may be drawn in RF for N (over-fertilisation) and P (soil mining); thus, further studies should aim to identify suitable agri-environmental indicators with particular attention to P as a nutrient. The role of P/N ratios in degraded manure fertilisers may provide further explanations.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Mean value of dry yield (DY), N output (N out), N input (N in), P output (P out), and P input (P in) according to crop and treatment (Treat) in long-term experiments. res: crop residues incorporation; fym: farmyard manure; slu+min: slurry + mineral fertiliser application; S.E.: standard error.

Crop	Treat	DY	S.E.	N out	S.E.	N in	S.E.	P out	S.E.	P in	S.E.
Sugar beet	fym	13,396	294.6	147	3.2	270	3.8	23	0.5	74	1.7
	res	9178	259.2	101	2.9	70	3.8	16	0.5	31	1.7
	slu + min	11,778	182.4	130	2.0	230	2.7	21	0.3	83	1.2
Wheat	fym	4650	91.4	103	2.2	70	3.8	18	0.4	31	1.7
	res	3730	66.6	84	1.6	70	2.5	15	0.3	31	1.1
	slu + min	4485	50.5	100	1.2	230	2.1	18	0.2	83	0.9
Silage mazie	slu + min	19,432	432.5	148	3.3	230	3.8	30	0.7	83	1.7
Grain maize	fym	10,845	115.4	152	1.6	278	2.1	33	0.4	72	0.9
	res	7771	116.7	109	1.7	95	3.3	24	0.4	31	0.9
	slu + min	10,266	88.0	143	1.2	254	2.4	31	0.3	89	0.8
Alfalfa	fym	13,556	206.0	369	5.7	0	0.0	30	0.5	31	1.7
	slu + min	15,155	193.3	412	5.3	160	0.0	33	0.4	83	1.7
Meadow	slu + min	13,368	227.0	241	4.1	230	3.8	16	0.3	83	1.7
Soybean	res	3746	61.9	261	4.3	70	3.8	28	0.5	31	1.7
	slu + min	3706	66.7	259	4.6	230	3.8	28	0.5	83	1.7

Table A2. Mean value of dry yield (DY), N output (N out), N input (N in), P output (P out), and P input (P in) according to crop and treatment (Treat) in real field conditions. CONV: conventional; ORG: organic; S.E.: standard error.

Crop	Treat	DY	S.E.	N out	S.E.	N in	S.E.	P out	S.E.	P in	S.E.
Winter wheat	CONV	6076	327.6	128	6.9	157	11.3	24	1.5	36	2.9
	ORG	4041	312.3	85	6.6	105	10.7	16	1.0	0	0.0
Silage maize	CONV	13,844	637.4	152	7.0	307	7.5	37	1.7	48	8.0
Grain maize	CONV	8372	622.4	126	9.3	324	28.2	26	2.2	43	6.4
	ORG	5082	640.8	76	9.6	154	12.0	16	1.7	20	2.3
Soybean	CONV	3445	218.9	240	15.3	7	4.5	26	1.6	24	2.9
	ORG	2703	223.1	189	15.6	105	14.3	20	1.7	13	1.4

Table A3. Nitrogen (N) and phosphorus (P) harvest indices for the agricultural products and residues of each studied crop.

Crop	Agricultural Product		Residue	
	N (kg kg ⁻¹)	P (kg kg ⁻¹)	N (kg kg ⁻¹)	P (kg kg ⁻¹)
Winter wheat	0.021	0.00396	0.005	0.00088
Silage maize	0.011	0.00264	-	-
Grain maize	0.015	0.00308	0.009	0.00176
Soybean	0.070	0.00748	0.023	0.00308

Table A4. Nitrogen (N) and phosphorus (P) content in the organic fertilisers used for the input calculations.

Fertiliser	N (kg kg ⁻¹)	P (kg kg ⁻¹)
Farmyard manure	0.005	0.0011
Slurry	0.004	0.00132

Table A5. Nitrogen (N) and phosphorus (P) limits that create the sustainability area for the N use efficiency (NUE) and P use efficiency (PUE) graphical evaluation.

Limit	N	P
Desired min. productivity (kg ha ⁻¹)	80	16
Min. use efficiency (%)	50	50
Max. use efficiency (%)	90	90
Desired max. surplus (kg ha ⁻¹)	80	16

Table A6. Interpolation parameters for the hyperbolic model applied to the long-term experiment data for nitrogen (N) and phosphorus (P). Max, a, and b are regression parameters and Res SS, RMSE, and Bias are the model residual sum of squares, root mean square error, and bias, respectively.

Nutrient	Crop	Max	a	B	Res SS	R	RMSE	Bias
N	Winter wheat	77.9	0.7	1.000	0.837	0.77	0.216	0.146
	Maize	99.3	1.0	0.997	0.661	0.82	0.148	0.119
P	Winter wheat	33.6	1.7	1.001	0.943	-0.64	0.229	0.191
	Maize	23.9	1.0	0.993	1.929	-0.51	0.254	0.199
	Soybean	131.6	4.6	1.000	0.500	-0.79	0.316	0.287

Table A7. The root means square error (RMSE) represents the goodness of fit of the long-term experiment-based hyperbolic model under real-field conditions.

Nutrient	Crop	RMSE		
		All Data	Organic	Conventional
N	Winter wheat	0.254	0.286	0.254
	Maize	0.443	0.494	0.197
P	Winter wheat	0.315	-	0.315
	Maize	0.483	0.562	0.422
	Soybean	0.868	1.180	0.257

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