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ORIGINAL ARTICLE

New approach combining food value with nutrient budgeting provides insights into the value of alternative farming systems

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Abstract

Sustainable farming systems provide food for humans while balancing nutrient management. Inclusion or exclusion of livestock has nutrient management implications, as livestock produce food from otherwise inedible crops and their manure is a valuable soil conditioner. However, plant-based diets are becoming more widespread due to perceived environmental benefits. We measure both food production in terms of nourishment to humans (in this study measured by protein, fat, starch and sugar production) and nutrient sustainability in terms of fertiliser use of six rotational farming systems with differences in nutrient management approaches. The arable practices included were the application of synthetic fertilisers, a range of organic amendments, incorporation of crop residues and legume cultivation. Livestock and associated products were included in some systems but excluded in others. The production of protein, fat, starch and sugar was combined with the balance of nitrogen (N), phosphorus (P) and potassium (K) into an overall measure of nutrient use efficiency of human macronutrient production. Across all systems considered, N use efficiency (5–13 kg protein/kg applied N) was lower than P (84–772 kg protein/kg applied P) or K (63–2060 kg protein/kg applied K), and combining synthetic fertiliser use with organic amendment applications raised production significantly while balancing P and K management, regardless of which organic amendment was used. Legume-supported rotations without livestock produced more protein, starch and sugar per unit area than those with livestock. Nutrient balances and nutrient use efficiencies were more sensitive to management changes than purely food production. Using this approach allowed us to identify areas for improvement in food production based on the specific nutritional value of offtakes as opposed to yield overall.

KEYWORDS

agriculture, crop rotation, macronutrients, nutrient cycling, nutrient use efficiency

1 | INTRODUCTION

Global agriculture needs to feed a rapidly growing human population while developing and implementing environmentally sustainable food production in the face of climate change, soil degradation and societal and economic pressures (Molotoks et al., 2021; Röös et al., 2021; Yang et al., 2021). Agriculture also faces changing public and policy perceptions of diet (Hallström et al., 2014; Willett et al., 2019). There are many options for the agricultural management of nutrients based on not only the form of nutrients (mineral or organic) but also different paradigms such as self-sufficiency, food security or the circular economy (Fu et al., 2022). Agricultural nutrient management not only affects crop performance but also has implications for environmental sustainability through greenhouse gas emissions, nutrient leaching, soil carbon storage and biodiversity (Crowder et al., 2010; Muller et al., 2017; Zomer et al., 2017). Agricultural productivity has been assessed across a wide range of farming systems and geographic regions (Bennett et al., 2012; Joensuu et al., 2019; Johnston & Poulton, 2018; Röös et al., 2021; Yang et al., 2021), but studies of crop performance do not always account for environmental impacts (Brisson et al., 2010; Major et al., 2010; Palosuo et al., 2011; Rempelos et al., 2020). While crop yield is an important indicator (Van Ittersum et al., 2013), yields are not always comparable between sites and production systems, and the food value of different crops can vary widely even if yields are similar. An alternative way of comparing crop value is to address it in terms of the human-edible protein, fat, starch and sugar that contrasting farming systems produce (Górska-Warsewicz et al., 2018; Röös et al., 2021).

The usage of synthetic fertilisers can aid crop yield stability, quality and stress tolerance (Macholdt et al., 2019). Organic amendments may also be used to supply and recycle nutrients; there are many available, with varying nutrient compositions and implications for management (Powlson et al., 2012). Compared to using organic amendments with fertilisers on their own, combining applications has been shown to improve yield stability (Macholdt et al., 2019). Moreover, the use of synthetic nitrogen fertiliser can have negative environmental impacts, so offsetting it with organic amendments or the cultivation of legumes has been suggested as a more sustainable means of nitrogen supply (Alford et al., 2018; Burri et al., 2019; Yin et al., 2020). Grain legumes provide high concentrations of plant-derived protein sources, so they are of interest to policymakers for future human consumption (Sajeev et al., 2020). There are concerns regarding the cultivation of legumes due to the depletion of soil nutrients other than N and poorer yield stability (Cooper et al., 2018; Cormack, 2006; Reimer et al., 2020). While legumes supply plant-available N to the soil, they do not provide P or K, thus systems that solely utilise legumes to cycle nutrients are liable to lose P and K over time (Cormack, 2006). Yields in systems with no synthetic fertiliser inputs are also lower than in farming systems that utilise fertiliser regardless of alternative means of nutrient supply (Barbieri et al., 2017; Cuvardic et al., 2004).

Soil fertility assessments, greenhouse gas emissions, water use efficiency and nutrient budgets are all used as indicators of environmental sustainability (Delate et al., 2015; Nesme et al., 2012; Råberg et al., 2018; Tenuta et al., 2019; Tricase et al., 2018; Yang et al., 2021). Nutrient budgets account for inputs and losses as well as providing overall balances (Reimer et al., 2020). They can be used to investigate the long-term viability of farming systems (Bassanino et al., 2007; Gadermaier et al., 2012; Råberg et al., 2018; Watson et al., 2006) and can be loosely categorised into farmgate and soil surface. Farmgate nutrient budgets consider the purchases and sales of nutrients onto and off the chosen farming system, thus the broad-scale implications of farm nutrient management (Oenema et al., 2003). Soil surface budgets account for the nutrients entering the surface of the soil and leaving the soil via crop uptake or leaching (Shober et al., 2017). A limitation of all forms of nutrient budgets is that inputs from biological N fixation are difficult to accurately estimate, so they create uncertainties (Einarsson et al., 2018; Merfield & Kennedy, 2008). Further uncertainty arises when large-scale nutrient budgeting is attempted due to field and farm management variability, but by budgeting at small plots or field scales the system can be well controlled and recorded, thus improving the accuracy of the data utilised in the budget (Oenema et al., 2003). On the other hand, national-scale budgets can identify large areas of unbalanced nutrient management, but they can incur large uncertainties (Pathak et al., 2010).

Our aim was to use budgeting methodologies (1) to assess whether fertilisation, organic amendment additions or crop rotation design (e.g., legume and livestock inclusion) had greater effects on food production (defined as edible protein, fat, starch and sugar produced); (2) to quantify the protein, fat, starch and sugar production achieved through both crop and livestock production; (3) to construct farmgate nutrient budgets of N, P and K for each of the systems studied and (4) to create an indicator derived from both these metrics: the nutrient use efficiency of macronutrient production (NutUE). This has previously been assessed as a unit of yield obtained per unit of applied fertiliser or partial factor productivity (van Zanten et al., 2016). Nutrient use efficiency results enable the value of human-edible macronutrients to society (Coomes et al., 2019) to be weighed alongside the desirability of achieving balanced nutrient management

(Watson et al., 2006) in a single measure. We assess six different rotational farming systems from two field sites in the United Kingdom. The chosen rotations represented a broad range of management options and are used to assess their ability to balance human macronutrient production with sustainable nutrient management. We hypothesised that legume-supported rotations would show deficits of P and K in their nutrient budgets, as has been found previously (Ohm et al., 2017), as compared with rotations that received recommended amounts of synthetic fertiliser inputs. The inclusion of a stockless, legume-supported rotation further allowed our analysis to compare a completely plant-based farming system with rotations using animal-derived products as nutrient sources.

2 | METHODS

2.1 | Experimental design

In this analysis, data from two field experiments were used: one legume supported (and managed according to the standards of the organic certification body of Soil Association) and other conventionally managed arable. The sites were the Tulloch rotations trial (subsequently referred to as Tulloch) in Aberdeenshire (57°10′33″ N, 002°15′33″ W), managed by Scotland's Rural College (SRUC), and the New Farming Systems Manure and Organic Replacement Experiment (subsequently referred to as MORE) in Norfolk (52°32′50″ N, 001°02′18″ E), managed by the National Institute of Agricultural Botany (NIAB). The sites have different soil conditions and climates (Table 1). Mixed legume-supported rotations, grazed by sheep, were established at Tulloch in 1991. In 2007, the rotations were split into two mixed legume-supported rotations and two stockless (Table 2). The mixed system was described in detail by Watson et al. (2011), and the stockless by Ball et al. (2014). Twelve years of data from the mixed and stockless legume-supported rotations at Tulloch, along with 8 years of data from MORE were used in the analysis.

Tulloch was arranged in two blocks. Within each block, there is a replicate of each of the mixed and stockless legume-supported rotations. Within each rotation, there are six plots, containing a single phase (crop), and so the entire six-course rotation is represented across the plots in any given year. The order of the crops cultivated in each plot is determined by the rotation design. All crops are spring sown.

In the mixed, legume-supported rotation, during periods of grass and clover ley and the undersown oats post-harvest (Year 6), a double plot area was used for grazing a small flock of 4–6 sheep, while silage yields are obtained for each plot. Livestock units (LUGD) were recorded across each double plot and grazing pressure was assumed to be equal. The silage was used as feed and the straw from the cereals was used as bedding by a herd of organic beef cattle on the farm. The resultant organic cattle manure was spread onto the plots. In the mixed, legume-supported rotation, the 2nd year grass and white clover ley received annual additions of organic cattle manure mixed with straw at 16 t ha^{-1}, the 3rd year grass received 10 t ha^{-1} to help balance silage offtake and the swedes received 12 t ha^{-1} (Table 3). In the stockless legume-supported rotation, the grass and red clover mix cultivated in the ley period were cut and mulched several

TABLE 1 The locations, soil types and typical performance of the Tulloch and MORE field experiments

Experiment name	Tulloch organic experiment	New farming systems manure and organic replacement experiment
Years of data	12	8
Time period	2008–2019	2012–2019
Latitude/Longitude	57°10.5′ N/2°15.7′ W	52°33.4′ N/1°01.38′ W
Mean min–max annual temperature (°C)	5.1–11.8	7.7–13.2
Mean total annual rainfall (mm)	879	620
Soil WRB	Leptic podzol	Endostagnic Luvisol
Soil texture	Sandy loam	Sandy clay loam
Soil pH (in water)	6.0	8.1
Soil organic matter (%)	8.3	2.7
Mean spring barley yield (t ha^{-1})	5.1	8.5
Regional Benchmark Spring Barley yield (t ha^{-1})	6.4[a] (Conventionally managed, Scotland)	7.0[b] (Conventionally managed, SE England)

[a]Rural and Environmental Science and Analytical Services.

[b]AHDB Cereals and Oilseeds (2018).

TABLE 2 The cropping sequences at the Tulloch and MORE field experiments, where rotation is not specified all cropping sequences are the same at that site

Year	Tulloch: Mixed A	Tulloch: Mixed B	Tulloch: Stockless A	Tulloch: Stockless B	MORE
1	Grass and white clover (*Lolium perenne* *Linnaeus/Phleum pratense* L./ *Trifolium repens* L.)	Grass and white clover	Grass and red clover	Grass and red clover	Winter wheat
2	Grass and white clover	Grass and white clover	Potato (*Solanum tuberosum* L.)	Spring Wheat undersown with white clover	Sugar beet (*Beta vulgaris* L.)
3	Grass and white clover	Grass and white clover	Spring Wheat (*Triticum aestivum* L.) undersown with white clover	Potato	Spring pea (*Pisum sativum* L.)
4	Spring Barley (*Hordeum vulgare* L.)	Spring Oat	Spring Bean (*Vicia faba* L.) undersown with white clover	Spring Bean undersown with white clover	Winter wheat
5	Swede (*Brassica napus* L.)	Swede	Spring Barley undersown with white clover	Spring Barley undersown with white clover	Winter oilseed rape (*Brassica napus* L. ssp. oleifera Metzg.)
6	Spring Oat (*Avena sativa* L.) undersown with grass and white clover	Spring Oat undersown with grass and white clover	Spring Oat undersown with grass and red clover	Spring Oat undersown with grass and red clover	Winter wheat
7					Sugar beet
8					Spring barley

times during the season prior to incorporation the following spring. All crop residues in the stockless, legume-supported rotation were chopped and ploughed into the field in autumn to a 20 cm depth.

At MORE, all plots were under the same rotation, and the same crop was grown across the entire site each year (Table 2), but with different organic amendment additions, namely green-waste compost, turkey manure or paper crumble and an unamended control. Management was further subdivided into plots that received augmented applications (every 3 years) and diminished applications (once) of amendments. For those plots with diminished applications, amendments were applied in autumn in 2011 only, and for augmented plots, further applications were also made in 2014 and 2017. All plots in the MORE experiment also received additions of synthetic fertiliser throughout the year (Table S1). All crop residues at the MORE experiment were incorporated in the autumn by ploughing the field to a depth of 20 cm. The flat fertiliser rate at all plots at MORE was intended to ensure that all plots had commercially viable yields, while the rates and applications of organic amendments were intended to manage soil properties under contrasting nutrient delivery options.

Spring barley was grown in both the stockless and mixed rotations at the Tulloch experiment and across all treatments of the MORE experiment in 2019. Table 1 shows the benchmark regional yield figures of spring barley in 2019 at both sites as a means of comparing yield performance across the experiments. Regional benchmark figures were unavailable for organic management in the United Kingdom, so the benchmark used for Tulloch was a comparison derived from conventional management.

2.2 | Nutrient budgeting

A farmgate nutrient budget was constructed for N, P and K in each of the rotations. The system boundaries of the budgets were established as the field area occupied by each rotation (Figure 1), thus any N, P or K that was brought onto or taken off the field was considered to contribute to the budget (Einarsson et al., 2018; Nesme et al., 2012; Reimer et al., 2020). The amount of biologically fixed N was estimated for each legume crop using figures published in previous literature and records of yield (Table 4). The contribution of agricultural inputs was accounted for through compositional analysis of the organic amendments and other additions to the field experiments. For commercial fertilisers, records of field management and application rates were used.

The livestock that grazed on the Tulloch plots were considered as being inside the farmgate system, as they

TABLE 3 N, P and K content of the organic amendment additions based on standard moisture content

Experiment	Organic amendment	DM (%)	N content (kg/t DM)	P content (kg/t DM)	K content (kg/t DM)
Tulloch rotations trial (Tulloch)	Cattle manure	20.67	5.80 ±0.27	2.61 ±0.13	6.51 ±0.36
New Farming Systems Manure and Organic Replacement Experiment (MORE)	Green waste compost	61.8	8.16 ±1.15	3.8 ±0.09	5.60 ±0.31
	Paper crumble	59.1	2.84 ±0.25	0.68 ±0.06	0.23 ±0.07
	Turkey manure	40.7	25.08 ±2.54	15.95 ±0.82	13.7 ±5.50

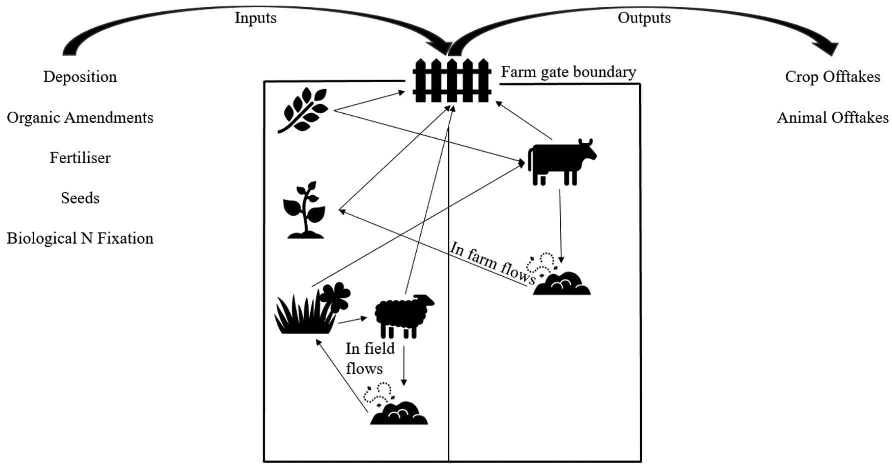

FIGURE 1 An illustration of the system boundary of the farm-gate nutrient budgets used

did not receive any additional feed inputs while grazing during the field experiment, and their manure and urine did not leave the plots (Figure 1). The following equation (adapted from Łukowiak et al., 2016) was used to calculate farmgate nutrient budgets:

$$Nut = \left(I_{dep} + I_{seed} + I_{agr} \right) - \left(L_{oft} \right) \quad (1)$$

where *Nut* is the annual balance of the given nutrient ($kg\,ha^{-1}$), I_{dep}, I_{seed} and I_{agr} are annual nutrient inputs ($kg\,ha^{-1}$) from deposition, seeds and agricultural inputs (manure, organic amendments and fertilisers) respectively, comprising the total nutrient inputs under the farmgate budgeting system, and L_{oft} is annual nutrient output ($kg\,ha^{-1}$) via crop and animal offtakes, calculated by multiplying the recorded yield at 100% dry matter (DM) by the nutrient concentration. Deposition estimates were derived from UK AIR Critical Load maps of N and P at each location (Department for Environment Food and Rural Affairs, 2014). The maps were composed of 5×5 km grids and the average N and P deposition rates in the squares corresponding to the field experiment were used.

To assess the nutrient value of the cattle manure applied to the mixed rotation at Tulloch, three subsamples of soil were collected from each plot on the day of the application using a Dutch auger to a depth of 10 cm. When all plots had been sampled, the subsamples were manually mixed into a total of three composite samples for analysis (Table 3). The N, P and K content of archived crop samples were analysed to estimate offtakes of these elements, with literature figures used when crop samples were not available (Table S2). Samples were collected in the field, dried, ball-milled and stored in air-tight containers. N was determined using the Kjeldahl method (Ma, 2003). To ascertain crop P and K content, samples were digested in a weak acid solution using a microwave-assisted reaction system (MARS) and subsequently analysed using inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) (Sliman, 2021). The grain, root or seed components of the crop were analysed to estimate N, P and K offtake in the case of the stockless legume-supported system, omitting crop residues because they were chopped and reincorporated into the field. In the mixed, legume-supported system, recorded straw yields ($t\,ha^{-1}$) were used to calculate the N, P and K offtake from the straw, which was subsequently used as bedding for the cattle and incorporated into the cattle manure additions.

The nutrient composition of organic amendment additions at MORE had been previously analysed for N, P and K content in 2011, 2014 and 2017 (Table 3).

TABLE 4 Total N, P and K inputs, offtakes and balances (kg ha^{-1}) from each rotation annually (6 years organic and 8 years conventional)

	Legume supported		Synthetically fertilised			
Rotation	**Mixed**	**Stockless**	**Green waste compost**	**Paper crumble**	**Turkey manure**	**Unamended**
Nitrogen (N)						
Seeds	3	9	6	6	6	6
Deposition	15	15	20	20	20	20
Biological fixation	*50*[1]	*78*[1,2]	*36*[3]	*37*[3]	*23*[3]	*32*[3]
Fertiliser			116	109	118	114
Amendment	33		404	203	241	
Total N inputs	100[d]	101[d]	581[a]	374[b]	408[b]	172[c]
Crop offtake	47	43	190	183	188	185
Animal offtake	2.6					
Total N offtake/% of inputs	49[b]/49	43[b]/42.6	190[a]/32.7	183[a]/48.9	188[a]/46.1	185[a]/107.6
N Balance/% of inputs	51[c]/51	58[c]/57.4	91[a]/67.3	191[b]/51.1	219[b]/53.7	−13[c]/−7.6
Phosphorus (P)						
Seeds	2	2	3	3	3	3
Deposition	0.3	0.3	0.3	0.3	0.3	0.3
Fertiliser			3	3	3	3
Amendment	10		24	5	30	
Total P inputs	12[b]	3[d]	30[a]	12[b]	37[a]	7[c]
Crop offtake	13	9	20	18	20	19
Animal offtake	0.2					
Total P offtake/% of inputs	13[c]/108.3	9[b]/300	20[a] /66.7	18[a]/150	20[a]/54.1	19[a]/271.4
P Balance/% of inputs	−1[b]/−8.3	−6[c]/−200	11[a]/36.7	−6[c]/−50	17[a]/45.9	−12[c]/−171.4
Potassium (K)						
Seeds	9	13	9	9	9	9
Fertiliser			24	24	24	24
Amendment	24		66	3	64	
Total K inputs	33[b]	13[c]	99[a]	36[b]	97[a]	33[b]
Crop offtake	46	23	41	39	41	40
Animal offtake	0.2					
Total K offtake/% of inputs	46[a]/139.4	23[b]/176.9	41[a]/41.4	39[a]/108.3	41[a]/42.3	40[a]/121.2
K Balance/% of inputs	−13[c]/−39.4	−10[c]/76.9	58[a]/58.6	−3[b]/−8.3	56[a]/57.7	−7[c]/21.2

Italic values derived from published literature (the literature in question is specified in superscript letters 1, 2, 3 in Table 4).

Within a row, values which share a superscript letter (a, b, c, d) were not significantly different ($p = < 0.05$, Bonferroni correction).

[1]Derived from Briggs et al. (2015).

[2]Derived from Fan et al. (2006).

[3]Derived from Mckay et al. (2003).

2.3 | Calculating human macronutrient value of offtakes

Human macronutrients are defined in this study as the protein, fat, starch and sugar content of the crops. Crop yields at 100% DM (a harvestable component in t ha^{-1}) were used to calculate annual protein, fat, starch and sugar offtake from each rotation. The outputs gave an indication of the potential food value of the recorded yields.

2.3.1 | Crude protein

Kjeldhal N was converted into crude protein by multiplying it by the appropriate factor (Table S4):

$$CP_{yield} = N_{yield} \times N_{conv} \tag{2}$$

where CP_{yield} is crude protein (t ha^{-1}), N_{yield} is N yield of the crop (t ha^{-1}) and N_{conv} is the N conversion factor.

Crop-specific conversion factors were used in the analysis (Food and Agriculture Organisation of the United Nations, 2002; Table S4). The yield was converted into 100% DM prior to the calculation of protein offtake.

2.3.2 | Fat, starch and sugar

Data on fat, starch and sugar content were largely obtained from Feedipedia (INRAE, CIRAD AFZ & FAO, 2018) to ensure consistency in the source material, but where information was not available alternative sources were used (Table S4). To calculate the fat component of crop offtake, the following equation was used:

$$F_{crop} = F_{lit} \times Y \tag{3}$$

where F_{crop} (t ha^{-1}) is the fat component of crop offtake, F_{lit} (%) is the literature value of the fat content of the corresponding crop and Y (t DM ha^{-1}) is the yield at 100% DM. For the starch and sugar content, the same calculation was carried out using the literature value of the starch and sugar content (Table S4) as opposed to the fat content.

2.3.3 | Livestock-derived macronutrient offtakes

The potential macronutrient value of grazing sheep on Tulloch was calculated using annually recorded livestock unit grazing days (LUGD) ha^{-1} from records of the sheep's age, sex and breed. Values assumed sheep were being grazed in preparation for slaughter. There were no supplementary feed inputs while the sheep grazed the experiment. The following equation was used to calculate the yield of human-edible meat from the sheep grazing the mixed legume-supported rotation:

$$Sheep_{meat} = W_{live} \times 35.24\,\% \tag{4}$$

where $Sheep_{meat}$ is the yield of human-edible meat (t ha^{-1}) from the sheep flock, W_{live} (kg) is the live weight of the grazing sheep derived from farm management records and 35.24 is the percentage of the live weight which is meat (AHDB, 2020). This $Sheep_{meat}$ figure was the basis for the calculated human-edible protein, fat, starch and sugar offtake provided by the grazing sheep in the mixed legume-supported rotations. Equation (5) was used to calculate the human-edible macronutrient composition of the sheep meat offtake:

$$Mnut_{sheep} = Sheep_{meat} \times Mnut_{comp} \tag{5}$$

where $Mnut_{sheep}$ is the human macronutrient offtake (t ha^{-1}), $Sheep_{meat}$ is the yield of human-edible meat (t ha^{-1}) and $Mnut_{comp}$ is the composition of the given macronutrient to be calculated (%), in this analysis either protein, fat or starch and sugar (Table S4).

In the mixed, legume-supported rotation, two cuts of silage were generally taken from the 2nd year ley plots and one cut from the 3rd year ley plots. This silage was fed to the same organic beef cattle herd that supplied the mixed plots with manure. To account for this production in terms of its contribution to food security, it was necessary to calculate the contribution that the silage made to the production of protein, fat, starch and sugars in the cattle herd. Records of farm management were used to determine the age, weight and breed of the cattle herd, as well as the length of time that they were kept on the farm (Table S3).

The contribution of silage to the weight of the calves was of most interest to our analysis as the calves were the component of the herd that was sold into food production. The farm targeted a daily weight gain of 0.7 kg for all calves, reflective of their native type. A mixture of calves that were entirely raised on the farm and weaned calves bought in at a later date were raised on the farm to be sold into meat production at 20 months of age. To convert the silage yields recorded annually into kg calf weight gained, Equation (6) was used:

$$A = \left(\frac{S_{tot}}{S_{day}}\right) \times \left(F_{sil} \times W_{day}\right) \tag{6}$$

where A is the calf weight (t ha^{-1}) gained from fed silage, S_{tot} is the total annual silage yield (t ha^{-1} fresh weight), S_{day} is the daily silage ration fed to each calf (t fresh weight), F_{sil} is the percentage of the calves' total metabolisable energy consumption that comes from their silage ration (70%) and W_{day} is the target daily weight gain for each calf (t). The cattle meat percentage was 40% (AHDB, 2020; Toušová et al., 2018). We multiplied A by the meat percentage to correct for the human-edible component of the weight gain of the calves and then multiplied this figure by the percentage of protein and fat to ascertain the final food value of the weight gained by the cattle that were fed the silage from the mixed rotation (Table S4).

2.3.4 | Human macronutrient production from rotational nutrient applications

To provide an indicator of the human nutritive value that each rotation was able to produce from nutrients applied, the calculated protein, fat and starch and sugar production was divided by the total N, P and K inputs that were utilised in the farmgate nutrient budgets. Each combination of human macronutrient and nutrient input was calculated separately and according to rotation management. In each case, Equation (7) was used:

$$NutUE = \frac{M_{human}}{Nut_i} \quad (7)$$

where M_{human} was the human macronutrient produced (kg ha^{-1}), protein, fat, starch or sugar, and Nut_i was the total input of nutrient (kg ha^{-1}) applied to each rotation. Results were expressed as *NutUE*, which was the total kg of food produced per kg of nutrient applied, *NutUE* (kg kg^{-1}).

2.3.5 | Food value of crop by-products

Oilseed rape and sugar beet were included in the cropping sequence of the conventional rotations included in this analysis. Although they produce human-edible products, the by-products from the processing of both crops are commonly utilised as livestock feeds, which also contribute nutrients to the wider system. The proportion of recorded yields that would be by-products typically utilised in animal feed production was calculated from industry figures (Table 5). Nutritional values of animal feed products were derived from industry and literature figures and used to calculate their potential contribution to livestock nutrition in the form of ruminant metabolisable energy (MJ ha^{-1}) (Table 5).

2.4 | Statistical analysis

Analysis was conducted in R 4.0.4 (R Core Team, 2019). The function lmer in the lme4 package (Bates et al., 2015) was used to create the models while the tidyverse package (Wickham et al., 2019) was used for data manipulation and graphing. Data were normalised by scaling to a mean of 0 and dividing by 1 standard deviation before running the models to ensure comparability of effect sizes. Results were subsequently back-transformed for predictions. The models assessed the effect of rotation management on macronutrient production. Analysis was conducted in two stages. Stage 1 was to determine the total rotational output of macronutrient offtake, and the second stage of the analysis was a comparison solely of crops that were the same across all rotations. For the Stage 1 analysis, the crop was not included as a fixed effect, while in the Stage 2 analysis, both rotation and crop were considered as fixed effects. The structure of the random effects for Tulloch (Equation 8) was rotation nested within the block and the year was crossed. For data from MORE (Equation 9), all plots were under the same rotation, so the amendment was a fixed effect, while random effects were rotation nested within augmented/diminished (aug_dim), and year. Both models used macronutrient offtake as the explanatory variable.

$$A \sim R + C + (1|Y) + (1|Y:B) + (1|Y:B:R) \quad (8)$$

$$A \sim M + C + (1|Y) + (1|Y:B) + (1|Y:B:Au) \quad (9)$$

where A is the variable to predict nutrient balances and crop macronutrient production, R is the rotation, C is the crop, B is the block, Y is the year, M is the amendment management and Au is whether management incorporates augmented or diminished amendment additions, specific to the MORE experiment. After checking model outputs and residual plots, predictions of protein, fat, starch and sugar content as well as inputs, outputs and balance of nutrients were calculated for each of the four rotations at Tulloch and the organic amendments at MORE. The p values generated in the analysis were adjusted using the Bonferroni procedure to correct for multiple comparisons.

3 | RESULTS

3.1 | Nutrient budgets

Input N in the green-waste compost amended rotation was greater than all other rotations, more than five times

TABLE 5 The amounts and potential livestock feed value of crop by-products from the MORE rotation systems

Amendment	Mean sugar beet pulp feed produced (t ha^{-1})[a]	Mean ruminant Metabolisable energy (MJ ha^{-1})[b]	Mean rapeseed meal produced (t ha^{-1})[c]	Mean ruminant Metabolisable energy (MJ ha^{-1})[b]
None	1.52 ± 0.31	170 ± 35	2 ± 0.6	243 ± 70
Paper crumble	1.48 ± 0.43	166 ± 48	2.1 ± 0.9	231 ± 94
Green waste compost	1.57 ± 0.45	176 ± 51	2.3 ± 0.9	249 ± 102
Turkey manure	1.52 ± 0.44	171 ± 49	2.3 ± 1.0	251 ± 102

[a]British Sugar (2021).

[b]INRAE, CIRAD, AFZ and FAO (2018).

[c]Rymer and Short (2003).

larger than the legume-supported rotations, while output N in all rotations that received synthetic fertiliser was four times greater than from either of the legume-supported rotations (Table 4). N balances showed large surpluses of N in the rotations with organic amendments. Surplus N in the green-waste compost amended rotation was greater than that in the paper crumble or turkey manure amended rotations, which did not significantly differ in their N balance (Table 4). The legume-supported and unamended rotations did not differ significantly in their N balances.

Input P in green-waste compost and turkey manure was greater than in paper crumble or unamended rotations, while input P in the stockless rotation was less than in the mixed rotation (Table 4). P outputs were consistent, with only 11.2 kg ha^{-1} in the difference between the highest P output of the turkey manure amended rotation and the lowest P output of the stockless rotation (Table 4). P balances showed that deficits in mixed rotations were smaller than those in paper crumble, unamended and stockless rotations, while surpluses were found in green-waste compost and turkey manure amended rotations.

Input K in the green-waste compost and turkey manure amended rotations was greater than all other rotations. K outputs from the mixed rotation were greater than those from all other rotations. Balances showed green-waste compost and turkey manure had surpluses of K, while deficits in paper crumble were smaller than all other rotations.

3.2 | Macronutrient offtakes

Animal feed production and the food value of the by-products of the sugar beet and oilseed rape did not vary across the rotations (Table 5). Macronutrient offtakes were greater in the rotations that received fertiliser than in the legume-supported rotations. Predicted protein offtakes were more than three times greater in farming systems that received fertiliser than those which did not (Figure 2). The predicted protein offtake in the stockless rotations was higher than the mixed rotations. Predicted fat offtakes were greater in fertilised farming systems than in legume-supported systems (Figure 2). The mixed rotations were found to provide at least twice as much fat offtake as either of the stockless rotations. There were no significant differences in fat offtake between the rotations that received fertiliser. Farming systems that received fertiliser were found to provide at least twice as much starch and sugar offtake as was produced from the legume-supported systems, and organic amendment made no further difference. No significant differences in starch and sugar production were found between the mixed and stockless rotations. Variability of offtakes was higher in the MORE rotations due to greater rotational diversity in the years of cropping studied, with a wider range of crops cultivated and no years of leys.

3.3 | Nutrient use efficiency of rotational macronutrient production

Across all nutrient use efficiencies, there were no differences found between the mixed and stockless rotations. The N use efficiency of protein, starch and sugar production in the unamended rotations was twice that of the green-waste compost, turkey manure and legume-supported stockless rotations (Table 6). Production of fat per kg of applied N in the mixed rotation was significantly higher than that from green-waste compost, paper crumble and unamended rotations. Fertiliser-receiving rotations all achieved at least five times higher P and K use efficiencies than the legume-supported rotations (Table 6). The macronutrient production of the unamended conventional rotation had the highest overall nutrient use efficiency of any of the rotation systems in eight of the nine parameters, significantly so in the case of protein, starch and sugar P use efficiency and starch and sugar K use efficiency.

4 | DISCUSSION

Rotations that received synthetic fertiliser produced at least twice the amount of protein, starch and sugar per unit area than the legume-supported rotations, as well as more fat. The consistent food production, achieved by the fertilised rotations, is expected given the greater yield stability of crops provided with balanced crop protection and nutrition (Macholdt et al., 2019). Because of the uniform cropping sequence at the MORE site, nutrient balances and NutUE were driven by nutrient supply. Lower yields in legume-supported rotations were unsurprising given the lower system inputs (Hallström et al., 2014). The geographical differences between the sites meant that directly comparing yields was not appropriate. It would be more appropriate to compare yields with regional benchmarks for organic and conventional systems where available (e.g., Ländell, 2022; Table 1). Including faba beans within the stockless rotation contributed to higher predicted protein, starch and sugar offtakes compared with the mixed rotation, highlighting the important role grain legumes could play in human nutrition going forward due to their high protein content and N-fixing properties (Zander et al., 2016). In Europe, the adoption of grain legumes is poor compared to cereals and oilseeds due to their relatively low productivity and low economic gains based on

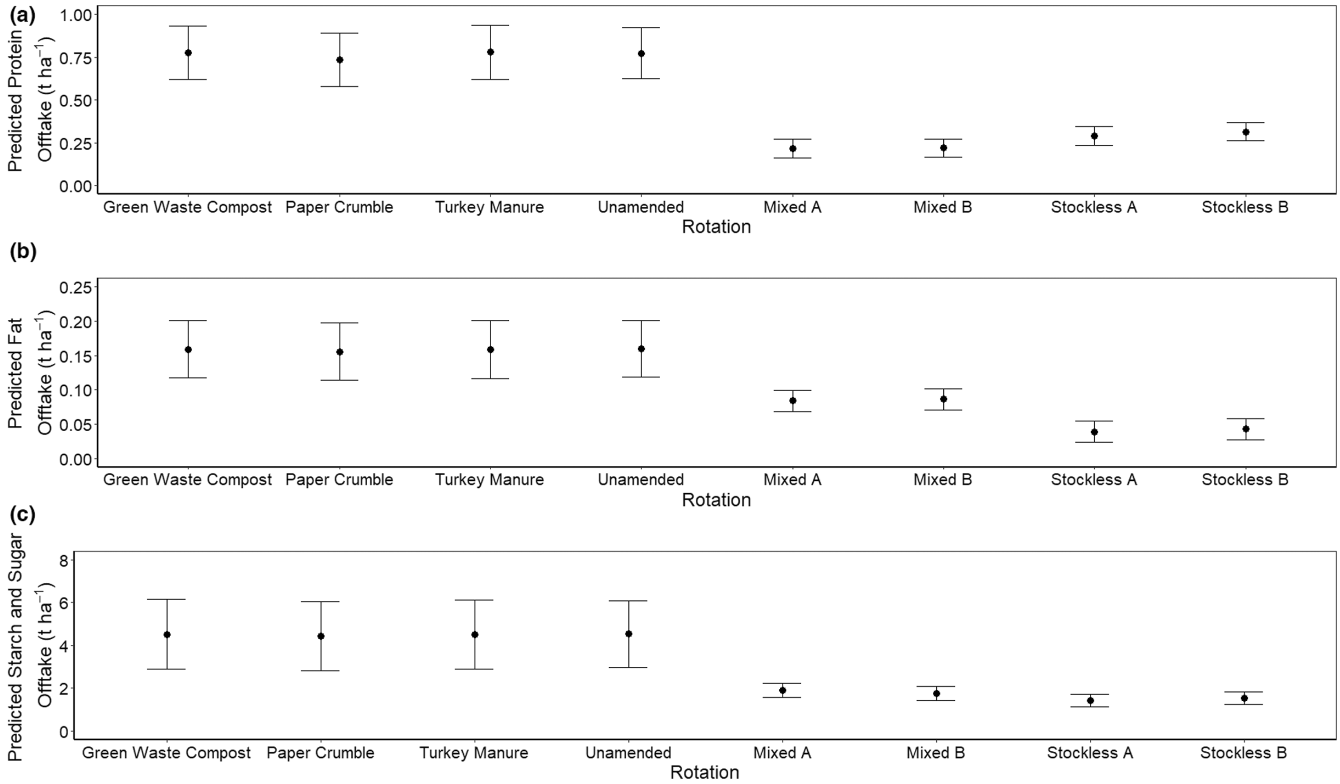

FIGURE 2 The predicted crude protein (a), fat (b), starch and sugar (c) offtake from the rotations analysed. Error bars are 0.95 confidence intervals

their offtake alone (Zander et al., 2016). However, the cereal yield gains achievable through the inclusion of grain legumes in cropping sequences have been documented in European experiments (Preissel et al., 2015) and they are a potential future lynchpin of food protein production (Manners et al., 2020).

N accumulation from biological fixation combined with low food production (Figure 2) drove lower N use efficiencies in legume-supported rotations (Pandey et al., 2017). The N inputs, losses and balances from the nutrient budget are total N, thus the form of the N added, its bioavailability and the implications of its addition on the soil structure and microbial community differ according to the inputs. Crops produced without synthetic N have lower yield stability regardless of other management factors, including organic amendments and cropping sequences (Macholdt et al., 2020). The production of harvestable crops in the stockless rotation (5 years of 6) mean N losses from the stockless rotation were higher than in the mixed, where crops were harvested in only 3 of the 6 years. N balances in the rotations with fertiliser reflected both the fertiliser applications and differences in the N content of organic amendments. In all synthetically fertilised rotations, higher yields drove higher N offtakes. Within each site, yield-derived differences in rotational N offtake were small compared with differences in N inputs from contrasting fertiliser and amendment applications (Table 4). Green manure amendments, like those in the stockless legume-supported system, can improve the environmental resilience and performance of crops cultivated in stockless rotations (Degani et al., 2019; Welsh & Philipps, 1999).

Legume-supported rotations had deficits of P and K, consistent with previous findings in organic, legume-supported farming systems (Cooper et al., 2018; Reimer et al., 2020). This was reflected in their lower P use efficiency compared with synthetically fertilised rotations. The deficits and surpluses of P and K reflected the nutrient contents of the amendments and fertilisers (Table 4). These findings reflect a global trend in P deficits of arable farmland that is driven by both reliance on mineral P inputs (Alewell et al., 2020) and legislative constraints upon the application of P to agricultural land (Amery & Schoumans, 2014).

The K deficit in mixed rotations was due to a greater overall K offtake, from the 3 years of crop production in the mixed rotation as opposed to the 5 years of production in the stockless rotation (Table 2). Composition and application of the organic amendments drove K balance differences in synthetically fertilised rotations. The K content of green waste compost and turkey manure drove modest annual surpluses in rotations that received these amendments compared to those which received paper crumble (Table 3). K surpluses are not subject to the same legislative

TABLE 6 The nutrient use efficiency of all the rotational management systems, nutrients applied and human macronutrient values calculated from yields

Rotation	Nitrogen use efficiency (kg food/kg applied N)			Phosphorus use efficiency (kg food/kg applied P)			Potassium use efficiency (kg food/kg applied K)		
	Protein	Fat	Starch and sugar	Protein	Fat	Starch and sugar	Protein	Fat	Starch and sugar
Legume supported									
Mixed	4.6^{c}	2.1^{a}	27.4^{c}	83.6^{c}	41.3^{b}	360.5^{c}	62.9^{b}	30.7^{b}	368.7^{c}
Stockless	6.7^{bc}	1.6^{a}	48.7^{b}	137.4^{c}	26.7^{b}	748.3^{c}	123.8^{b}	28.1^{b}	710.9^{c}
Synthetically fertilised									
Green waste compost	10.6^{ab}	1.1^{a}	75.0^{ab}	520.7^{b}	205.5^{a}	3464.3^{b}	1787.0^{a}	2837.0^{a}	3815.7^{b}
Turkey manure	11.0^{a}	1.2^{a}	84.5^{a}	547.5^{b}	206.7^{a}	3461.6^{b}	1915.0^{a}	2882.31^{a}	3863.8^{b}
Paper crumble	10.3^{ab}	1.2^{a}	77.7^{ab}	496.2^{b}	211.3^{a}	3397.2^{b}	1746.7^{a}	2964.21^{a}	3762.0^{b}
Unamended	13.3^{a}	1.7^{a}	104.2^{a}	771.9^{a}	226.1^{a}	5177.0^{a}	2059.7^{a}	2770.0^{a}	5773.0^{a}
F	17.11	2.432	22.78	97.52	30.63	101.3	37.52	19.82	104.7
Residual df	5 882	5 882	5 882	5 882	5 882	5 882	5 882	5 882	5 882
p	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Note: Within a column, values which share a superscript letter were not significantly different ($p = <0.05$, Bonferroni correction).

interest as N or P because K does not contribute directly to eutrophication, thus is not considered an environmental hazard in the same manner (Alfaro et al., 2008). Deficits nonetheless represent an economic loss to farmers as well as potential declines in soil fertility. Surpluses of K may be retained in the active layer of the soil by clay minerals and organic matter (Pavinato & Rosolem, 2008). Arable systems are at greater risk of K losses than pastures (Pavinato & Rosolem, 2008). Our analysis showed that K removal via silage led to deficits in rotations with leys but without external inputs (Table 4).

Findings highlighted the contribution of animal-derived co-products to agricultural systems in terms of both nutrient management and agronomic performance. The mixed rotation produced almost twice the amount of fat as the stockless rotation due to the inclusion of livestock (Table S4), and organic systems have traditionally relied upon animal-derived products as soil conditioners (Pandey et al., 2017). In-field cycling of nutrients took place in mixed rotation ley plots, in which nutrient losses through in-field grazing were returned in the form of dung and urine distributed by grazing livestock (Alves et al., 2019). In-field cycling was not included in the farmgate nutrient budget as it took place within the field, however, budgets captured an on-farm livestock loop formed through the return of offtake silage and cereal straw as cattle manure on selected mixed plots. Synthetically fertilised rotations formed part of an even larger-scale livestock loop, as the oilseed rape and sugar beet co-products contributed to the production of animal feed (Table 5) that was utilised off-site. The off-farm livestock that provided manure to the conventional rotations were potential consumers of the animal feed produced in these systems. There are, however, options for improving on-farm productivity that are not directly dependent on the livestock industry. Green-waste compost can improve long-term crop performance and soil health (Lehtinen et al., 2017), although its usage is restricted due to concerns regarding potential contaminants (Gibbs et al., 2005). In our analysis, the paper crumble was on par with other organic amendments in terms of nutrient use efficiency, but it has not been extensively researched (Bhogal et al., 2008). Its application may increase soil carbon stocks in the long term as well as ensure nutrient availability to crops (Powlson et al., 2012).

Evaluating each rotation only in terms of food production would have overlooked key differences between systems. While productivity was similar and nutrient use efficiency lower in amended compared with unamended rotations, the contribution of amendments to the farming systems was reflected in the nutrient budgets. While the present analysis was at the farm level, findings sit within a global context. The EAT-Lancet Commission's 2019 report stated that any increase in global livestock production should be considered unsustainable (Willett et al., 2019). There is a growing body of research highlighting long-term sustainability of livestock-free farming systems and dietary choices (Harwatt et al., 2017; Merfield & Kennedy, 2008; Sajeev et al., 2020). The livestock-free farming systems in this analysis produced higher human-valuable offtakes in general than the mixed systems that incorporated livestock. Nevertheless, livestock produces food-quality protein and fat from crops not otherwise used for food (Joensuu et al., 2019). Field trial-based European studies have also found that integrating fertilisation with organic amendment applications led to consistently higher agronomic performance than crops treated with only one or the other (Macholdt et al., 2019; Sihvonen et al., 2021). This approach has also been applied to farming systems in the developing world (Abid et al., 2020; Qazi & Khan, 2020), particularly in the cultivation of rice in which substantial improvements to crop performance and quality have been obtained through combining synthetic N additions with K inputs (Ye et al., 2021), retention and reincorporation of residues (Tang et al., 2021). An important next step is to connect findings from the efficiency index to soil quality. This will contribute to our understanding of the nutrient flows taking place in the field. There are promising prospects for future research in the application of integrated food value and nutrient budgeting calculations to a wider range of agricultural systems. Further work may use the approach to model the implications of future land management or policy changes, such as reduced use of fossil fuel-derived fertilisers or an increase in domestically grown protein crops. Future research may consider the stochiometric implications of nutrient applications, as opposed to treating applied nutrients as distinct from one another as in the present study. Furthermore, there is clear potential in scaling up this approach to regional and national scales due to the relatively simple and cost-efficient application, allowing an assessment of agricultural performance that accounts for the value of production and nutrient sustainability.

5 | CONCLUSIONS

The combining of food value and nutrient budgeting measures highlighted those rotations that received synthetic fertilisers had significantly higher food production and greater nutrient use efficiency overall than legume-supported systems without synthetic fertiliser. Efficiency calculations showed that integrating synthetic fertilisers with organic amendments in crop rotations led to greater nutrient use efficiency and balance in P and K, while N efficiency was greater in fertiliser-only systems. While legume-supported rotations had lower external inputs of nutrients, thus the appearance of better-balanced nutrient management in the budgets, the lower food value of production from these systems led to a lower nutrient use efficiency overall than those systems which received fertilisers. The reliance of the legume-supported systems on biological N fixation without attempting to adequately replace P and K meant that N use efficiencies were lower. The legume-supported rotations without livestock produced more protein, starch and sugar than those with livestock, which in turn produced more fat. This illustrates the potential value of including grain legumes as providers of plant-based protein in future farming systems. The contribution that livestock and their associated products make to UK agriculture was reflected in the nutrients supplied by cattle and turkey manure as organic amendments, as well as the production of food from otherwise inedible crops and residues. The integrated food value and nutrient budgeting approach allowed us to identify management systems that achieved both adequate food production and sustainable nutrient management in a manner that was easily comparable between highly different sites and systems. Findings overall provide an argument in favour of the inclusion of food value measures in further studies of agricultural nutrient management.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study from the SRUC trials are available from christine.watson@sruc.ac.uk, and the data from the NIAB trials are available from nathan.morris@niab.com upon reasonable request.

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