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Circularity of potassium in a grassland-based dairy farm on a clay loam soil

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ABSTRACT

A proportion of potassium (K) exits grassland-based dairy farms in tradeable products. Potassium imports are typically needed to offset depletion of soil reserves. The objectives of this study were to (i) quantify K entering and exiting a grassland-based dairy farm including K lost to water, (ii) to relate the balance between K entering and existing the farm to soil K fertility status in order to (iii) design a better K fertilisation strategy for grassland under temperate climatic conditions. The quantities of K entering and exiting a grassland-based dairy farm (Solohead Research Farm; 52°51'N, 08°21'W) were determined each year between 2005 and 2022. Potassium losses to groundwater were measured during the winters of 2020/21, 2021/22 and 2022/23. Averaged over 18 years, K entering (kg ha^{-1} ± standard error) was 82 ± 11 and exiting was 41 ± 4. The annual average farm K balance was 41 ± 12 kg ha^{-1} and ranged between −36 and 136 kg ha^{-1}. Annual K loss to groundwater (mean ± SE kg ha^{-1}) ranged between 6.9 ± 6.13 and 59 ± 7.4. Annual average soil test K (STK; following extraction using Morgan's solution (Na acetate + acetic acid, pH 4.8)) concentrations in paddocks across the farm ranged from 85 to 253 mg L^{-1}. The yearly change in average STK concentrations correlated with annual farm K balance in the preceding year (R^2=0.59; P<0.001). Annual farm-scale K budgets were useful in quantifying K flows in products and losses. Potassium leaching to groundwater represented the majority (55 %) of K exiting the farm; exceeding export of K in milk and other products. Maintaining overall farm STK status required annual fertiliser K inputs of 22.5 kg ha^{-1} between 2016 and 2022. This study elucidates the challenges in managing soil K fertility on grassland based dairy farms.

1. Introduction

Many soils have considerable capacity to make potassium (K) available for herbage production; e.g. O Donovan et al., (2022). Once this herbage is consumed by dairy cows very little is retained in products (milk and meat) and 99 % is recycled in excreta (Hutton et al., 1967; Williams, 1988; Aarons et al., 2020). Where herbage is harvested for silage and fed indoors most of the K in excreta is typically recycled to grassland via the application of slurry. It is also directly recycled in animal excreta under grazing. Considerable quantities of K are imported onto farms in concentrate and other feeds, in bedding and in other materials. Nevertheless, it is also often necessary to import artificial fertiliser K (AFK) onto farms to avoid a decline in soil K fertility (Keady and O'Kiely, 1998). This raises the question; if very little K is removed in products from a grassland-based dairy farm, why is it necessary to purchase AFK onto such a farm? Particularly since such purchases represent a considerable expense (White, 2013).

The efficiency of nutrient use within a dairy farm can be examined by accounting for the nutrient in question as it enters (in fertilisers, feeds and other inputs) and exits (in milk, meat and other products) the farm gate (Oenema et al., 2003; Schröder et al., 2003; Burchill et al., 2016). There have been many studies on nitrogen and phosphorus-use efficiency on dairy farms (Treacy et al., 2008; Ruane et al., 2014; Mihailescu et al., 2015), whereas K use efficiency (KUE) has been studied to a much lesser extent. Farm-gate balance sheets are relatively easy to compile (Williams, 1988). The set of accounts can be expanded to encompass other pathways such as K entering the farm in rainfall or exiting as leachate to groundwater.

Within the farm gate K fertilisation is sometimes managed at field scale on the basis of replacing offtakes in harvested herbage by inputs of slurry and AFK (Alfaro et al., 2004). In many countries a soil test is used to determine the capacity of a soil to supply plant available K; i.e. soil test K (STK). Calibrated soil testing results can be used to identify paddocks that are deficient in plant-available K or those with excessive

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levels. Hence, STK is typically an integral component of a decision support system whereby K fertilisation is customised to individual paddocks within a farm (Wall & Plunkett, 2016). One reason for inefficient recycling of K is the application of K to paddocks that already have high concentrations of STK. Such circumstances can lead to luxury uptake of K in herbage and depress uptake of calcium and magnesium (Hemingway, 1961), leading to problems such as hypomagnesaemia in dairy cows (Kayser and Isselstein, 2005; Lunnan et al., 2018).

The objective of the present study is to examine K use efficiency within a dairy farm (Solohead Research Farm) and ultimately answer the question raised above. The current work examines Farm-scale K Balances (FKB) compiled for each year between 2005 and 2022. Furthermore, K losses to groundwater were measured during the 2020/21, 2021/22 and 2022/23 drainage seasons. An equation using the latter measurements along with STK in the paddocks where the K leaching was measured and effective drainage in each drainage season was used to estimate K leaching loss across the farm in each of the earlier years. These losses to water along with K entering in rainfall were included in the FKB presented in this study. Hence, FKB is not the same as the farm-gate balances described previously. The impact of annual FKB (surplus or deficit) each year on the subsequent change in farm-average STK levels from year to year was examined. A field-plot scale study was conducted to examine the capacity of the soil on the farm to supply K for herbage production under a range of rates of AFK between 0 and 390 kg ha^{-1}.

2. Material and methods

2.1. Site description

This study was conducted at Solohead Research Farm, Co. Tipperary, Ireland (52°30’19”N, 08°12’34”W) and ground level is 96 m above sea level. Soils on the farm are comprised of poorly drained Gleys (90 %) and Grey Brown Podzolics (10 %) with a clay loam texture of 40 % sand and 29 % clay in the A1 horizon (Table 1). Soil organic matter was 13 %. Soil depth below the site is uneven ranging from 5 to 10 m and overlays Devonian Sandstone parent material. Topographic relief causes variation in shallow groundwater with the water table depth ranging from 0 to 2.2 m below ground level. Much of the farm area is seasonally wet or waterlogged, with poor permeability (Tuohy et al., 2016). The local climate is humid temperate oceanic with a long potential growing season (*circa* 10 months).

The farm has been used for grassland-based dairy production for over 50 years. It has been used for dairy systems research during the timeframe of this study (Phelan et al., 2014; Tuohy et al., 2016; Scully et al., 2021; Fenger et al., 2021). The overall farm average annual stocking rate was 2.37 livestock units (LU) ha^{-1}; ranging between 1.98 and 2.62 LU ha^{-1} (Table 2). The farm has been under permanent grassland for well over 50 years, with an average annual rate of reseeding of approximately 6 %. The farm was primarily used for grazing with surplus herbage conserved for silage for winter feed. Feed imported onto the farm, primarily in the form of concentrate typically accounted for <10 % of the farm feed budget each year on a dry matter (DM) basis.

2.2. Weather data collection

Soil temperature at 10 cm depth, volumetric soil moisture at 0.05 m depth and rainfall were recorded every 30 min at an automatic meteorological station on the farm (Campbell scientific Ltd, Loughborough, U. K.) from October 2020 to April 2023. Similar data were measured for each year between 2005 and 2019. Daily rainfall, maximum and minimum air temperatures, wind speed and solar radiation were used in the grassland hybrid model of Schulte (2005) to estimate daily effective drainage (ED) (mm day^{-1}) and soil moisture deficit (SMD) based on the moderately drained soil criterion. Daily ED was summed to calculate (i) weekly cumulative ED and (ii) total ED over the drainage season (October to April) each year, according to Necpalova et al. (2012).

2.3. Measurement of potassium leaching losses from the farm

Screened piezometers (HDPE pipes, internal diameter 19.6 mm were installed in 12 (out of 50) paddocks across the farm during the summer 2020. The piezometers were installed to 2.5 m below ground level using a soil pneumatic drill and accessed shallow groundwater. Four screened wells were installed within each paddock. Near the soil surface, the area between the soil and the pipe was filled with bentonite to prevent water channelling down the outside the piezometer.

Groundwater samples were taken weekly throughout the drainage seasons (October to April) of 2020/21, 2021/22 and 2022/23. At each sampling occasion each of the piezometers were emptied in the morning; all of the water standing in each piezometer was pumped out using a manual hand pump and discarded. During the following 2 h the piezometers were allowed to recharge; water seeped back into the piezometer from the surrounding soil through the piezometer screen. This ‘recharged’ water in each piezometer was sampled. Approximately 100 ml of water was taken from each piezometer using a large syringe and bulked for each of the four wells in each paddock. The bulked samples were filtered using Whatman millipore filter paper, d = 132 mm, 0.45 μm to remove detritus and other larger solids from the samples. Filtered samples were sent for laboratory analyses. Concentrations of K in these samples were determined using inductively coupled plasma spectrophotometry (ICP). K leachate load was calculated on a weekly basis using (i) the K concentration (mg L^{-1}) in the ground water samples in each week, and (ii) the cumulative ED (L ha^{-1}) in the corresponding week. The annual load (kg ha^{-1}) was the sum of each week during each of the drainage seasons.

2.4. Annual Farm K balance and K use efficiency (KUE)

A K budget for the entire farm was compiled from farm records for each year. The K content in livestock entering or exiting the farm was calculated using live-weight of the various categories of livestock (mostly sales of calves and culled cows) and a standard value of 3 g of K per kg of live-weight (Bennink et al., 1968; Suttle 2010; Berg et al., 2017). The K in concentrate feed entering the farm was quantified using a standard value of 12 g K per kg DM and assuming a DM content of 880 g kg^{-1} (Feedipedia.Org, 2022). Likewise K entering in imported silage was quantified with a standard value of 25 g K per kg DM. Imports of AFK were compiled for each year based on AFK purchasing records for

Table 1
Soil properties at Solohead Research farm at four different depths. Cation exchange capacity (CEC), total carbon (TC), total inorganic carbon (TIC) and soil organic carbon (SOC).

Depth (cm)	USDA soil textural class	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g cm^{-3})	Total porosity	CEC (cmol^{+} kg soil^{-1})	pH	TC (T ha^{-1})	TIC (T ha^{-1})	SOC (T ha^{-1})
0–10	Clay loam	40	31	29	1.01	61.71	14.8	6.5	119.7	2.4	117.3
10–30	Loam	41	20	39	1.05	60.32		6.8	83.1	2.5	80.6
30–60	Loam	34	20	46	1.21	54.31		7.5	7.2	0.7	6.5
60–80	Silty clay loam	11	31	58	1.33	49.81	8.5	7.5	6.8	0.8	6

Table 2

Annual farm K balance sheet outlining K entering and exiting the farm (kg ha^{-1}) with mean and standard error (SE) over and 18 year timeframe.

	Stocking rate	K entering (kg ha^{-1})					K exiting (kg ha^{-1})				K Balance	KUE	Mean STK
	(LU ha^{-1})	Livestock	Feed	Fertiliser	Rainfall	Total	Livestock	Milk	Leachate	Total	(kg ha^{-1})	(kg kg^{-1})	(mg L^{-1})
2005	1.98	0.03	8	6	4	18	0.8	13	20	34	−16	0.77	161
2006	2.20	0.03	16	0	4	20	0.9	15	2	18	2	0.80	131
2007	2.15	0.03	7	16	4	27	0.9	13	45	59	−32	0.51	159
2008	2.27	0.03	11	25	4	40	1.0	15	4	19	21	0.40	123
2009	2.32	0.03	14	46	4	64	1.0	12	16	29	35	0.20	89
2010	2.27	0.03	10	38	4	52	1.0	12	28	41	11	0.25	110
2011	2.31	0.03	17	20	4	42	1.0	14	18	33	9	0.36	111
2012	2.46	0.03	15	0	4	19	1.1	14	40	55	−36	0.79	112
2013	2.23	0.03	8	55	4	67	0.9	12	26	39	28	0.19	108
2014	2.54	0.03	19	100	4	123	1.1	15	43	59	64	0.13	118
2015	2.38	1.17	16	97	4	118	1.3	18	12	31	87	0.16	130
2016	2.46	1.39	22	74	4	101	1.5	20	50	71	30	0.21	85
2017	2.36	1.11	23	70	4	99	1.5	21	1	22	77	0.23	104
2018	2.62	1.00	25	108	4	138	1.5	19	23	43	95	0.15	116
2019	2.54	1.13	20	107	4	132	1.6	18	15	34	98	0.15	147
2020	2.56	0.93	25	134	4	164	1.6	20	7	28	136	0.13	178
2021	2.49	0.91	15	114	4	135	1.4	19	10	30	104	0.15	225
2022	2.56	0.94	28	81	4	114	1.5	21	59	81	32	0.20	253
Mean	2.37	0.50	17	61	4	82	1.2	16	23	41	41	0.32	137
SE		0.128	1.5	10.3		11.4	0.07	0.8	4.2	4.2	11.7	0.056	32.2

the farm and multiplied by their K contents to quantify this source of K entering the farm. K entering the farm in rainfall was based on Carrol and McCarthy (1972) and was included at an annual rate of 4 kg ha^{-1} in the present study. K exiting the farm in milk was quantified on the basis of milk sold from the farm each year using a standard value of 1.504 g L^{-1} of K based on a meta-analysis performed on collected published literature, i.e. (Manuelian et al., 2018; Pradhan and Hemken, 1968; Sasser et al., 1966; Tacer-Caba et al., 2015; Gaucheron, 2011). The total amount of K in each of the above categories was divided by the farm area in each year and expressed on a kg ha^{-1} basis.

The annual FKB was calculated as the difference between K entering and exiting the farm, including K in rainfall and estimated K leached to ground water as described above. KUE of the farm was the proportion of K entering the farm that was retained in products exiting the farm.

2.5. *Soil analyses*

In December each year approximately 50 soil cores were taken to sampling depth of 10 cm in each of the paddocks across the farm. These cores were bulked per paddock and a composite sub-sample was dried at 40°C for 5 days in a force-draft oven and then sieved (<2 mm) to remove stones and debris. Soil K concentrations were determined following extraction using Morgan's solution (Na acetate + acetic acid, pH 4.8). The soil extracts were filtered and subsequently analysed for K concentration by atomic emission at 766.5 nm using a Sherwood Flame Photometer (Sherwood Scientific Ltd, Cambridge, UK). Soil pH was determined by Jenway 3305 electrode pH Meter. The mean STK of paddocks was taken to represent STK levels on the farm in each year.

2.6. *Herbage production response to AFK*

2.6.1. *Site description*

In addition to the farm scale experiment, a field plot experiment was laid down at Solohead Research Farm to determine herbage production response to AFK under cutting and removal of the harvested herbage. A paddock was selected with low STK status (44 mg L^{-1} determined following extraction with the Morgan's solution as described above) or soil K index 1 according to the Irish soil fertility index (Wall & Plunkett, 2016). Soil test P (STP) was 3.1 mg L^{-1} (soil P index 2). To put these concentrations in context, agronomic response to additional AFK is unlikely at STK >100 mg L^{-1}, and not expected at STK >150 mg L^{-1} and STP >8.0 mg L^{-1} (Wall and Plunkett, 2016). Soil pH was 5.7 with a recommended ground limestone requirement of 6.25 t ha^{-1}. The sward was reseeded during the spring of 2020 and ground limestone was applied to each plot at a rate equivalent to 5 t ha^{-1} in November 2020 in order to increase soil pH level to within the agronomic optimum pH range for grassland in Ireland (6.3–7.0). The seed mixture contained 5 kg ha^{-1} of white clover (*Trifolium repens*), 5 kg ha^{-1} of red clover (*Trifolium pratense*), 15 kg ha^{-1} perennial ryegrass (*Lolium perenne*) and 7.5 kg ha^{-1} of hybrid ryegrass (*Lolium perenne* x *Lolium multiflorum*).

2.7. *Experimental layout and design*

A randomised complete block experiment was laid down during the autumn 2020. This experiment was repeated over two growing seasons: 2021 and 2022. There were four treatments randomly assigned to plots (10 m x 1.5 m) within each block and four replicated blocks. The treatments were four annual rates of AFK input; 0, 130, 260 and 390 kg ha^{-1} denoted K0, K130, K260 and K390, respectively. These rates of AFK were applied to each treatments during 2021 and during 2022 in the form of muriate of potash (50 % K). It was applied in four split applications during each growing season as outlined in Table 3. During 2021 and during 2022 fertiliser N was applied to each plot in the form of Calcium Ammonium Nitrate (27 % N) at an annual rate of 250 kg ha^{-1} of N. The fertiliser N was applied in seven splits during each year; the quantity in each split was in line with long-term average daily sward

Table 3
Monthly application rates (kg ha^{-1}) of artificial fertiliser K, N and P to experimental treatments during 2021 and 2022‡.

Fertiliser K Treatment:	K0	K130	K260	K390	N	P
	Application rate (kg nutrient ha^{-1})					
February	0	14	26	40	38	
March					50	45
April	0	45	91	136	50	
May					50	
June	0	45	91	136	25	
July					25	
August	0	26	52	78	12	

‡See text for description of the experimental treatments

growth rates over the course of a growing season (Table 3). Likewise fertiliser P was applied to each plot in the form of superphosphate (16 % P) in a single application in spring at an annual rate of 45 kg ha^{-1} of P (Table 3) to ensure that soil P availability was not limiting during this study.

2.8. Herbage production and uptake of K in herbage

Plots were harvested on a monthly basis from March to November throughout 2021 and 2022 using an Etesia Hydro 124DS plot Lawnmower (Etesia UK Ltd., Shenington, Oxon, UK) set to a cutting height of 40 mm. Herbage harvested from each plot was weighed. A subsample of 100 g fresh herbage was dried in a forced draught oven at 70°C for 72 h to determine herbage DM content. A subsample of the dried herbage was milled to pass through a 2 mm sieve using a Christy and Norris 5-inch hammer mill (Christy Turner, Suffolk, UK). The K concentration in this subsample was determined following HNO_3 digestion using ICP as described above. Uptake of K in herbage from each plot was determined by multiplying DM yield (kg ha^{-1}) by the K concentration (g kg^{-1}) in herbage DM.

Annual herbage K offtake was calculated as the sum of sward K uptake in herbage DM in each plot throughout each growing season. The critical K concentration in herbage DM was defined as the concentration necessary to achieve 90 % of maximum herbage DM yield in this study according to Smith et al. (1985) and McDonnell et al. (2018).

Apparent recovery of fertiliser K (ARFK) was calculated as the difference in K uptake between the fertilised and unfertilised (K0) plots in each replicated block between application of AFK and harvest of the herbage DM. This was expressed as a proportion of the total AFK applied.

$$\mathrm{ARFK} = (K_U - K_0)/\mathrm{AFK}$$

K_U = K uptake in fertilised plots

K_0 = K uptake in K0 plots

AFK = Applied fertiliser K

2.9. Measurement of K leaching losses from the plots

Screened piezometers (HDPE pipes, similar to above) were installed in the plots receiving the K0 and K390 treatments. The piezometers were installed to 2.5 m below ground level using the same procedures as described above. Groundwater was sampled weekly and analysed for K to determine the K leachate losses to groundwater in each drainage season of 2021/22 and 2022/23 using the same methodology as described above.

2.10. Plot-scale K balances (PKB)

It was assumed that K uptake in herbage DM under the K0 treatments represented the background capacity of the soil to supply plant-available K (K_0) in each year. It was also assumed that K_0 was equally available across all of the other AFK input treatments in each year of this study. Thus, the capacity of the soil to supply plant-available soil K consisted of the sum of AFK input, K input from rainfall and K_0. K offtake from each plot was the sum of K uptake in herbage DM and K leachate loss to groundwater. There was no difference in K leaching between the K0 and K390. Hence, it was assumed that the mean loss of K to groundwater was equal across all the AFK input treatments in each year. The difference between K offtake and soil K supply represented the net change in PKB, which was either a deficit or a surplus. Net change in PKB each year was calculated as follows:

$$\mathrm{PKB} = (K_0 + \mathrm{AFK} + K_R) - (K_U + K_L)$$

K_0 = K uptake in K0 plots

AFK = Applied fertiliser K

K_R = K in rainfall

K_U = K uptake in herbage DM

K_L = K leachate losses to groundwater

2.11. Soil analyses

Soil samples were taken from across the site before the commencement of the field plot study in 2020 and from each plot (20 cores per plot) at the end of the growing season in 2021 and in 2022 using the same sampling procedure as described above. STK was determined as described above. The change is STK between 2020 and 2021 and between 2021 and 2022 was calculated for each plot by deducting STK at the end of the year from the STK in the previous year and termed *delta*-STK.

2.12. Statistical analyses

Data were analysed using SAS 9.3 (SAS Institute, Cary, NC, USA). All raw data were collated to carry out basic descriptive statistics and check normality, homogeneity of variances and sphericity to ascertain appropriate statistical tests.

In the farm balance, the general least squares PROC GLM procedure was used to test the effect of soil pH trends in each year on STK status, and FKB on *delta*-STK over the 18-year dataset.

Similarly in the plot experiment PROC GLM was used to conduct analysis of variance (ANOVA) to test the level of variance of AFK level on the dependent variables above and to test the level of variance between replications (n=4) and year (n=2). Dependent variables included annual sward DM production, K concentration in herbage DM, K uptake in herbage DM and K leachate losses to groundwater and to test for interactions between AFK x Year.

Linear and quadratic regression analysis was used to examine the relationship between PKB and *delta*-STK in each plot for both years of this study. A quadratic equation was used to examine the relationship

Table 4
Multiple regression model describing annual K leachate losses from Solohead Research Farm.

Parameter	Coefficient	Standard Error	R^2
Model			0.90***
Intercept	−48.3		-
Soil test K (mg L^{-1})	0.063	0.0136	0.35***
Effective drainage (L ha^{-1})	0.128	0.1679	0.70***

***P<0.001

between annual FKB in the preceding year and *delta*-STK, which was the change in annual average farm STK from one year to the next.

A stepwise multi-regression analysis was conducted to assess soil pH and STK in each paddock and ED during each drainage season (2020/21, 2021/22, 2022/23) as independent variables in estimating the annual K leachate load per drainage season. Soil pH was omitted from the model as it was not correlated to annual K leachate load (P>0.05). The resulting equation (Table 4) was used to estimate annual K leachate load for each drainage season between 2005 and 2019 and included in the annual farm-gate K budget of the preceding year; i.e. the load lost during the 2020/21 drainage season was included in the 2020 farm K budget.

The differences in the FKB between years were not analysed against variables with single values. For example, total K entering and total K exiting the farm, overall annual farm K surplus or deficit. Propagation of error (standard error; SE) for all contributory factors (inputs, outputs and annual surplus or deficit) in the balance sheet were also calculated.

3. Results

3.1. Soil temperature, rainfall, and effective drainage

Mean monthly soil temperature (between 2005 and 2022) at 0–10 cm depth was 4.7°C in January and 16.6°C in July. The average annual precipitation between 2005 and 2022 was 1112 mm, ranging from 857 mm to 1296 mm. Within this timeframe, April was the driest month on average (60 mm) and December the wettest (131 mm). Annual rainfall was 1260 mm in 2020, 983 mm in 2021 and 1144 mm in 2022 (Fig. 1a). Effective drainage (ED) was 357 mm during the 2020/21 drainage season, 284 mm in 2021/22 and 595 mm in 2022/23 (Fig. 1b). The average ED for each drainage season between 2005 and 2023 was 477 mm.

3.2. Potassium leaching losses from the farm

Measured annual K leaching from the farm was (mean ± SE kg ha^{-1}) 6.9 ± 6.13 during the drainage season 2020/21, 9.6 ± 3.73 during 2021/22 and 59 ± 7.4 during 2022/23. K leaching was higher (P<0.001) during the 2022/23 than in the earlier two drainage seasons. Effective drainage and STK in each paddock explained 90 % of the variation in K leaching load from each paddocks during each drainage season (Table 4).

3.3. Farm K balances

AFK and animal feeds were the main sources of K entering the farm (Table 2). Annual (2005–2022) average importation of K in AFK and feed equated to 61 kg ha^{-1} and 17 kg ha^{-1}, respectively. Between 2005 and 2013 the mean annual AFK import was 23 kg ha^{-1}. There was a large increase in the quantity of AFK imported onto the farm each year between 2014 and 2022 (annual average = 98.4 kg ha^{-1}). In 2021 the import of K was 114 kg ha^{-1} in AFK, and 15 kg ha^{-1} in animal feeds. In 2022, these were 81 and 28 kg ha^{-1}, respectively. Annual K imported in livestock was comparatively small, averaging 0.5 kg ha^{-1} between 2005 and 2022.

Annual K leaching to groundwater was the largest overall contributor to K exiting the farm; averaging 25.2 kg ha^{-1} K as measured between 2020 and 2023 and estimated at 22.8 kg ha^{-1} between 2005 and 2020 (Table 2). The annual average export of K in milk accounted for 16.1 kg ha^{-1} (Table 2). Average K exiting the farm in the transfer of livestock off the farm each year was comparatively small (1.2 kg ha^{-1}; Table 2).

The annual FKB was 41 kg ha^{-1} averaged between 2005 and 2022 and ranged between −36 kg ha^{-1} in 2012 and 136 kg ha^{-1} in 2020 (Table 2). Annual average KUE was 0.32 ±0.056 (Table 2) and ranged

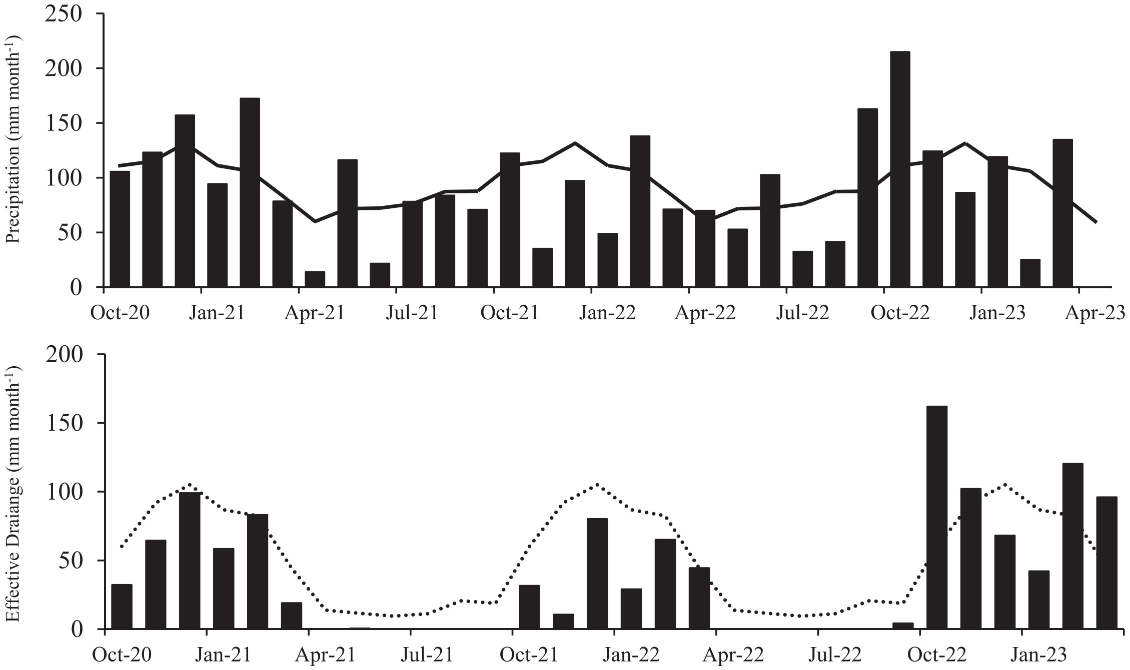

Fig. 1. (a) (i) Monthly precipitation at Solohead Research Farm (bars) between October 2020 and April 2023 (ii) mean monthly precipitation between 2005 and 2020 (dotted line). Fig. 1b (i) Monthly Effective Drainage (ED) at Solohead Research Farm (bars) between October 2020 and April 2023 (ii) mean monthly ED between 2005 and 2020 (dotted line).

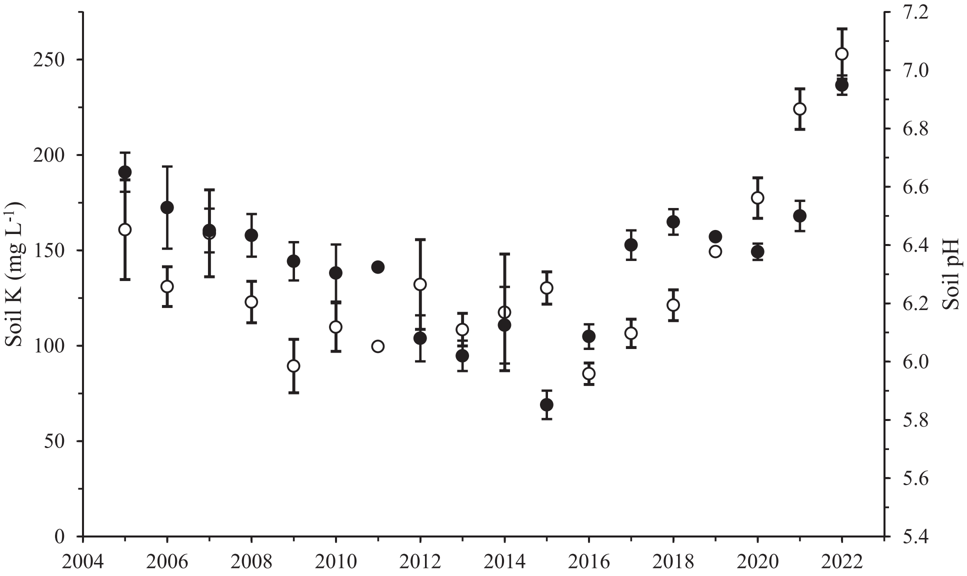

Fig. 2. Annual average soil K concentrations (STK; ○) and soil pH (●) at Solohead Research Farm between 2005 and 2022. I = ± standard error of the mean.

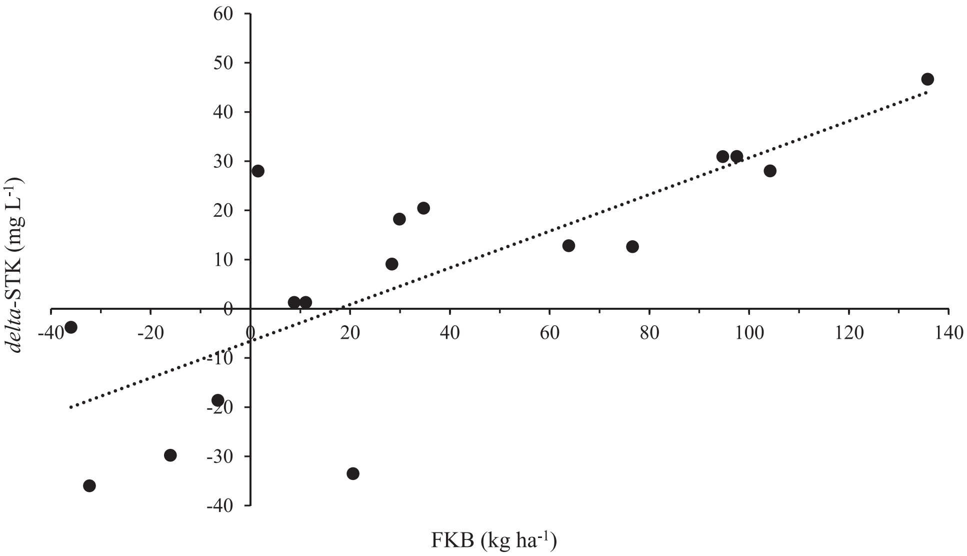

Fig. 3. The relationship between annual farm-scale K balance (FKB; kg ha^{-1}) and annual change in farm-average STK concentrations from one year to the next (*delta*-STK; mg L^{-1}) between 2005 and 2022: *delta*-STK = −6.60 + 0.37 x FKB; R^2=0.60 P<0.001.

between 0.80 in 2006 and 0.13 in 2020. KUE was correlated with FKB: KUE = 0.47–0.0037 x FBK; R^2 = 0.59; P<0.001.

Average soil pH across the farm declined from 6.7 in 2005 to 5.9 in 2015 and after the application of ground limestone ($CaCO_3$) increased to 6.9 in 2022 (Fig. 2). Likewise, the annual average STK across the farm was 161 mg L^{-1} in 2005 and declined to 85 mg L^{-1} in 2016 and increased to 253 mg L^{-1} in 2022 (Fig. 2). The change in average farm STK from one year to the next (*delta*-STK) was correlated with FKB (R^2=0.60; P<0.001; Fig. 3).

3.4. Herbage production response to AFK

3.4.1. Herbage DM production, K concentration and K uptake in herbage DM

In the plot-scale experiment, higher AFK input increased (P<0.001) herbage DM production. There was a diminishing response to higher AFK input with no difference (P>0.05) in herbage DM production between AFK inputs of 260 and 390 kg ha^{-1} (SEM = 0.29; Fig. 4). There was a significant effect of year on herbage DM production, with significantly higher yields in 2021 compared with 2022 (P<0.001). There was no significant (P>0.05) interaction between AFK and year (Fig. 4).

Herbage K concentration increased linearly with additional input of AFK (P<0.001; Fig. 4). The critical K concentration for 90 % of the maximum yield (Smith et al., 1985) and (McDonnell et al., 2018) in this study was 25.1 g kg^{-1} of K in herbage DM. This critical level corresponded with an average annual AFK input of 256 kg ha^{-1}.

Uptake of K in herbage DM increased (P<0.001) with additional AFK input. Averaged over both years it increased from 144 kg ha^{-1} for K0, 257 kg ha^{-1} for K130, 324 kg ha^{-1} for K260 and 417 kg ha^{-1} for K390 (SEM = 20.9 kg ha^{-1}). Averaged across the AFK treatments apparent recovery of fertiliser K applied was 0.62 in 2021 and 0.74 in 2022 (Fig. 5). K uptake in herbage was significantly lower (P<0.001) overall in 2022 compared with 2021 (Fig. 5).

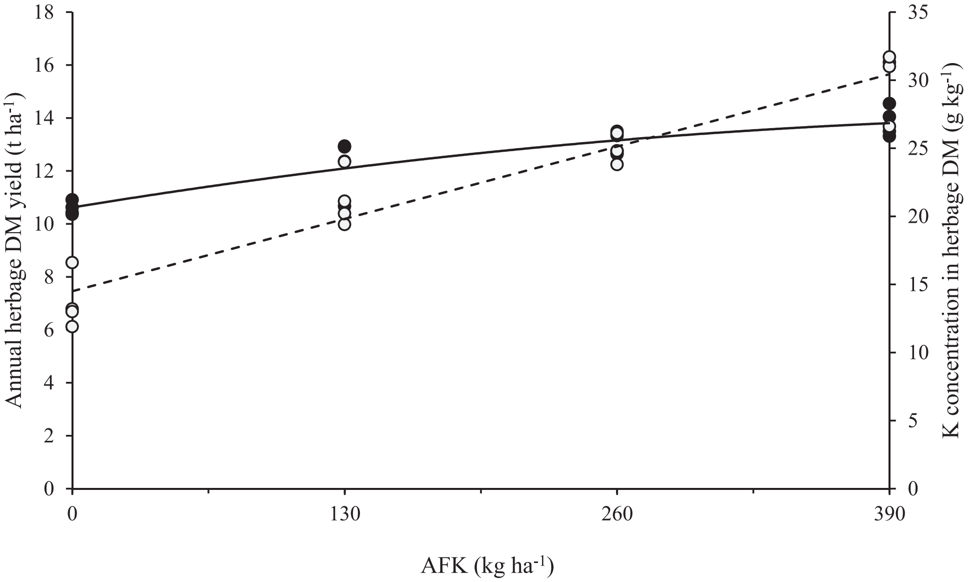

Fig. 4. The relationship between annual artificial fertiliser K (AFK) input and (i) annual herbage dry matter (DM) production (● and solid line) and (ii) herbage K concentration in herbage DM (○ and dashed line). Results are mean of two years. Annual herbage DM yield = 10.6 + 0.0129 x AFK – 0.00001 x AFK^2; $R^2 = 0.82$; P<0.001. K concentration in herbage DM = 14.5 + 0.041 x AFK; $R^2 = 0.91$; P<0.001.

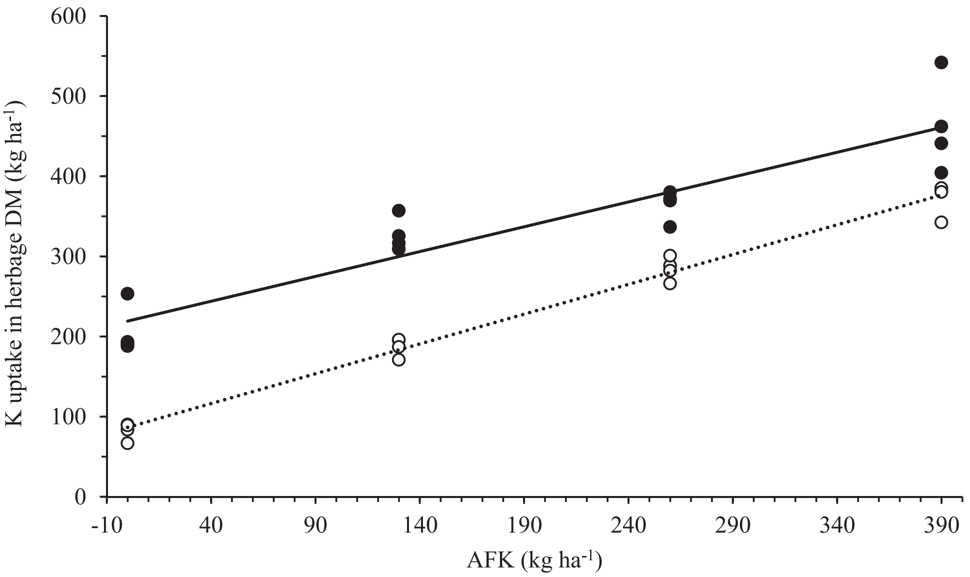

Fig. 5. Annual uptake of K in herbage dry matter (DM) under incremental inputs of fertiliser K (AFK) in 2021 (● and solid line) and 2022 (○ and dotted line): 2021: K uptake = 219 + 0.62 x AFK; $R^2 = 0.87$; P<0.001. 2022: K uptake = 86 + 0.74 x AFK; $R^2 = 0.98$; P<0.001.

3.4.2. *Soil test K (STK) in the plot experiment*

Mean STK across the experimental site was 44 mg L^{-1} before the commencement of the experiment in 2020 as outlined above. Where no K was applied, STK levels were 36 mg L^{-1} in 2021 and 30 mg L^{-1} in 2022 based on the intercept of the response curves (Fig. 6). STK at the end of both experimental years increased with higher AFK input, although there was no significant difference between K0 and K130 in either year (Fig. 6). There was an interaction (P<0.001) between AFK input and year, with a tendency for higher STK under K260 and K390 in December 2022 than in December 2021 (Fig. 6).

3.4.3. *Potassium leaching losses from the plot experiment*

There was no difference in K leaching losses between the different AFK treatments (K0 to K390). There was also no difference in the magnitude of K leaching losses between the two drainage seasons of 2021/22 and 2022/23 and no interaction between AFK and drainage season. Mean K leaching loss per drainage season was 13.6 kg ha^{-1}.

3.4.4. *Plot-scale K balances (PKB) and delta-STK*

PKB ranged from -12 to 164 kg ha^{-1} in 2021 and from −9.6–105 kg ha^{-1} in 2022 (Fig. 7). Likewise delta-STK ranged from −10–106 mg L^{-1} in 2021 and from −13–82 in 2022 (Fig. 7). Averaged over both years 2.04 kg ha^{-1} of PKB was required to increase STK by 1 mg L^{-1} ($R^2 = 0.66$; P<0.001; Fig. 7). There was no PKB x year interaction for delta-STK.

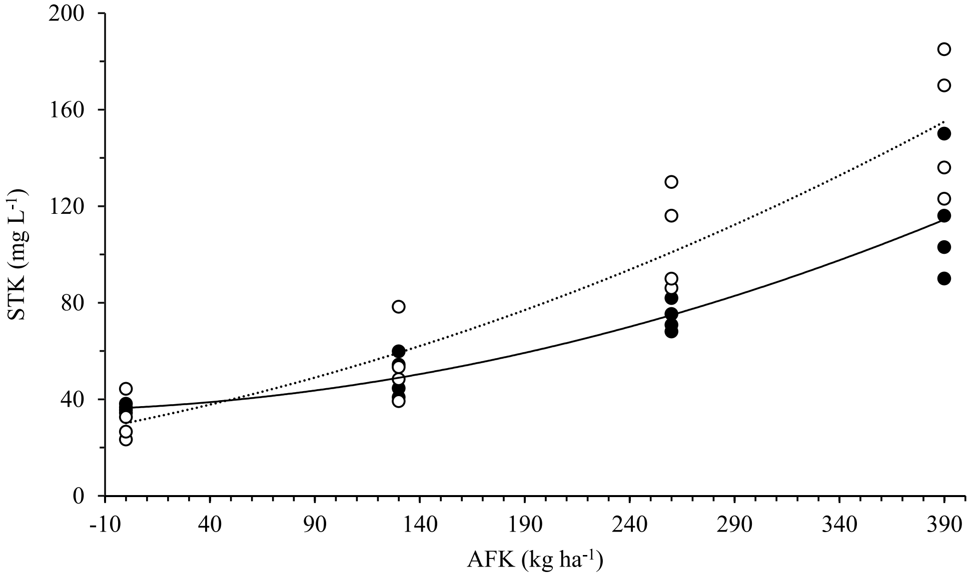

Fig. 6. Soil test K (STK) under incremental inputs of artificial fertiliser K (AFK) in 2021 (● and solid line) and 2022 (○ and dotted line): 2021: $STK = 36 + 0.044 \times AFK + 0.0004 \times AFK^2$; $R^2 = 0.86$; $P<0.001$. 2022: $STK = 30 + 0.176 \times AFK + 0.0004 \times AFK^2$; $R^2 = 0.87$; $P<0.001$.

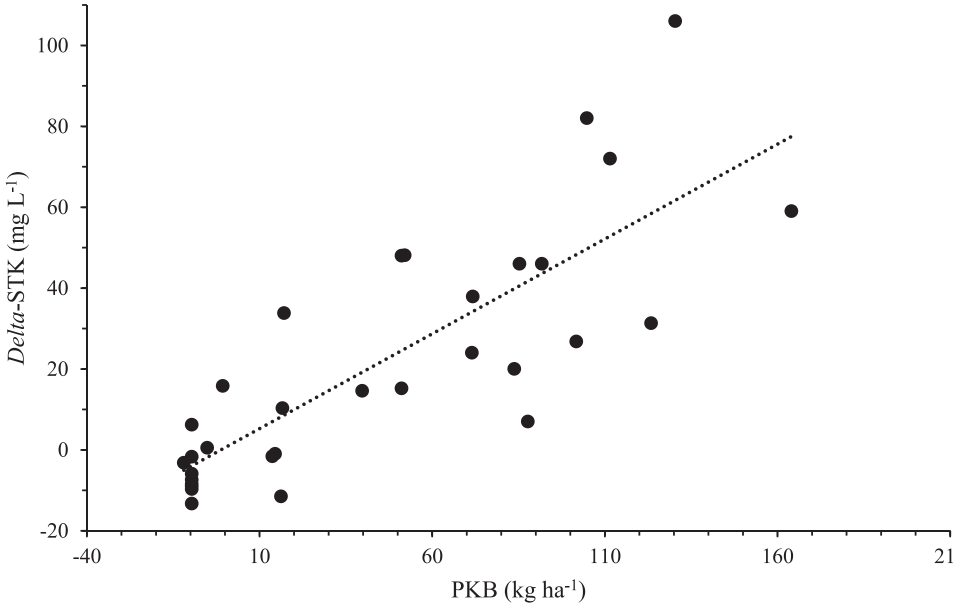

Fig. 7. The relationship between plot K balance (PKB) and the annual change in *STK* from one year to the next (*delta*-STK; mg L^{-1}). Data is combined from 2021 and 2022. Both years 2021 and 2022 combined: *delta*-$STK = 0.58 + 0.49 \times PKB$; $R^2 = 0.66$; $P<0.001$.

4. Discussion

4.1. Farm management, PKB, and STK

It is inevitable that data collected at farm-scale encompasses a certain amount of noise due to sampling error; for example soil samples taken for the measurement of STK (Griffiths and Rosenfeld, 1954). On the other hand using a large dataset, encompassing 50 paddocks over 18 years, helps to identify trends that might not be apparent (hidden in the noise) in shorter term studies. Weather conditions were also variable from year to year and rainfall impacted on leaching losses measured during the present study. Rainfall and effective drainage (Fig. 1) were substantially greater (590 mm total effective drainage) during the 2022/23 drainage season compared with the earlier years measured and influenced greater K leaching to groundwater. Weather conditions also influenced the amount of K imported onto the farm in feeds, with more feed per livestock unit imported when herbage production was curtailed by adverse weather conditions; due to high summer rainfall in 2009 and 2012 and a deficit of summer rainfall in 2006 and 2018.

Potassium imported in concentrate feeds was also influenced by stocking rate, which tended to increase over time, particularly from 2014 onwards. Higher stocking rates on the farm were a consequence of the phasing out of the milk quota between 2010 and 2015; the milk quota curtailed milk production on farms within the European Union between 1984 and 2015. Surplus K on the farm exceeded 98 kg ha^{-1} in each year between 2014 and 2022 whereas it did not exceed 67 kg ha^{-1} in any of the earlier years.

It is clear that AFK was the main source of K entering the farm; particularly from 2013 onwards. Higher AFK input coincided with increasing average STK across the farm. It also coincided with increasing soil pH due to higher application of ground limestone on the farm. The recommended soil pH for grass-only swards was 6.3 (Wall and Plunkett., 2016), however, from 2014 onwards ground limestone was spread across the farm to increase soil pH to within target range of 6.5 to 7.2 to improve the clover content of swards and biological fixation of N (Dilz and Mulder, 1962; Rice et al., 1977; McKenna et al., 2018). Bearing in mind that higher soil pH increases plant availability of K in the soil solution (Thomas and Hipp, 1968; Magdoff and Bartlett, 1980; Fageria, 2009) it is likely that the increase in average STK across the farm between 2014 and 2022 was partly due to increasing soil pH during this timeframe.

4.2. The farm K balance and managing soil K availability

Averaged over 18 years the amount of K entering the farm in livestock, concentrates and feed and rainfall (21.5 kg ha^{-1}; Table 2) exceeded that exiting the farm in livestock and milk (17.2 kg ha^{-1}; Table 2). When leachate losses are factored in however; averaged over 18 years the amount of K entering the farm in livestock, concentrates, and rainfall was approximately 46 % of the total K exiting in livestock, milk and leachate. Hence, AFK was being imported onto the farm primarily to balance K loss via leaching. It also increased STK concentrations across the farm, particularly from 2014 onwards. Potassium leaching on average was greater than previously reported; 11 kg ha^{-1} (Williams, 1988) and 19 kg ha^{-1} (Alfaro et al., 2003) and had a marked effect on FKB. Indeed, few other studies have examined long-term K leaching at farm-scale.

The cumulative FKB between 2005 and 2012 was −6 kg ha^{-1} and this is reflected in declining STK concentrations during this timeframe (Fig. 2). Between 2013 and 2022 the cumulative FKB was 751 kg ha^{-1} and this is likewise reflected in the strong increase in STK concentrations. It required 2.70 kg ha^{-1} of FKB to increase STK by 1 mg L^{-1} (Fig. 3). Likewise in the plot study it required 2.04 kg ha^{-1} of PKB to increase STK by 1 mg L^{-1} (Fig. 7). The somewhat higher K requirement in the farm-scale study (Fig. 3) compared with the plot study (Fig. 7) can be largely explained by inherently inefficient recycling of K in livestock excreta under grazing within the farm (Aarons et al., 2020; Richards and Wolton, 1976). This is in contrast to the plot-scale study where AFK was uniformly distributed to the sward. Another contributory factor to this difference was the initial STK concentration in both studies. In general initial STK concentrations were higher in the farm-scale study (Fig. 2) than in the plot study (44 mg L^{-1}). It is apparent from the quadratic equations in Fig. 6 that it took less AFK to increase STK by 1 mg L^{-1} at a higher initial STK concentration than it did from a lower starting point. This is probably due to increasing K saturation of exchange sites making K more plant-available in the soil solution.

In general, annual farm-scale KUE was low; averaging 0.32 (Table 2). Highest KUEs tended to be in years when there were greatest deficits in FKB; for example 2005 and 2012 (Table 2). Leaching losses partly explain the low KUEs recorded in the present study along with the increasing STK concentrations across the farm as described above; surplus FKB was either leached or otherwise accumulated in the soil (Fig. 2).

4.3. Variation between paddocks

Towards the end of this study mean STK concentrations on the farm were in excess of recommended levels and ranged between 114 and 500 mg L^{-1} in 2022; with the lowest STK levels in the target range of 100–150 mg L^{-1} (Index 3). In 2020 the range was between 84 and 392 mg L^{-1} and between 30 and 228 mg L^{-1} in 2017 (Fig. 2). In 2017, 13 % of paddocks were in index 1 for STK (<50 mg K L^{-1}), 32 % of paddocks in index 2 (50–100 mg K L^{-1}) and 35 % of paddocks in index 3 (100–150 mg K L^{-1}). In other words 45 % of paddocks were considered sub-optimal with fertiliser response likely, or very low with fertiliser response considered definite (Wall & Plunkett, 2016), although mean paddock STK in 2017 was 105 mg L^{-1} i.e. within index 3 a level where fertiliser response is considered unlikely/tenuous. While the STK status of paddocks in 2022 were more in line with the optimum agronomic range (Wall & Plunkett, 2016) to that in 2017 in terms of the proportion of paddocks in STK index 3 or above (and likely agronomic productivity), it is also clear that excessive quantities of AFK were applied during the intervening years (2017–2022). On average 98 kg ha^{-1} of AFK were imported onto the farm between 2016 and 2022 whereas it is possible to calculate that an annual average input of 22.5 kg ha^{-1} of AFK was needed over these years to balance the difference between K entering the farm in livestock, concentrates and rainfall and that exiting the farm in livestock, milk and as leachate.

Assuming that we wanted to increase STK concentrations to mid-way in index 3 (125 mg L^{-1}) from 2016 (85 mg L^{-1}) it would require an additional annual AFK input of 95 kg ha^{-1} over this timeframe, on the basis that it takes 2.7 kg ha^{-1} of FKB to increase mean STK by 1 mg L^{-1} (Fig. 3). This additional AFK can be justified also on the basis that not all of the applied AFK in the plot-scale study was recovered by in the herbage DM. On average 0.62 was recovered in 2021 and 0.74 in 2022 (Fig. 5). The fate of the unrecovered AFK is not entirely accounted for by leaching losses, which accounted for <2 % of applied AFK. It is likely that some of the AFK was adsorbed in non-labile forms on exchange sites, as outlined by (Moss and Herlihy, 1970). Differences in rates of uptake between 2021 and 2022 can be partly explained by differences in growing conditions between these two years, with sward DM production 17 % lower on average in 2022.

Hence, an average AFK of 22.5 kg ha^{-1} imported onto the farm in each year 2016–2022 would have been sufficient to maintain average STK concentrations across the farm mid-way in index 3; substantially less than the actual amount imported onto the farm over this timeframe. Bearing in mind the variation in STK concentrations between paddocks, the key is to target slurry recycled within the farm and AFK imported onto the farm to those paddocks with the greatest deficit of K (Murphy, 1986; Cooke, 1986; Wall and Plunkett., 2016). This can be easier said than done on grazed grassland-based farms where much of the K is recycled by grazing livestock characterised by inefficient excretal K redistribution to the sward in concentrated patches with greater potential for K loss via leaching (Dennis et al., 2011; Haynes and Williams, 1993). On dairy farms there can be a higher stocking rate on the 'grazing platform'; i.e. the area of the farm adjacent to the milking shed that is accessible by grazing dairy cows, than on inaccessible areas of the farm that are primarily used for silage production. The latter paddocks experience the greatest depletion of K during each growing season. On the other hand, most concentrate supplementation takes place during lactation when cows are outside grazing, which can generate a surplus of K on the grazing platform.

4.4. Risks to livestock health

Elevated K concentrations in herbage DM can cause hypomagnesaemia in grazing dairy cows and contribute to parturient paresis in freshly calved cows (Kayser and Isselstein, 2005; Lunnan et al., 2018). In the plot study the concentration of K in herbage DM increased linearly with higher AFK input (Fig. 4) in agreement with (Øgaard and Hansen, 2010). The critical K concentration in herbage DM to achieve 90 % of maximum yield was 25.1 g kg^{-1}. This is mid-way between 21 g kg^{-1} reported by Keady and O'Kiely, (1998) and 28 g kg^{-1} by Pinkerton & Randall (1994) as critical agronomic values for achieving 90 % of maximum yield. The critical K concentration for 90 % of maximum yield in the present study coincided with AFK input of 256 kg ha^{-1}. Higher AFK input resulted in higher K concentrations in herbage DM up to 32 g kg^{-1} at AFK390. This is a consequence of 'luxury consumption' of available soil K (Dampney, 1992). Avoiding elevated K concentrations in herbage DM helps to mitigate associated risks to animal health outlined above.

5. Conclusions

The generation of AFK recommendations for grassland in the past were typically based on AFK responses in controlled plot studies; for example Ryan (1977) and Keady and O'Kiely (1998). Interpretation of such studies for the purposes of designing AFK recommendations for grassland-based farms are somewhat limited as they don't fully account for K recycling, particularly under grazing, and complicated aspects such as the potential for luxury uptake. The present study elucidates the challenges in managing soil K fertility on a grassland-based dairy farm. Annual farm-scale K budgets were a useful tool for quantifying farm-scale K flows in products and losses. Leaching of K to groundwater represented the majority (55 %) of K exiting the farm averaged over the 18-year dataset; exceeding export of K in milk and other products. Few previous farm-scale studies have quantified the extent of system K depletion attributed to leaching. The effect of groundwater K leaching on FKB was greater than anticipated bearing in mind that the clay loam textured soil on the farm was not previously considered to be vulnerable to leaching losses. Balancing leaching losses was the primary reason for importing AFK onto the farm. Variation in K offtakes in herbage DM and the extent of recycling under grazing or otherwise created substantial differences in STK concentrations between paddocks within the farm. Hence, K management needs to be tailored to each individual paddock. A tool such as an App that helps to account for and calculate K offtakes and inputs, including under grazing, on a paddock basis would be helpful for this purpose.

CRediT authorship contribution statement

Thomas P McCarthy: Writing – review & editing, Writing – original draft, Visualization, Validation. **David P Wall**: Writing – review & editing, Supervision, Funding acquisition. **Patrick J Forestal**: Writing – review & editing, Supervision. **Imelda Anne Casey**: Supervision, Project administration. **James Humphreys**: Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. David Wall reports financial support was provided by Government of Ireland, Department of Agriculture Food and the Marine. 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.

Data Availability

Data will be made available on request.

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References

Aarons, S.R., Gourley, C.J.P., Powell, J.M., 2020. Nutrient intake, excretion and use efficiency of grazing lactating herds on commercial dairy farms. Animals 10 (3), 1–20. https://doi.org/10.3390/ani10030390.

Alfaro, M.A., Jarvis, S.C., Gregory, P.J., 2004. Factors affecting potassium leaching in different soils. Soil Use Manag. 20 (2), 182–189. https://doi.org/10.1079/sum2004249.

Alfaro, M.A., Jarvis, S.C., Gregory, P.J., 2003. Potassium budgets in grassland systems as affected by nitrogen and drainage. Soil Use Manag. 19 (2), 89–95. https://doi.org/10.1079/sum2002172.

Bennink, M., Ward, G., Johnson, J., 1968. Potassium content of carcass components and internal organs of cattle as determined by 40K and atomic absorption spectrometry. J. Anim. Sci. 27, 600–603.

Berg, M., Plöntzke, J., Leonhard-Marek, S., Müller, K.E., Röblitz, S., 2017. A dynamic model to simulate potassium balance in dairy cows. J. Dairy Sci. 100 (12), 9799–9814. https://doi.org/10.3168/jds.2016-12443.

Burchill, W., Lanigan, G.J., Li, D., Williams, M., Humphreys, J., 2016. A system N balance for a pasture-based system of dairy production under moist maritime climatic conditions. Agric. Ecosyst. Environ. 220, 202–210. https://doi.org/10.1016/j.agee.2015.12.022.

G. Cooke Nutrient Balances and the Need for Potassium in Humid Tropical Regions *Nutrient balances and the need for potassium* 1986 17 35.

Dampney, P.M.R., 1992. The effect of timing and rate of potash application on the yield and herbage composition of grass grown for silage. Grass Forage Sci. 47 (3), 280–289. https://doi.org/10.1111/j.1365-2494.1992.tb02272.x.

Dennis, S.J., Moir, J.L., Cameron, K.C., Di, H.J., Hennessy, D., Richards, K.G., 2011. Urine patch distribution under dairy grazing at three stocking rates in Ireland. Ir. J. Agric. Food Res. 50 (2), 149–160.

Dilz, K., Mulder, E.G., 1962. The effect of soil pH, stable manure and fertilizer nitrogen on the growth of red clover and of red clover associations with perennial ryegrass. Neth. J. Agric. Sci. 10 (1), 1–22. https://doi.org/10.18174/njas.v10i1.17602.

Fageria, N.K., 2009. In the use of nutrients in crop plants. The Use of Nutrients in Crop Plants. CRC Press Taylor & Francis Group LLC. https://doi.org/10.1201/9781420075113.

Feedipedia.org. (2022). https://www.feedipedia.org/content/about-feedipedia.

Fenger, F., Casey, I.A., Humphreys, J., 2021. Accumulating herbage during autumn to extend the grazing season in pasture-based dairy systems. Grass Forage Sci. 76 (4), 522–532. https://doi.org/10.1111/gfs.12547.

Griffiths, J., Rosenfeld, M., 1954. Operator variation in experimental research. J. Geol. 62 (1) https://doi.org/10.1086/626134.

Haynes, R.J., Williams, P.H., 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Adv. Agron. 49 (C), 119–199. https://doi.org/10.1016/S0065-2113(08)60794-4.

Hemingway, R.G., 1961. Magnesium, potassium, sodium and calcium contents of herbage as influenced by fertilizer treatments over a three-year period. Grass Forage Sci. 16 (2), 106–116. https://doi.org/10.1111/j.1365-2494.1961.tb00221.x.

Hutton, J.B., Jury, K.E., Davies, E.B., 1967. Studies of the nutritive value of New Zealand dairy pastures. V. The intake and utilisation of potassium, sodium, calcium, phosphorus and nitrogen by lactating dairy cattle. N.Z. J. Agric. Res. 10, 367–388.

Kayser, M., Isselstein, J., 2005. Potassium cycling and losses in grassland systems: a review. Grass Forage Sci. *60* (3), 213–224. https://doi.org/10.1111/j.1365-2494.2005.00478.x.

Keady, T.W.J., O'Kiely, P., 1998. An evaluation of potassium and nitrogen fertilization of grassland, and date of harvest, on fermentation, effluent production, dry-matter recovery and predicted feeding value of silage. Grass Forage Sci. 53 (4), 326–337. https://doi.org/10.1046/j.1365-2494.1998.00136.x.

Lunnan, T., Øgaard, A.F., Krogstad, T., 2018. Potassium fertilization of timothy-based cut grassland—Effects on herbage yield, mineral composition and critical K concentration on soils with different K status. Grass Forage Sci. 73 (2), 500–509. https://doi.org/10.1111/gfs.12341.

Magdoff, F.R., Bartlett, R.J., 1980. Effect of liming acid soils on potassium availability. Soil Sci. *129* (1), 12–14. https://doi.org/10.1097/00010694-198001000-00003.

Manuelian, C.L., Penasa, M., Visentin, G., Zidi, A., Cassandro, M., De Marchi, M., 2018. Mineral composition of cow milk from multibreed herds. Anim. Sci. J. 89 (11), 1622–1627. https://doi.org/10.1111/asj.13095.

McDonnell, R.P., Staines, M. v H., Bolland, M.D.A., 2018. Determining the critical plant test potassium concentration for annual and Italian ryegrass on dairy pastures in south-western Australia. Grass Forage Sci. *73* (1), 112–122. https://doi.org/10.1111/gfs.12286.

McKenna, P., Cannon, N., Conway, J., Dooley, J., 2018. The use of red clover (Trifolium pratense) in soil fertility-building: A Review. Field Crops Res. *221* (July), 38–49. https://doi.org/10.1016/j.fcr.2018.02.006.

Mihailescu, E., Murphy, P.N.C., Ryan, W., Casey, I.A., Humphreys, J., 2015. Phosphorus balance and use efficiency on 21 intensive grass-based dairy farms in the South of Ireland. J. Agric. Sci. *153* (3), 520–537. https://doi.org/10.1017/S0021859614000641.

Moss, P., Herlihy, M., 1970. Availability of soil potassium to ryegrass: 2. potassium buffering capacity. Ir. J. Agric. Res. *9* (1), 109–117. ⟨https://www.jstor.org/stable/25555566⟩.

Murphy, W., 1986. Nutrient cycling in different pasture ecosystems. In Nutrient Balances and the Need for Potassium. International Potash Institute, pp. 227–228.

O Donovan, T., Casey, I.A., Humphreys, J., 2022. Effectiveness of dock (Rumex obtusifolius L.) control in new leys and established grassland following the application of herbicides. Grass Forage Sci. *77* (1), 79–88. https://doi.org/10.1111/gfs.12553.

Oenema, O., Kros, H., de Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur. J. Agron. 20, 3–16. https://doi.org/10.1016/S1161-0301(03)00067-4.

Øgaard, A.F., Hansen, S., 2010. Potassium uptake and requirement in organic grassland farming. Nutr. Cycl. Agroecosystems *87* (1), 137–149. https://doi.org/10.1007/s10705-009-9320-5.

Phelan, P., Casey, I.A., Humphreys, J., 2014. The effects of simulated summer-to-winter grazing management on herbage production in a grass-clover sward. Grass Forage Sci. 69 (2), 251–265. https://doi.org/10.1111/gfs.12041.

Pinkerton, A., Randall, P.J., 1994. Critical potassium concentrations in trifolium balansae, medicago murex and trifolium subterraneum as affected by sampling date. Aust. J. Exp. Agric. 34 (4), 469–477. https://doi.org/10.1071/EA9940469.

Pradhan, K., Hemken, R.W., 1968. Potassium depletion in lactating dairy cows. J. Dairy Sci. *51* (9), 1377–1381. https://doi.org/10.3168/jds.S0022-0302(68)87198-X.

Rice, W.A., Penney, D., Nyborg, M., 1977. The effect of soil acidity on rhizobia numbers, nodulation and nitrogen fixation by alfalfa and red clover rhizobia. Can. J. Soil Sci. 203 (May), 197–203. 〈https://cdnsciencepub.com/doi/pdf/10.4141/cjss77-024〉.

Richards, R., Wolton, K.M., 1976. The spatial distribution of excreta under intensive cattle grazing. Grass Forage Sci. *31* (2), 89–92. https://doi.org/10.1111/j.1365-2494.1976.tb01123.x.

Ruane, E.M., Treacy, M., McNamara, K., Humphreys, J., 2014. Farm-gate phosphorus balances and soil phosphorus concentrations on intensive dairy farms in the South-West of Ireland. Ir. J. Agric. Food Res. *53* (2), 105–119.

Ryan, M. , 1977. Grassland Productivity : Effect of Potassium on Herbage DM Yield at 26 Sites. Ir. J. Agric. Res. 16 (1), 1–10. https://www.jstor.org/stable/25555847%0D.

Sasser, L.B., Ward, G.M., Johnson, J.E., 1966. Variations in potassium concentration of cow's milk. J. Dairy Sci. *49* (7), 893–895. https://doi.org/10.3168/jds.S0022-0302(66)87965-1.

R.P. Schulte *Soil Moisture Defecit Drainage Model* 2005.

Scully, K.M., Keogh, B., O' Brien, B., Casey, I.A., Humphreys, J., 2021. The effect of fertilizer nitrogen input to grass-clover swards and calving date on the productivity of pasture-based dairy production. J. dairy sci. 104 (8), 8870–8884. https://doi.org/10.3168/jds.2020-19898.

Smith, G.S., Cornforth, I.S., Henderson, H.V., 1985. Critical leaf concentrations for deficiencies of nitrogen, potassium, phosphorus, sulphur, and magnesium in perennial ryegrass. N. Phytol. *101* (3), 393–409. https://doi.org/10.1111/j.1469-8137.1985.tb02846.x.

Suttle, N.F., 2010. Mineral Nutrition of Livestock. CABI, Oxfordshire, United Kingdom. White.

Tacer-Caba, Z., Nilufer-Erdil, D., Ai, Y., 2015. Chemical composition of cereals and their products. Handb. Food Chem. https://doi.org/10.1007/978-3-642-36605-5_33.

Thomas, G.W., Hipp, B.W., 1968. Soil factors affecting potassium availability. In: Kilmer, V., Younts, S., Brady, N. (Eds.), Potassium in Agriculture. American Society of Agronomy, pp. 269–271.

Treacy, M., Humphreys, J., Namara, K.M., Browne, R., Teagasc, C.J.W., 2008. Farm-gate nitrogen balances on intensive dairy farms in the south west of Ireland. Ir. j. agric. food res. 47 (2), 105–117.

Tuohy, P., Humphreys, J., Holden, N.M., Fenton, O., 2016. Runoff and subsurface drain response from mole and gravel mole drainage across episodic rainfall events. Agric. Water Manag. 169, 129–139. https://doi.org/10.1016/j.agwat.2016.02.020.

Wall, D., Plunkett, M., 2016. Nutrient Advice for Productive Agricutural Crops. Teagasc.

White, P.J., 2013. Improving potassium acquisition and utilisation by crop plants. J. Plant Nutr. Soil Sci. *176* (3), 305–316. https://doi.org/10.1002/jpln.201200121.

Gaucheron, F., 2011. Milk and Dairy Products : A Unique Micronutrient Combination. CERIN SYMPOSIUM, Paris, France hal-01454316 HAL.

Williams, P.H. (1988). The fate of potassium in grazed dairy pastures. PhD Thesis submitted to *Soil Science Dept.* Massey University, Palmerston North, New Zealand.

Schröder, J.J., Aarts, H.F.M., ten Berge, H.F.M., van Keulen, H., Neeteson, J.J., 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. Eur. J. Agron. 20, 33–44.

Carroll, N. O., & Mccarthy, R. (1972). *Potassium supplied by precipitation and its possible role in forest nutrition.*