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Research article

Balancing nutrients and metal contaminants: sustainable land application rates for livestock manures in Ireland

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ABSTRACT

Livestock manures are valuable nutrient sources for crop production, but variable composition and inappropriate application rates can cause nutrient imbalance, phosphorus accumulation and trace-metal loading, increasing the risks to water quality and the wider environment. This study evaluated manure-specific application rates by considering nutrient and trace-metal composition, crop requirements and soil phosphorus status. It was applied to cattle, sheep and chicken manures used for perennial ryegrass (*Lolium perenne* L.) and spring wheat (*Triticum aestivum* L.) under Irish nutrient-management recommendations. Maximum application rates ranged from 0.96 to 7.62 t dry matter ha^{-1} yr^{-1} for perennial ryegrass and from 0.99 to 9.76 t dry matter ha^{-1} yr^{-1} for spring wheat across Morgan's soil phosphorus indices 1 to 3, representing increasing soil phosphorus status. No manure application was permitted at index 4. Cattle manure permitted the highest application rates because of lower total phosphorus concentration, whereas sheep manure supported the lowest. The governing nutrient constraint varied with manure composition, crop nutrient requirements and soil nutrient status, with phosphorus generally limiting cattle and sheep manure application, while nitrogen limited chicken manure application under specific conditions in TN-based calculations. Regulated trace-metal loadings remained below the annual permissible limits. Zinc and copper reached approximately 31% and 14% of their respective limits, while cadmium remained below 10% and chromium, nickel and lead below 2%. These findings demonstrate the importance of considering manure nutrient composition, crop requirements, soil nutrient status and trace metal loading limits together when determining manure application rates to protect crop productivity and water quality.

1. Introduction

Globally, livestock production generates more than 13 billion tonnes of manure annually (Zheng et al., 2022). In the European Union (EU)-27 and the UK alone, approximately 1.4 billion tonnes are produced each year (based on 2016–2019 data), with around 90% recycled to agricultural land as organic fertiliser (Köninger et al., 2021). Livestock manures provide essential plant nutrients, including nitrogen (N), phosphorus (P) and micronutrients (Velthof et al., 2024), while improving soil biological activity (McBride et al., 2020), soil structure, soil health and carbon sequestration (Rayne and Aula, 2020; Huang et al., 2022). Despite these agronomic benefits, excessive manure application can result in significant losses of N through ammonia volatilization and nitrate leaching, and P losses through surface runoff. Manure application can also contribute to soil nitrous oxide (N_2O) emissions, thereby increasing the risk of groundwater contamination, climate change and eutrophication (Yan et al., 2024; Velthof et al., 2024; Xia et al., 2020).

Livestock manures contain essential elements, such as zinc (Zn) and copper (Cu), and potentially toxic elements, including cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) (Hejna et al., 2018), which may be introduced into agricultural soils through manure applications

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(Rashid et al., 2023). Repeated manure applications over many years may result in the gradual accumulation of these metals in agricultural soils, potentially increasing soil contamination and associated environmental risks (Zhen et al., 2020; Sun et al., 2023). This highlights the importance of assessing the trace metal inputs alongside nutrient management.

The EU Nitrates Directive (EU, 1991) provides the legislative framework to protect water quality from agricultural nutrient losses, while in Ireland, these measures are implemented through the Good Agricultural Practice (GAP) Regulations (S.I. No. 610 of 2010) (Government of Ireland, 2010),which regulate agricultural N and P applications. In this context, determining manure application rates is essential for effective nutrient management. The nutrient and trace metal composition of livestock manures varies considerably among manure types and is influenced by livestock species, diet, housing systems, manure handling and storage practices (Dadrasnia et al., 2021). Differences in animal diets and nutrient requirements influence the proportion of nutrients excreted in manure, resulting in considerable variation in manure nutrient composition (FAO, 2012; Erickson and Kalscheur, 2020).

In addition, manure handling and storage can alter nutrient concentrations through dilution, evaporation and ammonia volatilization (Dadrasnia et al., 2021). For example, Thapa et al. (2025) reported higher concentrations of N, P and magnesium (Mg) in chicken manure than in cattle manure, whereas calcium (Ca) was higher in dairy cattle manure. Trace metal concentrations, particularly Zn and Cu, can also vary among livestock manures depending on animal feeding practices and dietary mineral supplementation (Hejna et al., 2018; Qiu et al., 2023). Moreover, phytase supplementation in poultry feed can enhance P utilisation while reducing its excretion (Bougouin et al., 2014). This variability in manure composition presents a major challenge for nutrient management, as different manure types require different application rates to meet the crop nutrient requirements while minimising the environmental risks.

Previous studies have characterised the nutrient and trace metal composition of livestock manures and evaluated their agronomic value and environmental implications (Qi et al., 2023; Rayne and Aula, 2020). However, crop nutrient requirements and trace metal loading limits are often considered separately when evaluating manure land application rates. Therefore, the present study quantitatively integrates crop nutrient requirements (Wall and Plunkett, 2020) with regulatory trace metal loading limits (Fehily Timoney and Company, 1999) to determine the manure-specific application rates across different crops and soil nutrient classifications.

Accordingly, the objectives of the current study were to: (1) provide a comprehensive overview of the nutrient and metal composition of three animal manures: cattle, sheep and chicken and assess seasonal variations within each manure type (2) calculate the maximum application rates of each manure for ryegrass (*Lolium perenne* L.) and spring wheat (*Triticum aestivum* L.) (representative grassland and cereal crops in Ireland) based on crop N and P requirements across relevant soil nutrient indices and annual trace metal loadings, using the most restrictive rate; and (3) calculate the equivalent annual loading rates of regulated metals associated with each application rate scenario. Although the present study uses Irish crop nutrient recommendations and trace metal loading limits, the integrated assessment approach is applicable beyond Ireland and can be adapted to other agricultural systems by incorporating locally relevant crop nutrient requirements, soil nutrient classifications and regulatory limits.

2. Material and methods

2.1. Sample collection

A total of 120 manure samples were collected from 30 farms across Ireland between 2023 and 2024 from cattle, sheep and chicken production systems. Ten farms were included for each manure type, with the same farms sampled across four seasons to capture temporal variability in manure composition, resulting in 40 samples per manure type. The county-level distribution of participating farms is presented in Table S1 of the Supplementary Material. Cattle manure samples were collected as liquid slurry from storage tanks in beef production systems, while chicken manure samples consisted of broiler litter (manure mixed with bedding material) collected from poultry shed floors. None of the three manure types had undergone intentional composting prior to sampling. All the samples were collected in trace metal-free plastic test tubes (Labcon, USA). The sample size was determined based on sample availability, logistical feasibility and available project resources. Therefore, no formal statistical sample-size calculation was performed. The study was not designed as a statistically representative survey of Irish livestock farms and potential spatial correlation among farms was not assessed. Information regarding animal diet, production stage, bedding and manure storage practices was not systematically recorded, which may have contributed to the variability in manure composition.

2.2. Sample analysis

All manure samples were stored at −20 °C until analysis. Prior to chemical analyses, individual samples were freeze-dried at −52 °C (Freezone 12, Labconco, Kansas City, MO, USA) and ground into a homogenous fine powder using an agate mortar and pestle, which was cleaned with absolute ethanol (≥99%; Fisher Scientific, Loughborough, UK) between samples to prevent cross-contamination. Mineral N (NH_4-N) was extracted by mixing 1.0 g of freeze-dried sample with 20 mL of 0.1 M hydrochloric acid (HCl) (ROMIL-UpA™, ROMIL Ltd., Cambridge, UK) solution. The mixture was shaken at 120 rpm for 1h using a Stuart SSL1 orbital shaker (Cole-Parmer, UK) and subsequently centrifuged at 3000 rpm for 5 min (Shi et al., 2022). The supernatant was filtered through a 0.45 μm nylon syringe filters (Fisher Scientific, Loughborough, UK), and the resulting filtrate was analyzed for mineral N concentrations using a Gallery™ Plus discrete analyzer (Thermo Fisher Scientific, Waltham, MA, USA). Total nitrogen (TN) and total carbon (TC) concentrations were determined by high-temperature combustion using a LECO 928 Macro CN analyzer (LECO Corporation, St. Joseph, MI, USA).

Approximately 0.10 g of oven-dried manure was transferred to microwave digestion vessels and pre-digested overnight with 8 mL of ultrapurity nitric acid (HNO_3; ROMIL-UpA™, ROMIL Ltd., Cambridge, UK). Subsequently, 2 mL of hydrogen peroxide (30%, for ultra trace analysis; Supelco, France) was added, and samples were digested using a microwave digestion system (Multiwave 3000, Anton Paar, Graz, Austria) with a 15 min ramp to 160 °C followed by a 15 min hold at 160 °C. After cooling, the digests were quantitatively transferred to 50 mL trace metal-free plastic test tubes (Labcon, USA), diluted with Milli-Q water (Merck Millipore, Burlington, MA, USA), and filtered through 0.45 μm nylon syringe filter (Fisher Scientific, Loughborough, UK) prior to ICP analysis. Total P, sulphur (S), Ca, Mg, and boron (B) concentrations were determined by inductively coupled plasma optical emission spectrometry (Agilent 5100, ICP-OES). Trace elements, including aluminium (Al), arsenic (As), Cd, chromium (Cr), Cu, iron (Fe), potassium (K), manganese (Mn), Ni, Pb, selenium (Se), sodium (Na) and Zn, were determined by inductively coupled plasma mass spectrometry (Agilent 7850, ICP-MS). Quality assurance and quality control (QA/QC) were performed using certified reference material (CRM; Sewage Sludge 2; Sigma-Aldrich, USA), together with method blanks. The recoveries obtained for the certified reference material are presented in Table S2.

2.3. Calculation of maximum application rate

The application rates were determined using an approach adapted from Shi et al. (2022), based on crop nutrient recommendations (Wall and Plunkett, 2020) and the regulatory limits for annual trace metal

loading (Fehily Timoney and Company, 1999). In Ireland, soil nutrient status is classified into index levels ranging from 1 to 4, which are used to determine crop nutrient recommendations (Wall and Plunkett, 2020). Soil P status is classified according to Morgan's P Index system, with Index 1 indicating low soil P status and Index 4 indicating high soil P status. For ryegrass (grassland), Morgan's P ranges for Indices 1–4 are 0–3.0, 3.1–5.0, 5.1–8.0 and > 8.0 mg L^{-1}, respectively, corresponding to approximate Olsen P equivalents of 0–13.9, 14.3–20.7, 21.0–29.7 and > 29.7 mg kg^{-1}. For spring wheat (other crops classification), the corresponding Morgan's P ranges are 0–3.0, 3.1–6.0, 6.1–10.0 and > 10.0 mg L^{-1}, with approximate Olsen P equivalents of 0–13.9, 14.3–23.8, 24.1–35.3 and > 35.3 mg kg^{-1}. Olsen P equivalents were estimated using Olsen P = 5.96 (Morgan P)^0.773 (Foy et al., 1997). The corresponding crop nutrient recommendations used in this study are presented in Table 1. For each manure type, separate maximum application rates (t DW ha^{-1} yr^{-1}) were determined according to the crop P and N requirements and the maximum permissible annual loading of regulated metals (Zn, Cu, Cr, Cd, Ni and Pb). The lowest of these application rates was selected as the maximum application rate for each manure, crop and soil index combination, as this represents the rate at which the first nutrient requirement or trace metal loading limit is reached. Application rates above this threshold would exceed at least one constraint. Where the application rate was limited by P, any additional crop N requirement would need to be supplied separately. The calculations were based on total nitrogen (TN) concentrations. The general Irish regulatory limit of 170 kg N ha^{-1} yr^{-1} from livestock manure was considered but was not included as an additional constraint, as the crop N allowances used in this study (60–160 kg N ha^{-1} yr^{-1}; Table 1) were already below this limit (Government of Ireland, 2010).

For perennial ryegrass, application rates were evaluated across soil P indices 1–4. The recommended N rate for ryegrass remains constant (125 kg N ha^{-1}) across all soil N indices (Wall and Plunkett, 2020). Therefore, separate calculations across soil N indices were not required. However, for spring wheat, N recommendations vary with soil N index, and application rates were evaluated across both soil P and soil N indices (1–4). Based on the calculated application rates, the annual equivalent loading rates for nutrients and regulated metals were determined for each scenario. These loading rates were compared against the maximum permissible annual average metal loading rates over a 10-year period (Fehily Timoney and Company, 1999) to ensure the application scenarios remained within the regulatory limits. All manure application rate and corresponding trace metal loading calculations were performed using Microsoft Excel for Microsoft 365. The complete manure-specific calculations, including mean, minimum and maximum composition scenarios, governing nutrient constraints, application rates, and corresponding nutrient and trace metal loadings, are provided in Supplementary Data S1.

2.4. Statistical analysis

Seasonal differences in manure composition were assessed within each manure type, with no statistical comparisons among manure types. The same farms for each manure type were sampled across all four seasons. For each element, data were tested for normality using the Shapiro–Wilk test and for sphericity using Mauchly's test. Based on these assumptions, seasonal differences were assessed using repeated-measures ANOVA or the Friedman test. P-values were adjusted separately for each manure type using the Benjamini–Hochberg FDR procedure. Where seasonal effects remained significant, pairwise comparisons were conducted using paired Wilcoxon signed-rank tests with Holm correction. Statistical significance was set at an FDR-adjusted $p < 0.05$. All statistical analyses were performed in R (version 4.3.3; R Core Team, 2024) using the rstatix package (Kassambara, 2026). Detailed results of the statistical analyses are provided in Table S3.

Table 1
Crop N and P requirements for perennial ryegrass (*Lolium perenne* L.) and spring wheat (*Triticum aestivum* L.) across Irish soil P and N indices. **Source:** adapted from Wall and Plunkett (2020).

Soil P Index	Ryegrass P (kg P ha^{-1})	Spring wheat P (kg P ha^{-1})
1	40	45
2	30	35
3	20	25
4	0	0
Soil N Index	Ryegrass N (kg N ha^{-1})	Spring wheat N (kg N ha^{-1})
1	125	160
2	125	130
3	125	95
4	125	60

3. Results and discussion

3.1. Physicochemical composition

Seasonal variation was significant only for Na in cattle manure after FDR correction (Friedman test, $p < 0.001$; FDR-adjusted $p = 0.006$). Post-hoc pairwise comparisons revealed higher Na concentrations during winter compared with spring and autumn (Holm-adjusted $p = 0.012$ for both comparisons). Seasonal effects were not significant for any other elements. The seasonal distributions of nutrients and trace elements for each manure type are presented in Fig. S1, with the detailed statistical results provided in Table S3. Pooled mean concentrations across the four seasons were used to provide an overall estimate of manure composition for the maximum application-rate calculations, while recognising that the limited sample size may have constrained the assessment of seasonal variability.

The overall metal and nutrient composition of each type of manure is presented in Table 2. All of three manures contained substantial concentrations of essential plant nutrients, including N, P, K, Ca, Mg and S. However, nutrient content and TN:TP ratio varied. These differences

Table 2
Physicochemical composition (mean ± standard deviation) based on d.w. Of cattle, sheep and chicken manure collected across four seasons (spring, summer, autumn, winter) across Ireland (n = 40 per manure type).

Parameter	Cattle (n = 40)	Sheep (n = 40)	Chicken (n = 40)	EU (2019)
TN (g kg^{-1})	23.1 ± 3.4	29.8 ± 6.2	40.8 ± 8.2	
TC (g kg^{-1})	378 ± 32.1	421 ± 32.1	407 ± 14.3	
NH_4-N (g kg^{-1})	1.5 ± 1.3	1.2 ± 0.8	4.5 ± 3.4	
TP (g kg^{-1})	7.7 ± 1.9	11.9 ± 3.3	9.6 ± 2.5	
S (g kg^{-1})	4.8 ± 1.1	3.74 ± 0.7	4.5 ± 0.7	
Al (g kg^{-1})	2.0 ± 1.3	1.9 ± 2.0	0.32 ± 0.07	
Ca (g kg^{-1})	32 ± 14	21 ± 8.9	18.1 ± 4.1	
Fe (g kg^{-1})	2.6 ± 1.5	1.8 ± 1.7	0.58 ± 0.2	
K (g kg^{-1})	30 ± 21.1	17.02 ± 8.5	30.5 ± 5.5	
Mg (g kg^{-1})	8 ± 3.2	6.5 ± 2.3	6.5 ± 1.5	
Na (g kg^{-1})	4.5 ± 4.4*	3.3 ± 2.3	2.8 ± 1.4	
Mn (mg kg^{-1})	313 ± 99.5	496 ± 244.3	485 ± 99.2	
B (mg kg^{-1})	16.4 ± 6.8	10.1 ± 4.0	52.3 ± 12.6	
Zn (mg kg^{-1})	275.8 ± 143.7	164.3 ± 139.8	434.8 ± 107	800
Cu (mg kg^{-1})	90.3 ± 61.8	31.3 ± 9.7	95.8 ± 21.4	300
Cd (mg kg^{-1})	0.41 ± 0.3	0.40 ± 0.5	0.40 ± 0.2	1.5
Cr (mg kg^{-1})	4.2 ± 2.02	3.4 ± 3.2	4.6 ± 2.0	—
Ni (mg kg^{-1})	6.1 ± 2.5	5.8 ± 3.5	6.4 ± 1.7	50
Pb (mg kg^{-1})	3.0 ± 2.2	2.9 ± 3.2	0.4 ± 0.2	120
As (mg kg^{-1})	0.8 ± 0.5	0.6 ± 0.6	0.3 ± 0.2	40
Se (mg kg^{-1})	1.6 ± 1.2	1.0 ± 1.1	1.3 ± 0.3	-

Notes: * Indicates a significant seasonal effect within the respective manure type after FDR correction (adjusted $p < 0.05$). No statistical comparisons were performed among manure types. The EU chromium limit applies specifically to Cr (VI), whereas total Cr was measured in this study; therefore, no directly comparable EU benchmark is provided. **Source:** Authors' own experimental data; EU benchmark values from Regulation (EU) 2019/1009.

have major implications for determining safe application rates, as applying manure without considering their nutrient composition may result in nutrient applications which exceed crop requirements. This increases the potential risk of nutrient surpluses and associated environmental impacts (Velthof et al., 2024; Withers et al., 2014). Chicken manure had the highest mean TN concentration (40.75 ± 8.20 g kg^{-1}), followed by sheep (29.80 ± 6.20 g kg^{-1}) and cattle (23.06 ± 3.40 g kg^{-1}). These results are consistent with broader manure nutrient datasets, where chicken manure generally contains higher total N concentrations than sheep and cattle manures (Cawood, 2023).

Variation in manure TN concentration can be influenced by the balance between dietary protein consumption and animal nutrient requirements, which affects the amount of N excreted in manure (Bougouin et al., 2022). In addition, manure handling and storage can further modify TN concentrations through N losses, particularly via ammonia volatilization (Dadrasnia et al., 2021; Genedy and Ogejo, 2023). Ammonium-N (NH_4-N) represented only 4 – 11% of the total N in all three manures, indicating that organic nitrogen was the dominant form rather than the readily available mineral form. The relatively low proportions of the NH_4-N may reflect volatilization losses during manure storage, although the contribution of this process was not directly assessed in the present study.

For TP, sheep manure had the highest mean concentration (11.9 ± 3.3 g kg^{-1}), followed by chicken (9.6 ± 2.5 g kg^{-1}) and cattle manure (7.7 ± 1.9 g kg^{-1}). The observed variation in manure TP concentrations may reflect differences in animal feeding and P management practices. Previous studies have shown that phytase supplementation in poultry diets can influence P utilisation and excretion (Bougouin et al., 2014); however, phytase use was not recorded in the present study. Differences in manure nutrient composition may therefore influence the application rates depending on crop nutrient requirements and soil P status.

The mean concentrations of other essential elements also differed among manure types (Table 2). Cattle manure contained higher levels of Ca (32 ± 14 g kg^{-1}), Mg (8 ± 3.2 g kg^{-1}), and Fe (2.6 ± 1.5 g kg^{-1}), while chicken manure had higher K (30.5 ± 5.5 g kg^{-1}) and B (52.3 ± 12.6 mg kg^{-1}). Mn was comparatively higher in both sheep (496 ± 244 mg kg^{-1}) and chicken (485 ± 99 mg kg^{-1}) manures. These elements contribute to the fertiliser value of manure (Wall and Plunkett, 2020); however, repeated inputs may increase soil nutrient concentrations, potentially contributing to nutrient imbalances (Wu et al., 2025).

The concentrations of trace metals such as Zn, Cu, Cd, Ni, Pb, and As were below the threshold limits specified by EU regulations for organic fertilisers (EU, 2019). The EU chromium limit applies specifically to Cr (VI), while this study measured total Cr; therefore, a direct comparison with the regulatory limit was not possible (Table 2). Chromium accumulation in soil may be of concern due to its potential toxic effect on soil biota and plants, although its toxicity depends on Cr speciation and soil properties (Shahid et al., 2017; Zhang et al., 2022). Mean Zn concentration was higher in chicken manure than in cattle and sheep manure, whereas mean Cu concentrations were similar in chicken and cattle manure but lower in sheep manure. This may reflect the dietary supplementation of Zn and Cu as feed additives in livestock feeds to meet physiological requirements for growth, immunity, and production (Hill and Shannon, 2019; Duffy et al., 2023; El Sabry et al., 2021; Broom et al., 2021). However, excess amounts of these essential metals can accumulate in manure due to incomplete absorption and subsequent excretion by livestock (Gourlez et al., 2024). Although Zn and Cu are essential micronutrients, their accumulation at elevated concentrations can induce toxic impacts in plants and interfere with soil microbial activity and nutrient cycling (Rashid et al., 2023). Therefore, manure application should consider both its nutrient value and the associated trace metal inputs to agricultural soils.

3.2. Safe application rates for manures

Across soil P indices 1–3, the maximum application rates ranged from 0.96 to 7.62 t DW ha^{-1} yr^{-1} for ryegrass and from 0.99 to 9.76 t DW ha^{-1} yr^{-1} for spring wheat (Fig. 1). However, no manure application was permitted at soil P index 4, because the corresponding crop P recommendation was zero (Wall and Plunkett, 2020). The maximum application rates for cattle, sheep and chicken manure for ryegrass and spring wheat are shown in Fig. 1. For ryegrass, the crop N allowance is fixed at 125 kg N ha^{-1} yr^{-1} regardless of soil N index (Wall and Plunkett, 2020), whereas for spring wheat, it decreases from 160 to 60 kg N ha^{-1} yr^{-1} between soil N indices 1 to 4. Therefore, only the spring wheat results for soil N Index 1 are presented in Fig. 1, while the corresponding results for soil N indices 2, 3 and 4 are presented in Fig. S2–S4, respectively.

Application rates were governed by either crop N allowance or soil P status, depending on manure nutrient composition. For ryegrass, cattle and sheep manure were mostly P-limited across all soil P indices 1–3, whereas chicken manure was N-limited at lower soil P indices 1 and 2 and P-limited at soil P index 3. For spring wheat, chicken manure was N-limited at lower soil P indices, while the governing nutrient depended on both soil N and P status. The specific N- and P-limited scenarios and corresponding manure-specific calculations are provided in Supplementary Data S1. These nutrient constraints were identified using TN-based calculations and do not account for differences in plant-available N among manure types.

Based on the observed mean nutrient concentrations, cattle manure generally permitted higher calculated application rates than sheep and chicken manure across both crops, reflecting its comparatively lower mean TP concentration. These findings are descriptive and do not imply statistically significant differences among manure types. These results demonstrate how crop nutrient requirements and soil P condition determine the manure application rates and the nutrient constraint governing application rate for different crop and soil conditions.

Previous studies have identified P as an important constraint for organic fertiliser application. Lucid et al. (2013) reported that P-based application can reduce excessive P inputs, while Shi et al. (2022) identified P as the governing constraint for dairy processing-derived fertilisers. In contrast, the present study found that chicken manure was N-limited under specific crop and soil conditions, highlighting that the governing nutrient constraint depends on manure composition, crop nutrient requirements and soil nutrient status. Although the application rates were based on TN and TP, only 4–11% of manure N was present as NH_4-N, which indicates that most N was present in organic forms. Consequently, a proportion of manure N becomes available gradually through mineralization following land application, depending on manure characteristics and environmental conditions. (Bhogal et al., 2016; Breza and Grandy, 2025). As the calculations were based on TN concentrations without accounting for the gradual release of N from organic forms, the identification of N as a limiting factor, particularly for chicken manure, reflects the assumptions of the calculation approach rather than necessarily representing the nutrient limitation under actual field conditions.

The assessment of manure application rates was based on crop N and P requirements together with permissible trace metal loading limits. The calculated application rates provide reference estimates for manure management under different crop and soil nutrient conditions. However, variations in manure composition arising from production systems, handling and storage should be considered when applying these findings to other farm conditions. Additional nutrients were also characterised to provide a comprehensive understanding of manure composition. Following land application, the fate and mobility of nutrients can be influenced by soil properties. Physicochemical characteristics, including soil pH, mineral composition and clay content, can influence P availability and the mobility and bioavailability of trace metals (Jindo et al., 2023; Wan et al., 2024). These soil-specific processes were not

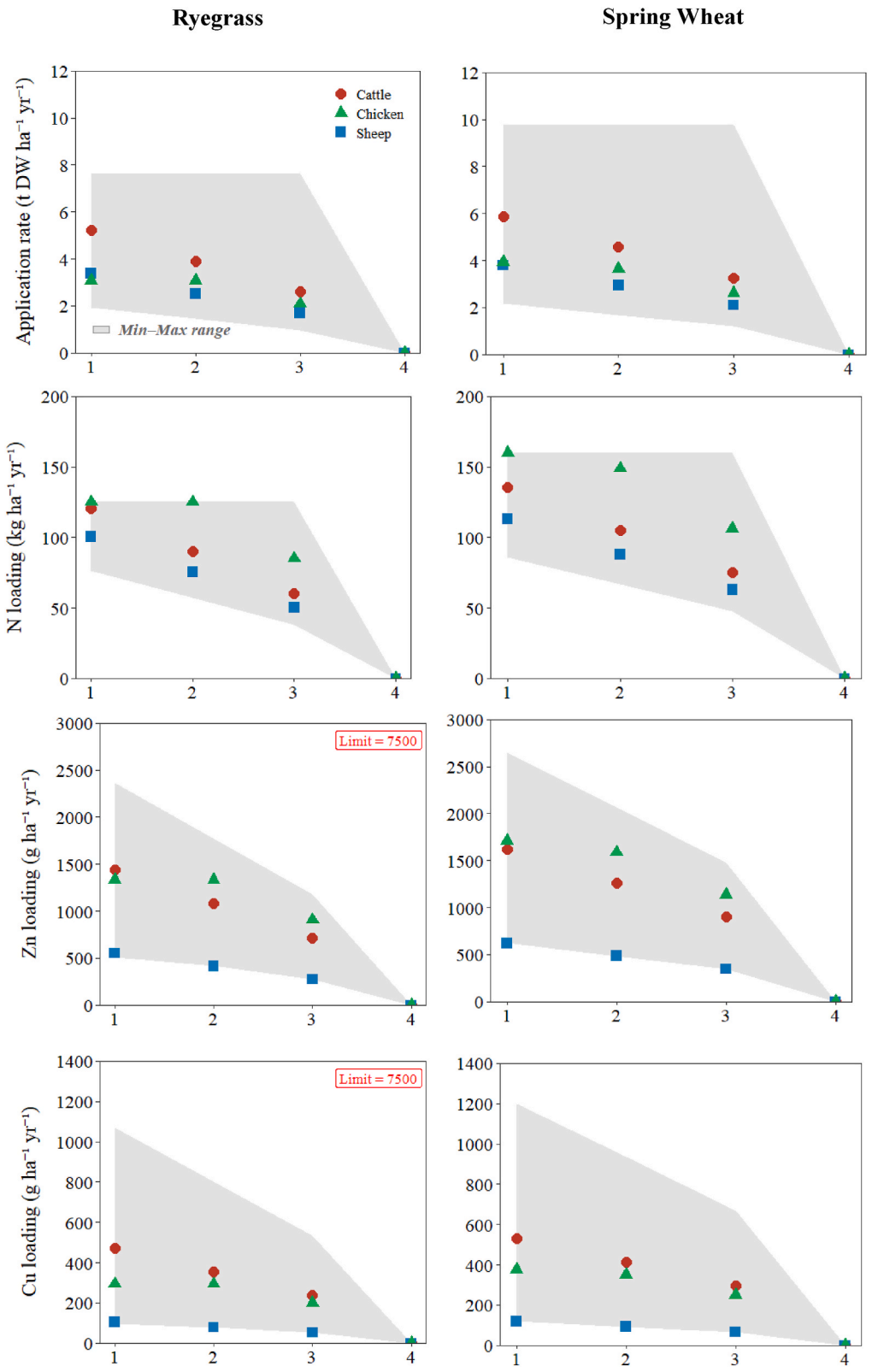


Fig. 1. Maximum manure application rates and corresponding nitrogen and regulated metal loadings for ryegrass and spring wheat across soil phosphorus indices. **Notes:** The maximum application rates (t dry weight (DW) ha^{-1} yr^{-1}) of cattle (●, red), sheep (■, blue) and chicken manure (▲, green) applied to ryegrass and spring wheat at soil N Index 1, across soil phosphorus (P) indices 1–4, and the equivalent loading rates of nitrogen (N) and regulated metals calculated at these application rates. Application rates for each manure type were calculated separately using the mean composition of the corresponding manure samples (n = 40). The shaded areas represent the minimum-to-maximum range of calculated application rates derived from the manure-specific composition scenarios at each soil P index; cattle, sheep, and chicken manure samples were not combined. Red text indicates the applicable annual Irish regulatory limit. Mercury (Hg) loading is not presented as concentrations were not determined in this study. **Source:** Authors' own experimental data and calculations based on crop nutrient recommendations (Wall and Plunkett, 2020) and trace-metal loading guidelines (Fehily Timoney and Company, 1999).

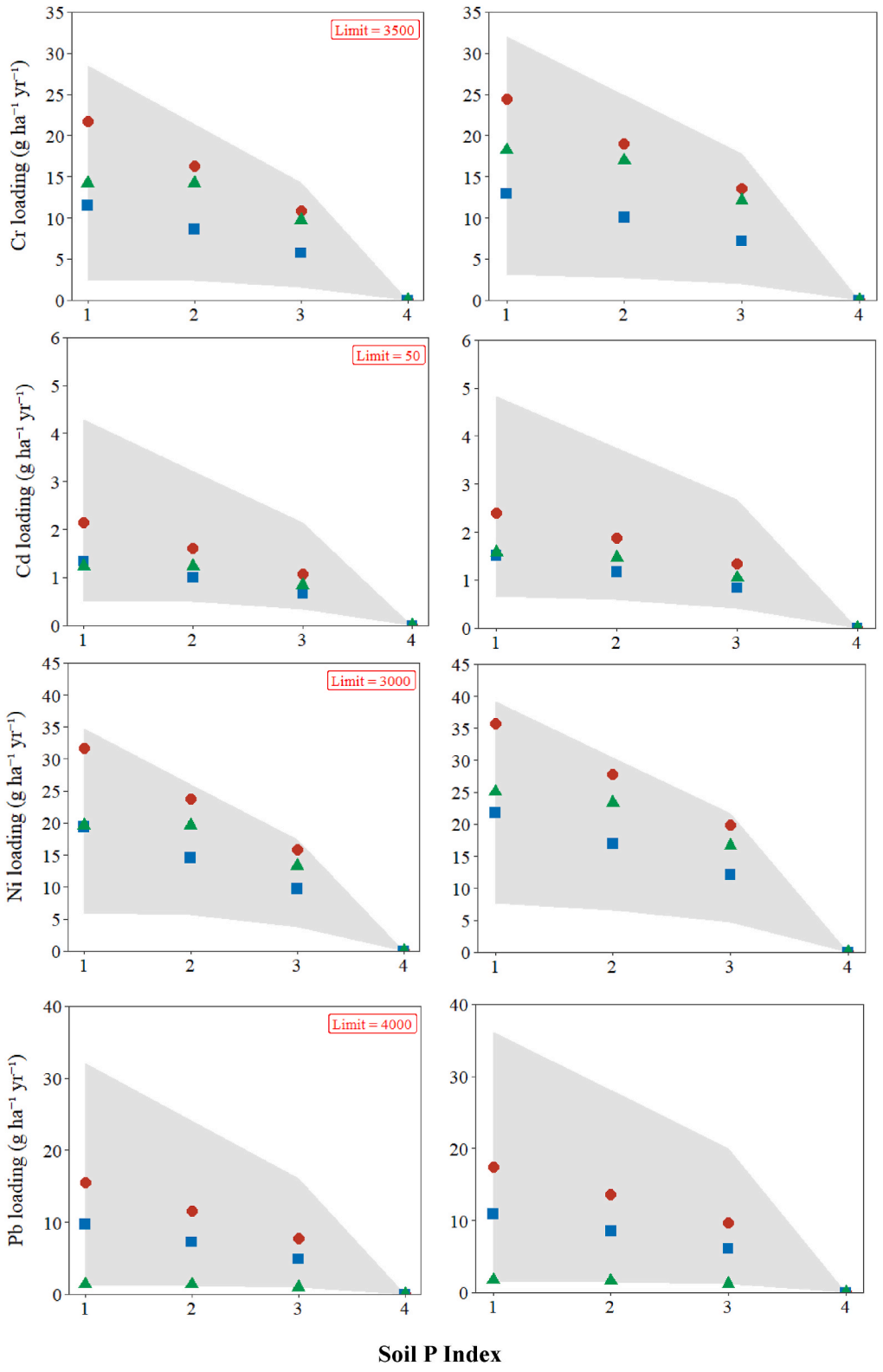


Fig. 1. (*continued*).

considered in the calculation of application rates and therefore represent a limitation when applying the calculated manure rates to specific field conditions.

3.3. Estimation of equivalent loading rates of N and trace metals

Equivalent loading rates of the six regulated metals (Zn, Cu, Cr, Cd, Ni and Pb) were estimated from the calculated application rates of cattle, sheep and chicken manure and compared with the annual loading limits for agricultural soils specified by Fehily Timoney and Company

(1999). Across all crop and soil-index scenarios, estimated metal loadings remained well below the regulatory thresholds (Fig. 1 and S1–S3), indicating that nutrient-based application rates maintain trace metal loadings below the annual regulatory limits.

Among the regulated metals, Zn and Cu had the highest equivalent loading rates, reflecting their comparatively higher concentrations in the manures (Table 2). However, even the maximum Zn and Cu loadings represented only approximately 31% and 14% of their respective annual regulatory limits, while Cd remained below 10% and Cr, Ni, and Pb remained below 2% of their corresponding annual limits for both crops and soil scenarios. Although total Cr concentrations could not be directly compared with the EU Cr (VI)-specific concentration limit the equivalent Cr loading remained well below the soil annual loading limit, because manure application rates were constrained by the crop nutrient requirements rather than by the metal alone.

Despite the low annual loading of Cr, its potential long-term environmental implications require particular attention, as Cr mobility, toxicity, and bioavailability are strongly influenced by oxidation state (Shahid et al., 2017). Cr(III) is generally less mobile in soil, whereas Cr (VI) exhibits greater mobility, bioavailability and toxicity (Shahid et al., 2017; Mortada et al., 2023). This greater mobility of Cr(VI) enhances its potential to migrate through the soil profile to the water resources, increasing the potential for human exposure through contaminated drinking water (Zhitkovich, 2011). However, Cr speciation was not determined in the present study, limiting the assessment of its mobility and bioavailability. Although the estimated annual metal inputs remain within the regulatory limits, these calculations reflect only the annual loading and do not account for long-term metal fate in soil-plant system. Under repeated manure application, metal accumulation in soil will not only depend on annual inputs but also on plant uptake capacity, leaching and runoff losses and the soil properties which can impact the mobility and bioavailability of metals (Rashid et al., 2023). Therefore, continuous monitoring of soil metal concentrations are recommended for long-term manure management practices.

The integrated assessment used in this study provides an approach for optimising manure application, while maintaining compliance with both nutrient requirements and trace metal loading limits. Future research is needed to develop and validate an integrated decision-support tool for manure application that incorporates manure composition, crop nutrient requirements, soil properties, nutrient availability, and potential long-term trace metal accumulation. Its broader applicability should be assessed across different crops, manure types, soil properties, and regulatory settings.

4. Conclusions

This study highlights the importance of considering manure nutrient composition, crop nutrient requirements, soil nutrient status and trace metal loading limits when determining sustainable manure application rates. Phosphorus was the primary nutrient constraining the application rates for cattle and sheep, while nitrogen limited chicken manure application under specific crop and soil conditions within the TN-based calculation framework. Although regulated metals were present in all three manures, their annual loadings at the calculated application rates remained below the permissible limits. These results demonstrate the importance of assessing trace metal loadings along with nutrient requirements for sustainable manure application. However, the application rates were based on the total nutrient concentrations and annual trace metal loading limits and may not fully represent actual field conditions. In particular, the use of TN does not account for the gradual mineralisation and availability of organic N following land application. Furthermore, the potential accumulation of trace metals under repeated manure application requires further consideration. Therefore, long-term field studies incorporating nutrient availability and soil properties are needed to support sustainable manure management strategies that promote nutrient recycling while protecting soil quality.

CRediT authorship contribution statement

S. Farid: Writing – original draft, Methodology, Formal analysis, Conceptualization. **L. Morrison:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **M. Danaher:** Writing – review & editing, Methodology. **C. Laffey:** Resources, Methodology, Formal analysis. **G. Kealy:** Methodology, Formal analysis. **D. Costello:** Resources, Methodology. **L. Moloney-Finn:** Methodology, Formal analysis. **O. Fenton:** Resources, Formal analysis. **M.G. Healy:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.131318.

Data availability

Data will be made available on request.

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