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# Quantification of antimicrobial use on Irish dairy farms: A comparison of 3 recording methods

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## ABSTRACT

Antimicrobial use (AMU) data are essential for monitoring usage over time, facilitating reduction strategies to combat the threat of antimicrobial resistance (AMR) to both human and animal health. The objective of this study was to measure and describe AMU over a 12-mo period in Irish dairy herds and compare 3 different recording methods to a reference method. A sample of 33 Irish dairy herds were randomly selected from 6 private veterinary practices across Ireland. The herds were followed for a 12-mo period, and their AMU was monitored using 3 recording methods: (1) veterinary prescription data (VET), (2) the inventory of medicine bins on the farms (MB), and (3) farmer treatment records from herd recording software (APP). Each recording method was compared with a previously developed reference method for AMU. The reference method used was based on pre- and poststudy medicine stock on the farms combined with VET. Antimicrobial use was analyzed using both mass- and dosed-based metrics, including mass (mg) of antimicrobial active ingredient per population correction unit (PCU), defined daily doses for animals ($DDD_{VET}$) and defined course doses for animals ($DCD_{VET}$). Median AMU was 16.24, 10.47, 8.87 and 15.55 mg/PCU by mass, and 2.43, 1.55, 1.19 and 2.26 $DDD_{VET}$ by dose for VET, MB, APP, and reference method data, respectively. Reliability of the agreement between each pair of methods was quantified using the concordance correlation coefficient (CCC). When compared with the reference method, VET data had excellent reliability (95% CI of CCC: 0.992–0.998). The MB data had good to excellent reliability (95% CI of CCC: 0.776–0.936). The APP data had poor reliability when compared with the reference method (95% CI of CCC: −0.167 to 0.156). Our results highlight that a small number of herds were contributing most to overall use and farmers showed varying levels of consistency in recording AMU. Veterinary data were the most reliable approach for assessing AMU when compared with a reference method of AMU. This is an important finding for the future monitoring of AMU at a national level.
**Key words:** antimicrobials, antimicrobial stewardship, Ireland, medicine bins, veterinary prescriptions

## INTRODUCTION

Antimicrobial resistance (**AMR**) is listed by the World Health Organization as one of the top global public health and development threats (WHO, 2015). In 2019, AMR was one of the leading causes of death globally, with researchers estimating that 4.95 million human deaths globally were associated with bacterial AMR, of which 1.27 million deaths were directly attributable to AMR (Murray et al., 2022). Antimicrobial use (**AMU**) has been linked with AMR on farms (Tang et al., 2017) and AMU data are essential for reducing AMU through targeted intervention strategies. The latest National Action Plan on Antimicrobial Resistance from the Irish government outlines enhancing surveillance of AMR and AMU as one of the key strategic objectives to tackling the complex One Health challenge that is AMR (Government of Ireland, 2021a).

Veterinary AMU data collection is now a requirement in the European Union (**EU**) under EU Regulation 2019/6 (European Union, 2019). In Ireland, national veterinary AMU sales data are published annually by the Health Products Regulatory Authority (HPRA, 2023). Further, from 2024 all veterinary prescriptions will be collated in the National Veterinary Prescription System (**NVPS**) run by the Department of Agriculture, Food and the Marine (**DAFM**; Government of Ireland, 2021b). Within the various livestock sectors, farm-level data have been

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collected in the pig and poultry sectors; however, this level of granularity in data collection is not yet available for the cattle (dairy or beef) and sheep sectors (Martin et al., 2020). The National Antimicrobial Usage Database for pigs was launched by DAFM in November 2019, and since September 2021, it is a requirement under the Bord Bia Pig Quality Assurance Scheme that all pig farmers submit their AMU data to DAFM on a quarterly basis (https://www.gov.ie/en/publication/fc9b3-pigs-farming-sectors/#national-antimicrobial-usage-database-for-pigs). Within the dairy sector, there is a legal obligation that all medicines administered are recorded on-farm (European Communities, 2007); however, these data are not collected, and unlike the pig sector, farmers are not currently required to submit data to any form of online database.

Dairy cattle account for a large proportion of Ireland's total animal biomass, comprising nearly 30% of cattle in the country in 2019, with dairy cow numbers on the rise (Brock et al., 2022; CSO Ireland, 2023). With over 1.6 million dairy cows in Ireland in 2022, usage in this sector is important when considering total veterinary AMU (CSO Ireland, 2023). However, our understanding of AMU in this sector is limited as most veterinary AMU data are national sales data, rather than at the sector or farm level. Although comprehensive research studies have been conducted in the pig sector (O'Neill et al., 2020), the dairy sector remains relatively less studied. To date, studies in the dairy sector in Ireland have analyzed antimicrobial (**AM**) sales of intramammary products (More et al., 2012, 2017; McAloon et al., 2021) and farm-level usage in calves (Earley et al., 2019). However, none have considered farm-level AMU in all pharmaceutical forms and across all age groups of cattle.

Various methods exist for collecting AMU data, including veterinary records, the inventory of medicine bins, and the treatment records of farmers. The collection of farmer treatment records and medicine bin contents have been widely used to capture AMU data on dairy farms in research studies in Switzerland (Pucken et al., 2021), the United Kingdom (**UK**; Rees et al., 2021), Canada (Saini et al., 2012; Nobrega et al., 2017; Lardé et al., 2021; Warder et al., 2023), Peru (Redding et al., 2014), and India (Vijay et al., 2023). However, these data collection methods are labor-intensive and require farmer compliance to yield accurate results. Each method has their own advantages and limitations and comparing methods can allow us to assess which is the most accurate estimate of on-farm use.

In the UK, Rees et al., (2021) compared the accuracy of recording methods on dairy farms utilizing a reference method, including veterinary prescriptions, farmer treatment records and the inventory of medicine bins. By establishing a reference method measurement of actual AMU a priori, all 3 recording methods could be compared with the reference method and an estimate of the agreement of each method made. The use of veterinary sales data as a proxy for on-farm AMU in the UK exhibited excellent statistical reliability and offered clinically good agreement with the reference method when used to measure injectable antimicrobials. The Rees et al. (2021) study applies to the UK context; however, the Irish and UK dairy sectors exhibit notable differences in terms of farm management (seasonal vs. not), the pattern of etiological pathogens (*Staphylococcus* predominantly vs. not), and legislative basis (EU vs. not). Milk production in Ireland is primarily based on spring-calving, pasture-based systems (Dillon et al., 2008). Approximately 84% of Irish cows calve between the months of January to April (ICBF, 2023), and cows are at pasture for more than 240 d/yr (O'Brien et al., 2014). Although in the UK, approximately 80% of dairy herds operate all year-round calving and only 4% operate a spring-calving system (AHDB, 2016). Additionally, research suggests differing attitudes toward sustainability, welfare, and economics in the dairy sectors of the UK and Ireland. While close in proximity, the differences between the dairy sectors in Ireland and the UK highlight the potential for varying outcomes if the Rees et al. (2021) study were replicated in Ireland.

In previous research studies comparing the accuracy of these recording methods, farmer treatment records usually had lower quantities of AMU recorded than in veterinary records or the bin, which was partly attributed to missing dosages in the treatment entries (Nobrega et al., 2017). Additionally, in a recent study assessing AMU data capture accuracy on dairy farms in England and Wales the use of electronic records was associated with higher recording accuracy (Strang et al., 2023). In that study drug names, withdrawal periods and dates that products were fit for human consumption were often incomplete or incorrect. To address the issues associated with using paper records, the current study asked farmers to use herd recording software, requiring dosage input before saving a treatment.

The main aims of this study were, first to describe the farm-level AMU data from a sample of Irish dairy herds in terms of the quantities, routes of administration, and antimicrobial classes used. Second, to compare data consistency between 3 different data collection methods: (1) antimicrobial prescription data from the veterinary practice software (**VET**), (2) on-farm collection of discarded drug packages in a medicine bin (**MB**), and (3) farm treatments recorded in a herd recording software (**APP**). Each method for recording will be compared with a reference method of AMU.

## MATERIALS AND METHODS

This study was granted an exemption from a full ethical review (Research Ethics Exemption Reference Number [REERN]: LS-E-21–91-Martin-McAloon) by the Human Research Ethics Committee – Sciences (HREC-LS) in University College Dublin.

### Herd Recruitment

Using a network of private veterinary practices (PVP) with links to University College Dublin, veterinary practitioners were contacted for participation in the study and 6 PVPs agreed to participate. Using the random number function on Microsoft Excel (Microsoft Corporation, 2018), 6 to 7 herds per practice were randomly selected from the dairy client list of each practice. The randomly selected herds were then reviewed by the practice veterinarian, and those suspected of using multiple veterinary practices to purchase AM were excluded. Farmers were contacted by the practice veterinarian and asked for their permission to be contacted by the researchers. The researcher received a list of 42 farmers willing to be contacted and these farmers were then contacted by phone call. The majority agreed to participate, 3 farmers refused to participate, and 3 did not answer the phone call. In total, 36 dairy herds participated at the beginning of the study. Farmers were initially assigned an identifying code. However, once all data were collected, analyzed and reported back to the farmer, all identifying details were deleted. One farmer withdrew participation from the study, and 2 farmers did not complete the final data collection leaving a final total of 33 dairy herds in the study. Farmers were enrolled in the study between June and October of 2021 and each farmer participated for a 12-mo period.

### Herd Characteristics

The median herd size for the participating herds was 100 milking cows, ranging from 24 to 360 milking cows, the current national average in Ireland is 93 milking cows (Teagasc, 2023). The average age of the farmers was 48 yr old, ranging from 22 yr old to 64 yr old, the national average age of dairy farmers according to the 2020 census is 52 yr old (CSO Ireland, 2022). Thirty-two (96.9%) of the participating farmers were male and one was female; in Ireland, 92.2% of dairy farm holders are male (CSO Ireland, 2022). Participants were farming in the Ulster (Co. Cavan), Munster (Cos. Cork, Kerry, Tipperary), Connaught (Co. Roscommon), and Leinster (Co. Meath) provinces of Ireland. The majority of dairy herds in Ireland operate a spring-calving system, however, calving cows in autumn to generate a planned winter milk supply is practiced on approximately 2,700 (18% of total) dairy farms nationally. For the vast majority of these latter herds, a "split calving" system is employed, whereby a proportion of cows (typically 20%–50%) calve in autumn, and the remainder calve in spring (Patton and Lawless, 2019). Just over one-third of the herds (n = 12/33) were "split calving" systems, with the majority of cows (>70%) calving in the spring. Just under two-thirds (n = 21/33) were spring-calving only systems. Three herds were milking cows through robotic milking systems. Table 1 provides an overview of the demographic and management characteristics of the 33 participating herds.

### Medicine Stock

The stock of medicines on the farm was taken at both the initial and final farm visits. Drug name, pack size, number of packs, and quantity remaining in each pack were recorded for all AM found in the stock. Volume remaining was estimated by eye to the nearest 10% of pack size (i.e., for a 100-mL pack of liquid, volume was estimated to the nearest 10 mL, and for a 50-g pack of powder, quantity was estimated to the nearest 5 g). Intrauterine and intramammary medicines were recorded as single units per tube; boluses and tablets were recorded as single units per bolus or tablet. Three herds (9.1%) had no medicine stock on the farm during the initial visit and stocktake. These herds were small (<50 milking cows) spring-calving herds, visited initially in late summer, therefore this was not considered unusual. Three herds (9.1%) had only intramammary AM on the farm, whereas 27 herds (81.8%) had a stock of medicines on farm at the initial farm visit and stocktake, including injectables, intramammary AM, intrauterine AM, powders, and tablets.

### Herd Recording Software

Before the study commenced, a pilot study was carried out with a convenience sample of 3 herds, selected by their veterinary practitioner based on the expectation of comprehensive treatment records. The pilot study revealed significant deficiencies in hand-written farm treatment records with frequent instances of missing information including correct drug name, dosage used or duration of treatment. Additionally, illegible handwriting emerged as a notable concern. Considering these shortcomings, coupled with previous research highlighting challenges with paper-based records (Pucken et al., 2021), the decision was made to adopt computerized herd-recording software as the preferred method for collecting farmer treatment records. At the start of the study, 12 farmers (36.4%) were not using any form of herd-recording software on their farm. These farmers were given access to

**Table 1.** Demographic, geographic, and management characteristics of 33 Irish dairy herds participating in a 12-mo study to monitor antimicrobial use on farms

| Characteristic | Response | Herds (n) |
|---|---|---|
| Age of farmer (yr) | 18–29 | 2 |
| | 30–39 | 5 |
| | 40–49 | 12 |
| | 50–59 | 11 |
| | >60 | 3 |
| Geographical location of farm (province) | Ulster | 1 |
| | Leinster | 13 |
| | Munster | 16 |
| | Connaught | 3 |
| Agricultural education level of farmer | Basic schooling | 3 |
| | Green Cert[1] | 28 |
| | University bachelor's degree | 2 |
| Total number of milking cows | <50 | 4 |
| | 50–99 | 9 |
| | 100–199 | 10 |
| | 200–299 | 5 |
| | >300 | 5 |
| Calving pattern | Spring | 21 |
| | Split (Spring–Autumn) | 12 |
| Primary cow type | Holstein Friesian | 21 |
| | Majority Holstein Friesian and some crossbred | 7 |
| | Jersey crossbred | 5 |
| Dry cow antimicrobial therapy | Blanket therapy | 22 |
| | Selective therapy | 11 |

[1]Teagasc Certificate in Agriculture, an educational qualification in Irish agriculture.

a commercially available herd recording software to use for the study. Farmers received "how-to" guides showing them how to input a drug-remedy into the herd-recording software, as well as tutorial videos. Any issues with recording remedies were discussed at farm visits; however, these instances were rare, the barriers and facilitators associated with using the technology to record AMU are discussed further in a separate publication (Martin et al., 2024).

Twenty-one farmers (63.6%) were already using a herd recording software on their farm before the beginning of this study. However, 5 of these farmers (23.8%) were not using the software to record their drug treatments. The farmers were using 6 different commercially available herd recording software. For this study, the data from the software was accessed by one of 2 ways: (1) the farmer gave access to their software for the researcher to download the data in portable document format (**PDF**) forms or (2) the farmer sent the data required via email in PDF form. A PDF to Excel converter tool (Adobe Acrobat Pro) was used to convert the PDFs into Microsoft Excel files for analysis (Adobe, 2023). Farmers who used the software during the study (n = 23/33, 69.7%) were asked to score the reliability of their use of the software. The farmer treatment data collected from the herd recording software will be referred to throughout the paper as APP. The analyses of the APP data were split into $APP_{true}$ (n = 33) comprising all farmers in the study and $APP_{used}$ (n = 23) for the farmers who used the software during the study.

## Bin Collections

One 60-L medical waste bin was placed on each farm, with a 60-L garbage bag placed in the bin and 2 spare 60-L garbage bags provided. The garbage bags were labeled with the herds unique identifying code for the study.

Due to the seasonality of Irish dairy systems, it was anticipated that there would be 2 periods of high AMU on the farms: the drying off period and calving season. For this reason, the bin contents were collected once after the drying off period and again after the calving season, at the end of the study. Farmers were contacted to find out when they would have the majority of cows dried off, and farms were visited for bin collection in January 2022 and at the end of the study, between June and October 2022.

Following collection, the contents of each farm bin was individually sorted and quantified using large plastic trays. Information about the contents was entered into pre-prepared spreadsheets, one per participating farm. These data included the medicine identity, pack size, quantity of packs, any waste medicine remaining within each pack, the expiry date, and the presence of a veterinary dispensing label. Where medicine packages had lost all identifying feature (the label had perished completely), these were disregarded, although such instances were rare (n = 21/28,482 items, 0.001%). Any waste medicine remaining within each item was estimated by eye to the nearest 10%.

Farmers were asked to score the reliability on a scale of 1 to 10 of their use of the bins (Stevens et al., 2016), overall and separately for injectables (**INJ**), for dry cow intramammary preparations or dry cow tubes (**DCT**), lactating cow intramammary preparations or lactating cow tubes (**LCT**), where 1 was poor use and 10 was excellent use.

The data collected from the inventory of the medicine waste bins will be referred to throughout the paper as MB.

### Veterinary Data

Veterinary prescription data were collected retrospectively from each farm's veterinary practice for the years 2021 and 2022 to ensure they included the full duration of the study period. All participating PVPs were using a veterinary software for their prescriptions, and the required data for each farm were received from the veterinarians via email, in either comma-separated values or PDF form. A PDF to Excel converter tool (Adobe Acrobat Pro) was used to transfer the PDF data into Excel files for analysis (Adobe, 2023). Where PDFs were unsuitable for the PDF to Excel tool, the data were transcribed manually. Data collected from the veterinary prescriptions included date, product name, and quantity dispensed. Veterinary prescription data and on-farm treatment record data were sorted, cleaned, and entered into the workbook.

The veterinary prescription data collected from the participating herds veterinary practices will be referred to throughout the paper as VET.

### Reference Method

A previously developed reference method for AMU was used to compare the 3 methods of recording in this study, as per Rees et al. (2021). By assuming a reference method measurement of actual AMU a priori, all 3 recording methods could be compared with the reference method and an estimate of the agreement of each method made. The reference method used was based on veterinary prescription data and the medicine stock on the farm pre- and poststudy:

$$\text{Reference method} = (\text{initial stock} + \text{veterinary prescription data}) - \text{end stock}$$

The veterinary data formed the basis of the reference method as this source is deemed to be least open to bias as they are not dependent on farmer compliance or memory. The use of medicine stock on the farm would account for medicines dispensed to the farm before the veterinary data were analyzed, or those medicines dispensed during the study period but not used before the end of the study.

### Quantitative AMU Analysis

Antimicrobial use was calculated using both the mass-based metric milligrams of active ingredient per population correction unit (**PCU**), using 425 kg as the standardized weight as per European Surveillance of Veterinary Antimicrobial Consumption (**ESVAC**) guidelines (EMA, 2015), and the 2 dose-based metrics defined daily dose for animals (**$DDD_{VET}$**) and Defined course dose for animals (**$DCD_{VET}$**). The $DDD_{VET}$ is the assumed average dose per kilogram animal per species per day; the $DCD_{VET}$ is the assumed average dose per kilogram animal per species per treatment course (EMA, 2015). Calculations were carried out using the Dairy AMU calculator developed with Microsoft Excel by The University of Nottingham School of Veterinary Medicine and Ruminant Population Health Group and adapted by the first author (HM) for use in an Irish setting (Hyde et al., 2017a). Adaptations included the addition of products available in the Irish market to the calculator. The equations used to calculate these 3 metrics are as follows:

$$\text{mg/PCU} = \text{Total use (mg)/total weight of cattle at risk of treatment (no. of milking cows} \times 425\text{ kg)}$$

$$DDD_{VET} = \text{Total use (mg)/[daily dose (mg/kg)} \times \text{total weight of cattle at risk of treatment]}$$

$$DCD_{VET} = \text{Total use (mg)/[course dose (mg/kg)} \times \text{total weight of cattle at risk of treatment],}$$

where daily dose and course dose were as defined by ESVAC within the European Medicines Agency (EMA, 2016); ESVAC obtained data on dosing (daily dose and number of days of treatment) from summaries of product characteristics for AM veterinary medicinal products from 9 EU countries.

### Route of Administration

To describe use in this sample of herds, overall use was disaggregated according to route of administration; INJ, intramammary preparations for lactating cow therapy or LCT, intramammary preparations for dry cow therapy or DCT, and other AM including oral and intrauterine AM (Other).

### Antimicrobial Class

To describe use in this sample of herds, overall use was disaggregated according to the Antimicrobial Expert Group (**AMEG**) of the EMA, AM classification system (category A, avoid; category B, restrict; category C, caution; category D, prudence) and AM class (EMA, 2019). Third- and fourth-generation cephalosporins, fluoroquinolones, and polymyxins are all defined as highest priority critically important antibiotics (**HP-CIA**) by the WHO (WHO, 2019), and category B or restrict for use in animals by the AMEG of the EMA (EMA, 2019). In this study, HP-CIA use refers specifically to the use of third- and fourth-generation cephalosporins and fluoroquinolones.

### Data Analysis

Mixed effects generalized linear regression models were used to compare recording methods. Three separate models were developed for each of the 3 AMU metrics (mg/PCU, $DDD_{VET}$ and $DCD_{VET}$). Herd was included as a random effect (EHERD) and collection method (Method) as a fixed effect with the "reference method" used as the referent category. All AMU metrics were found to be positively skewed and were therefore transformed using the formula [log (x + 1)], to satisfy assumptions of normality. The results of the data transformation (mean, median, 25th, and 75th quartiles) are shown in Supplemental Table S1 (see Notes). Descriptive statistics were carried out using Microsoft Excel (Microsoft Corporation, 2018). Mixed effects models were implemented with R (R Core Team, 2022), using RStudio version 4.2.2 (RStudio Team, 2020) and using the 'lme4' package (Bates et al., 2009). The model equation is as follows:

$$\log(\text{AMU}) = \beta0 + \beta1 \times \text{Method} + \text{EHERD} + \text{Error},$$

where β0 the intercept of the true regression line, and β1 is the slope of the true regression line. An additional set of models was created for each route of administration: INJ, LCT, DCT, and Other.

The reliability of the agreement between each method and the reference method was then quantified using the concordance correlation coefficient (**CCC**; Watson and Petrie, 2010; Rees et al. 2021) using the 'epiR' package (Stevenson et al., 2024). Based on the 95% CI of the CCC estimate, values less than 0.50 indicate poor reliability, values between 0.50 and 0.75 indicate moderate reliability, values between 0.75 and 0.90 indicate good reliability, and values greater than 0.90 indicate excellent reliability (Koo and Lee, 2016).

## RESULTS

### Herd Recording Software

Twenty-three farmers (69.7%) used the herd recording software during the study. The analyses were performed for all farmers in the study, n = 33 ($APP_{true}$) and repeated excluding the farmers who did not use the software during the study, n = 23 ($APP_{used}$). Ten farmers (30.3%) did not use their software at all during the study; these farmers either kept written paper records or did not record their usage during the study, for $APP_{true}$ their use was recorded as zero (0). Six different herd recording software programs were used during the study. Farmers who used the software during the study (69.7%) scored the reliability of their use of the software an average (mean) of 7.3 out of 10.

### Bin Collections

In total, there were 28,482 items collected in the waste bins from 33 herds over the 12-mo period. Farmers scored the reliability of their use of the bins highly overall and for the various products, the average (mean) score for all 33 farmers was 9.3/10 for DCT, 9.2/10 for LCT, 9.2/10 for INJ and a score of 9.1/10 overall.

### Veterinary Data

In Ireland, it is not a requirement for farmers to have only one designated veterinary practice. Seven herds (21.2%) said they used more than one veterinary practice, usually using one for callouts and purchasing medicines, and one for herd tuberculosis testing. All herds listed the veterinary practice which the study received their records from as their main suppliers of AM. However, upon examining the contents of the bins, it was discovered that one herd had a substantial quantity of products from a different veterinary practice than the one from which their records were collected, evident by the presence of different veterinary dispensing labels. This was an isolated case.

### Comparison of Antimicrobial Quantities

The quantities of AMU in the participating herds varied across the 3 recording methods used. Table 2 shows the quantities of AMU in the 3 recording methods and the reference method across the 33 herds using the mass-based metric mg/PCU and the dose-based metrics $DDD_{VET}$ and $DCD_{VET}$. Figure 1 illustrates the distributions and the differences between the methods. The median quantity of AMU in mg/PCU was 16.24 for the VET data, 10.47 for the MB data, 8.87 for the $APP_{used}$ data, and 4.91 for the $APP_{true}$ data. The median AMU for the reference method was 15.55 mg/PCU. The results show that on average almost half the mass of AM prescribed to the farm were not recorded in the herd recording software by farmers who used the herd recording software ($APP_{used}$), whereas only 30% of the mass of AM prescribed to the farm were recorded in the herd recording software overall ($APP_{true}$).

**Table 2.** Antimicrobial use over a 12-mo period (2021–2022; mg/population correction unit [PCU], defined daily doses for animals [$DDD_{VET}$], defined course doses for animals [$DCD_{VET}$]) in 33 Irish dairy herds from 3 recording methods and a reference method

| | | Record source (number of herds) | | | | |
|---|---|---|---|---|---|---|
| Metric | Item | VET (n = 33) | BIN (n = 33) | $APP_{true}$ (n = 33) | $APP_{used}$ (n = 23) | Reference method (n = 33) |
| mg/PCU | Minimum | 2.86 | 2.05 | 0 | 1.04 | 1.93 |
| | Maximum | 84.55 | 86.27 | 23.44 | 23.44 | 83.53 |
| | Median | 16.24 | 10.47 | 4.91 | 8.87 | 15.55 |
| | Mean | 18.59 | 13.89 | 6.36 | 9.13 | 18.34 |
| | SD | 15.26 | 14.90 | 6.36 | 5.70 | 15.17 |
| $DDD_{VET}$ | Minimum | 0.80 | <0.01 | 0 | 0.02 | 0.60 |
| | Maximum | 10.95 | 9.68 | 6.25 | 6.25 | 10.74 |
| | Median | 2.43 | 1.55 | 0.66 | 1.19 | 2.26 |
| | Mean | 2.96 | 2.15 | 1.05 | 1.51 | 2.96 |
| | SD | 2.21 | 2.02 | 1.36 | 1.40 | 2.20 |
| $DCD_{VET}$ | Minimum | 0.24 | 0.43 | 0 | 0.14 | 0.01 |
| | Maximum | 3.87 | 3.71 | 2.42 | 2.42 | 3.81 |
| | Median | 1.31 | 1.13 | 0.77 | 1.04 | 1.31 |
| | Mean | 1.50 | 1.29 | 0.71 | 1.02 | 1.47 |
| | SD | 0.84 | 0.65 | 0.61 | 0.47 | 0.87 |

The findings indicated that a small number of herds were contributing the most to the overall mass of use, with just 4 herds (i.e., 12%) accounting for one-third (33%) of the overall AMU across all participating herds in terms of mg/PCU (reference method [**REF**] data).

Additionally, the results showed varying levels of consistency in recording AMU across the herds. Although some herds had a good level of agreement between the recording methods, some showed differences (Figure 2). Results showed 24% of herds had a difference of more than −50% in mg/PCU between the $APP_{used}$ data and the REF data, while 10% of herds had a difference of more than −90% in mg/PCU. Analyzing the difference between $APP_{true}$ data and REF data, this figure raises to 55% of herds exhibiting a difference of more than −50% in mg/PCU and 39% of herds exhibiting a difference of more than −90% in mg/PCU. However, there were 9% of herds who showed less than a ±10% difference in mg/PCU between $APP_{true}$ data and the REF data. In contrast to the APP data, the results showed that 85% of herds showed less than a ±10% difference in mg/PCU between the VET data and the REF data. For the MB data, 30% of herds had a difference of ±50% in my/PCU compared with the REF data, whereas 18% of herds showed less than a ±10% difference in mg/PCU.

The results of the regression model on association between recording method and AMU are shown in Table 3. In the mg/PCU model, there was strong evidence of a difference between the APP data and the reference method ($P < 0.001$). Changing recording method from the reference method to $APP_{true}$ and $APP_{used}$ was associated with a 71% and 51% decrease in recorded use, respectively. In contrast using VET records rather than the reference method was associated with a 3% increase in use, with very weak evidence of a difference between methods ($P = 0.883$). In the $DDD_{VET}$ model changing recording method from the reference method to $APP_{true}$, $APP_{used}$, and MB, was associated with a 50%, 40%, and 23% decrease in recorded use, respectively ($APP_{true}$: $P < 0.001$; $APP_{used}$: $P < 0.001$; MB: $P = 0.003$). In the $DCD_{VET}$ model, changing recording method from the reference method to MB and VET was associated with a 5% decrease and 2% increase in recorded use, respectively, with weak evidence of a difference (MB: $P = 0.532$; VET: $P = 0.768$). In this model, using the $APP_{used}$ records rather than the reference method was associated with a 16% decrease in use ($P = 0.025$).

The results of the regression model on association between recording method and AMU by route of administration are shown in Table 4. Analysis of the differences between recording methods and the reference method based on route of administration, found extremely weak evidence of differences for any route of administration for the VET records (VET: INJ $P = 0.789$; LCT $P = 0.958$; DCT $P = 0.784$; Other $P = 0.979$; Table 4). There was very strong evidence that the MB records differed from the reference method for Other (oral and intrauterine) routes (MB: Other $P < 0.001$). In the INJ model, the use of $APP_{true}$ records rather than the reference method was associated with a 70% decrease in recorded use, which was significant ($P < 0.001$), suggesting a potential lack of accuracy in farmers recording these types of treatments. Although in the DCT model, the use of $APP_{true}$ records rather than the reference method was associated with a 25% decrease in recorded use, suggesting that farmers may be more likely to record DCT treatments than INJ treatments.

The CCC estimates between total AMU measured by the different recording methods are presented in Table

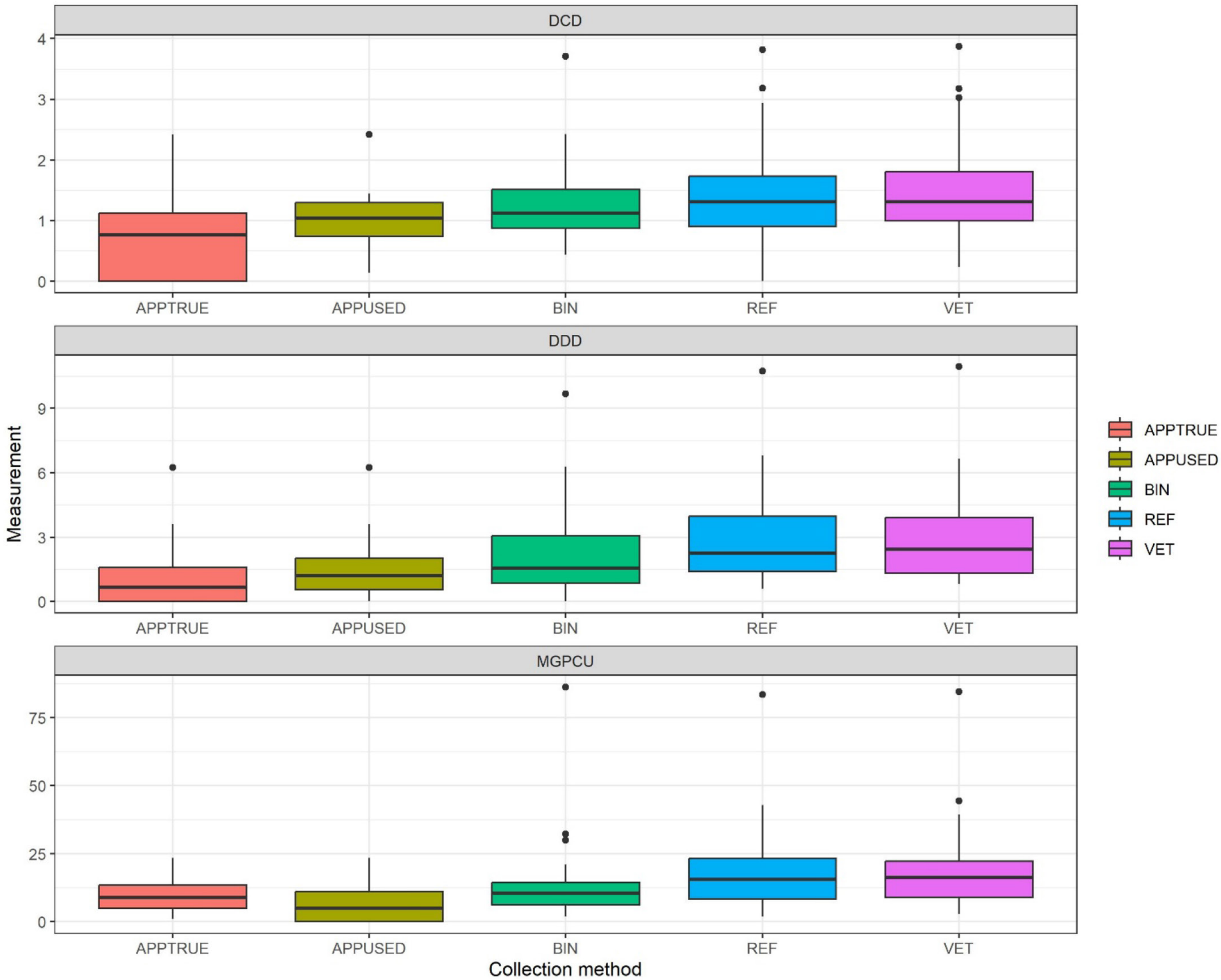


**Figure 1.** Antimicrobial use in a 12-mo period in 2021–2022 (in defined course doses for animals [$DCD_{VET}$], defined daily doses for animals [$DDD_{VET}$], and milligrams per population correction unit [PCU],) by collection method from 33 Irish dairy herds. Box plots illustrate interquartile range and median (upper and lower edges and midline, respectively), 1.5× the interquartile range (whiskers), and outliers (dots). APPTRUE = farmer treatment records from herd recording software for all farmers (n = 33); APPUSED = farmer treatment records from herd recording software for farmers who used the software (n = 23); BIN = bin collection method; VET = veterinary data; REF = reference method.

5. Overall, the VET data had excellent reliability (95% CI 0.983–0.996), the MB data had good to excellent reliability (95% CI 0.776–0.936) and the $APP_{true}$ and $APP_{used}$ data had poor reliability ($APP_{true}$: 95% CI −0.167 to 0.156; $APP_{used}$: 95% CI −0.219 to 0.169; Table 5).

Based on the CCC estimates, the VET data had excellent reliability when measuring all routes of administration (95% CI > 0.900; Table 6). The MB data had good to excellent reliability for INJ (95% CI 0.864–0.963) and LCT (95% CI 0.871–0.964); however, had poor to moderate reliability for DCT (95% CI 0.312–0.695) and poor reliability for Other products (95% CI 0.053–0.273; Table 6). The $APP_{true}$ data showed poor reliability for all routes of administration apart from LCT, which exhibited poor to good reliability (95% CI 0.445–0.805). The $APP_{used}$ data had good to excellent reliability for LCT (95% CI 0.771–0.949), poor to moderate reliability for DCT (95% CI 0.131–0.651) and poor reliability for INJ and Other products.

## Route of Administration

Exploring the data using the dose-based metric $DCD_{VET}$, the DCT route contributed the most use, constituting

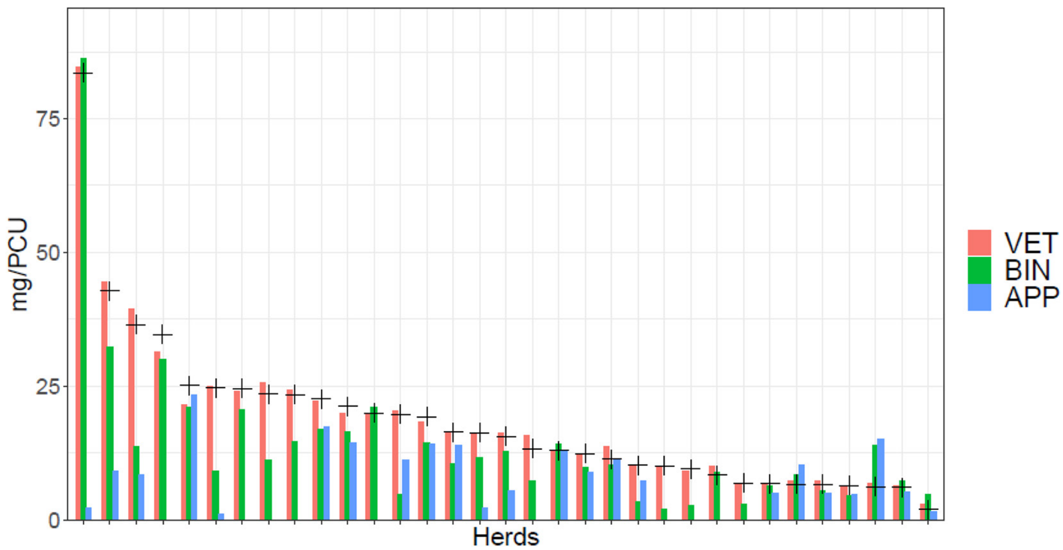


**Figure 2.** Comparison of the antimicrobial use (AMU) quantities over a 12-mo period (2021–2022) of 33 Irish dairy herds by recording method in milligrams per population correction unit (PCU) in order of descending AMU from the reference method data (REF). + indicates the reference method value (REF); APP = farmer treatment records from herd recording software for all farmers (n = 33); BIN = bin collection method; VET = veterinary data.

42.5% of total use in the VET data, almost half of total use in the MB data (49.5%) and over half of all recorded use in the APP data (55.3%). This was followed by INJ treatments, accounting for 32.7% (VET), 28.7% (MB), and 24.5% (APP) of use. Lactating cow intramammary preparations (LCT) made up 20.7% (VET), 21.5% (MB), and 19.2% of (APP) recorded use. The remaining 4.1% (VET), 0.1% (MB), and 1.0% (APP) of total use comprised the Other products. Considering HP-CIA use, the largest contribution was via the intramammary (**IMM**)

**Table 3.** Results of a mixed effects generalized linear regression model comparing the (log-transformed) antimicrobial use (AMU) over a 12-mo period (2021–2022) of 33 Irish dairy herds recorded from 3 recording methods to a reference method of AMU using 3 metrics for use[1]

| Metric | Recording method comparison[2] | Estimate log-scale (95% CI) | Estimate untransformed scale (95% CI) | *P*-value |
|---|---|---|---|---|
| mg/PCU | Reference method | Referent | | |
| | Intercept | 2.74 (2.47, 3.01) | 15.48 (11.8, 20.32) | |
| | VET | 0.03 (−0.29, 0.34) | 1.03 (0.75, 1.41) | 0.883 |
| | BIN | −0.31 (−0.63, 0.01) | 0.73 (0.53, 1.01) | 0.055 |
| | $APP_{true}$ | −1.25 (−1.57, −0.94) | 0.29 (0.21, 0.39) | <0.001*** |
| | $APP_{used}$ | −0.71 (−1.07, −0.36) | 0.49 (0.34, 0.70) | <0.001*** |
| $DDD_{VET}$ | Reference method | Referent | | |
| | Intercept | 1.25 (1.08, 1.43) | 3.5 (2.94, 4.18) | |
| | VET | 0.001 (−0.17, 0.17) | 1 (0.84, 1.19) | 0.995 |
| | BIN | −0.26 (−0.43, −0.09) | 0.77 (0.65, 0.92) | 0.004** |
| | $APP_{true}$ | −0.70 (−0.87, −0.53) | 0.5 (0.42, 0.59) | <0.001*** |
| | $APP_{used}$ | −0.51 (−0.70, −0.32) | 0.6 (0.49, 0.73) | <0.001*** |
| $DCD_{VET}$ | Reference method | Referent | | |
| | Intercept | 0.84 (0.73, 0.95) | 2.32 (2.08, 2.59) | |
| | VET | 0.02 (−0.12, 0.16) | 1.02 (0.89, 1.17) | 0.768 |
| | BIN | −0.05 (−0.18, 0.09) | 0.96 (0.83, 1.1) | 0.532 |
| | $APP_{true}$ | −0.37 (−0.51, −0.23) | 0.69 (0.6, 0.79) | <0.001*** |
| | $APP_{used}$ | −0.18 (−0.33, −0.02) | 0.84 (0.72, 0.98) | 0.025* |

[1]Metrics include milligrams per population correction unit (mg/PCU), defined daily doses for animals ($DDD_{VET}$), and defined course doses for animals ($DCD_{VET}$).

[2]APPtrue = farmer treatment records from herd recording software for all farmers (n = 33); APPused = farmer treatment records from herd recording software for farmers who used the software (n = 23); BIN = bin collection method; VET = veterinary data.

*$P < 0.05$. **$P < 0.01$. ***$P < 0.001$.

**Table 4.** Results of 4 mixed effects generalized linear regression models comparing the (log-transformed) antimicrobial use over a 12-mo period (2021–2022) of 33 Irish dairy herds measured by 3 recording methods to a reference method for each route of administration in milligrams per population correction unit (PCU)

| Antimicrobial use by route (mg/PCU)[1] | Comparison[2] | Estimate (95% Confidence Interval) | Estimate untransformed scale (95% CI) | *P*-value |
|---|---|---|---|---|
| INJ | Reference method | Referent | | |
| | Intercept | 2.45 (2.15, 2.75) | 11.62 (8.6, 15.69) | |
| | VET | 0.05 (−0.27, 0.35) | 1.05 (0.77, 1.43) | 0.789 |
| | BIN | −0.34 (−0.65, −0.03) | 0.71 (0.52, 0.97) | 0.032* |
| | $APP_{true}$ | −1.22 (−1.53, −0.91) | 0.3 (0.22, 0.4) | <0.001*** |
| | $APP_{used}$ | −0.80 (−1.15, −0.45) | 0.45 (0.32, 0.64) | <0.001*** |
| LCT | | | | |
| | Intercept | 0.41 (0.29, 0.52) | 1.5 (1.34, 1.69) | |
| | VET | −0.002 (−0.08, 0.08) | 1 (0.92, 1.08) | 0.958 |
| | BIN | −0.08 (−0.15, 0.004) | 0.93 (0.86, 1) | 0.064 |
| | $APP_{true}$ | −0.24 (−0.32, −0.16) | 0.78 (0.72, 0.85) | <0.001*** |
| | $APP_{used}$ | −0.16 (−0.25, −0.07) | 0.85 (0.78, 0.93) | 0.001** |
| DCT | | | | |
| | Intercept | 0.92 (0.72, 1.12) | 2.51 (2.06, 3.05) | |
| | VET | 0.03 (−0.18, 0.25) | 1.03 (0.83, 1.28) | 0.784 |
| | BIN | 0.09 (−0.12, 0.30) | 1.09 (0.88, 1.36) | 0.420 |
| | $APP_{true}$ | −0.29 (−0.51, −0.08) | 0.75 (0.6, 0.92) | 0.008** |
| | $APP_{used}$ | −0.04 (−0.28, 0.21) | 0.96 (0.75, 1.22) | 0.730 |
| Other | | | | |
| | Intercept | 0.49 (0.31, 0.68) | 1.63 (1.36, 1.96) | |
| | VET | 0.003 (−0.22, 0.22) | 1 (0.8, 1.25) | 0.979 |
| | BIN | −0.43 (−0.65, −0.21) | 0.65 (0.52, 0.81) | <0.001*** |
| | $APP_{true}$ | −0.40 (−0.62, −0.18) | 0.67 (0.54, 0.83) | <0.001*** |
| | $APP_{used}$ | −0.38 (−0.63, −0.13) | 0.68 (0.53, 0.88) | 0.003** |

[1]INJ = injectables; LCT = lactating cow tubes (intramammary antimicrobials); DCT = dry cow tubes (intramammary antimicrobials); Other = all other forms of antimicrobial.

[2]APPtrue = farmer treatment records from herd recording software for all farmers (n = 33); APPused = farmer treatment records from herd recording software for farmers who used the software (n = 23); BIN = bin collection method; VET = veterinary data.

**P* < 0.05. ***P* < 0.01. ****P* < 0.001.

route accounting for just over 60% of HP-CIA use, the remaining nearly 40% of HP-CIA use was attributed to INJ treatments ($DCD_{VET}$ VET data). When analyzing the routes of administration, the choice of metric used to quantify use affected the attribution of each route to overall use and HP-CIA use. When employing the mass-based metric mg/PCU, the route contributing the greatest amount of use changed and detailed figures are presented in Supplemental Table S2 (see Notes).

### Antimicrobial Class

Antimicrobial classes are presented using the VET data. The AM class contributing the most use when looking at $DCD_{VET}$ is cephalosporins (47.8%; first and second generation [39.2%] and third and fouth generation [8.6%]), followed by penicillins (36.5%), tetracyclines (7.0%), macrolides and lincosamides (3.9%), sulphas and trimethoprim (2.8%), amphenicols (1.1%), fluoro-

**Table 5.** Concordance correlation coefficients (CCC) and statistical interpretation of reliability comparing antimicrobial use from 33 Irish dairy herds from 3 recording methods (VET, BIN, and APP [$APP_{true}$ and $APP_{used}$]) with a reference method when measured by milligrams per population correction unit (PCU)

| Method comparison[1] | CCC | 95% CI of CCC | Statistical interpretation of CCC results |
|---|---|---|---|
| VET vs. REF | 0.996 | 0.992 to 0.998 | Excellent |
| BIN vs. REF | 0.879 | 0.776 to 0.936 | Good to excellent |
| $APP_{true}$ vs. REF | −0.006 | −0.167 to 0.156 | Poor |
| $APP_{used}$ vs. REF | −0.026 | −0.219 to 0.169 | Poor |

[1]$APP_{true}$ = farmer treatment records from herd recording software for all farmers (n = 33); $APP_{used}$ = farmer treatment records from herd recording software for farmers who used the software (n = 23); BIN = bin collection method; REF = reference method; VET = veterinary data.

**Table 6.** Concordance correlation coefficients (CCC) and statistical interpretation of reliability comparing antimicrobial use over a 12-mo period (2021–2022) from 33 Irish dairy herds from 3 recording methods with a reference method for different routes of administration when measured by milligrams per population correction unit (PCU)

| Method comparison[1] | Route of administration[2] | CCC | 95% CI of CCC | Statistical interpretation of CCC results |
|---|---|---|---|---|
| VET vs. REF | INJ | 0.992 | 0.983 to 0.996 | Excellent |
| | LCT | 0.991 | 0.982 to 0.995 | Excellent |
| | DCT | 0.962 | 0.925 to 0.981 | Excellent |
| | Other | 0.999 | 0.999 to 0.999 | Excellent |
| BIN vs. REF | INJ | 0.928 | 0.864 to 0.963 | Good to excellent |
| | LCT | 0.932 | 0.871 to 0.964 | Good to excellent |
| | DCT | 0.530 | 0.312 to 0.695 | Poor to moderate |
| | Other | 0.165 | 0.053 to 0.273 | Poor |
| $APP_{true}$ vs. REF | INJ | 0.044 | −0.135 to 0.220 | Poor |
| | LCT | 0.662 | 0.445 to 0.805 | Poor to good |
| | DCT | 0.213 | −0.037 to 0.438 | Poor |
| | Other | −0.042 | −0.214 to 0.133 | Poor |
| $APP_{used}$ vs. REF | INJ | 0.042 | −0.185 to 0.264 | Poor |
| | LCT | 0.890 | 0.771 to 0.949 | Good to excellent |
| | DCT | 0.425 | 0.131 to 0.651 | Poor to moderate |
| | Other | −0.058 | −0.274 to 0.164 | Poor |

[1]APPtrue = farmer treatment records from herd recording software for all farmers (n = 33); APPused = farmer treatment records from herd recording software for farmers who used the software (n = 23); BIN = bin collection method; REF = reference method AMU; VET = veterinary data.

[2]INJ = injectables; LCT = lactating cow tubes (intramammary antimicrobials); DCT = dry cow tubes (intramammary antimicrobials); Other = all other forms of antimicrobial.

quinolones (0.7%), and aminoglycosides (0.2%). The high percentage of cephalosporin use is primarily driven by the use of DCT products containing cephalosporins. In terms of $DCD_{VET}$, cephalosporins account for just over 70% of DCT usage, with 59.5% being first and second generation cephalosporins, and 10.8% being third-and fourth-generation cephalosporins. The remaining 29.7% of DCT usage comprises penicillins, with 24.1% being anti-staphylococcal penicillins and 5.6% being natural, narrow-spectrum penicillins. Notably, the distribution of AM classes changed when using the mass-based metric mg/PCU, and detailed figures are presented in Supplemental Table S3 (see Notes).

Antimicrobials categorized as category D (Prudence) by the AMEG accounted for 46.3% of AMU, category C (Caution) AM accounted for 44.34% of AMU and category B (Restrict) AM accounted for 9.36% of AMU across the 33 herds ($DCD_{VET}$ VET data). Of the 33 participating herds, 7 (21.2%) had no prescriptions for HP-CIAs in their veterinary records. However, 4 of these herds had products containing HP-CIAs in their medical waste bins, these products were prescribed to the herd before the study commenced. Just 3 herds (9.1%) had no record of HP-CIA use in any of the recording methods. The third and fourth generation cephalosporins, ceftiofur, and cefquinome accounted for 92% of HP-CIA use across all the herds ($DCD_{VET}$ VET data). Fluoroquinolones, typically marbofloxacin, made up the remaining 8% of HP-CIA use. There was no recorded use of polymyxins in this sample of herds.

## DISCUSSION

This study is the first in Ireland to investigate AMU in dairy herds at farm level including all routes of administration and all age groups of cattle on the farm. The study provides the first opportunity to benchmark AMU at farm level in the Irish dairy sector and provides valuable insights into the patterns of use and practices of recording AMU. The findings could be used as a baseline for future research around AMU in dairy herds in Ireland.

The results of this study agree with earlier research, indicating differences in AMU quantities depending on recording method used, with the highest quantity of AMU recorded with the veterinary practice prescription software and the lowest recorded with the farm treatment records (Menédez González et al., 2010; Kuipers et al., 2016; Pucken et al., 2021). This paper employed a methodology previously developed by Rees et al., (2021) and tested with UK dairy farmers. Despite differences in farming practices and attitudes between Irish and UK dairy farms, the results of this study compared similarly to Rees et al., (2021). As found in the UK paper, the use of a reference method to compare results has confirmed in this study that despite a potential risk of overestimation due to products kept in stock on the farm, veterinary prescription data provides the most accurate representation of on-farm usage, demonstrating excellent reliability across all administration routes. Where farmers are sourcing medicines from one PVP, this method should provide a lower risk of underestimating usage than the bins and farmer records as it should include all medicines prescribed to the farm, including those administered by the veterinarian. These treatments will not appear in the medicine bins if the veterinarian does not leave the packaging, and risk being omitted from farm treatment records if not administered by the farmer. Issues can arise with analyzing veterinary records if farms source medicines from more than one PVP and the records from all PVP are not collected. Although many of the results are comparable to the UK study, the seasonality of Irish dairy systems may have influenced one particular finding. In the UK study medicine bins exhibited good to excellent reliability based on CCC estimates for intramammary products; the current study, divided intramammary products into DCT and LCT and found good to excellent reliability for LCT products but poor to moderate reliability for DCT products. This is possibly due to the large volume of DCT products that would have needed to be disposed of in the bin at once, given that cows are dried off in batches. If one batch of DCT products were not disposed of in the bins, this could have led to differences in recorded use and a reduced reliability of this method. Considering injectable products, medicine bins exhibited excellent reliability based on CCC estimates, possibly attributed to farmers using this opportunity to discard empty glass medicine bottles conveniently and at no cost. However, although effective for recording injectable treatments, the medicine bins proved unreliable for other administration routes, particularly "Other" (oral and intrauterine) treatments, similar to results found by Lardé et al., (2021) on Canadian dairy farms. Some farmers may have been less inclined to take advantage of the medicine bin for disposing these types of products as they are not typically made of glass therefore could, in theory, be discarded with general waste. Considering the substantial effort involved in this data collection method and its limitations, it becomes challenging to justify its use where veterinary data are a viable alternative. However, farmers rated their reliability of use of the bins higher than the herd recording software, likely due to the ease of using bins compared with recording use. This method remains useful in situations where collecting farmer treatment records may yield poor results due to poor compliance or farmer literacy issues, and where the collection of veterinary records is not feasible.

One of the main concerns highlighted by this study is the discrepancy observed between the reference method and the computerized farm treatment records. This outcome is not entirely unexpected, given prior research indicating that farmer treatment records are usually lower than veterinary records (Pucken et al., 2021). However, the statistically significant difference between the reference method and computerized farm records is disappointing as this partly reflects a lack of farmer engagement with software rather than as a result of errors in recording as seen in prior research. In previous studies, the comparably low quantities recorded in farmer records were partly attributed to missing dosages in the treatment entries (Nobrega et al., 2017). To address this, the current study asked farmers to use herd recording software, requiring dosage input before saving a treatment. However, this approach is only effective if the treatment is indeed recorded, if a treatment is entirely overlooked due to poor farmer compliance or forgetfulness, it is lost from the records altogether. To scale the collation of farm-level data, leveraging technology is crucial, however our results indicate that farmers have low levels of engagement with software to record AMU. With 55% of herds exhibiting a difference of more than −50% in mg/PCU and 39% of herds exhibiting a difference of more than −90% in mg/PCU when their herd recording software data are compared with the REF. This underscores the need for improved strategies to enhance farmer participation and accuracy in recording AMU data. Additionally, the farmer treatment records ($APP_{used}$) showed extremely strong evidence of differences to REF when analyzing daily doses ($DDD_{VET}$), however these differences were weaker when analyzing course doses ($DCD_{VET}$). This can be attributed to the farmers being more meticulous in recording dry cow treatments, which are excluded from $DDD_{VET}$, compared with injectable treatments. Although dry cow treatments are considered individual cow treatments, in Ireland cows, are dried off in batches depending on expected calving data (Clabby et al., 2022), prompting farmers to record the treatments collectively. The findings indicate that farmers are more adept at recording these "group" treatments than individual therapeutic cow treatments with injectable AM, posing implications for future farm-level AMU monitoring in this sector. Recent research has shown that Irish dairy farmers often record AMU into their official records retrospectively (H. Martin University College Dublin, Dublin Ireland, and Teagasc Food Research Centre Moorepark, Co. Cork, Ireland; E. G. Manzanilla, University College Dublin and Teagasc Food Research Centre Moorepark; A. Burrell, Animal Health Ireland, Co. Leitrim, Ireland; and A. Regan, Teagasc, Co. Galway, Ireland, and University College Dublin; unpublished data), which increases the risk of treatments, particularly individual therapeutic cow treatments, being lost due to poor farmer recall. Although AMU recording is legally mandated, the data are not collected in real-time, rather, they are audited annually to ensure compliance with national dairy quality assurance schemes (**QAS**; https://www.bordbia.ie/globalassets/sdas-producer-standard-v1.2-nov-2023.pdf). Within the pig sector, the DAFM has introduced an online system for farm-level AMU data collection, which is compulsory for participation in the national pig QAS. However, AMU on Irish pig farms occurs mostly in the form of prophylactic group treatments (O'Neill et al., 2020), which require one instance of recording per treatment, reducing the inherent risk of missed treatments in farm records compared with the dairy sector. The study's findings raise questions about the feasibility of implementing similar farm-level collection systems in the dairy sector, particularly considering the lack of engagement with technology to record use and the underreporting of individual therapeutic treatments.

Monitoring AMU at the farm-level allows for high-users to be identified. This study found a low number of high AM users were contributing the most to overall use, with just 4 farms (12%) contributing to a third of overall use. Similar patterns were observed by Hyde et al. (2017b) where 25% of farms were contributing to over 50% of overall AMU. These findings are important to consider when developing strategies to reduce AMU in the dairy sector. Identifying these high-user farms has not been possible in the past as there is no national herd-level monitoring. In the Netherlands, the identification of high-user farms through the country's traffic light benchmarking system and subsequent follow-up visits with these farms to address their high usage, contributed to a 47% reduction in AMU on dairy farms between 2009 and 2015. Since then, AMU in the Dutch dairy sector has remained more or less stable (SWAB and RIVM, 2023). Similar to the yellow-card initiative in Denmark (Jensen et al., 2014), the system has signaling and action thresholds based on color codes. Green signals that AMU is at an acceptable level and no further action is required at that point. Orange means the signaling threshold is passed and indicates there is room for improvement, whereas red means the action threshold is passed, and immediate action must be taken by the farmer and veterinarian to address the issue. The introduction of similar systems in Ireland may be a useful tool for improving antimicrobial stewardship (**AMS**) through addressing issues of high-users, similar to those identified in this study, contributing significantly to overall use within the sector. Currently herd-level data are not collected in the Irish dairy sector; however, from 2024 the NVPS will provide data on medicines prescribed to all herds in the country, thus allowing for high-users to be identified. The introduction of this system provides an opportunity for benchmarking farmers and veterinarians. Identifying high-users and supporting these farmers to change their behavior has great potential to reduce overall use within the dairy sector.

This study compares similarly to international studies in terms of the routes of administration used on dairy farms. In the current study, IMM use accounted for approximately 63% of total use ($DCD_{VET}$ VET), with injectable administration accounting for around 33% and other administrations (oral and intrauterine) accounting for approximately 4% of use. These figures compare similarly to the most recent Canadian study, in which IMM, injectable, and other use accounted for 66%, 31% and 3%, respectively (Warder et al., 2023). These findings highlight the importance of efforts to reduce IMM AMU, particularly as a strategy to reduce overall AMU in food-producing animals and reduce the risk of AMR. At the European level, Regulation 2019/6 (European Union, 2019) has placed a ban on the prophylactic use of AM, thus banning the use of blanket dry cow therapy and necessitating the adoption of selective dry cow therapy (**SDCT**) on farms. Within Ireland, the CellCheck program, initiated by Animal Health Ireland (**AHI**), is an initiative aimed at promoting udder health and reducing the need for IMM AMU in the Irish dairy industry. Under CellCheck, AHI have published guidelines for the use of SDCT (AHI, 2022). Farmers in this study were drying off cows during the winter of 2021, the last winter where farmers were not legally required to use SDCT, and just one-third of the farmers were using SDCT. Although there has been a substantial shift from blanket to SDCT in the national herd (McAloon et al., 2021), efforts should continue to focus on supporting farmers in the adoption of this practice. The technical working group of the CellCheck program have highlighted a range of national and farm-level actions required to improve IMM AMS, including increased data collection (AMU data and milk recording on farms), improved veterinary oversight, and improved supporting infrastructure (diagnostics, data analysis, and education supports; More et al., 2022).

Similarly, to the routes of administration, this study agreed with previous research that found the most commonly used AM classes on dairy farms to be cephalosporin (Saini et al., 2012; Stevens et al., 2016; Zuliani et al., 2019), penicillins, and penicillin combinations (Bryan and Hea, 2017; Firth et al., 2017). Cephalosporins (first and second generation) were found to be the AM class contributing most use (VET $DCD_{VET}$), which was attributed to the use of DCT on the farms, as the majority of these products contained cephalosporins. The use of HP-CIA (fluoroquinolones and third- and fourth-generation cephalosporins) was detected in at least one recording method on 30 farms (91.0%). Earley et al. (2019) reported the most commonly used AM in Irish dairy calves were fluoroquinolones; however, in this study the use of fluoroquinolones was low, accounting for just 0.7% of use (VET $DCD_{VET}$). Although the use of HP-CIA was low on these farms in terms of overall mass (2.2%), their frequent use in IMM products particularly the fourth-generation cephalosporin, cefquinome, is concerning. The increasing use of fourth-generation cephalosporins in dry cow products has previously been highlighted by McAloon et al. (2021), who suggested there may be an inadequate use of suitable diagnostics to support evidence-based prescribing of HP-CIA or category B AM for IMM use. The overuse and misuse of broad-spectrum AM such as cefquinome can contribute to the development of AMR (Llor and Bjerrum, 2014). This research further emphasizes the need for farmers and veterinarians to have access to adequate diagnostics to ensure the prescribing of these AM is justified, to support prudent use and reduce the risk of AMR. The Irish government has published a policy on the use of HP-CIA, which indicates that these products should not be used prophylactically or as a first line of treatment (DAFM, 2020). However, the findings of this study indicate that further efforts need to be made to ensure that farmers and veterinarians have the means and support to follow these policies.

### *Limitations*

The study had several limitations that need to be considered. One major limitation is the farmer engagement with the herd recording software. Ten farmers (30.3%) in the study chose not to use the software to record their AMU entirely. The farmers engagement with the software in the study is discussed in a separate publication (Martin et al., 2024). The collection of written paper records from these farmers may have given a more accurate estimate of the correlation between farmer treatment records and the reference method, although it is unlikely that this would have significantly altered the overall results. As these herds were not expected to keep comprehensive records, including all data required for calculating use (i.e., drug name, dosage used, duration of treatment).

Second, during farmer recruitment, veterinarians were asked to exclude herds they believed were sourcing medicines from more than one veterinary practice (a legal practice in Ireland). However, some herds included in the study reporting using multiple veterinary practices. Because records from only one practice per herd were analyzed, there is a potential risk that the VET data could underestimate usage for herds that sourced medicines from more than one practice. Although, due to the presence of veterinary dispensing labels on items in the bins we believe only one farmer obtained a substantial quantity of AM from a different veterinary practice. Additionally, the veterinarians had the authority to audit the herds that were randomly selected for participation, introducing the possibility of selection bias. Veterinarians may have excluded herds that they perceived could reflect negatively on the practice due to high levels of AMU without informing the research team. Selection bias is also a potential concern as the farmers in the study participated voluntarily. Their willingness to participate may suggest a higher likelihood of accurately recording AMU, leading to data that is of above-average quality.

For certain herds, the discrepancies in AMU observed between recording methods could be attributed to AM products, particularly IMM products, being prescribed or used outside of the study period. In some instances, herds exhibited no purchases of dry cow treatment in their veterinary records analyzed during the 12-mo study period, despite these products being documented in the medicine bins or farm treatment records. Because veterinary records were collected for the entire duration of 2021 and 2022 it was possible to identify cases where dry cow products were dispensed to the farm outside of the study period. As a result, the analysis of veterinary records over a 12-mo study period had the potential to either overestimate usage when AM prescribed during those 12 mo were used poststudy or underestimate usage when AM prescribed before the study commencement were used within the 12-mo study period. It is likely that the purchase of DCT before the commencement of the study period (2021–2022) was a result of the impending EU veterinary medicine regulations placing a ban on the use of SDCT. Anecdotal evidence from the Irish dairy sector has suggested that some farmers may have purchased additional DCT pre-emptively in response to concerns about potential difficulties in accessing these products once the legislation was implemented.

Another limitation is the inclusion of one herd with other stock (beef and sheep) on their farm and the exclusion of this stock on the farm in the calculation of AMU. It was not possible to differentiate AM used in dairy with that used in the beef and sheep stock on this farm. Additionally, a limitation is observed in the use of estimating the remaining volume of AM in products by eye. Although this method could be considered subjective, it was carried out by the same researcher each time. Weighing the products could be a more accurate means of estimating remaining product. Moreover, the study's sample included a higher proportion of split-calving herds than is seen nationally, this may affect the generalizability of the results.

Lastly, the final farm visits and bin collections were carried out within 7 d of the 12-mo anniversary of the study. This led to a potential 7-d difference in the length of time some herds were studied, although it was assumed that this was unlikely to substantially affect the farm's medicine recording given that for each farm the veterinary data and farm treatment records were measured for the same time period that the bins were present.

## CONCLUSIONS

This study demonstrates that using veterinary prescription data may offer a more accurate means of estimating on-farm usage than farm treatment records or the use of medicine bins. Relying on farmer treatment records poses the risk of underestimating on-farm usage due to poor farmer compliance, whereas the use of medicine bins does not provide sufficient accuracy to justify the effort involved in collecting these data. The introduction of the NVPS in Ireland is anticipated to offer a more comprehensive understanding of AMU in the dairy sector, with this research affirming that veterinary prescriptions currently represent the most effective approach for collecting herd-level data. It is important to acknowledge that although our study provides valuable insights, it also raises crucial questions regarding AMS in the Irish dairy industry. The results highlight a need for monitoring of herd-level AMU in the Irish dairy sector to address the issues of high users contributing substantially to overall use and the continued use of HPCIA for DCT.

## NOTES

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**Nonstandard abbreviations used:** AHI = Animal Health Ireland; AM = antimicrobial; AMEG = Antimicrobial Expert Group; AMR = antimicrobial resistance; AMS = antimicrobial stewardship; AMU = antimicrobial use; APP = herd recording software; CCC = concordance correlation coefficient; $\text{DCD}_{\text{VET}}$ = defined course doses for animals; DCT = dry cow tubes; $\text{DDD}_{\text{VET}}$ = defined daily doses for animals; ESVAC = European Surveillance of Veterinary Antimicrobial Consumption; EU = European Union; IMM = intramammary; INJ = injectables; REF = reference method; LCT = lactating cow tubes; MB = on-farm collection of discarded drug packages in a medicine bin; NVPS = National Veterinary Prescription System; PCU = population correction unit; PDF = portable document format; PVP = private veterinary practices; QAS = quality assurance schemes; SDCT = selective dry cow therapy; UK = United Kingdom; VET = veterinary practice software.

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