Received: 16 September 2021 | Accepted: 7 March 2022

DOI: 10.1002/cft2.20158

Crop, Forage & Turfgrass Management

RESEARCH

Forage and Grazinglands

Implementation of irrigation with dairy cattle manure for tropical perennial pastures in Costa Rica

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Assigned to Associate Editor Murali Darapuneni.

Abstract

Animal manures allow nutrients recycling in cropping systems, while contributing to the fulfillment of environmental standards. Pasture irrigation with animal manures has been fostered for Costa Rican dairy farms over the last 15 yr. A lack of information and training regarding irrigation and management of animal manures has led to the implementation of diverse methods by producers, but those have not yet been characterized. This study aimed to describe the current management of Costa Rican dairy farms irrigating perennial pastures with slurries. The farms were mostly grass-based systems with supplements fed to cows during the time spent at the milking parlor and/or in feeding stalls through the day. Farms collect manure when facilities are washed with water, which is then stored in plastic tanks or cement structures for less than 1 day before irrigating pastures. The amount of water used by dairy producers was greater than the recommended water/manure ratio (13.4 vs. 4.0 L kg^{-1}), with only one farm reporting values below this ratio. Slurries were sampled and analyzed for their nutrient and microbial content. Both nutrient and microbial content varied in this study due to factors specific to each farm, especially with respect to water management. The variability found in water use among farms and regions (2.4–36.7 L kg^{-1}) may generate unintended consequences from an environmental standpoint. Sustainability of Costa Rican dairy farms can be enhanced if specific guidelines for manure irrigation are developed, which could have benefits for chemical fertilizer use and environmental effect.

1 | INTRODUCTION

Animal manures are arbitrary mixtures of feces, urine, water, and bedding from livestock species managed under confinement (Parera i Pous et al., 2010). Application of animal manures to croplands provide significant amounts of residual organic N that will be released from the soil and transferred to the crops in the long term (Reijs et al., 2005). Fertilization with animal manures remains the top management strategy for these resources, whereas added-value processes may restrain their real value as soil amendments due to the extra labor and transportation costs that need to be compensated (Kleinman et al., 2017).

Animal manures must be appropriately applied to avoid water and air pollution as well as financial losses that may occur due to nutrient excess that negatively influences crop

Abbreviations: Conf, confinement; ConfTime, confinement time; EC, electrical conductivity; MlkCws, milking cows; MnrCollec, manure collected; N-CH_4N_2O, urea nitrogen; N-fixers, nitrogen fixing microorganisms; NH_4^+–N, ammonia nitrogen; N-NO_3^-, nitrate nitrogen; Pastlnd, pastureland; SemiConf, semi-confinement; SlurVol, slurry volume; StockRate, stocking rate; WtrMnrRatio, water/manure ratio; WtrUsd, water used.

yields and quality. Nitrogen losses may occur in slurries as a result of management (Lalor et al., 2011; Pérez-Castillo et al., 2021; Reijs et al., 2005), raising environmental concerns that need to be effectively solved to improve the management after the implementation of such technologies. Animal manures can also act as a vehicle for microbial pathogens, especially after heavy precipitation events that generate runoff and could affect water bodies (Thurston-Enriquez et al., 2005).

With the intensification of the Costa Rican dairy sector in the last 15 years, more farms have implemented facilities to house the lactating cows for periods of time during the day (Vargas-Leitón et al., 2013). At the same time, the Costa Rican government approved the Decree 37017-MAG (Costa Rican Juridical Information System [CRJIS], 2012) to provide a basic framework for cattle operations using manure irrigation with fewer negative effects on ground and surface waters. However, the guidelines stated in the decree are vague and require further examination, as evident by the various storage and application systems currently used by dairy farmers in Costa Rica. By developing more accurate guidelines for the utilization of animal manures, not only would producers benefit, but it would also contribute to environmental goals that have been set by the government in recent years, such as a pledge to reach C neutrality by 2021 (Flagg, 2018).

Intensified dairy systems tend to collect more manure per day, creating a need to manage these residues with the least effect on both the environment and human health (Kleinman et al., 2017). Unlike swine and poultry operations functioning with vertically integrated systems, dairy farms tend to be more diverse in terms of their overall management, thus creating a whole array of manure management systems that require consideration of on-farm variables (Kleinman et al., 2017). Whether irrigation systems with animal manures are implemented to ameliorate environmental effects and fulfill regulatory mandates and/or for nutrient recycling within the farms, there is an expectation that the investment in machinery and infrastructure should be offset by fertilizer savings at the farm level (Lalor et al., 2011). This perspective, however, may contrast with the production objectives at the farm level, creating limitations for a more accurate approach when manure management systems are implemented (Kleinman et al., 2017).

Regulatory government agencies in Costa Rica have not performed studies to identify current management practices used by livestock operations that have already adopted manure irrigation systems. This study aimed to describe the nutrient and microbial characteristics of dairy manures applied to perennial pastures in Costa Rica. We also describe how dairy farms are currently handling and applying manure to pastureland with the goal that the Costa Rican dairy sector, together with private and public entities, will develop guidelines for dairy producers.

Core Ideas

- Manure is a valuable resource for Costa Rican dairy farms that are mostly grass-based.
- Most dairy farms irrigate their pastures daily by following the rotational grazing system.
- Water/manure ratio was above the recommended value which resulted in diluted slurries.
- Nutrient and microbiological traits varied presumably due to manure management and water use.
- Guidelines for manure application would bring various benefits to the Costa Rican dairy sector.

2 | MATERIALS AND METHODS

2.1 | Sites of data collection

The data for this study were collected from May 2017 through December 2018 from 22 dairy farms in Costa Rica. The farms were located in four regions: Cartago (9°55′09″ N, 83°55′49″ W, 1,911–2,800 masl), Monteverde-Tilaran (10°29′96″ N, 84°54′41″ W, 619–1,278 masl), San Ramón (10°09′50″ N, 84°28′43″ W, 1,072–1,092 masl), and Zarcero (10°14′56″ N, 84°23′94″ W, 1,690–1,876 masl). In order to ensure demographic representation, sampled farms were selected from the population based on advice given by sector experts as well as extension agents of the main dairy companies in each region. The distribution of the variables of the farms according to their specific region was based on similarities of the productive systems within each region. Surveys were limited to dairy farms in this study due to recent increases in the number of operations using manure irrigation in this sector.

2.2 | On-farm survey application

A two-section survey was used to collect data about the use of manure for irrigation of pastures of dairy farms in Costa Rica. After having the farmers' consent to be surveyed, in-person visits were scheduled, thus allowing us to give further explanations and collect more accurate data than with phone or electronic surveys. The first section of the survey consisted of general information about the farm such as number of animals per category, breeds, forage crops used, available pastureland (Pastlnd), and type of feed supplementation (confinement [Conf], grazing [Gra], semi-confinement [SemiConf]). We also surveyed information about water use, amount of fresh manure and times of confinement through the day via in-person interviews to the dairy farmers or managers at each farm. Further data were collected by direct on-site assessments of water flow (time necessary to fill a 20-L bucket multiplied by the time spent to clean the facilities in the farm per day) and dimensions of the storage facilities (to estimate the total capacity to store slurries [mixture of manure, urine, and water] before being irrigated). By doing so, the direct assessments were supported by the storage capacity for slurries as well as the amounts reported by the farmers surveyed. The second section of the survey was aimed at understanding current knowledge of the farmers and managers of dairy farms about the Decree 37017-MAG (2012) and the restrictions related to the irrigation of manure near waterbodies and residential areas.

2.3 | Slurry sampling and nutrient and microbiological analyses

Samples of slurries were collected directly from the storage facilities at each farm. The slurries were mixed for 3 min prior to collection using the same automated stirring system that is activated right before pasture irrigation. Once the slurry was mixed, a 4.55 L (1-gal) plastic bottle was submerged in the storage facility and sealed for transportation within a plastic cooler. The slurry was later separated in two subsamples for nutrient and microbiological analyses. The slurries were analyzed in the Agronomy Research Center at the University of Costa Rica for N by using persulfate digestion and colorimetric determination with flow injection analysis. The other macronutrients (N, P, Ca, Mg, K, and S) and micronutrients (Fe, Cu, Zn, Mn, and B) were digested with nitric acid (HNO_3) and then quantitatively determined by mass spectrophotometry. Nitrogen was further analyzed for its ureic, ammonia and nitric fractions by using a water extraction followed by nitric acid digestion and mass spectrophotometry. Finally, pH and electrical conductivity (EC) of the slurries were measured, as they are variables used to estimate acidic potential and nutrient concentration (Provolo & Martínez-Suller, 2007), respectively.

The slurries were also analyzed for microbial concentration of *Escherichia coli* (most probable number of bacteria per hundred milliliters) following the Standard Methods for the examination of water and wastewater (Federation & APH Association, 2005). The colony forming units of Actinomyces and N_2-fixing microorganisms (N-fixers) were estimated following the Test Methods for the Examination of Composting and Compost (Leege, 1998). Concentration of *E. coli* is a typical assessment of fecal contamination while Actinomyces and N-fixers were considered indicators of biological enrichment potential of soils by slurries. The concentration of the nutrient fractions was reported as percentages from the laboratory and then transformed and expressed as g m^{-3} of slurry.

2.4 | Data analysis

This monitoring study was based on the availability of dairy farms in the four regions visited and was not designed to evaluate experimental factors within the farms, but rather to describe the current state of slurry use on Costa Rican dairy farms. Also, the different number of farms surveyed in each region did not allow for a balanced study to explore further statistical approaches. All the data from this study is presented with descriptive statistics (means and range) for each variable. Means across the four regions were used to express the data with specific details provided when relevant for the variables studied. We ran a Pearson correlation test using eight numerical variables assessed in the first section of the survey with the objective to get insight of how production and management factors within the farms may influence to some extent the manure collection process.

3 | RESULTS

3.1 | Productive indicators of the farms

The dairy farms surveyed were mostly grass-based and grow perennial grass species, with only one farm in San Ramón under a confinement system (Conf) (Table 1). In Cartago and Monteverde-Tilaran, only 1 out of 12 of the farms surveyed used semi-confinement (SemiConf), which contrasts with 70% fewer grazing systems (Gra) in San Ramon and Zarcero combined. SemiConf systems on these farms consisted of facilities (stalls) where animals can be housed and fed either seasonally or all-year-round. These systems tend to harvest grass species such as *Cenchrus purpureus* and hybrids under cut-and-carry (green chop) for the times of confinement. All the farms supplemented their lactating cows with commercial formulas (concentrates) or agriculture byproducts from crops grown locally such as banana (*Musa acuminata* Colla), pineapple [*Ananas comosus* (L.) Merr.], and citrus pulp (*Citrus sinensis*).

Except for two of the farms in Cartago, where pastureland (Pastlnd) was threefold to fivefold those from other regions, this study was mostly comprised of small operations (Table 1). The farms in Cartago also had a greater number of milking cows whereas the stocking rate (StockRate) was similar to the farms in Zarcero.

3.2 | Systems for manure collection and irrigation

The system of manure collection at the dairy farms was consistent among regions. Farms from Cartago and Zarcero only used water (hose or bucket) to wash the housing facilities or the milking parlor (Table 2). The farms from the other two

TABLE 1 Productive indicators of 22 dairy farms using slurries for pasture irrigation in four dairy regions in Costa Rica. Values in parenthesis for region and system are the number of dairies participating in each region and type of system. Values for Pastlnd, MlkCws, StockRate are the mean (range) for each region

Region	Forage species	Supplements fed to cattle	System	Pastlnd	MlkCws	StockRate
				ha	head	head ha^{-1}
Cartago (3)	Ryegrass, kikuyu grass	Concentrate and banana by-products	Gra (3)	50.0 (10–90)	130.7 (82–210)	4.2 (2.0–8.2)
Monteverde-Tilaran (9)	Stargrass (*Cynodon nlemfuensis* Vanderyst)	Concentrate, molasses, citrus pulp, and poultry litter	Gra (8), SemiConf (1)	14.8 (6–40)	39.1 (14–90)	3.2 (0.9–7.5)
San Ramon (6)	Stargrass, guineagrass [*Megathyrsys maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs], tanner [*Brachiaria arrecta*) (T. Durand & Schinz) Stent]	Concentrate and wet brewer grains	Gra (2), SemiConf (3), Conf (1)	16.7 (5–48)	16.8 (12–24)	1.7 (0.4–3.0)
Zarcero (4)	kikuyu grass	Concentrate and cassava, pineapple and citrus by-products	Gra (1), SemiConf (3)	10.5 (4–25)	33.5 (24–55)	4.2 (2.2–6–0)
Average				19.5	44.5	3.3
Max.				90	210	8.2
Min.				4	12	0.4

Note. Conf = confinement; Gra = grazing; MlkCws = milking cows; Pastlnd = pastureland; SemiConf = semi confinement; StockRate = stocking rate.

TABLE 2 Manure management at dairy farms using slurries for pasture irrigation in four dairy regions in Costa Rica. Values are the mean (range) for each region

Region	System of manure collection	ConfTime	MnrCollect	WtrUsd	SlurVol	WtrMnrRatio
		h d^{-1}	kg d^{-1}	l d^{-1}	kg d^{-1}	l kg^{-1}
Cartago	Water	4.6 (4.0–6–0)	842 (583–1,225)	16,741 (6,032–22,775)	17,583 (6,750–24,000)	21.2 (8.4–36.7)
Monteverde-Tilaran	Water and floor scraping	5.1 (3.0–14.0)	274 (92–787)	2,667 (1,261–3,795)	2,940 (1,375–4,500)	12.0 (4.7–18.6)
San Ramón	Water and floor scraping	11 (4.0–24.0)	249 (111–490)	1,619 (1,175–2,389)	1,868 (1,665–2,500)	8.7 (2.4–21.6)
Zarcero	Water	8.7 (3.0–14.0)	420 (109–642)	5,642 (3,550–10,562)	6,062 (3,659–11,000)	17.9 (7.3–32.5)
Average		7.3	371	4,842	5,212	13.4
Max.		24.0	1,225	22,775	24,000	36.7
Min.		3.0	92	1,175	1,375	2.4

Note. ConfTime, confinement time; MnrCollect, manure collected; SlurVol, slurry volume; WtrMnrRatio, water/manure ratio; WtrUsd, water used.

regions scraped the floor before washing with water at their facilities. The time spent by cattle under confinement were, on average, shorter for farms in Cartago and Monteverde-Tilaran, whereas San Ramón and Zarcero farms had longer periods of confinement.

The amount of manure collected (MnrCollec) at the farms varied both among regions (Figure 1a) and farms within each region (Table 2). The farms from Cartago reported the highest amounts of MnrCollec per day followed by Zarcero (Figure 1a). The average and ranges were less and similar for farms from San Ramón and Zarcero, respectively (Table 2). Both the volume of water (WtrUsd) and total amount of slurries (SlurVol) applied were greater for farms located in Cartago, while smaller fractions of these variables were found for farms in Zarcero, Monteverde-Tilaran, and San Ramón. Similarly, the ratio of water/manure (WtrMnrRatio) had wide

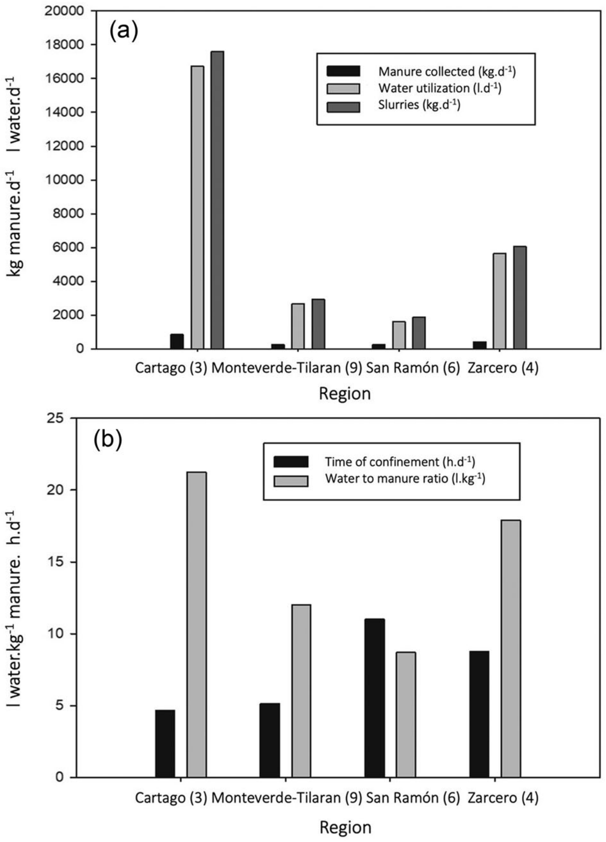

FIGURE 1 Manure, water and slurries collected per day (a) and time of confinement vs. water/manure ratio (b) from four dairy regions in Costa Rica. Values in parentheses next to the region name on the *x* axis are the number of dairies in that region participating in the survey

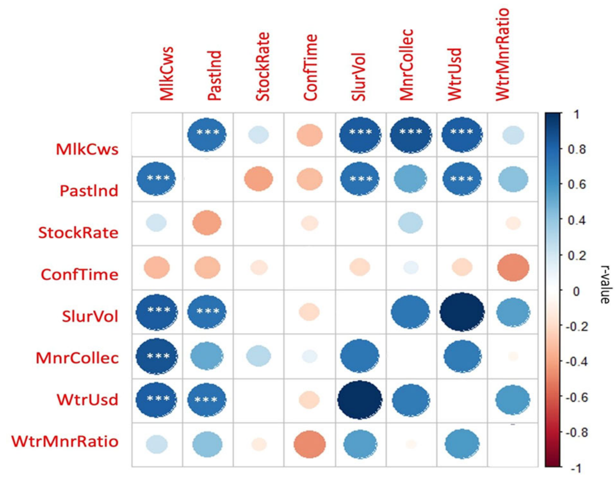

FIGURE 2 Correlogram showing the relationship among eight productive indicators of 22 dairy farms using slurries in Costa Rica. Asterisks indicate correlation coefficients statistically significant ($p < .0001$). MlkCws, milking cows; Pastlnd, pastureland; StockRate, stocking rate; ConfTime, confinement time; SlurVol, slurry volume; MnrCollec, manure collected; WtrUsd, water used; WtrMnrRatio, water/manure ratio; *r* value, correlation coefficient

deviations both among regions (Figure 1b) and within regions (Table 2).

Two-thirds of the producers participating in the survey were aware that the Decree 37017 regulates the use of cattle slurries for irrigation in Costa Rica (Table 3). However, fewer producers could provide specific details beyond the existence of the regulation. A similar proportion of the producers apply chemical fertilizers and have not adjusted their fertilization since implementing the irrigation with slurries in their farms. Only half of the producers have run soil analyses in their pastures and <20% have analyzed either the nutritional value or the mineral content of their pastures. The two latter analyses were not specific to irrigation with slurries, implying that the analyses might have been run even before the implementation of irrigation with slurries.

Because SlurVol is influenced by WtrUsd in the farms, both indicators had a correlation value of 1 (Figure 2). We found high correlations between the number of milking cows (MlkCws) and Pastlnd (0.74, $p < .0001$) and MnrCollec (0.86, $p < .0001$), WtrUsd (0.83, $p < .0001$) and, consequently, of SlurVol (0.84, $p < .0001$) collected per day at the farms surveyed (Figure 2). We also found high correlations between Pastlnd and WtrUsd (0.74, $p < .0001$) and SlurVol (0.74, $p < .0001$).

3.3 | Nutrient and microbial concentrations in slurries

Nutrient content of the slurries analyzed varied among regions (Figure 3). Nitrogen content was on average 338 g m^{-3} (98–1,262 g m^{-3}) having greater concentrations on farms

TABLE 3 Percentage response of dairy farmers and managers regarding legal and management-related issues of slurries for pasture irrigation in Costa Rica

Question	Yes	No
	%	
Knowledge about the existence of Decree 37017 to regulate the use of cattle slurries for irrigation	15 (68.2)	7 (31.8)
Current application of chemical fertilizers	16 (72.7)	6 (27.3)
Has done soil analyses before or after implementing the irrigation of slurries	11 (50)	11 (50)
Has done forage analyses (nutritional value and/or mineral content) of pastures	4 (18.2)	18 (81.8)

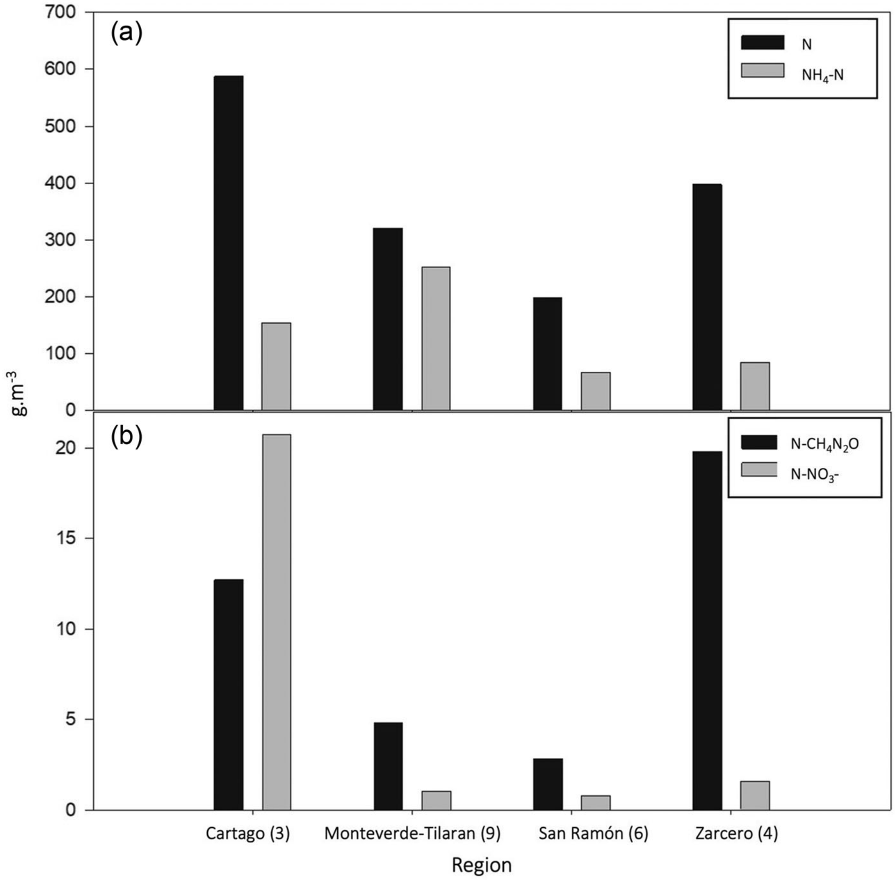

FIGURE 3 Total N and N-fractions of slurries applied to pastures in four dairy regions in Costa Rica. Values in parentheses next to the region name on the *x* axis are the number of dairies in that region participating in the survey. NH_4^+–N, ammonia N; N-CH_4N_2O, urea nitrogen; N-NO_3^-, nitrate nitrogen

in Cartago and Zarcero (Figure 3a). Among the nitrogenous fractions analyzed, NH_4–N had greater content, while NO_3–N and N-CH_4N_2O were lesser (Figure 3b). The latter followed the same tendency of total N, having greater concentrations for farms in Cartago and Zarcero. Concentration for all nitrogenous fractions was least for farms in San Ramón. Except for the farms in Cartago, the nitrate fraction of slurries was consistently low and in fact was not detected in some laboratory analyses.

Phosphorus concentration in slurries also varied among regions (99–195 g m^{-3}), as the farms in Cartago had almost twice the concentration reported for the other three regions (Figure 4a). The concentration of P was not detected in nine of the samples collected from Cartago (1), Monteverde-Tilaran (2), San Ramón (5), and Zarcero (1). Potassium, on the other hand, was the macronutrient with the greatest average concentration in dairy slurry (Figure 4a), although greater concentrations of total N were found in slurries collected from Cartago (Figures 3 and 4).

Sulfur concentration had values more than threefold that of farms in Cartago with respect to the other regions (Figure 4a). Also, S concentration could not be detected in eight samples from Monteverde-Tilaran (1), San Ramón (5), and Zarcero (2). The farms from Cartago had greater concentrations of Ca and Mg (Figure 4b) than the other regions. Calcium concentrations were less in farms in Zarcero followed by the farms in Monteverde-Tilaran and San Ramón. Magnesium concentrations were similar for these three regions. We did not detect Ca and Mg in two and half of the samples, respectively.

Iron was the micronutrient with greater concentrations (Figure 4c), followed by Zn, Mn, Cu, and B (Figure 4d). Copper was not detected in eight of the samples collected. Overall, farms from Cartago tended to have greater concentrations of Zn and Mn. The latter was also high in Zarcero and similar in the other two regions. Boron and Cu had similar concentrations among regions (Figure 4d).

The pH of the slurries collected was similar and close to neutral (6.30–7.17) among regions (Figure 5), while the EC was twice as high at farms in Cartago relative to those in San Ramón. Farms in Monteverde-Tilaran and Zarcero had intermediate values.

The microbiological indicators showed greater concentrations of *E. coli* and Actinomyces for the farms in Zarcero (Figure 6a and 6b, respectively), while N-fixers were

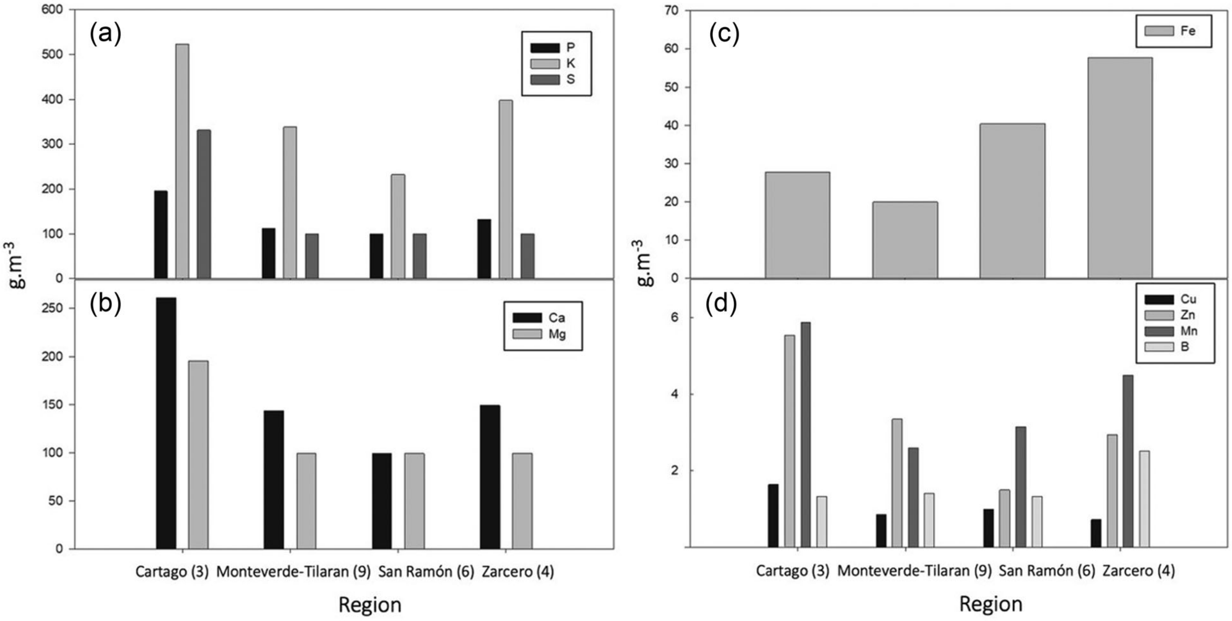

FIGURE 4 (a) Macro and (b) micro mineral contents of slurries applied to pastures in four dairy regions in Costa Rica. Values in parentheses next to the region name on the *x* axis are the number of dairies in that region participating in the survey

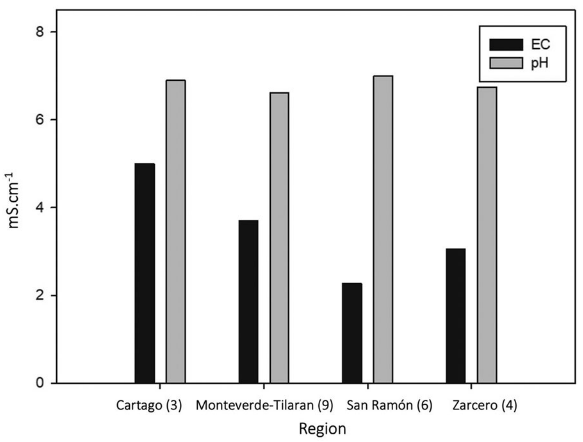

FIGURE 5 Electrical conductivity (millisiemens per centimeter) and pH of slurries applied to pastures in four dairy regions in Costa Rica. Values in parentheses next to the region name on the *x* axis are the number of dairies in that region participating in the survey

more abundant in San Ramón (Figure 6c). The farms in Monteverde-Tilaran had the lowest concentrations of microorganisms among the regions visited, with four samples testing negative for *E. coli* in this same region.

4 | DISCUSSION

Most of the dairy farms in Costa Rica are located in the central and Northeast regions, and many of them are concentrated near the volcanic areas that are spread throughout the mountain ranges of the country (Vargas-Leitón et al., 2013). The farms surveyed on this study were also located within these regions with a long history of milk production, and they have implemented irrigation systems with manure in the last 10 years. In spite of the increasing number of farms using semi-confinement and total confinement systems, dairy operations in Costa Rica are still mostly grass-based (Vargas-Leitón et al., 2013). These authors reported 72% of dairy farms in Costa Rica using grazing systems, which is similar to our study, with 63% of farms sampled being grass-based. One-third of the farms used semi-confinement systems under seasonal conditions (drought or extreme rainy events) or year-round for those systems with greater levels of intensification, and only one of the farms used a confinement system. The latter was the second smallest farm (5 ha) among all the farms surveyed. The use of rotational grazing in most of the farms surveyed allows them to redistribute manure across pastures both from the grazing animals and from the irrigation that is applied within the next 2 days after grazing (Kleinman et al., 2017).

The average stocking rate for the farms surveyed was similar to that reported by Vargas-Leitón et al. (2013). The range of data was wider in our study as we surveyed operations with very low intensification (0.4 cows ha^{-1}), while their study only comprises associates of the biggest dairy cooperative in Costa Rica. Only two farms in our study had more than 50 ha of pastureland, whereas the others had an average extension of 14 ha. Even though the pastureland cannot be unequivocally the only factor related to intensification of dairy farms, our study mostly comprised small operations

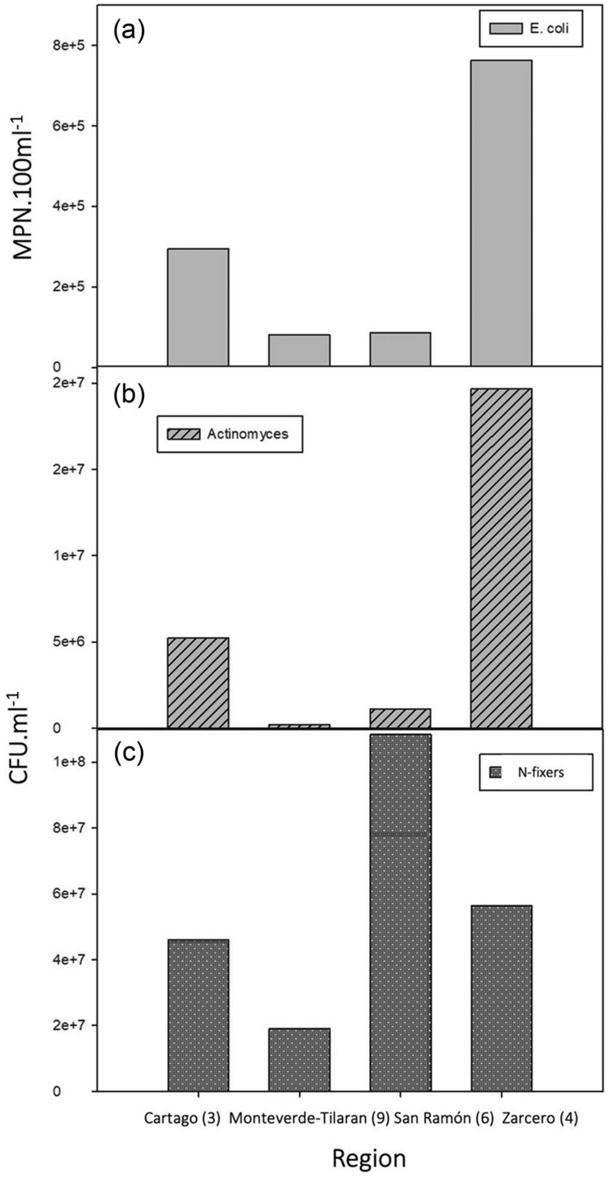

FIGURE 6 Microbiological indicators of slurries applied to pastures in four dairy regions in Costa Rica. Values in parentheses next to the region name on the *x* axis are the number of dairies in that region participating in the survey. MPN 100 ml^{-1}, most probable number of bacteria per hundred milliliters; CFU ml^{-1}, colony forming units per milliliter

with low input use. The supplementation practices – feeding exclusively by-products as supplements in nine of the farms – reflects a much lower dependency on imported feedstuffs that are used in concentrates. Vargas-Leitón et al. (2013) analyzed three factors related to different components of dairy farms in Costa Rica and found that intensification is strongly correlated with stocking rate and use of concentrates for cattle supplementation.

Different systems for manure collection in combination with water were used by the dairy farms surveyed (Table 2). Typically, the farms with largest herds of milking cows collect more manure per day (Morse Meyer et al., 1997; Saggar et al., 2004), while more control over manure supply and quality has been mentioned as a key component of precision manure management (Kleinman et al., 2017). Very few farms reported using a combination of scraping followed by water to clean their facilities. This contrasts with year-round indoor systems, which require more intensive manure collection due to the time spent by the cows within milking, feeding, or resting facilities (ConfTime) (Morse Meyer et al., 1997). The correlation found for PastInd and the number of MlkCws (Figure 2) could be somehow related to StockRate in the sense that operations with more cattle will require more pasture to feed their cattle. Because of the strong correlations found between PastInd and WtrUsd and SlurVol, we consider that the use of water is a key factor influencing the decision-making process of the degree of slurry dilution when irrigating pastures. The slurry dilutions applied to pastures in the dairy farms surveyed seem to be related mostly to the need to evacuate the manure storage structure, rather than to adjust to crop requirements (Kleinman et al., 2017). Solid manure separation and composting could reduce the use of water; however, these practices have been rarely reported at dairy farms (Morse Meyer et al., 1997; Parera i Pous et al., 2010). Kleinman et al. (2017) indicate that separation of feces and urine at dairy operations by scraping the floor before washing has not been a management approach favored by farmers, consequently slurry irrigation systems generate an unintended and ineffective use of water, much as we found among most of the farms surveyed (Table 2). Only two of the farms surveyed irrigated their pastures every other day while the rest irrigated every day, and, although we did not ask about the specific reason behind this type of management in the survey, presumably it has more to do with the capacity of the storage structures (filled daily) than with aiming to balance pasture nutrient requirements.

Nutrient concentration in slurries from different livestock species has been shown to be variable due to the management given at farm (Parera i Pous et al., 2010; Reijs et al., 2005) and nutrient transformations and losses that occur as a result of manure handling (Kleinman et al., 2017; Patni & Jui, 1991). Macronutrient analysis showed an imbalance between N–P–K pasture fertilization at dairy operations in Costa Rica (Villalobos et al., 2013). Although N content in the slurries sampled was, on average, lower than those reported by Parera i Pous et al. (2010, 3.24 kg m^{-3}) and Lalor et al. (2011, 2.03–4.39 kg m^{-3}), our results (Figure 3a) were similar to the average N content of 339 g m^{-3} reported by Pérez-Castillo et al. (2021) for slurries from a dairy farm in Costa Rica. All of these studies concur that slurries typically show considerable variation in N concentration with values up to 12-fold between the minimum and maximum concentrations in the slurries, as was the case in our study (Figure 3a). Also, N concentration in the slurries sampled in our study were about 10% of those found in slurries from temperate regions (2,300–3,200 g m^{-3}) stored for extended periods of time (Patni & Jui, 1991). Likewise, P and K were lower in the slurries sampled (Figure 4a) relative to those from dairy operations with totally confined systems (1.40 and 3.04 kg m^{-3}, respectively) (Parera i Pous et al., 2010). Ammonia has been reported as the main nitrogenous fraction in dairy manure slurries (Lalor et al., 2011; Parera i Pous et al., 2010; Patni & Jui, 1991; Pérez-Castillo et al., 2021; Reijs et al., 2005), as was the case in our study (Figure 3a). Reijs et al. (2005) found that ammonium shows a linear correlation with mineral fertilizer equivalent in either high or low protein diets of dairy cows; therefore, a proportion of the N applied in slurries may be available to the irrigated crop (Lalor et al., 2011). Parera i Pous et al. (2010) and Pérez-Castillo et al. (2021) found N/K ratios close to 1:1, just as in this study (Figures 3a and 4a). These authors attributed these variations in nutrient concentrations to differences in storage structures and water managements among farms.

Nutrient concentrations in slurries have been previously associated with the rations fed to dairy cows, with protein and fiber concentrations being the two main factors influencing the variations in C/N ratio (Reijs et al., 2005). Adjustment of protein content in the rations to match cattle requirements has been evaluated as a measure with potential to reduce N excretion (Kleinman et al., 2017). Although the rations of the farms surveyed were not analyzed in the current study, some of the differences found in nutrient concentrations may be attributed to the level of specialization of the productive units among the regions. The farms surveyed in Cartago are, for instance, located in high elevation where high rates of N are applied to pastures of kikuyu (*Cenchrus clandestinus* Hochst. ex Chiov.) and ryegrass (*Lolium* spp.) (Andrade, 2006; Villalobos & Sánchez, 2009). Under these conditions, the rations tend to be denser in protein with respect to farms at mid- and low elevations, consequently influencing the nutrient concentration of the manures collected for pasture irrigation (Reijs et al., 2005).

Electrical conductivity has shown a strong correlation with the concentration of macronutrients (N–P–K) in animal manures used for irrigation (Parera i Pous et al., 2010; Provolo & Martínez-Suller, 2007). In our study, the concentrations of macronutrients were less than those of slurries from highly intensive dairy systems (Parera i Pous et al., 2010), showing lesser EC values as well (Figure 5). The pH values found in the slurries were similar to the results of Patni and Jui (1991), with most of their samples below 6.8. These authors did not find variations in pH at different depths in different storage structures, suggesting that slurries were well buffered.

Slurries have shown an increase in annual N mineralization between 50 and 80 kg ha^{-1} within the first 50 years of application (Reijs et al., 2005). The N concentrations (Figure 3a) found in this study make it hard to reach forage requirements for this nutrient just by applying manure irrigation, mainly because of the water volume needed. Even if irrigation based on N rates used in Costa Rica (Villalobos et al., 2013) was logistically feasible, this strategy risks overdosing other macronutrients such as K and P. Mainly because of nearly 1:1 – N/K, and 2:1 – N/P relationships (Figures 3a and 4a) found in the slurries sampled. Kleinman et al. (2017) indicate that the N/P ratios in slurries will barely reach plant needs (8:1). Parera i Pous et al. (2010) found wide variations in the concentrations of P (0.13–3.03 kg m^{-3}) and K (0.89–6.07 kg m^{-3}). Therefore, the most sensible strategy would be to equally distribute the slurries collected throughout the pastureland and supplement the unfulfilled nutrient requirements with chemical fertilization (Kleinman et al., 2017). Through a combination of slurries and chemical fertilizers, the dairy farms could go a long way in reducing chemical fertilization use, minimizing nutrient waste, and avoiding eutrophication of ecosystems. On top of these benefits, using mineral fertilizers to make up for the shortfall in N would allow producers to sustain the carrying capacity in their pastures (Kleinman et al., 2017), especially for specialized dairy farms that have shown a strong dependency on mineral fertilizers to maintain high stocking rates (Vargas-Leitón et al., 2013).

Unlike in temperate conditions where most dairy farms have to store manure for several months of the year until appropriate conditions are met for application to croplands (Morse Meyer et al., 1997), the tropical conditions of Costa Rica allow for year-round irrigation, which implies that imbalances in irrigated soils may consequently occur more often. As shown in our survey, almost a third (27.3%) of farmers did not apply chemical fertilization at all (Table 3), and most of those who did, did not consider the nutrient contribution of slurries when calculating forage requirements. Nutrient concentration in slurries is neglected by dairy farmers, which is consistent with what Morse Meyer et al. (1997) found, where dairy farmers seldom performed sampling and nutrient analyses of soils and manure. Both strategies are strongly recommended as a routine practice to ensure that soil tests match field recommendations (Kleinman et al., 2017), especially when pasturelands are irrigated year-round, as is the case for the dairy farms surveyed here.

Manure management in dairy farms transcends minimizing nutrient losses, and also is a key factor to reduce pathogens such as *E. coli* in ground and surface waters (Kleinman et al., 2017). Concentration of *E. coli* is considered a reliable indicator of fecal contamination, as it exists in the intestinal flora of both healthy animals and humans (Manyi-Loh et al., 2016). Microbial concentration of the slurries showed the presence of *E. coli*, a pathogen that may become an issue after extreme rainfall events due to runoff coming from agricultural fields (Thurston-Enriquez et al., 2005). The four samples that tested negative for *E. coli* were from the region of Monteverde-Tilaran, the same region with the lowest microbial concentrations of Actinomyces and N-fixers (Figure 6). To our knowledge, these negative results cannot be attributed to a particular manure management in the farms. The concentrations of *E. coli* in the samples collected was lower ($0.81–7.62 \times 10^5$ 100 ml^{-1}) than values reported by Thurston-Enriquez et al. (2005) in runoff water (5.52×10^5 to 4.36×10^9) from cornfields (*Zea mays* L.) irrigated with fresh cattle manure.

Irrigation leaves the manure exposed on the pasture, which makes it vulnerable to runoff of nutrients and pathogens (Kleinman et al., 2017). Thurston-Enriquez et al. (2005) evaluated the influence of extreme rainfall events on the microbial load of runoff waters from crop fields with and without cover. These authors found that *E. coli* concentrations increased over a 3-day period in plots fertilized with fresh cattle manure, suggesting that these microorganisms were able to multiply in the soil. They indicate, however, that only a small fraction (0.01–6.99%) of the fecal indicators evaluated (*E. coli*, enterococci, *Clostridium* and coliphage) were carried by runoff after 30 min of rainfall. The dairy farms surveyed are located in regions where precipitation regimes above 2,400 mm yr^{-1} (Quesada Monge, 2007) impose risks during extreme rainfall events, indicating that producers must consider weather conditions before irrigating their pastures.

Actinomyces are microorganisms predominantly found in soil that have characteristics of both bacteria and fungi but are phylogenetically located in the kingdom bacteria (Bhatti et al., 2017). Concentrations found in dairy manures used for irrigation (Figure 6) were within the ranges reported for soil and composts of 10^4–10^8 per gram (Bhatti et al., 2017). Residual compounds found in dairy cattle manures such as cellulose, hemicellulose, and lignin, are used by Actinomyces as sources of C and N through slow decomposition processes (Bhatti et al., 2017). Considering that the dairy farms surveyed are continuously irrigating their pastures with manures, one can expect that the activity of Actinomyces can be sustained in the soil to perform a constant breakdown of the organic matter after bacteria and fungi attacked the more labile compounds (Bhatti et al., 2017).

Because Actinomyces can thrive under aerobic or anaerobic conditions (Bhatti et al., 2017), and dairy farms tend to implement diverse manure management systems (Morse Meyer et al., 1997), one can expect that perennial pastures irrigated with dairy manures would, in the long term, benefit from this combination of a constant influx of organic matter and microorganisms that break it down for further plant uptake.

Nitrogen-fixing bacteria are vital microorganisms within the N cycle in soils, supplying up to 15% of the world's N through symbiotic relationships with host plants (Bhatti et al., 2017). Despite the differences in concentration of N-fixers found in slurries (Figure 6c), pasturelands may indirectly increase N supply through the rotational irrigation with slurries. Both Actinomyces and N fixers contained in dairy slurries are providing side benefits that need further examination to assess their potential in perennial pastures.

Overall, this study echoes the need for training and educational programs for dairy farmers in Costa Rica that are using manure irrigation. The lack of consistent criteria to use slurries found in the farms surveyed concurs with other evidence suggesting that a myriad of approaches used by dairy farmers can indicate a lack of technical assistance following implementation of manure management systems (Morse Meyer et al., 1997). The quality of the manure from Costa Rican dairy farms is likely affected by several factors including the feeding practices at each farm as well as the handling and storage given to the slurries prior to application to pasturelands (Kleinman et al., 2017).

5 | CONCLUSIONS

This is the first study to analyze the current management of dairy manures at the farm level in Costa Rica. With the data provided, we aim to raise awareness among farmers and entities working closely with the dairy sector about the fact that unintended consequences, especially those of water use, need to be addressed in order to fulfill environmental goals for livestock operations at the country level. The dairy farms surveyed in this study were mostly small operations that will need technical assistance from both public and private entities to enhance their manure management systems. Costa Rican entities may also use our findings as a starting point to prioritize the main issues to be resolved prior to the implementation of irrigation systems at dairy farms.

Application of manure through tillage practices is not ideal for the steep conditions found in most dairy farms in Costa Rica. Guidelines for manure applications must consider the conditions of dairy farms in Costa Rica and must be aimed at reducing environmental and human health risks. Based on the results obtained in this study, these guidelines should focus on protocols to implement soil analyses at the farm level, minimization of chemical fertilizer use, manure collection best practices and rational use of water in slurry irrigation, as well as slurry application planning based on specific farm topography and climatic conditions.

Microbiological analyses showed the presence of potential soil improving microorganisms (Actinomyces and N-fixers) in slurries, but further research is required to establish the long-term effects these microorganisms could have on perennial pastures and, ultimately, on the systems' performance.

We encourage the Costa Rican dairy sector to develop clear guidelines for the management and application of manures to pasturelands through participatory approaches that involve producers as well as public and private entities. These guidelines should be comprehensive and specific to the country, rather than directly emulating models from conditions in other regions of the world.

ACKNOWLEDGMENTS

We gratefully acknowledge the Research Provost Office at the University of Costa Rica by funding this research project (code no. B7063 "Waste management systems used in Costa Rican intensive bovine production systems") from January 2017 to December 2018. https://vinv.ucr.ac.cr/sigpro/web/projects/B7063. We also acknowledge the producers that voluntarily participated in the study and by opening their operations for data collection.

AUTHOR CONTRIBUTIONS

Juan Ignacio Herrera-Muñoz: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Writing – review & editing. Luis A. Villalobos-Villalobos: Formal analysis; Investigation; Supervision; Visualization; Writing – original draft; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders (Research Provost Office at the University of Costa Rica) had no role in the design of the study nor the collection of data, analyses performed, interpretation of the results, writing of the manuscript, or in the decision to publish the results.

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How to cite this article: Herrera-Muñoz, J. I., & Villalobos-Villalobos, L. A. (2022). Implementation of irrigation with dairy cattle manure for tropical perennial pastures in Costa Rica. *Crop, Forage & Turfgrass Management*, *8,* e20158. https://doi.org/10.1002/cft2.20158