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An Evaluation of Manure Management Strategies, Phosphorus Surface Runoff Potential and Water Usage at an Arkansas Discovery Dairy Farm

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Abstract

Manure management is an essential component of dairy production. Nutrient-laden, field-applied dairy manure often serves as a fertilizer source, but can also pose environmental threats if not properly managed. The Haak dairy farm, located in Decatur, Arkansas, was granted a permit by the Arkansas Department of Environmental Quality (ADEQ) to employ a unique method in treating and storing cattle manure generated during the milking process. This method includes minimizing water use in wash water, dry scraping solids to combine with sawdust for composting and pumping effluent underground into a sloped concrete basin that serves as secondary solid separator before transporting the manure effluent into an interception trench and an adjacent grassed field to facilitate manure nutrient uptake and retention. The Arkansas Discovery Farm program (ADF) is conducting research to evaluate the environmental performance of the dairy's milk center wash water treatment system (MCWW) by statistical analysis, characterization of phosphorus (P) migration in soil downslope from the inception trench, temperature measurements, and nutrient analysis of a stored dry stack manure/sawdust mixture. Goals included determining possible composting effectiveness along with comparisons to untreated dairy manure and quantifying the use of on-farm water. Results from this research demonstrated that: 1) The MCWW was effective at retaining manure-derived nutrients and reducing field nutrient migration as the MCWW interception trench had significantly higher total nitrogen (TN) (804.2 to 4.1), total phosphorus (TP) (135.6 to 1.5), and water extractable phosphorus (WEP) (55.0 to 1.0) concentrations in milligrams per liter ($mg \cdot L^{-1}$) than the downhill freshwater pond respectively; 2) temperature readings of the manure dry stack indicated heightened levels of microbial and thermal activity, but did not reach a standard composting temperature of 54˚C; 3) manure dry stack nutrient content was typically higher than untreated dairy manure when measured on a "dry basis" in ppm, but was lower on an "as is basis" in ppm and kg/metric ton; and 4) water meter readings showed that the greatest use of on-farm water was for farm-wide cattle drinking (18.77), followed by water used in the milking center (3.45) and then followed by human usage (0.02) measured in cubic meters per day ($m^3 \cdot d^{-1}$). These results demonstrate that practical innovations in agricultural engineering and environmental science, such as the Haak dairy's manure treatment system, can effectively reduce environmental hazards that accompany the management of manure at this dairy operation.

Keywords

Manure Management, Soil Test Phosphorus, Surface Runoff, Water Usage, Manure Composting, Environmental Hazards, Arkansas, Milk Center Wastewater Treatment System, Statistical Analysis

1. Introduction

Effective manure management is vital in agricultural production regarding environmental stewardship and the reduction of manure-derived nutrients through surface runoff events that transports nitrogen (N) and phosphorus (P) off site [1]. Swine and dairy production facilities that produce liquid manure (manure mixed with wash water used to clean facilities) are continuously beset by challenges regarding the environmentally-sound management of manure [2]. Although the percentage of dairy farms in Arkansas is relatively low when compared to the number of farms in the state dedicated to row crops [3], dairy farms can still have a significant impact on the surrounding environment in terms of handling, storing and field-applying cattle-generated manures.

Unfortunately, dairy farms in Northwest Arkansas are located hundreds of miles from row crop production which makes the transport and use on row crops economically unfeasible. Therefore, dairy farmers in northwest Arkansas have historically land-applied on-farm produced manure in order to provide N and P as a source of fertilizer for permanent grazing lands [4]. These applications were primarily made concerning N, which is often the most limiting nutrient in plant growth and development, while consideration of P was not as prevailing [5]. As a result, P was usually applied in excess of plant demand and soil holding capacity which can be attributed to dairy manure having documented N:P ratios around 4:1 [6] [7] to as high as 6:1 [8]. This has led to elevated soil test phosphorus (STP) levels well above the optimum level for forage needs in northwest Arkansas and increased susceptibility of P loss to off-farm waterways. Furthermore, excessive amounts of land-applied P can render it susceptible to loss during occurrences of surface runoff, potentially having damaging consequences to aquatic aesthetics and overall wellbeing due to an increased capacity of P loading into neighboring streams and rivers [4] [9].

In an attempt to alleviate environmental concerns ascribed to P migration through surface runoff, a myriad of strategies has been proposed and implemented [10] such as rotational animal grazing, vegetative filter strips and the use of aluminum (Al)-compound treated manures [11] [12]. Another method for reducing surface runoff P involves the use of Al and iron (Fe) based water treatment residuals, which have been shown to be effective agents at binding soil-applied P in laboratory experiments [13] and in field trials [14]. While these methods have been shown to impede field P movement in surface runoff, the storage and handling of farm-generated manure also play a crucial role in the on-site retention of nutrients.

The storage of farm-generated manure can be performed in a variety of ways for instance storage in lagoons or holding ponds, clay-based storage pits and in open-air facilities [15]. Lagoons and holding ponds provide outside storage wherein manure can be received by gravimetric means or by physical removal in order to facilitate separation of the liquid and solid manure fractions [16]. The liquid fraction can then be pumped into motorized spreaders and applied to fields by broadcasting on the ground surface. Clay and earth-based storage pits collect manure that is usually washed or scraped out of containment areas used for the collection of animal byproducts [17]. The manure is then allowed to settle until removed for field-applications. Open-air storage typically involves raw manure mixed with additives such as Al-based compounds. While Al-based compounds can assist in making manure-derived P immobile, additional additives (*i.e.* sawdust) can reduce rank odors from manure [18], and rice residues have shown a propensity to stimulate manure composting processes [19]. The use of an open-air storage facility as well as mixing manure with sawdust is key components of the Haak dairy farm in its management of farm-generated dairy manure.

The Haak dairy farm along with Arkansas Discovery Farms (ADF) and the Natural Resources Conservation Service (NRCS), has devised an innovative treatment system in which dairy-generated manure and milk center wash water are managed. Therefore, the objectives of this research are: 1) to assess the effectiveness of the milk center wash water treatment system (MCWW) as to its impacts on possible P migration and soil health across portions of the Haak dairy; 2) to determine if the dairy's open-air storage of manure mixed with sawdust can technically be considered compost and if biological activity is occurring; 3) to compare chemical characteristics of the manure/sawdust mixture to untreated (or raw) dairy manure; and 4) to visualize and ascertain trends in the water use over time by the Haak dairy.

2. Materials and Methods

2.1. Experimental Site Information

The research presented in this paper was conducted from 2017-2022 at the Haak dairy farm located near Decatur (36˚21'54.29", 94˚26'30.4") in Benton County, Arkansas. The farm had 80 head of cattle in 2017 at the start of the study increasing to 160 head in 2018 and the milk produced is collected daily. The Haak dairy employs a rotational grazing system where pastures are planted with a mix of crops such as rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.) and soybeans (*Glycine max* L.) over bermudagrass (*Cynodon dactylon* L.), which are grown and in turn are used for feed. A grassed walkway was established through the middle of the pastures to decrease the distance cows must walk to get to the milking parlor. For cattle grazing purposes, a rotational paddock system is used with distributed cattle watering tanks. The fields at the Haak dairy receive applications of litter in the form of a manure/sawdust mixture produced in the dairy's milking facility based on the farm's nutrient management plan (NMP) (United States Department of Agriculture-NRCS. 2015).

2.2. Haak Dairy Milking Facility

The dairy's milking facility consists of a pre-milking holding area and the milking parlor proper. Prior to milking, cattle are led up along two inclining paths abutting the inside walls of the pre-milking holding area where they await their turn to be milked. The cattle are then directed into the parlor and steered towards customized stalls where their milk is collected. The parlor is constructed so that 20 cows can be milked at once. This milking process occurs twice a day. Manure that remains after the milking process is shoveled out and deposited on the floor of the pre-milking holding area in order to separate the solid and liquid manure fractions. This is done to alleviate cleaning efficacy of the milking parlor and to reduce the volume of waste.

After milking, cattle are led down a wide, centrally located incline in the pre-milking holding area and released back into the field. The floor of the pre-milking holding area is overlain with a layer of sawdust that serves to increase the traction of approaching/departing cattle and to mix with deposited cattle manure in order to facilitate its removal. The resulting manure/sawdust mixture is then removed by dry scraping and deposited in an open-air storage area.

2.3. Open-Air Manure Storage Area

The manure/sawdust mixture that is removed from the pre-milking holding area is placed and stored in a concrete, roofed, open-air containment area measuring 9.1 meters (m) by 12.2 m and is directly adjacent to the holding pen. This mixture is allowed to sit in the storage area until time for field applications or for transport to other nearby farms. This manure mixture is used as a fertilizer source: mainly for suppling N to the forage or crop being grown at that time.

Mixing sawdust with deposited cattle manure is advantageous for a number of reasons. First, adding sawdust greatly facilitates handling and storage by its capacity to absorb much of the liquid present in raw, untreated cow manure. This serves not only to alleviate handling concerns but to allow for easier field applications and transport. Second, the sawdust greatly reduces the odor and insect activity around the manure in the storage area: especially beneficial during the hot summer season.

2.4. Milk Center Wash Water Treatment System (MCWW)

After the manure is removed from the milking parlor, the remaining material gets washed into a drain system that transports the mixture into an underground pump approximately 9.1 m from the parlor. From there, the mixture is pumped into an aboveground concrete basin in which the solid and liquid manure fractions are separated by a mesh screen. The resulting liquid fraction is then transported into an interception trench measuring 24.4 m by 3 m with a depth of 1.2 m.

The interception trench is equipped with a lipped weir that allows for the overflow of liquid manure to enter a grassed filter strip approximately 0.12 hectares (ha) in size. Bermudagrass is the primary species grown in this area. The grassed strip is periodically cut for hay and is off limits to grazing cattle. While the grassed strip is not a part of the dairy's rotational grazing system, it does serve as a retention area for nutrients contained within the manure and impedes their migration to other areas of the farm.

2.5. Water Meters

Throughout the dairy, water meters are installed at three locations with the goal of documenting how water is used at the farm for various purposes. In the milking center, one meter is located by tanks storing the collected milk and one is directly adjacent to a communal restroom. Another water meter is located in an operation shed approximately 18.3 m from the milking center. This meter measures the total amount of water usage from the dairy.

2.6. Sample Collection and Statistical Analysis

Liquid manure and water samples were collected from the MCWW in two locations: a point where liquid manure exits the concrete basin via PVC piping (Basin Discharge) and the point of PVC effluent entry into the interception trench (Trench Entrance). Another sampling area was a freshwater pond (Pond) located approximately 305 m downhill (3% - 8% slope) from the MCWW grassed strip. Pond samples were collected to determine if the MCWW grassed strip was effective in retaining and restricting nutrient migration from the concrete basin and interception trench.

Statistical analysis of the three sampling sites was performed using a generalized linear mixed model, gamma distribution and a log link using Proc Glimmix in SAS 9.4 (SAS Institute Inc., Cary, NC, USA) in order to compare nutrient concentration means between the sampling sites with sampling year as the random effect. Means were separated by using a protected least significant difference (LSD) procedure ($P \leq 0.05$). For tabulation purposes, the log link values were converted back to their respective whole number values. Analytes of interest included total nitrogen (TN), total phosphorus (TP), water extractable P (WEP), total potassium (TK) and percent (%) solids content. Statistical analysis was performed using Proc Glimmix in SAS 9.4 software. Differences in nutrient concentrations of the pond were conducted by using an unpaired t-test ($P \leq 0.05$) in JMP$^{®}$, Pro 16 (SAS Institute Inc., Cary, NC, 1989-2023) with sampling year as the main effect. Pond analytes included TN, TP, WEP and TK. Statistical analysis was performed using JMP Pro 17 software. Data analyzed are from 2017-2021.

Soil sampling events monitoring soil nutrient content and health occurred in February 2017, 2018, and 2020 and in March 2022. Ten soil sampling transects (each containing five sampling points) were created using LIDAR (Light Detection and Ranging) GIS (Geographical Information Systems) information and NRCS Total Station Elevation Surveys to map contour lines along with surface runoff pathways on the farm encompassing the milking facility, the MCWW, and the paddock upslope and adjacent to the freshwater pond (**Figure 1**). A total

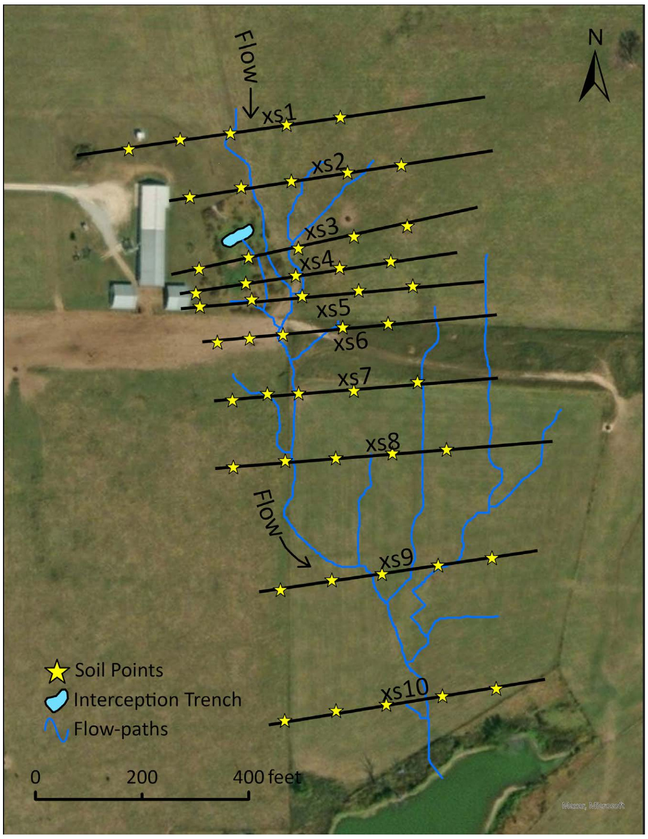

Figure 1. Haak dairy soil sampling transects (1 through 10) used for sampling events in 2017, 2018, 2020 and 2022.

of 100 soil samples were collected during each sampling event. Soil samples contained 6 cores collected at depths of 0 - 10 centimeters (cm) and 10 - 20 cm within a 1.5-m radius of each respective GPS point along with being divided and blended into one composite sample for each grid point per depth. The area encompassing the transects was represented as a Peridge silt loam comprising 3% - 8% slopes. Transects and soil sampling points were produced in ArcMap Version 10.1 [20] and coordinates entered into a GPS unit (GPSMap 64st, Garmin International) so that grid soil sampling could be performed at prearranged sites. In addition, GIS raster maps were created examining differences in STP for 2017, 2018, 2020, and 2022 at both sampling depths. Samples were sent to the Marianna Soil Testing Laboratory in Marianna, Arkansas for soil nutrient analysis by using the Mehlich-3 extraction procedure and determined by using an inductively coupled plasma-atomic emissions spectrometer (ICAP-AES; [21]).

Soil transects were graphically analyzed for trends and differences in STP at both sampling depths. The STP values for each transect are the means for their respective five sampling points. The area between transects two and three is where the concrete basin, interception trench and the grassed strip of the MCWW are located. The cattle travel path is located between transects five and six. Standard error was shown for each transect to denote significant differences in STP between the three sampling years.

Statistical analysis of STP between 2017, 2018, 2020, and 2022 consisted of using a generalized linear mixed model, gamma distribution and a log link in order to compare STP means by “sampling year” and “transect” using Proc Glimmix in SAS 9.4. When “sampling year” was analyzed as a fixed effect, “transect” was used as the blocking/random effect while “sampling year” was used as a blocking/random effect when “transect” was used as the fixed effect. Means were separated by using a protected least significant difference (LSD) procedure ($P \le 0.05$).

Temperature measurements were made from the manure/sawdust mixture located in the dairy’s open-air storage facility on a monthly basis. A thermometer approximately 1.2 m in length was inserted into selected spots within the dry stack where a temperature reading was generated. Four temperature readings were recorded from every side of the storage area where the manure/sawdust mix was available to measure. These temperatures were then compared to minimum and maximum ambient temperatures on the day of sampling, obtained along with precipitation amounts from National Oceanic and Atmospheric Administration (NOAA, https://www.noaa.gov). Another comparison was made between the manure/sawdust mix temperature and a target temperature of 54˚ Celsius (C), which is classified as being the temperature at which the composting of organic material begins.

Starting in 2020, core samples from a predetermined area within the manure dry stack were collected monthly. The core sampling device is composed of a metal tube approximately 1.8 m long that has a concealed auger. Near the handle is a plastic container used to house the dry stack sample. The metal tubing is inserted into the manure dry stack and drill operated, pulling a manure/sawdust mix sample up the metal tube and into the plastic container. The cores were analyzed for N, P, K, calcium (Ca) and WEP in various units consistent with manure testing and reporting. Data was analyzed from 2020-2021 in order to compare dry stack manure nutrient values with untreated Haak dairy manure sampled and analyzed in 2015.

Water meter readings were collected monthly. By taking the total amount of water used at a particular reading and subtracting the readings from the combined milking center and restroom water meters, a value for the amount of water used for cattle drinking was obtained. The collected water meter data was then analyzed in order to assess how the water usage is distributed across the farm and to identify any areas of possible concern. Additional analysis of milk center water use was conducted using a Kendall's tau nonparametric correlation in units of cubic meters per day ($m^3 \cdot d^{-1}$) using JMP®, Pro 16 to ascertain a water usage trend from 2017-2021.

3. Results and Discussion

3.1. Milk Center Wash Water Treatment System

Total nitrogen (TN) ($P < 0.0001$), TP ($P < 0.0001$) and TK ($P < 0.0001$) followed similar trends significantly decreasing concentration order of the sampling sites: trench entrance > basin discharge > pond (Table 1). Data is displayed according to preferential effluent flow within the treatment system (Table 1). Water extractable P concentration for the pond was significantly lower than the basin discharge and trench entrance while the two MCWW sites were not significantly different ($P < 0.0001$). Percent solids content was significantly higher in the trench entrance than in the basin discharge area ($P < 0.0001$).

Table 1. Milk center wash water treatment system (MCWW) total nitrogen (TN), total phosphorus (TP), water extractable phosphorus (WEP), and total potassium (TK) concentrations in milligrams per liter ($mg \cdot L^{-1}$) and percent solids (%) means comparisons by sampling site (2017-2021) ($P < 0.05$).

Site	No. of samples	TN	TP	WEP	TK	Solids
		$mg \cdot L^{-1}$				%
Basin Discharge	50	313.2 b$^{\varphi}$	69.3 b	56.8 a	171.5 b	0.6 b
Trench Entrance	32	804.2 a	135.6 a	55.0 a	202.4 a	1.9 a
Freshwater Pond	53	4.1 c	1.5 c	1.0 b	16.1 c	ND

$^{\varphi}$Columns connected by the same letter are not significantly different ($P < 0.05$). ND = Not determined.

The data show that the trench entrance portion of the MCWW is effectively restricting the migration of nutrients contained in the discharged manure downhill to the freshwater pond. As some liquid manure eventually pours over the trench's lipped weir, the data also show that the grassed strip directly adjacent to the trench is assisting with impeding nutrient migration. This grassed strip most likely facilitates the uptake and assimilation of manure nutrients as well. The increase in percent solids for the trench entrance may be indicative of the need for a finer mesh screen located in the concrete basin that separates the liquid and solid manure fractions.

Analysis of pond water samples in (**Table 2**) shows significant decreases in TN ($P = 0.0480$), TP ($P = 0.0008$) and WEP ($P < 0.0001$) from 2019 to 2021, while TK was not significantly different during that time frame. These significant decreases in TN, TP and WEP indicate that the MCWW system is working to reduce the downhill movement of these manure-laden nutrients to the pond. If there was significant nutrient migration out of the MCWW system, then the pond's TN concentration would likely be higher due to the increased mobility of N in the soil and via surface runoff pathways.

3.2. Soil Sampling Transects

Soil test P was significantly greater at both sampling depths for most of the transects from 2017 to 2018 (**Figure 2** and **Figure 3**). Additionally, STP was significantly higher among transects for both sampling depths from 2017 to 2020. Soil test P for 2018 and 2020 remained statistically insignificant for the majority of transects at both sampling depths but displayed similar trends. Soil test P for 2022 was significantly lower than 2018 and 2020, but higher than 2017 for the majority of transects at both sampling depths. The significant increases in STP from 2017 to 2018 and 2020 could be attributed to the Haak dairy adding more cows to its overall herd (*i.e.*, from 80 in 2017 to 160 in 2018). When the grazing rotation was in the paddock between the cattle travel lane and the freshwater

Table 2. Freshwater pond total nitrogen (TN), total phosphorus (TP), water extractable phosphorus (WEP), and total potassium (TK) concentrations in milligrams per liter ($mg \cdot L^{-1}$) means comparisons by sampling year (2017-2021) ($P < 0.05$).

Year	TN	TP	WEP	TK
	mg·L⁻¹			
2017	5.12 ab[φ]	0.93 c	0.40 d	17.58 a
2018	3.09 b	1.33 bc	0.81 cd	15.91 a
2019	5.83 a	2.29 a	1.68 a	16.59 a
2020	4.05 ab	1.62 b	1.28 ab	17.41 a
2021	2.76 b	1.31 bc	0.96 bc	13.63 a

[φ] Columns connected by the same letter are not significantly different ($P < 0.05$).

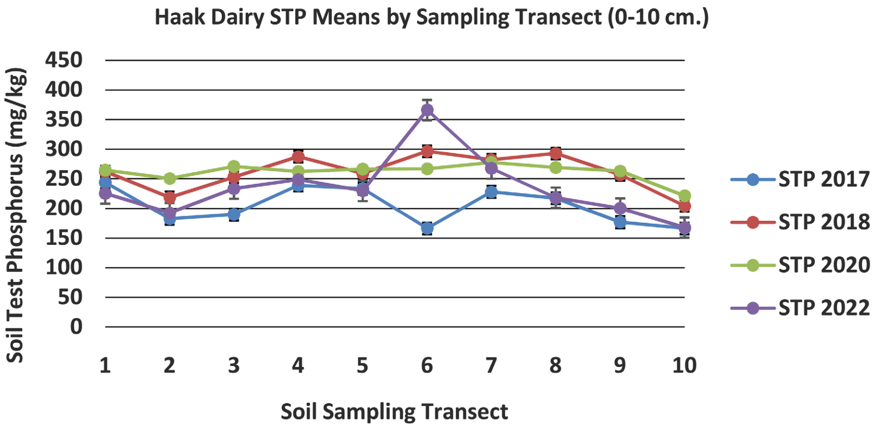

Figure 2. Haak dairy soil test phosphorus (STP) means for 10 soil sampling transects at a sampling depth of 0 - 10 centimeters (cm). Error bars represent ± 1 standard error.

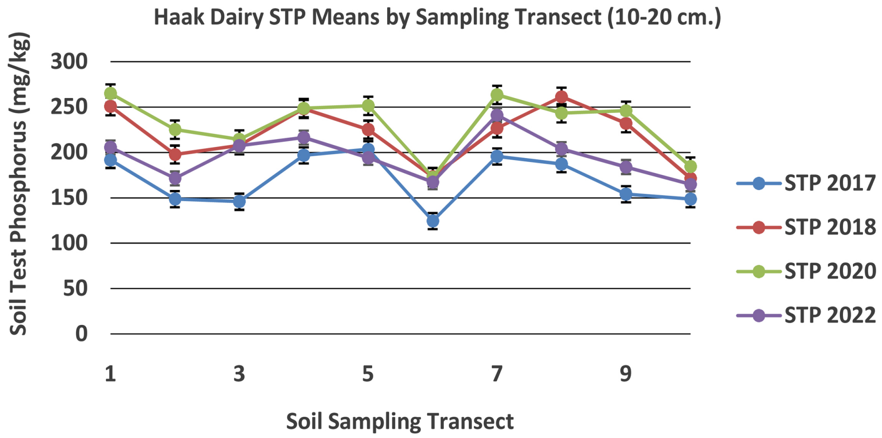

Figure 3. Haak dairy soil test phosphorus (STP) means for 10 soil sampling transects at a sampling depth of 10 - 20 centimeters (cm). Error bars represent ± 1 standard error.

pond, this allowed for additional manure deposits to build up and become noticeable in soil test results. The significant decrease in STP observed in 2022 from 2018 and 2020 may be ascribed to cattle being excluded from grazing in this paddock around mid-2020.

At the 0 - 10 cm sampling depth, there was a similar trend in all four years that saw an elevation in STP right after transect 3. This elevation peaked between transects 6 and 8 until decreasing as the transects neared the freshwater pond (transects 9 and 10). However, STP significantly decreased at transect 6 in 2017 and significantly increased in 2022 when compared to STP in 2018 and 2020 at the same transect. The heightened STP at 0 - 10 cm for 2018 and 2020 at transect 6 may also be indicative of increased manure deposition along the cattle travel lane by the additional number of cows. The further increase in STP at 0 - 10 cm for 2022 at transect 6 may be reflective of terminated grazing within the downhill paddock around mid-2020 and forcing cattle to congregate more predominantly in and around transect 6, resulting in substantial increases of surface manure accumulation. Similar trends in STP were observed for the 10 - 20 cm sampling depth for all years, increasing after transect 3 and then dramatically decreasing at transect 6 before rising again and dropping off towards transect 10.

Statistical analysis of STP by sampling year shows that for both the 0 - 10 cm ($P < 0.0001$) and 10 - 20 cm ($P < 0.0001$) depths, STP significantly increased from 2017 to 2018 and 2020, which in turn were not significantly different (**Table 3**). The causes for this can also be attributed to an increase in cattle number from 2017 to 2018 with resultant increases in grazing activity and manure deposition. Soil test P in 2022 was significantly lower than 2018 and 2020, but significantly higher than 2017, further emphasizing the effect of reduced grazing activity in areas near the freshwater pond. In addition, this also indicates that subsurface migration of P is occurring down to a soil depth of 20 cm.

Statistical analysis of STP along soil sampling transects found that transects 4, 6 and 7 had significantly higher STP means at the 0 - 10 cm depth than transects 2, 9 and 10 ($P < 0.0001$) (**Table 4**). Statistical analysis of STP along soil sampling

Table 3. Haak dairy Mehlich-3 soil test phosphorus (STP) means in milligrams per kilogram ($mg \cdot kg^{-1}$) for soil sampling events in 2017, 2018, 2020 and 2022 ($P < 0.05$).

Year	**STP (0 - 10 cm)**[†]	**STP (10 - 20 cm)**
	($mg \cdot kg^{-1}$)	
2017	204 c	168 c
2018	260 a	218 a
2020	261 a	230 a
2022	232 b	195 b

[†] Columns not sharing the same letter are significantly different ($P < 0.05$).

Table 4. Haak dairy Mehlich-3 soil test phosphorus (STP) means in milligrams per kilogram ($mg \cdot kg^{-1}$) by sampling transect for soil sampling events in 2017, 2018, 2020 and 2022 ($P < 0.05$).

Transect	**STP (0 - 10 cm)**[†]	**STP (10 - 20 cm)**
	($mg \cdot kg^{-1}$)	
1	249 ab	226 ab
2	210 cd	184 cde
3	235 abc	192 bcd
4	259 a	226 ab
5	247 ab	218 abc
6	271 a	158 e
7	263 a	231 a
8	248 ab	222 ab
9	222 bc	201 abc
10	189 d	167 de

[†] Columns not sharing the same letter are significantly different ($P < 0.05$).

transects at the 10 - 20 cm depth showed that transect 7 was significantly higher in STP than transects 2, 3, 6 and 10 (P < 0.0001) (**Table 4**). Transect 4 had points located in the MCWW grassed interception field, indicating effective retention of manure generated P while transects 6 and 7 were located in or directly adjacent to the cattle travel lane, indicative of the effect of excess manure deposition affecting soil test results. However, the significant decreases in STP found in transect 10 for both depths imply that the efficacy of the MCWW in regard to P retention is optimal while suggesting other localized areas along these transects have a substantial influence on STP results.

3.3. Soil Test P Differences

Further analysis of soil sampling transects by individual soil sampling points indicates that STP transect means are highly influenced by specific points of positive and negative STP differences (**Figure 4** and **Figure 5**). At both the 0 - 10 and 10 - 20 cm sampling depths, the majority of STP differences from 2017 to 2022 along most of the transects are positive, including localized STP "hotspots" above 50 ppm for the 0 - 10 cm depth which is classified as "above optimum" by the University of Arkansas Division of Agriculture (UADA) (**Figure 4**). However, the majority of STP differences from both 2018 to 2022 and 2020 to 2022 at both depths on each transect are negative (**Figure 4** and **Figure 5**), with STP "hotspots" confined to the cattle travel lane along transect 6 near the milking

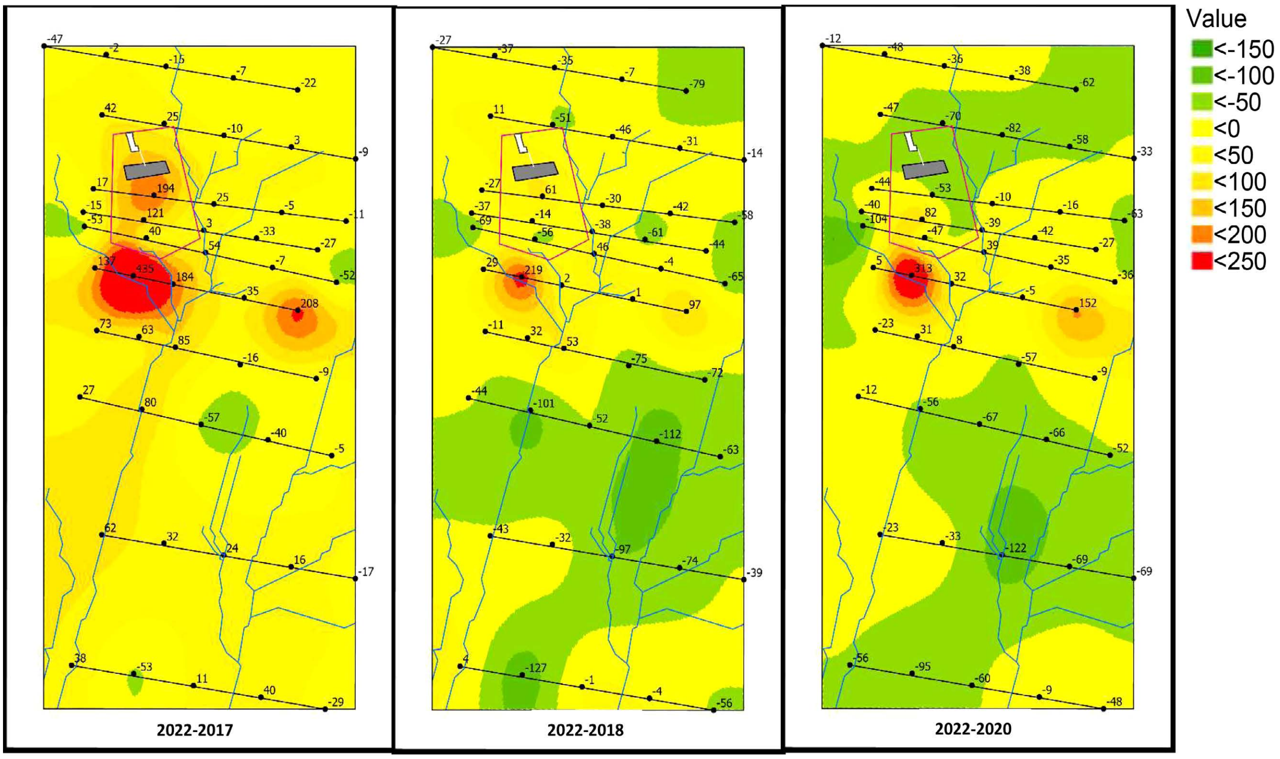

Figure 4. Geographical Information System (GIS) color-coded raster maps displaying the change in soil test phosphorus (STP) in milligrams per kilogram (mg/kg) for individual soil sampling points at the 0 - 10 centimeter sampling depth comparing the sampling years 2022-2017, 2022-2018, and 2022-2020 at the Haak dairy.

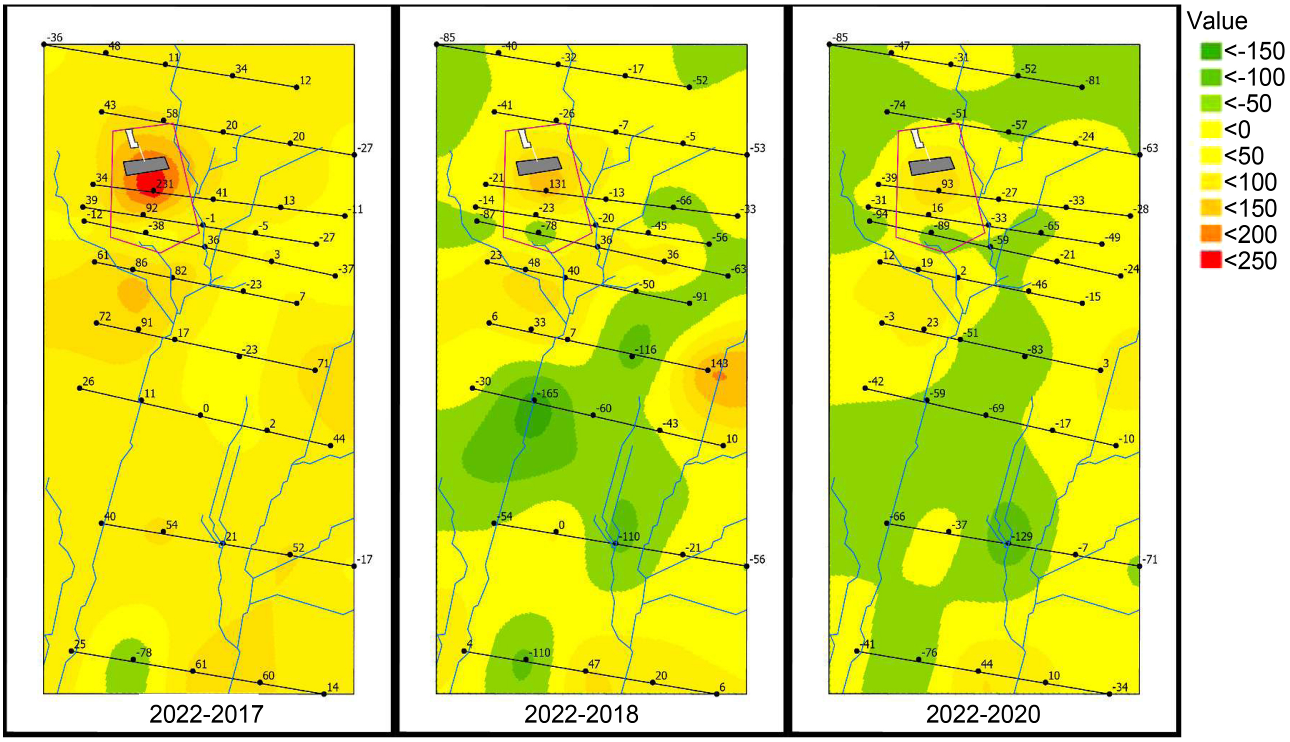

Figure 5. Geographical Information System (GIS) color-coded raster maps displaying the change in soil test phosphorus (STP) in milligrams per kilogram (mg/kg) for individual soil sampling points at the 10 - 20 centimeter sampling depth comparing the sampling years 2022-2017, 2022-2018, and 2022-2020 at the Haak dairy.

parlor entrance at the 0 - 10 cm depth (**Figure 4**).

The negative STP differences shown along transects 7 - 10 from 2018 to 2022 and 2020 to 2022 at the 0 - 10 cm depth indicate reduced grazing in the paddocks above and adjacent to the freshwater pond during these time periods (**Figure 4**). In addition, the substantial amount of individual negative STP differences along the majority of transects from both 2018 to 2022 and 2020 to 2022 at both sampling depths suggest that STP "hotspots" are more likely the result of manure deposition and subsequent surface accumulation than surface P runoff from the MCWW and the interception grassed field.

Prior to being converted to a dairy farm, the land presently occupied by the Haak dairy was pasture and hay land that had a history of poultry litter applications by the previous owner. The 2015 Haak dairy NMP, developed prior to the introduction of dairy cattle, showed that the field average STP values ranged from 225 - 229 milligrams per kilogram (mg/kg). These values are considered "above optimum" according to soil fertility guidelines and recommendations. Nevertheless, when incorporating other P-indexing (PI) features, the NMP detailed numerous procedures and circumstances that brought about acceptable, medium scale PI runoff risk levels.

In response to mounting concerns of nutrient enrichment in northwest Arkansas streams, the State of Arkansas regulates livestock operations that primarily deal with liquid manure management under State Regulation 5, which involves a permitting process that requires approval of a liquid manure treatment system and public notice of new system. Typically, most permitted livestock-manure management systems in Arkansas involve the management of effluent storage lagoons that must be maintained at specified standards with the effluent ultimately being land applied to pastures as fertilizer that is governed by a state approved nutrient management plan based on the Arkansas P-Index for pastures.

3.4. Manure Dry Stack Temperatures

Across all sampling dates, the manure/sawdust mixture temperatures were consistently higher than ambient measurements but did not reach the composting target of 54˚C (**Figure 6**). This may possibly be explained by the thermal mass and heightened microbial activity within the manure/sawdust mixture keeping temperatures elevated, but not at the composting target temperature. Nevertheless, chemical and biological activities occurring within the manure dry stack are similar to processes associated with composting organic materials.

3.5. Manure Dry Stack Nutrient Content

Comparisons of the chemical concentrations collected from the manure/sawdust mixture stored in the open-air dry stack facility from 2020 to 2021 to a sample of manure collected at the Haak dairy in 2015 show that the N, P, Ca and WEP concentrations of dry stack manure were numerically higher than the 2015 dairy manure sample on a "dry basis" in ppm while the inverse was observed for K (**Table 5**). On an "as is basis" in ppm and kg/metric ton, the dairy manure from

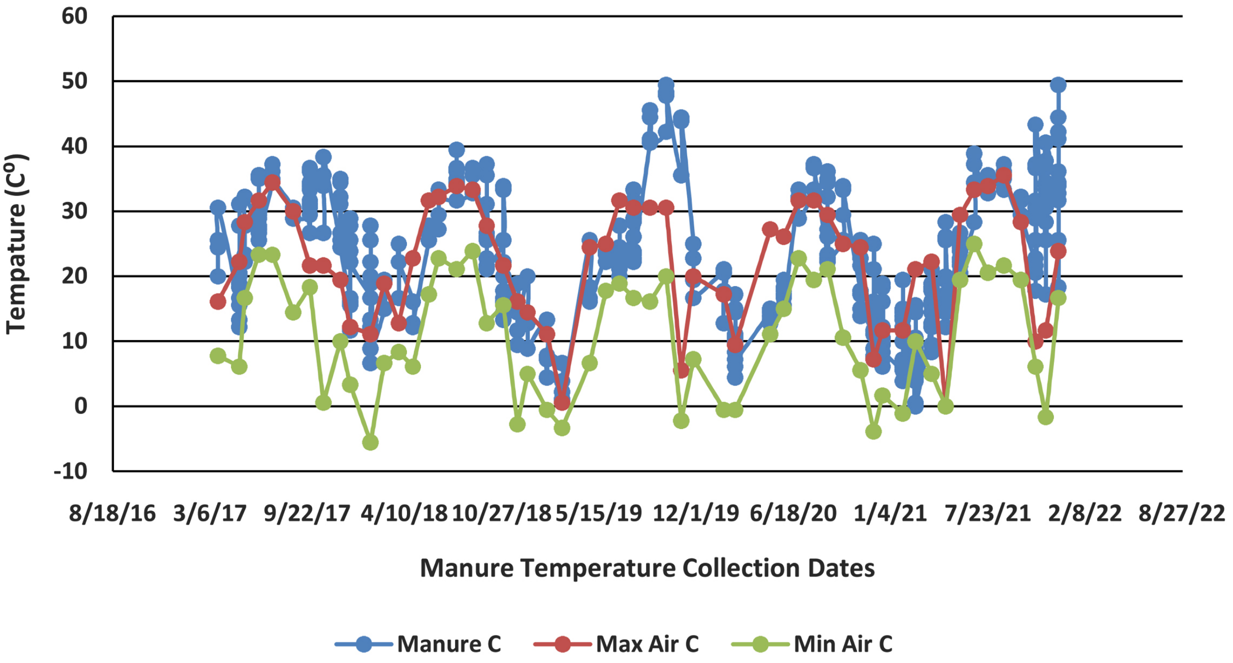

Figure 6. Graph comparing manure/sawdust mixture and minimum and maximum ambient temperatures at the time of sampling (2017-2021) in relation to a composting temperature of 54˚C.

Table 5. Untreated dairy manure and dry stack manure core nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and water extractable phosphorus (WEP) means in milligrams per kilogram (mg·kg^{-1}) and kilograms per metric ton (kg metric ton^{-1}) for 2015 and 2020-2021 (n = 23).

Sample date	N	P	K	Ca	WEP
			mg·kg^{-1} on dry basis		
2015	1.85	0.28	1.47	0.94	711
2020-2021	2.44	0.53	1.34	2.21	1253
			mg·kg^{-1} on as is basis		
2015	1.65	0.25	1.31	0.84	635
2020-2021	0.85	0.18	0.47	0.74	418
			kg metric ton^{-1} on as is basis		
2015	16.3	2.5	13.1	8.4	0.7
2020-2021	8.5	1.8	4.7	7.4	0.5

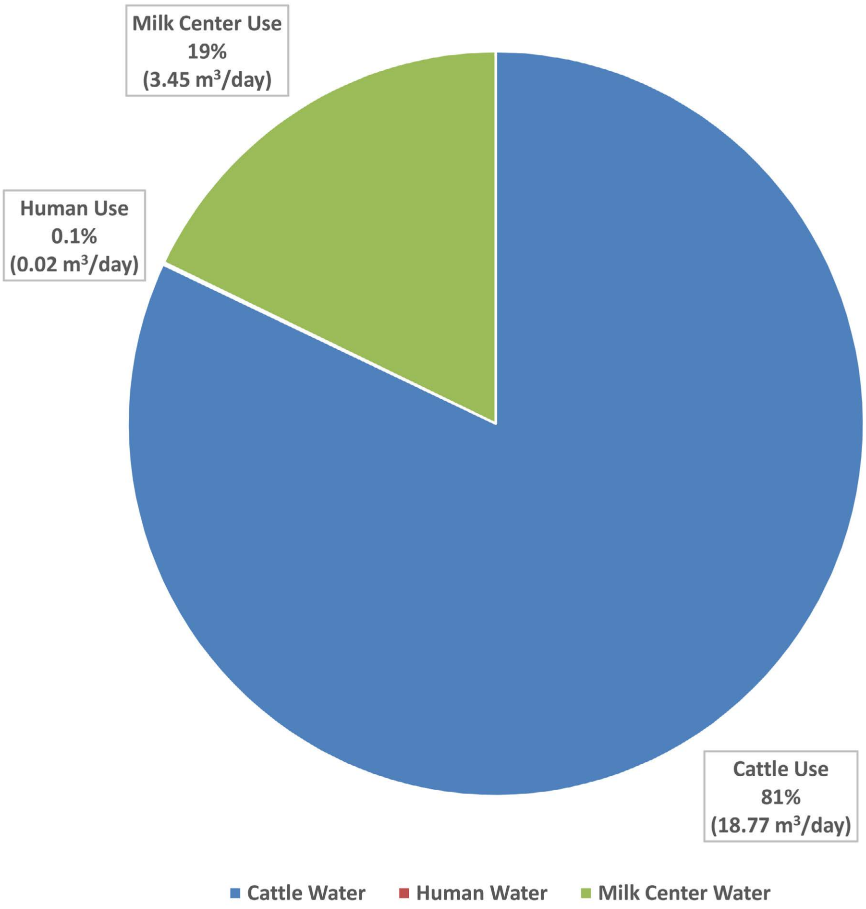

Figure 7. Chart displaying the amount of water used for various purposes at the Haak dairy from 2017-2021. Values are expressed as percentages of the overall total and as whole number averages expressed in cubic meters per day (m^3/day).

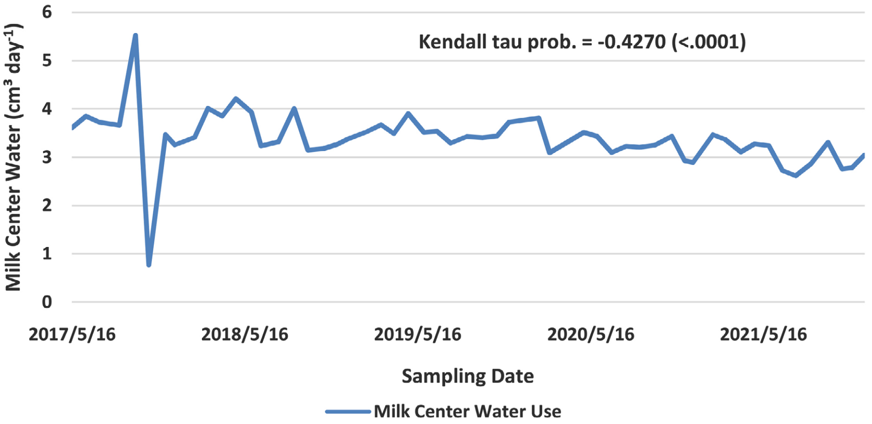

Figure 8. Chart displaying Haak dairy milking center water usage from 2017-2021 calculated and analyzed by the Kendall's tau non-parametric statistical trend method ($P < 0.05$).

2015 was numerically higher in all chemical constituents than the dry stack manure/sawdust mixture.

Storing and land-applying manure mixed with sawdust generated at the Haak dairy, although higher in N and P than untreated manure, can provide nutrients to meet crop and/or forage demand during a growing season. Additionally, applying dairy manure blended with sawdust to fields and pastures can reduce immediate N and P availability due to addition of organic material provided by the sawdust. Timing manure applications based on estimated N and P mineralization rates can be beneficial in reducing N and P lost through surface runoff and from oversaturating areas of the farm where a substantial amount of STP has been observed.

3.6. Haak Dairy Water Usage

Overall, the largest amount of water used on the farm was for cattle drinking by a wide margin ($18.77\ m^3 \cdot d^{-1}$) over milk center use ($3.45\ m^3 \cdot d^{-1}$) and human needs ($0.02\ m^3 \cdot d^{-1}$) (**Figure 7**). With an increase in cattle in 2018, this should remain the highest use of farm water for a prolonged period of time. The distributed watering stations throughout the farm are numerous and each hold an abundant amount of water to meet cattle needs and their field locations are easily accessible for grazing. The physical removal of solid manure from the milking center makes the water used for rinsing the remaining manure out of the parlor minimal compared to other uses. Additional analysis of milking center water usage over time showed a significant downward trend (<0.0001) from 2017 to 2021 (**Figure 8**).

4. Conclusions

The milk center wash water treatment system designed by the NRCS for the Haak dairy was intended to be used as a sustainable method in which to handle the copious amount of manure the dairy generates. This system has been shown to contain manure generated P on the farm without endangering STP levels. Therefore, this method may be considered a viable option for dairy operations concerning manure management.

The overall cost to install this manure treatment system at the Haak dairy was $16,000. This makes it an effective economic alternative to the construction and maintenance of on-site storage lagoons, which has to factor in substantial expenses such as labor, travel and fuel as well as charges related to the amount of soil excavated and the volume of manure pumped for application purposes.

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Author Contributions

James M. Burke: Report writing and preparation, data management, statistical analysis, graphic creation. Mike B. Daniels: Contributing text and edits. Pearl Webb: Contributing text, edits, and graphics. Andrew N. Sharpley: Contributing text and edits. Timothy Glover: On-site maintenance and sample collection. Lawrence G. Berry: Graphic creation and GIS contributions. Karl W. VanDevender: Contributing text and edits. Stan Rose: Project design implementation and technical input.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

Abbreviations used throughout this report with definitions provided.

Abbreviation	Definition
ADEQ	Arkansas Department of Environmental Quality
ADF	Arkansas Discovery Farms
AES	Agricultural Extension Service
GIS	Geographical Information Systems
ICAP	Inductively Coupled Plasma-Atomic Emissions Spectrometer
LIDAR	Light Detection and Ranging
MCWW	Milk Center Wash Water Treatment System
NMP	Nutrient Management Plan
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
STP	Soil-Test Phosphorus