Manure Nutrient Recovery, Removal, and Reuse on California Dairies

October 15, 2022 (Updated on May 2025)

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Acknowledgments

This research was funded based on a grant from the California Department of Food and Agriculture, focused on dairy manure management for methane and surplus nutrient reduction (Agreement #: 19-0284).

Several people contributed information and advice, and/or helped review earlier versions of this report. In particular J.P. Cativiela, head of the Central Valley Dairy Representative Monitoring Program, provided data collected for that program for use in this report. He consulted frequently about technical and policy issues from the perspective of that organization and helped review portions of this draft report. Till Angermann, from Luhdorff and Scalamini, an engineering and consultancy firm in Woodland, California, and a technical advisor to the CVDRMP, helped with data, advice and technical review; Paul Sousa, of Western United Dairies, Denise Mullinax of the California Dairy Research Foundation; and Jim Wallace, formally with Newtrient, Inc, and now a private consultant (Wallace Consulting) all reviewed portions of the of the report and provided advice during its writing. Additional advice and/or reviews were provided by Dr. Peter Robinson, Extension Dairy Nutritionist in the Department of Animal Science at UC Davis, Nathan Heeringa of Innovative Ag Services, and Gene Aksland, of Agronomic Services in Visalia, CA. Several dairy farmer members of the executive committee of the CVDRMP meet with us to discuss current and future nutrient management technologies that might be adopted on dairy farms and possible constraints. Sabina Dore helped with technical editing and provided reading. Dairy farming and manure management are complicated topics with a long history of technical evolution, monitoring and research. We are grateful to all those mentioned here who helped with this report. Any errors or omissions are the authors'.

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List of abbreviated terms

Abbreviation	Description
AMMP	Alternative Manure Management Program
AR	Application Ratio
BPTC	Best practicable treatment or control
CAWQCB	California Water Quality Control Board
CDFA	California Department of Food and Agriculture
CVDRMP	Central Valley Dairy Representative Monitoring Program
Cwt	Hundred weight
DAF	Dissolved Air Flotation
DDRDP	Dairy Digester Research and Development Program
GHGs	Green House Gases
GNLM	Groundwater Nitrogen Leaching Model
LCA	Life Cycle Assessment
LM	Liquid manure
MNAA	manure N available for field application
MRIP	Manure Recycling and Innovative Products Taskforce
MVR	Mechanical Vapor Compression
NDN	Nitrification/denitrification
NMP	Nutrient management Plan
NMZ	Nutrient Management zone
NSJV	Northern San Joaquin Valley
NUE	Nitrogen Use Efficiency
SGMA	Sustainable Groundwater Management Act
SISC	Sustainability Index for Specialty Crops
SJV	San Joaquin Valley
SM	Solid Manure
SPARS-LCA	Scalable, Process-based, Agronomic-Responsive Cropping System Life Cycle Assessment model

SNMP	soil N management plans
SR	Stocking Rates
SRMR	Summary Representative Monitoring Report
SSJV	Southern San Joaquin Valley
WDR	Water Discharge Regulations

Overview

Introduction

California is home to the largest dairy herd in the US and milk production is the leading agricultural commodity in the state (Njuki, 2022; Matthews and Sumner, 2019). Dairy farmers in the Central Valley produce nearly 20% of the nation's milk supply with related benefits to consumers in the state, nationally and internationally. Milk production has remained largely constant despite a slow decline in the number of cows and dairies in the state (Matthews and Sumner, 2019). In 2018, the dairy industry supported approximately 180,000 jobs considering the direct and indirect employment effects, $22B in gross state product sales and $58B in total when including the full effects of sales and related marketing activities (Matthews and Sumner, 2019). Most direct employment effects are in the Central Valley of California, a region that includes many counties with the highest overall poverty ratings in the state according to the US Census Bureau[1], and correspondingly with the largest need for jobs.

Although farms vary, many California dairy operations are highly efficient and produce safe, affordable milk and other dairy products, and large amounts of beef and other valuable by-products. Fig 1.0 summarizes milk production from Central Valley dairies, where most milk in California is produced. About half of milk production occurs on dairies with approximately 2000 cows or less, and half on dairies with larger numbers of cows. The state's dairies are among the most efficient in the world, with correspondingly favorable greenhouse gas (GHG) emissions for dairy foods and by-products[2]. These characteristics make California dairy products beneficial from a climate mitigation perspective. Dairy consumption continues to increase worldwide, so dairies in California are important both quantitatively and as examples of efficient dairy production.

[1] https://www.indexmundi.com/facts/united-states/quick-facts/california/percent-of-people-of-all-ages-in-poverty#map

[2] https://clear.ucdavis.edu/explainers/how-dairy-milk-has-improved-its-environmental-and-climate-impact

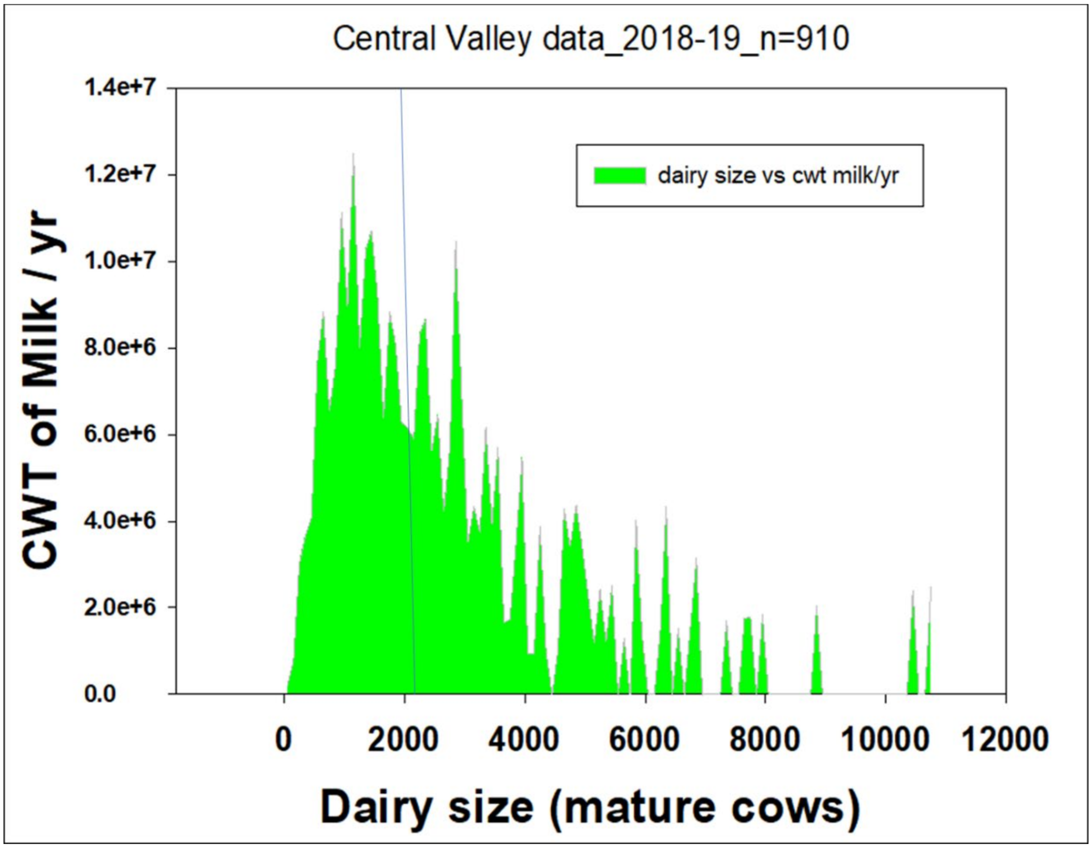

Figure 1.0. Cumulative estimated milk production on Central Valley dairies in California by farm size in cow numbers. Data (2018-2019) from reports to the Central Valley Water Quality Control Board assembled by the Central Valley Dairy Representative Monitoring Program. This data has been used in the remainder of this report. (CWT = hundredweights)

Dairy operations also produce large amounts of manure which have valuable soil amendment properties and contain nutrients needed as fertilizer for crops grown on the farm. Additional nutrients are added to the manure collected on farms in the form of by-products and grains purchased off the farm and fed to cattle to optimize their diets. All livestock feeding operations characteristically concentrate nutrients in this way. But due to economic pressures resulting from the price of milk, prices in other commodity markets, changes in technology, increasing productivity of cows, and improved understanding of livestock feeding and management, most dairy farms have been compelled to increase their herd sizes to remain economically viable. All these changes taken together increase overall productivity, with improvements being largest for larger dairy herds (Njuki, 2022). As herd size increases relative to the land available for manure application on dairy farms, nutrients like nitrogen and phosphorus (N and P) accumulate in large amounts. In turn, this can lead to groundwater pollution problems and other undesirable emissions, creating a conundrum for dairy producers and society as a whole: Intensification sustains farms economically and can improve (reduce) some of the climate effects of dairy farming, but results in increasing amounts of nutrients to be managed on the farm.

Manure management is linked to crop production and crop production is linked to water available for irrigation. As cow numbers increase in relation to land receiving manure, more manure nutrients may be produced than can be recovered by crops on some dairy farms. Beneficial application rates of manure are linked to crop nutrient requirements and crop uptake and removal. Without water for irrigation, fewer crops or crops with lower yields and less N recovery will be produced, increasing problems related to surplus nutrient management. Evolving restrictions on groundwater pumping and a lack of alternative sources of irrigation water under the Sustainable Groundwater Management Act (SGMA[3]) will intensify this problem.

Reuse of a portion of the manure produced, or the nutrients contained in manures, on non-dairy farms as a substitute for commercial fertilizers can produce additional opportunities for dairy operators to generate useful products. Reuse can convert a waste and source of pollution into an asset, with additional potential benefits for climate. An example is the capturing of fugitive methane (CH_4) emissions from manure storage on dairy farms (a short-lived climate pollutant) and its use as transportation fuel (a climate asset) through the state's Dairy Digester Research and Program[4]. Using surplus nutrients offsite will reduce problems with nitrate loss to groundwater on dairy farms and substitute for commercial fertilizer use elsewhere.

Manure management is a complex, demanding and often labor-intensive task on all dairy farms. This complexity constrains solutions to managing surplus manure nutrients. A mature, large breed dairy cow sheds approximately 150 pounds of solid manure and urine per day or more, depending on cow size, breed and diet. This quantity of manure contains approximately 1 pound of nitrogen (N) (ASAE, 2005). Given the large amount of material, modern dairies are designed to minimize the labor and costs of managing manure. Manure is managed variously among farms, and even within an individual farm. Most dairies have some portion of manure managed using water to flush concrete surfaces in barns and feeding areas, and some manure falls in corrals and pens (Miller et al., 2017, Meyer et al., 2019). Additionally, manure is biologically dynamic and undergoes constant transformations based on the character of the manure, temperature, handling and storage (Task 1, Fig. 1.2). In turn, all these factors affect its value as a fertilizer for crops and the way it can be distributed across the landscape. The co-location of many dairies near each other also limits potential markets for solid or composted dairy manure or manure products on neighboring farms, requiring distribution over greater distances. Maintaining the benefits of an efficient dairy sector while reducing problems associated with surplus nutrient accumulation is thus a significant challenge.

Goals of this Report.

This report focuses on new developments in the field of dairy manure management, specifically the treatment of manures to recover nutrients for use on non-dairy farms as substitutes for existing conventional fertilizers. With supportive policies, new methods for manure management could contribute to establishing a circular biomass economy for recycled primary fertilizer nutrients and organic amendments that more closely integrate California's dairy and non-dairy agricultural sectors, while reducing GHGs and other emissions from both dairies and agriculture as a whole. The California Department of Food and Agriculture's (CDFA) Dairy Digester Research and Development Program already links methane production and recovery on dairies to the creation of bio-based electricity and ultralow

[3] https://water.ca.gov/programs/groundwater-management/sgma-groundwater-management
[4] https://www.cdfa.ca.gov/oefi/ddrdp/

GHG transportation fuels[5]. CDFA's Alternative Manure Management Program (AMMP[6]) supports measures which reduce the amount of manure collected from concrete and stored in dairy lagoons, the source of most methane (CH_4) from manure storage. Outcomes from these programs include reduction of GHG emissions and other co-benefits such as odor reduction and production of useful, low carbon renewable natural gas (RNG). Similarly, prudently designed and implemented programs may support more effective and efficient use of manure nutrients as well, transforming surplus nutrients from a pollution problem into a source of environmental benefits.

The overall goals of this report are (1) to provide an overview of the amount and location of surplus nutrients within the dairy sector, and (2) to evaluate selected manure treatment technologies capable of recovering manure nutrients in useful form or otherwise reducing surpluses safely. Because of time and resource constraints, this analysis focused on dairies within the priority 1 Nitrogen Management Zones (NMZs) as defined within the state's Central Valley Salts and Nitrates Program[7] (Task 1: Fig 1.1). These zones include a majority of the state's commercial dairies and have the most urgent need for improved manure nutrient management.

There are seven specific tasks that serve as an outline for this report (Table 1). They were chosen in consultation with CDFA staff to provide an overview of the most important considerations affecting potential changes in dairy manure management. Since the timeline for the creation of this report was limited to a six-month period, open questions remain associated with each task. It was our goal, given the time limitations, to provide an initial assessment of the subject matter and data available in each area, and to point to the need for further refinement or research where that seems necessary. Nitrogen is identified specifically because state policy is focused on groundwater pollution by nitrates, especially in the San Joaquin Valley (SJV) where most dairy farms are located. Assessing, remediating, and reducing the effects of current farming practices, including dairy farm manure management and cropping practices, on groundwater pollution with nitrates is an important state priority.[8] The methods used in this report can be applied, with appropriate modification, to formal comparisons of different technologies that will be useful if the state adopts policies to improve nutrient management and creates competitive programs similar to its DDRDP and AMMP programs to support technology adoption. These programs use quantification tools to compare the overall merit of competing proposals.

Topics for additional research and development are incorporated at the end of each task. Suggestions for quantitative assessment of technologies are embedded in the tasks that focused on engineering issues and costs, fertilizer equivalency of new manure products, and life cycle assessment.

This report supports a recent effort initiated by Secretary Karen Ross of the California Department of Food and Agriculture who appointed a technical advisory committee called the Manure Recycling and Innovation Products Taskforce (MRIP)[9] to focus on surplus nutrient accumulation on dairies and the management and beneficial use of those surpluses. The MRIP taskforce provided policy focused recommendations to guide future policy development at the state level. There was close collaboration between these two efforts with this report providing preliminary technical background to potential policy

[5] https://asmith.ucdavis.edu/news/cow-power-rising
[6] https://www.cdfa.ca.gov/oefi/AMMP/
[7] https://www.cvsalinity.org/nitrate-program/
[8] https://www.cvsalinity.org/nitrate-control-program.html
[9] MRIP: **M**anure **R**ecycling and **I**nnovative **P**roducts Taskforce.

recommendations proposed by the MRIP committee. There was some unavoidable overlap of effort between both groups, however, and a number of recommendations are similar, while some differ.

Table 1. Manure nitrogen recovery removal and reuse: Tasks	
1.	Estimate amount of surplus manure nutrients, type, and location.
2.	Review, analyze and compare selected existing and potential systems for nutrient recovery and reuse.
3.	Identify the effects on dairy farms and dairy farm management of surplus nutrient removal.
4.	Estimate the potential fertilization value, crop use, and effects on soil organic matter of existing and potential manure products.
5.	Evaluate the greenhouse gas effects (via Life Cycle Analysis) of selected manure nutrient recovery and reuse systems.
6.	Suggests methods for quantitative comparison of different nutrient recovery and reuse systems.
7.	Identify requirements for additional research to address uncertainties or better quantify key elements of nutrient recovery and reuse systems.

Results are summarized in the final section of this report.

References Overview

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TASK 1:

Estimate the amount of surplus manure nutrients, types, and locations

The focus of this task is estimating manure nutrient surpluses (especially N and P) on dairy farms located within the six high priority Nutrient Management Zones (NMZ) in the San Joaquin Valley. These zones contain the majority of the state's commercial dairy farms. Surpluses are amounts of manure N and P in excess of permitted rates of nutrient application. These rates are based on estimated crop uptake and removal, after accounting for volatilization and other losses from the amounts of manure nutrients deposited on farms. Both traditional and new technologies for recovering, removing and reusing surplus manure nutrients are considered as pathways for reducing the adverse effects of surplus manure nutrient accumulation on dairy farms. Surpluses vary by farm and location. Stocking rates, calculated from the reported numbers of cows per farm (milking cows + replacements) and the reported amount of land receiving manure on each farm were used to estimate amounts of surplus manure nutrients by farm and NMZ. This information is necessary to estimate the amounts of nutrients and types of manure that are surplus to crop needs. These amounts potentially are available for manure nutrient recovery, removal and reuse, and are needed to identify the likely technologies needed for this purpose.

1.1 Current data on California dairy farms including location, cow numbers, land available for manure application, and manure management systems in use.

Dairy farmers are required to report yearly manure and fertilizer application to farmland used for feeds produced on their farms based on waste discharge regulations (WDR). Reports are part of required nutrient management plans (NMPs). Farmers must monitor the ratio between manure N applied to crops and manure N removed. The WDR restricts N-application to 140% of the N harvested in each crop (an Application Ratio (AR) of 1.4)[10]. N application beyond the regulatory limit may result in groundwater nitrate (NO_3) loads that exceed the drinking water limit of 10 ppm NO_3-N per liter (Miller et al., 2017; Harter et al., 2017; Parsons and Harter, 2018). Compliance requires data collection at the farm and field level, including cow populations, crop production, land available for manure application, and application rates to individual fields. Nitrogen in manure in excess of 1.4 times crop uptake and removal is surplus and potentially available for export off farm, depending on its form and manure treatment practices.

These guidelines are broad and do not account for specific factors that influence the transformation of manure N applied to fields, such as the character of the manure applied, season, soil type, physical and chemical characteristics and their variation at the field level, crop type and weather. Rather, the assumption of a 1.4 AR was thought to be sufficiently conservative with respect to the potential for nutrient loss to groundwater to provide a margin of safety (Chang et al. 2006) and is considered the most pragmatic approach to dairy manure nutrient management (Burt et al., 2014).

[10] (R5-2013-0122, 2013). This ratio is assumed to remove at least 71% of applied manure N.

1.1.1 CV Salts and Nitrate Programs and Nitrogen Management Zones (NMZs).

The Regional Water Quality Control Board (CVRWQCB) has adopted revisions to its Water Quality Control Plans to include salt and nitrate management programs throughout the Central Valley. Best efforts must now be made to reduce emissions to ground water. The need for a balance between maintaining the economic viability of farms in the Central Valley and protecting groundwater resources is articulated, but the characteristics of this balance are not defined. The lack of definition allows for solutions to manure management problems and corresponding changes in dairy farm management to evolve (Cativiela et al., 2019).

The State Water Quality Control Board has a salinity and nitrate management program (referred to as CV Salts**)**[11] that focuses on reducing salt and nitrate loading to soils and groundwater in the Central Valley. The program regulates all sources of salt and nitrate loading to groundwater. The nitrate control program has three goals: 1. Provide safe drinking water supplies to rural users dependent on ground water wells that might exceed public health limits for nitrates, 2. Reduce nitrate contamination of groundwater supplies over time (or replace them where this is infeasible), and 3. Restore groundwater quality, where reasonable and feasible. The terms r*easonable* and *feasible* allow the CVRWQCB time and flexibility to support gradual improvements in groundwater management over time. The high priority regions, known as Nitrogen Management Zones or NMZs, are watersheds or geographic regions where immediate organization and action are required to address groundwater NO_3-N pollution. These coincide with areas with the largest concentrations of dairy farms, though dairies are not the only sources of excess nitrates in groundwater wells (Harter et al., 2017).

"Best efforts" by dairy farmers are required or will be required to develop soil N management plans (SNMPs) that will allow them, over time, to achieve regulatory compliance with groundwater nitrate standards while remaining in business. Potential practices are referred to as Best Practicable Treatment or Control (BPTC) measures, however they are not defined in the regulation[12]. Local adaptation is a feature of this approach, as is adoption of appropriate technologies that address nutrient management and improved irrigation practices as they become available (CVRWQCB, 2017).

1.1.2 Characteristics of dairy farms by nitrate management zones.

Nitrogen management zones were formed to allow water users and affected parties to self-organize to address nitrate pollution of groundwater. Districts roughly follow watershed boundaries, called groundwater basins (Fig. 1.1). These basins are ordered by the severity of nitrate contamination of wells in a basin and given a priority associated with regulatory timelines. The majority of priority 1 and 2 NMZs are in the San Joaquin Valley and includes dairy farms.

[11] https://www.cvsalinity.org/public-info

[12] The term BPTC is not defined in the Water Code or in the Policy, however, the State Water Resources Control Board has stated that one factor to be considered is the water quality achieved by other similarly situated dischargers, and the methods used to achieve that water quality. (See Order WQ 2000-07, at pp. 10-11.) The State Water Board has further interpreted BPTC to include, "[a] comparison of the proposed method to existing proven technology; evaluation of performance data (through treatability studies); comparison of alternative methods of treatment or control, and consideration of methods currently used by the discharger or similarly situated dischargers."… Further, the term "practicable" means that the Regional Board must consider costs associated with the treatment or control measures when prescribing requirements. Cativiela et al., 2019_SRMR (2019), pg 23-24.

In response to new regulatory requirements to provide alternative sources of water to communities and individuals affected by nitrate pollution of their wells, the Central Valley Dairy Representative Monitoring Program (CVDRMP) organized a data collection and assessment effort aimed at apportioning costs for water replacement within the NMZs on the part of dairy producers. This program allows the dairy industry time to better address the regional board's regulatory objectives to protect groundwater.

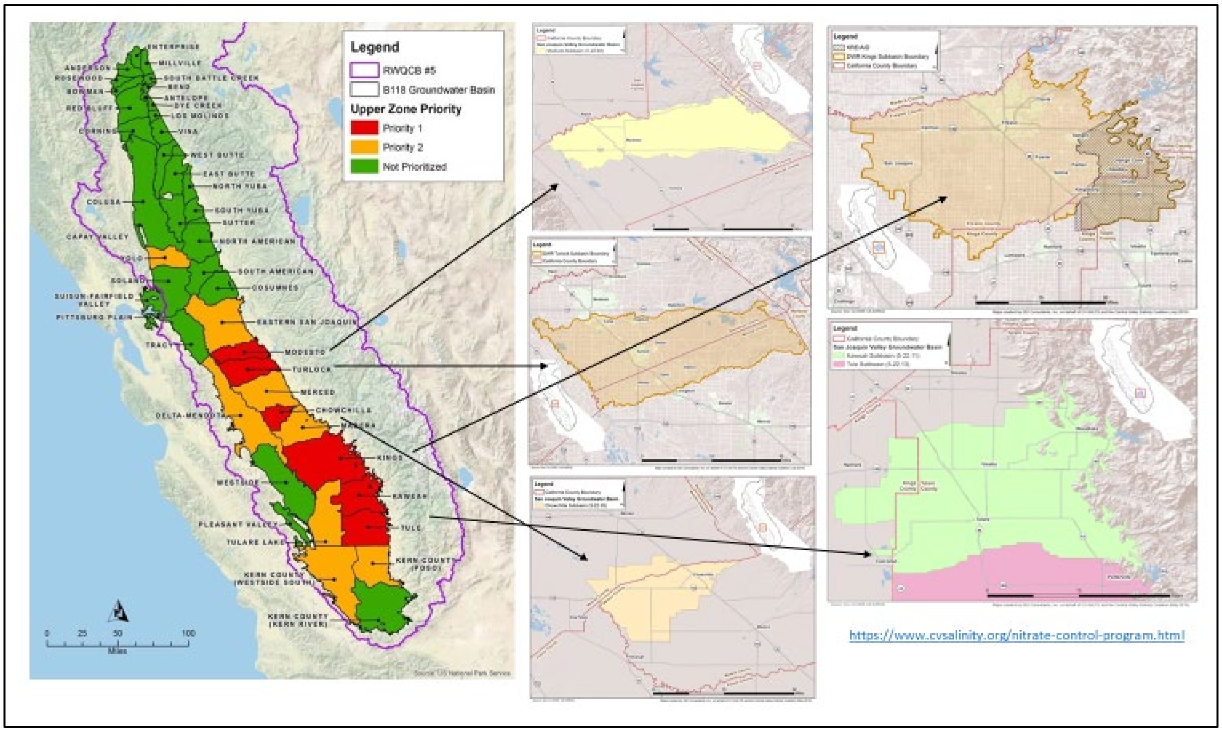


Figure 1.1. Nitrogen Management Zones and groundwater sub-basins.

1.2 Data quality and uncertainty

In estimating the amount, location, and timing of surplus nutrient accumulations on the state's dairy farms, and to create programs and policies that help address this issue, it is important to consider the amount of error in surplus nutrient estimates. Especially when substantive changes in management may be required or expensive investments in new treatment technologies must be made, accuracy in estimating surpluses is required. There are many sources of uncertainty when estimating manure nutrient surpluses on farms. These include the nature of manure itself, variations in management within and among farms, and practical limits on measurement of the quantity of manure nutrients collected and applied. These limitations must be considered when addressing pathways and policies for improved management of manure nutrients.

Estimating the nutrient content of manure is difficult because manure is not biologically or chemically stable. It is a living, dynamic material and continuously undergoes transformations depending on the character of the material and the conditions under which it is collected, stored, managed and applied. Practices designed to reduce emissions of one form of N may result in emissions of another form (Fig. 1.2).

Nutrient contents in fresh manure are affected by the diets fed to cattle, breeds of cattle, and classes of cattle from which it is collected (ASAE, 2005). Once excreted, subsequent management of the manure affects the amount and form of nutrients conserved, most especially N, which occurs in diverse forms: as organically bound N containing compounds, in soluble forms of N, (NO_3-N and NH_4-N) and as gaseous losses (NH_3, N_2O, NO_x, N_2). The proportions of manure N in each category also are affected by where it is excreted (in corrals, on pastures or on concrete surfaces in barns and feeding areas), how it is subsequently collected and stored, and temperature, aeration, and manure moisture content during collection and storage. Some N in manure occurs or is transformed into volatile forms that are subject to loss to the atmosphere during collection and storage. NH_3 and N_2O may be lost directly to the atmosphere, as well as unreactive N_2 (Fig. 1.2). Rotz et al (2021) calculate that NH_3 losses to the atmosphere are the major pathway for N losses from dairies in the southwestern USA.

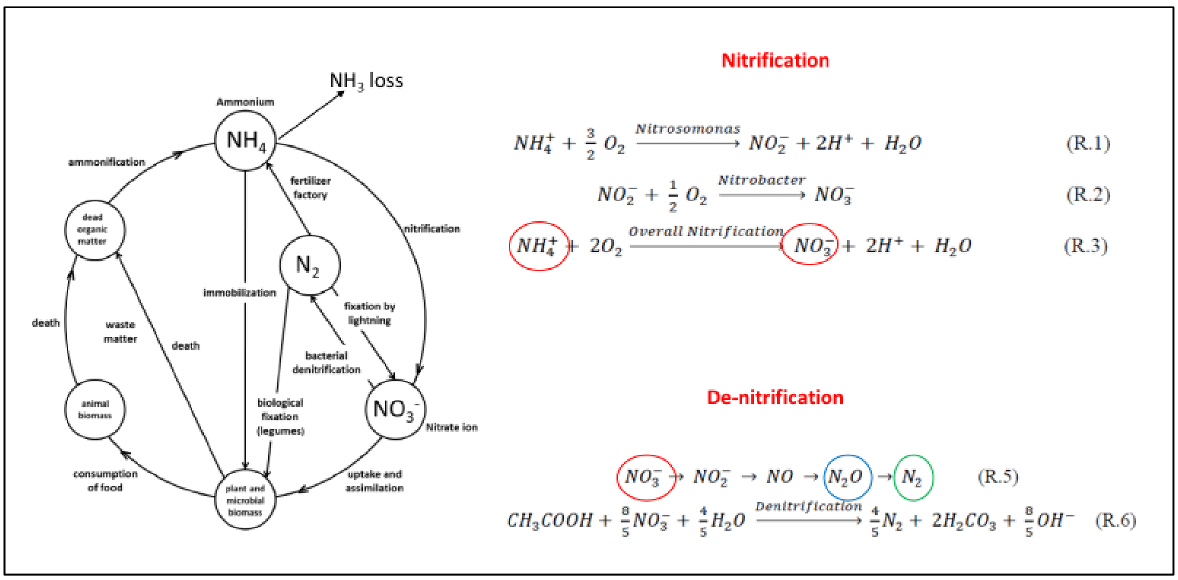


Figure 1.2. Nitrogen transformation processes in manure, composts, and soils. Adapted from Viers et al. (2014) and other sources.

Because of this dynamic character and for other reasons related to management, errors are unavoidable when accounting for manure nutrient amounts, application rates, and other effects of manure management. For larger scale calculations, average values have to be used.

Knowing what level of error is associated with an estimate affects its usefulness for guiding farm management practices, evaluating the potential value of alternative manure management systems for individual dairies, or for groups of dairies, and for other purposes including policy making. It is relatively simple to determine that excess manure nutrients exist on dairy farms if large uncertainties are accepted. This conclusion is sufficiently accurate to motivate proposing changes in management and policy to support improving nutrient balances between land application and crop uptake, to reduce harmful emissions from manure management, and to redirect nutrients from dairy farms to non-dairy farms. The level of inaccuracy associated with these estimates, however, makes them insufficient to guide specific improvements at the level of an individual farm or to guide investments in expensive, more technical nutrient recovery systems.

Regulations currently require analysis of liquid manures four times per year and solid manures twice a year (Miller et al., 2017). Since diverse biological transformations of manure N occur continuously once excreted, manure analysis only provides estimates of the N content and character of manure at any point in time. There can be sampling biases when sampling large manure piles or lagoons, especially if the material is heterogenous. Even within large amounts of stored liquid or solid manure, N values among samples will vary, making representative sampling difficult and expensive. For example, Pettygrove et al. (2009) reported data on manure analyses from 11 dairies in the Central Valley from corrals, manure ponds, screened solids and composted materials. Samples varied widely within individual farms by source, and among farms. This level of variance makes quantifying actual application rates difficult, as well as integrating nutrients in manure with crop fertility requirements and uptake. Manure application rates to fields and crops are also subject to errors in estimation and unevenness when applied across the field. Consequently, crop yield and uptake also vary across a field and among different fields on a farm. A goal of the recent Summary Representative Monitoring Report (SRMR) analysis carried out by the CVDRMP is to reduce the errors associated with the estimation of solid manure materials and crop removal to approximately 10% (Cativiela et al., 2019).

The source of error affects estimates of nutrient surpluses and must be considered when evaluating policies that regulate dairy farms. They are more or less important depending on the intended use of the data collected. Oenema et al. (2003) summarized many years of research and experience in The Netherlands with farm nutrient management and accounting. Their recommendations are useful to consider for California as well. In general, they reported that nutrient budgets estimated at the farm gate (inputs and outputs) were considered much more accurate than budgets estimated from field application and crop uptake measurements. Records of sales of milk and livestock, manure or compost transported off the farm, and purchase of feeds and fertilizers typically are accurately accounted. Nutrient budgets at the farm gate can be calculated based on these data with good accuracy. Measurements within the farm boundary and for fields are less certain.

Table 1.1. Farm Level Uncertainty in Manure Management

Source	Challenges	Sources of uncertainty
Nutrient budgets	Difficult to quantify	N-fixation; gaseous losses, leaching losses, other losses
Variation in space and time	Influences of external factors like weather, irrigation water supplies, access to fields, etc.,	Collection, timing, amounts, and application rates of manures, manure characteristics and quality[1]
Seasonal or related changes	Changes common part of operating a dairy business in CA	Crop types, yields, nutrient removal, agricultural methods and technology, irrigation practices, and other management choices

Notes:
Based on Oenema et al., 2003; EurJAgron
[1] Sludges cleaned from ponds and solid manure piles may be managed and reported inconsistently and carried over across reporting years.

Predicting crop responses prior to planting or early in the season including uptake and removal of nutrients vary and can only be estimated. This affects the balance between nutrients applied and crop removal. Even these estimates can be more accurate than budgets based on calculations of soil related state variables, transformation processes and resulting emissions (Oenema et al., 2003; Burt et al., 2014; Miller et al., 2017; Cativiela et al., 2019) (Table 1.1; Fig. 1.2). Table 1.2 classifies the level of expected error associated with farm-level data characteristic of research and regulatory efforts in The Netherlands estimated over many years and many studies. This level of uncertainty caused Burt et al. (2014) in their review of manure management issues in California to focus instead on the relationship between nutrients applied to crops and crop removal (Application Ratios) and to recommend that regulatory efforts be directed at improving accuracy and efficiency for this comparatively simpler metric. Cativiela et al. (2019) supported this conclusion and the SRMR recommends improvements in the measurement and accounting of manure samples, application rates, crop yields, and crop nutrient removal estimates. They particularly mentioned difficulties in the management of liquid manures[13]. Because of the errors inherent in estimating nitrates leaching to groundwater across highly diverse farm settings and errors associated with modeling, they recommended against the use numerical estimates and generalized quantitative limits as a regulatory philosophy.

Table 1. 2. Estimated range of uncertainty for dairy manure nutrient budgeting

Level of uncertainty	Activity
< 5 %	Commercial fertilizer application rates, marketed products (milk, livestock, manure sold), purchased feeds[2,3].
5% to 20%	Atmospheric deposition[1], manure nutrient content and application rates[2,3]; irrigation amounts[3], crop yields[2,3]; (*SRMR recommended target is ≤10 % uncertainty for manure and crop samples*).
> 20%	Leaching of nutrients[4], volatilization[5], denitrification[6], immobilization[7].

Notes:
Based on Oenema et al., 2003; EurJAgron.
[1] Assumed constant (15.7 kg ha^{-1} yr^{-1}).
[2] Reported to the regional board as part of the annual WDR report. Manure excretion based on ASAE values for typical livestock class and breed. Manure nutrient content estimation errors may be > 20%.
[3] Farm records.
[4] Estimated (literature and modeling), or from studies on representative farms.
[5] Estimated as the difference between N applied to fields or exported in manure and the amount excreted (calculated), or estimated based on measurements of affected groundwater, or via modeling.
[6] Not directly accounted, quantitatively smaller in amount than other losses, but important for climate concerns. Not recommended for regulatory use in Burt et al., 2014.
[7] Assumed to be at steady state.

[13] The primary technical reason for inaccuracy of estimated reported values is the difficulty of accurately estimating individual crop field N applications, especially from liquid manure. The inaccuracies associated with inexact measurement propagate through the sum of all irrigations/fertigations per year on an average dairy and result in questionable whole-farm N balances. (from SRMR, page 32).

1.3 Other data relevant to manure surplus nutrient estimation

1.3.1 Crop nutrient uptake and removal

Crop uptake and removal of nutrients from fields is a key consideration in calculating manure nutrient surpluses. Chang et al. (2006, UC Committee of Experts) summarized earlier research and understandings about manure N management in California. Their summary included all relevant research conducted in California up until its publication and many other relevant and important references to manure composition and management from other sources. It was a primary source for state policy on the adoption of application ratios (ARs) for dairy manure management. Chang et al. (2006) proposed a range of 1.4 to 1.65 for this ratio[14]. The State Water Resources Control Board chose the lower value, adopting a conservative approach to groundwater protection.

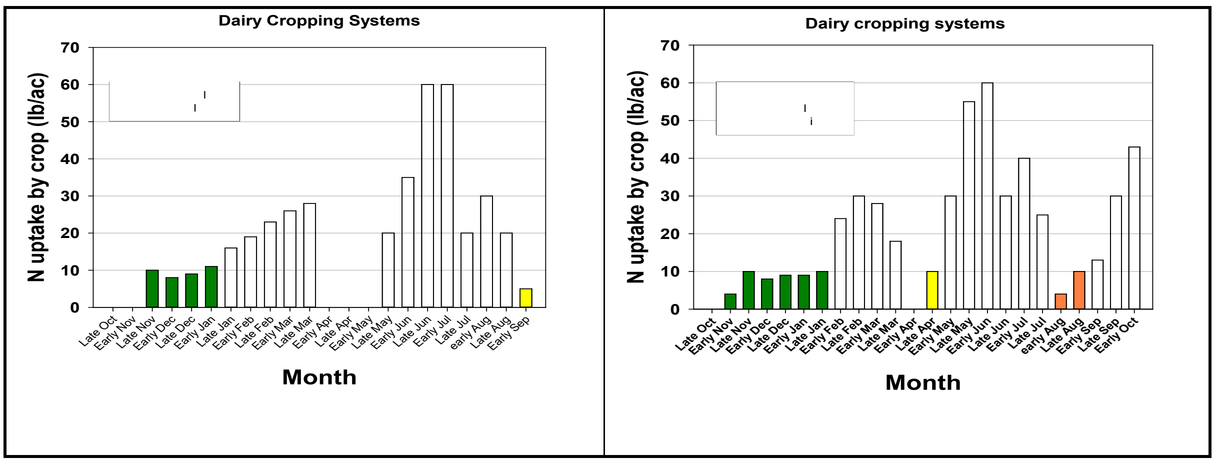


Figure 1.3. Crop N uptake by month for typical dairy cropping system (excluding alfalfa) in the San Joaquin Valley. Maximum crop uptake for a three-crop system was estimated as 500 lb N $ac^{-1}yr^{-1}$. For a two-crop system, maximum uptake was 400 lb N $ac^{-1}yr^{-1}$. At an application ratio of 1.4, 560 lbs of N as manure can be applied for a two-crop system, and approximately 700 lb N $ac^{-1}yr^{-1}$ can be applied for a three-crop system. Adapted from Chang et al. (2006), Figure 5-2. More recent crop yields and N uptake are somewhat higher.

Chang et al. (2006) published a table relating stocking rates, manure N amounts, and crop uptake (simplified and reproduced in Table 1.3). They also reported data from a limited number of farms applying both manure and fertilizer N to similar crops, noting some crop recovery values greater than 800 lbs N per acre. Higher crop yields affect the level of nutrient recovery from applied manure and increase the effective stocking rate on a farm. The relationship between crop growth and nutrient uptake for typical dairy crop production systems was reported by them as well, based on a survey of dairy farm cropping practices and yields judged to be representative for these crops (Fig. 1.3). Miller et al. (2017), using crop production data from 2012, reported similar values for corn silage nutrient uptake, but larger amounts for cereal silages (180-195 lb N ac^{-1}) than used in Chang et al, (2006).

[14] "Given that practically achievable leaching fractions in border check and furrow systems are 15 to 30%, nitrate leaching is at best in the range of 10% to 15% of the N applied. Based on the above-described (nutrient uptake estimates) of 140 to 165% of N removal at harvest, at annual crop yields that typically remove 400 – 600 lbs N ac^{-1} yr^{-1}, input requirements will be in the range of 560-990 lbs N ac^{-1} yr^{-1}. " Page 9 Chang et al., 2006.

Table 1.3. Dairy manure nutrient budgeting (Chang et al., 2006)					
N uptake:	**270**	**360**	**450**	**540**	**630**
N excreted[1] and applied (lb yr^{-1})	480	640	800	964	1130
Salt excreted[2] and applied (lb yr^{-1})	620	810	1020	1220	1430
Stocking rate (cows ac^{-1})	1.4	1.9	2.4	2.8	3.3

Notes:
Adapted from Chang et al., 2006, Table 7.1.
[1]N excreted = total N in manure from # of cows that can be applied to sustain a 1.4 ratio. Assumes that manure is applied as lagoon water (LM) with 75% NH4-N.
[2]Salt excreted = Na^{+} + K^{+} + Cl^{+}
Values are rounded.

Harter et al. (2017, 2012) Parsons and Harter (2018), Rosenstock et al., (2012), and Viers et al. (2012) carried out a series of comprehensive assessments of N use on farms, businesses, septic systems, and urban areas and estimated the potential for groundwater contamination from N from all these sources. They relied on data reported to the regional board by farmers and used a mass balance approach to estimate the amount of N available in manures and fertilizers, deposition or application rates in corrals, lagoons, and croplands, and estimated leaching rates and losses. They concluded that for the San Joaquin Valley, in areas with large numbers of dairy farms, an unmet challenge was to make more efficient use of nutrients on dairy farms from both manure and supplemental fertilizer use. They noted that it is more difficult to apply enough available nutrients (especially N) to crops like corn silage from manure at the maximum AR ratio allowed by regulation because a proportion of N in manure is organically bound. Organic N must subsequently mineralize to a plant available form at rates dependent on temperature and moisture and the characteristics of the manure itself (Pratt et al., 1973)[15]. How this occurs depends in part on whether liquid or solid manures are applied. The organic N fraction in manures also persists over time and can contribute N to subsequent years' crops, especially following repeated applications of manure over many years (ibid). But manure applications typically are accounted only annually.

Nitrogen derived from manure might not meet crop needs, especially for a crop like corn silage, which has a short period of time when large amounts of plant available N are required for economically viable yields. Lagoon water has larger amounts of soluble ammonia that can be readily available to crops compared with solid manures. But irrigation and blending can be non-uniform when surface irrigation is used to

[15] Pratt et al. (1973) presented an approach for calculating the annual rates of N mineralization expressed as a series of fractional proportions of any given application of manure, referred to as a decay series. For fresh bovine manure with 3.5% N dry weight, they used a 0.75, 0.15, 0.10, 0.05 decay series, meaning that if 100 kg of organic N were applied in this form, 75% of the N would be mineralized the first year (75 kg); 15% of the remaining 25 kg would mineralize the second year (4 kg); 10% of the remaining 21 kg would mineralize the third year (2 kg); and so on. Subsequent releases will be negligible. The amount of N available in the first year is much larger because it includes the N already in mineral form and organic N that is readily mineralizable. Much less N would mineralize the first year if the manure had been exposed over time to the weather while deposited and dried outdoors before collection for disposal. Consequently, the total N content of the dried and weathered dairy manure can be considerably lower than liquid manure collected from concrete.

apply lagoon water (the most common method), and is less efficient than fertilizer N. This can lead to spatially variable losses to the atmosphere and to groundwater and uneven crop yields within the field (Matthews, 2004). The fibrous material in manure inhibits the use of inherently more efficient forms of irrigation like sprinklers and drip systems. Consequently, it was and remains common practice to supplement manure applications with mineral fertilizers, adding to overall N loading rates and reducing apparent crop recovery of N on dairies to levels lower than those reported for fertilizer-based cropping systems in general (Table 1.4). In using ARs, accounting is carried out on an annual basis, and residual amounts of N available from prior year's manure applications are discounted. This contributes to nitrate losses from dairies, but losses are uncertain and difficult to account accurately (Oenema et al., 2003; Burt et al., 2014). Parsons and Harter (2018; Table 1.4) and Cativiela et al. (2019)[16], estimated that the majority of N appearing in groundwater on dairy farms resulted from manure application to croplands, and that losses from corrals and manure storage ponds were quantitatively much less important. This was the key to improving the N management of crops.

Table 1.4. Reported loading rates to San Joaquin Valley lands on dairies and dairy cropland

Location	*area (ac)*	*Total N (ton yr^{-1})*	*Total N (lb ac^{-1} yr^{-1})*	*Proportion (%)*
Corrals				
NSJV	10,000	1,000	200	
SSJV	19,000	2,000	160	
Ave/Sum	29,000	2,500	185	1.3
Lagoons				
NSJV	2,750	1,435	1,040	
SSJV	3,020	1,575	2,000	
Ave/Sum	5,770	3,010	1,040	1.5
Irrigated Crop Land				
NSJV	136,500	77,240	1,130	
SSJV	278,800	108,730	780	
Ave/Sum	429,400	192,050	895	97.2
N Use Efficiency (NUE) %				
NSJV			42	
SSJV			41	

Notes:
Based on Harter et al., (2017). Tables 11.10, 11.11, 11.14 and 11.16, on data from 2005, 2007, 2009 and 2010.
NSJV: Northern San Joaquin Valley, Contra Cost, Madera, Merced and San Joaquin counties.
SSJV: Southern San Joaquin Valley, Fresno, Kern, Kings and Tulare counties.
Manure amounts account for mature cows + replacements after volatilization losses. Based on Pettygrove et al. 2010.
NUE includes reported fertilizer use and applied manure N (2005 data).
All values in the table are rounded.

[16] In the SRMR, the amount of N surplus occurring in field application was estimated slightly lower, at 94%.

1.3.2 Previous estimates of manure nitrogen surpluses.

There have been several estimates of dairy manure nutrient surpluses since Chang et al., 2006. These have relied for the most part on data on manure production, application, and crop removal at the farm level reported annually to the CVRWQCB. All these analyses agree that reported amounts of nutrient application and crop removal underestimate actual amounts of nutrients present in the state's dairy systems, and that data are inconsistent (Cohen-Davidyan et al., 2019; Parsons and Harter, 2018). Various methods were used, resulting in estimates of large amounts of unaccounted N in manures, but all are affected by data quality problems and other sources of uncertainty. They are important however because even if uncertain, they identify large amounts of manure N that are in surplus on dairy farms in the central valley.

Miller et al. (2017) performed a mass balance analysis of nutrients, including N, on 62 Central Valley dairies over a three-year period (2011-2013). They provided data and estimates of manure deposition and management systems based on surveys of data reported to the CVRWQCB by the dairy farms selected, which were considered representative of large numbers of dairies in the San Joaquin Valley (SJV). Data included cow numbers and breed, livestock classes on the farm, average daily milk production, crops grown, and crop acreages. They estimated excretion rates in manure based on standard values. The data were compiled from annual reports that these dairies submitted to the regional board from 2012-2014.

Data were compared to calculations of N amounts present on dairy farms. They employed two methods to estimate N volatilization rates. Method A used N:P ratios in both fresh and aged manure. This method indicated mean and median N volatilization rates of 21% and 35%, respectively. The median value calculated lies on the upper end of the range (20–35%) reported by Chang et al. (2006), who employed the same method based on data from a group of 20 free stall-flush dairies in Merced County. Nitrogen volatilization tends to be greater from open lot systems than from free stall-flush systems. Therefore, the relatively high median value reported by Miller et al. (2017) is consistent with the fact that their data set included many dairies located farther south of Merced County in the southern San Joaquin Valley, where open lot dairies are more common, and less manure falls on concrete.

Method B computed apparent atmospheric N losses as the difference between excreted N and the sum of exported N and N applied to cropland reported by the farms. This method indicated mean and median N volatilization rates of 58% and 69%, respectively, compared with amounts of manure excreted. Based on the differences between these methods, the authors concluded that the magnitude of the implied N volatilization amounts reported by farmers within the framework of the current regulatory scheme were inconsistent with known loss pathways. Reported N volatilization rates (losses) from many manure management systems appeared higher than biologically reasonable. Inconsistencies were attributed to inadequate sampling and analysis of manure, inaccurate measurement of application rates and crop yields, and reporting errors.

Harter et al. (2017 and previous studies) estimated the annual N excretion of the total Central Valley dairy herd to be 385,875 tons of N based on a dairy herd of 1,768,577 milk cows, based on 2005 data. After subtraction of 30% N volatilization, this yields 270,110 tons of Manure N Available for field Application (MNAA). Adjusting for reported manure exports, they estimated that 41% of manure N was unaccounted, or excess. This equated to 110,750 tons (Fig.1.4). Supporting this conclusion was the development of a Groundwater Nitrogen Leaching Model (GNLM) used to estimate potential N losses from fertilizer use and manure applications in the Central Valley. Use of the model resulted in an estimated rate of loss of fertilizer equivalent N from all sources of 67%, with forage crops on dairies accounting for approximately 40% of all potential losses in 2005. Nitrogen use efficiency (NUE) was reported to be lower on dairies (Table 1.4) than in other farming sectors, approximately 40 % compared to 50 to 60 % or greater. They also identified that most potential losses to groundwater in dairy farming systems occurred via manure application to crop land. Low or declining NUE contributes to the problem of N losses. They also estimated that N loading rates had increased with time reflecting increases in cow numbers and other changes in dairy management including feeding practices, and that NUE had declined with time.

The most comprehensive compilation of N balance data on Central Valley dairies to date was carried out by Parsons (2018). This analysis relied on data reported by farms to the CVRWQCB from 2007 to 2014, a total of 9,066 annual reports. Based on data quality analyses, data from three of the years (2007, 2008, and 2010) were regarded as compromised. Data from the years judged to be of sufficient quality (n=5,727) indicated a mean implicitly reported atmospheric N loss rate of 59%.

Based on detailed accounting of crop uptake for a range of crops receiving or potentially receiving manure N, they reported an average of approximately 500 lb N per acre per year of unaccounted manure N across all dairies. They attributed this large estimate to potentially higher rates of atmospheric losses of N (primarily as ammonia) than the 30 to 38% cited in most reports, potential long-term storage in the vadose zone on farms, leaching to groundwater, and reporting errors.

Cativiela et al. (2019) recently summarized multiple years of ground water studies on representative dairies in the San Joaquin Valley supported by the Central Valley Dairy Representative Monitoring Program. The Summary Representative Monitoring Program (SRMR) summarized the results of measured manure retention pond seepage rates, soil and water impacts from cattle housing, nutrient use efficiency for on-farm forage crops, and other features of manure management on dairies. They reviewed reported values from representative farms and, consistent with other studies reported here, stated that annual reports to the CVRWQCB suggested that substantial amounts of unaccounted manure N exist on many dairies[17]. They referred to this quantity not as surplus N but as "unaccounted-for" N or "excess" N. The concept of excess N explicitly addresses the regulatory assumption of a constant or standard N volatilization rate of 30%, which was adopted by regulators based on the work of Chang et al. (2006). Specifically, 70% of excreted N was regarded as Manure Nitrogen Available for Application (MNAA). Excess N is then calculated as the difference between MNAA and the sum of reported applied N and exported N. Using this approach and relying on reported N balance data, the CVDRMP reviewed more recent annual reports (2014-2016) from those participating member dairies monitored using the online Merced County regulatory reporting tool (Cativiela et al. 2019). This group of 36 dairies is a subset of dairies that were investigated by Miller et al. (2017). The annual reports indicated that 59% of MNAA were applied to land and exported, while 41% of MNAA remained unaccounted for. Expressed differently (as a proportion to excreted N, i.e., not MNAA) to provide a direct comparison to the results of Miller et al. (2017), calculations yielded an implicitly reported median N volatilization rate of 58%. Parsons' results were remarkably similar. Expressed on the basis of MNAA, the data used for this comprehensive effort resulted

[17] "The primary technical reason for this is the difficulty of accurately estimating individual crop field N applications from liquid manure. The inaccuracies propagate through the sum of hundreds of irrigations/fertigations per year on an average dairy and result in questionable whole-farm N balances that are unreliable." SRMR, Page 31; "…most reported AR ratios do not represent true, field-scale conditions but rather they are estimates based on averaging or other allocation schemes." Page 38.

in estimates of the same proportion of unaccounted-for N as CVDRMP (2019), i.e., 41% (Fig 1.4). This equates to 81,855 tons for reporting years 2009, and 2011-2014, for all dairies in the Central Valley.

Rotz et al. (2021) carried out a detailed, cradle-to-farm gate environmental impact assessment of the US dairy industry using the Integrated Farm System Model (Rotz et al., 2022). Typical dairy farms were modeled in five different regions of the United States, including the southwest region, dominated by dairies in California. This assessment included estimations of reactive nitrogen emissions. On a national level, they reported that 66% of all reactive N emissions from dairies in the US was in the form of ammonia (NH_3) gases (Fig. 1.2). But modeled N emissions varied by region, with losses to groundwater estimated as a larger proportion of total losses in wetter regions like the Northeast and Midwest, and losses as NH_3 larger in the warmer regions, including the Southwest, with drier, more arid conditions and higher temperatures (Fig. 1.5; Rotz et al, 2021). In these areas, housing, including both free stall barns and especially open lot dairies, contributed the largest amount of NH_3 losses based on model results. On open lot dairies, most urination occurs in corrals followed by NH_3 loss and cannot be collected from concrete surfaces as in free stall barns and recovered prior to volatilization. Rotz et al (2021) argue that gaseous NH_3 losses are characteristic of dairies in conditions like those found in California and elsewhere in the southwestern portions of the US, and that they will be difficult to control completely, especially under open lot conditions.

These gaseous N losses are difficult to account and can help explain the inaccurate estimations of N losses and the large amounts of unaccounted N on a total farm basis commented on by the researchers assessing reported farm N balances, cited earlier. Gaseous losses of N reduce N surpluses and the amount of N that can be recovered and recycled to non-dairy farms.

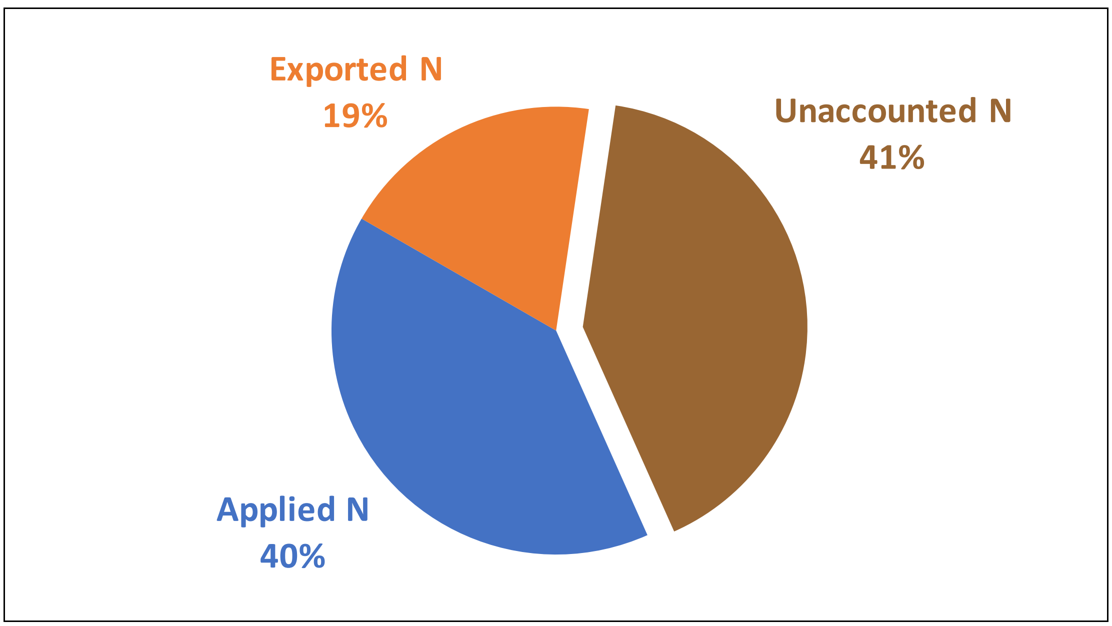


Figure 1.4. Generalized N balance for central valley dairies. Based on data reported to the CVRWQCB from 2016 to 2017[18].

[18] Till Angermann; CVDRMP. (used with permission). As noted, approximately similar estimates have been reported by others.

These separate estimates vary in terms of absolute amounts of manure N involved but are important because the portion of implicitly reported N volatilization, inadequately accounted in reported loss pathways, can be considered an estimate of surplus N. They are also useful for identifying industry-wide patterns that support the need for improved nutrient accounting and management on dairies. But they are not specific or accurate enough to support investment in improved manure management practices or new technology that recovers surplus nutrients for use elsewhere at the individual farm level. Providing such an estimate is the goal of the analysis that follows.

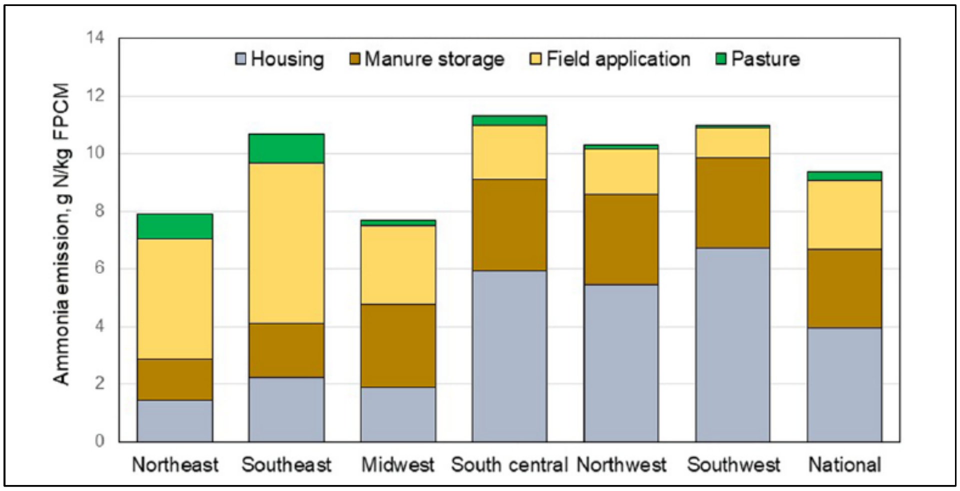


Figure 1.5. Ammonia emissions from major farm sources for each region compared with the weighted average for the US as a whole. Emissions are expressed on fat and protein corrected milk basis (FPCM). NH_3 emissions are largest in the southwest and south-central regions. The southwest region is dominated by California dairies of all sizes. The majority of emissions are from housing and manure storage (From Rotz et al., 2021).

1.3.3 Characterizing dairy structures, manure management systems, and manure N volatilization.

How manure is collected and managed affects the nutrients conserved and their use. There are diverse ways of collecting and managing manure on California dairy farms. Often different methods are used on the same farm, depending on the housing and corral structures used to manage different cattle groups. To estimate nutrient surpluses manure collection and management systems must be taken into consideration.

Cohen-Davidyan et al. (2017) focused on CH_4 emissions from manure and manure storage systems. They carried out detailed assessments on four representative dairy farms. Two were free stall and two were open lot dairies. They created a model for time spent on concrete by cattle and corresponding manure deposition amounts. Manure falling on concrete is more easily collected and largely ends up in dairy lagoons, an important source of CH_4 emissions. Their analysis is useful because it identified the relative proportions and forms of manure on these farms, factors that also influence manure N content and its fate. The modeled free stall system transferred approximately 65% of volatile solids (VS, the primary substrate for CH_4 emissions) to lagoons, while open lots farms transferred 35% of VS to lagoons. The remainder of manure on these farms fell in corrals or feed areas without concrete and did not end up in lagoons.

Meyer et al., (2019) carried out additional analysis to characterize how many dairies were predominantly free stall, open lot, or mixed (both systems) based on 2016 data from the CVRWQCB. They reported that 62% of cows resided predominantly on free stall farms, 32 % on non-free stall farms, and 6% on mixed farms (Fig. 1.6). Replacements and dry cows were reported to be on concrete between 20 % and 35 % of their time at the dairies studied. A second objective was to characterize how much time cows spent on concrete under different housing types, and to evaluate the use of solid-liquid manure separation systems. They reported large variability among farms and within the year on individual farms with respect to manure collection and management. Diet and other factors influencing manure nutrient composition were also reported to be variable.

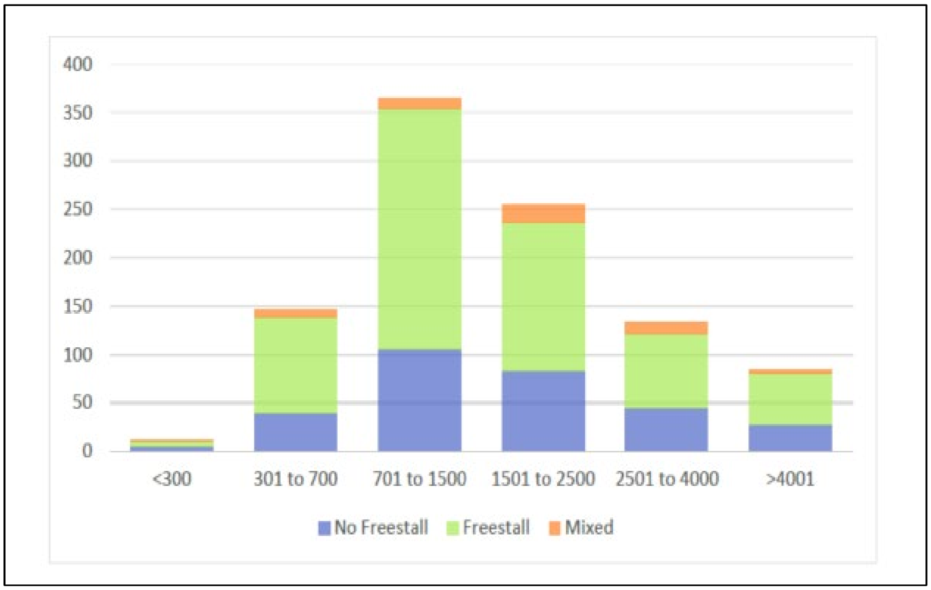


Figure 1.6. Frequency distribution of manure cattle housing by herd size category. Meyer et al. (2019).

1.4 Estimate amounts and types of dairy manure N available for nutrient recovery, reuse, and export from dairy farms.

1.4.1 Stocking rates and dairy size in target NMZs.

This report emphasizes manure nutrient surpluses within priority 1 NMZs. Surpluses exist in priority 2 NMZs and among farms outside of current NMZs, but time limitations, the fact that priority 1 NMZs are currently required to compensate water users for nitrate contamination of drinking water, and the preferences of the CDFA sponsors of our work limited our focus (Fig. 1.1). Our specific goal is to estimate the amount and location of surplus nutrients that may require improved management, up to and including the adoption of new technologies to help farms comply with state groundwater protection goals.

Data were acquired from nutrient management plans submitted to the CVRWQCB and used to estimate amounts for each dairy. These data include cow numbers and the amount of land receiving manure on the farm. Data are derived from 2017-2019 reports and are the most recent assessment available for this analysis. These data are used with CVDRMP's permission to estimate the amounts of manure produced in the San Joaquin Valley overall and by NMZ. Average or typical dairies used for more detailed analysis are derived from these data. All older reports cited in this review rely on data that are less recent, and in some cases more than a decade older. Over the last several years, the number of farms and cows in milk reported have decreased marginally[19], so older analyses, when based on larger numbers of cows included in all regional or statewide dairies, are in effect maximum estimates.

Economic pressures, technology improvements, new science, and their combination have led to much greater efficiency in milk and dairy by-product production over time, but also to growth in the size of individual dairies (though a decline in cow numbers overall) (Njuki, 2022). Dairy farms that continue to survive profitably in California and elsewhere in the USA have tended to increase cow numbers per farm, and overall stocking rates. Stocking rates are the number of mature cows plus replacements on a farm compared to the land available for manure application and crop nutrient removal. Farms with more mature cows plus replacements per acre of available land will tend to have more surplus nutrients relative to crop uptake and removal than farms with lower stocking rates, all things being equal. However, all things are seldom, if ever, equal when discussing dairy farming. To analyze the location and amount of surplus nutrients available on dairy farms, stocking rates provide a useful basis for assessing numbers and sizes of farms. Simple estimates of the amount of manure N potentially available as a function of stocking rates are presented in Fig. 1.7, which illustrates how the amount of N to be managed in manure increases with the number of cows per acre.

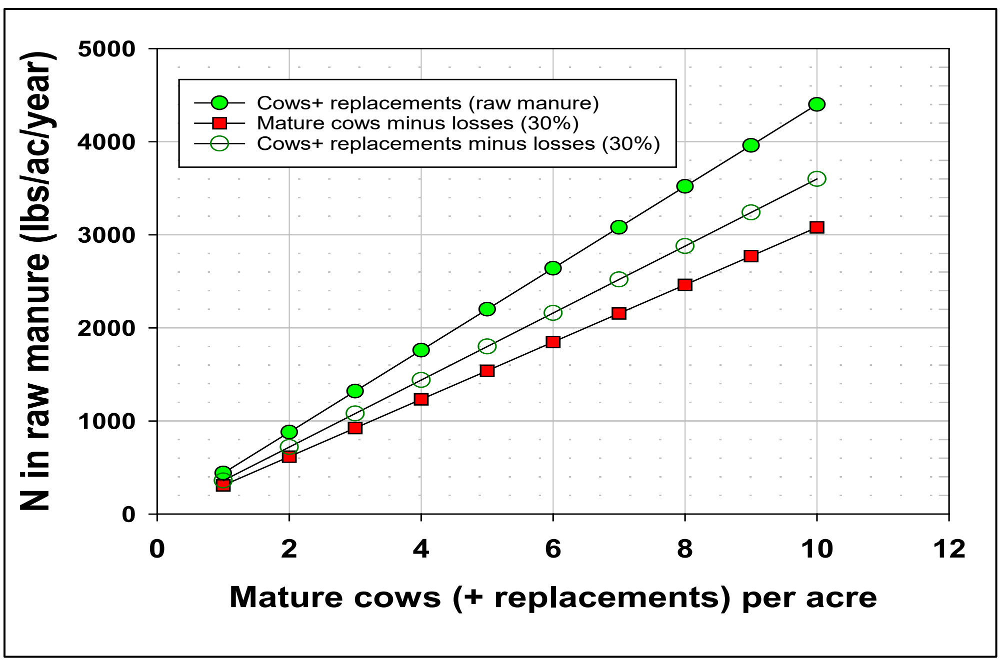


Figure 1.7. Stocking rate vs manure N supply. It is assumed that mature cows + replacements on average deposit 440 lb of N in manure and urine per year (Harter et al., 2012) and manure cows deposit 360 lbs per year. The value of 30% is used for losses via ammonia volatilization or other pathways.

[19] (https://www.statista.com/statistics/194962/top-10-us-states-by-number-of-milk-cows/)

For example, Miller et al., (2017) provided an estimate of cow numbers and land available for nutrient application based on 2012 data from the CVRWQCB, from which stocking rates could be calculated (Table 1.5). In this estimate, at least half the dairies in the SJV have a stocking rate greater than 4 cows per acre, which corresponds to ≥ 1800 lb of manure N per acre potentially available for crop production (Fig. 1.6). But there are also many dairies with stocking rates less than 4 cows per acre with correspondingly smaller amounts of manure N to manage that are or close to approximate balance with crop uptake.

Table 1.5. Characteristics of study dairies; (Miller et al, 2017)

Category	Mean	Median	Max	Min
Lactating cows	1670	1390	5415	55
Dry cows	250	220	860	0
Replacements	1320	750	9020	0
Milk production (lb yr^{-1})	21750	21825	26760	15580
Manured area (ac)	570	415	2660	0
Stocking Rate	**3.7**	**4.1**	**3.0**	

Notes:
Based on Miller et al,(2017), 2012 data, Table 2.
Values rounded.
Milk production: 305 day lactation.
Stocking rate: (lactating cows + dry cows*0.5 +replacements *0.27)/manured area.
Assumes manure from replacements equals 0.42*mature cow amount.

Using more recent CVDRMP data including mature cow numbers (lactating plus dry cows, not including replacements) and land available for manure application on each farm, stocking rates (SR) can be calculated for all dairies currently reporting and organized by NMZs (Table 1.6)[20]. The SR is larger on average than the one calculated from Miller et al.'s data for all dairies, and varies by NMZ. There is a large

[20] The Central Valley Dairy Representative Monitoring Program, a voluntary association of dairy farmers assembled data by farm on cow numbers and land available for manure application over the 2018-19 period. This represents the most recent available data useful for estimating manure amounts and characteristics on dairy farms. Data are reported annually by farms to the CVRWQCB and are publicly available. They were compiled from the California Open Data Portal. APNs were requested directly from CVRWQCB staff. These data are not easily publicly available and are in the category of "personal communication." The data was from a 2017 "one-time" effort by RWQCB staff to compile this information. Since then, the RWQCB has not updated this information. Additional comparisons since 2017 have been made using Google Earth, County Assessor APN maps, Data available here did not include breeds or barn types. Land available for manure application likely also includes the footprint of the dairy structures. Replacements are reported as well, but separately from mature cow numbers and sometimes as separate farms. For simplicity, mature cow numbers were used and replacement numbers estimated, and their manure included in total N in manure on farms. Mandated reports to the CVRWQCB also include N-P-K applications to all fields as manure and fertilizer and nutrient recovery by harvested crops (estimated at the field level by tests of harvested material). Manure is analyzed up to 4 times a year (lagoon materials) or twice a year (for solid materials). Manure sold and its characteristics is also reported, but is estimated here.

difference between average and median values, indicating that large dairies raise the average and that many dairies have below average numbers of cows per manured acre.

These data are used to compare stocking rates and dairy farm size based on reported numbers of mature cows per dairy in Figure 1.8. Higher stocking rates are not correlated with dairy size (based on cow population) in the California dairy industry. Many farms report stocking rates less than 3 cows per acre, and smaller farms in terms of land area and/or total cow numbers tend to report higher stocking rates. These data are further divided by NMZs and within the northern and southern SJV (Fig. 1.9 and 1.10).

Table 1.6. Number of mature cows (lactating and dry) for dairies within priortiy 1 and 2 NMZs

Location	# of farms	Mature cows		Acres		Stocking rate	
		AVE	Median	AVE	Median	AVE	Median
All dairies	**948**	**1458**	**1070**	**554**	**312**	**4.67**	**3.3**
Chowchilla	32	1685	1103	910	553	3	1.85
Modesto	53	880	700	265	202	4	3.33
Turlock	182	980	1057	290	295	5	3.79
Kaweah	116	1580	1200	566	462	5	3.3
Kings	119	1730	1379	750	507	5	3.1
Tule	101	2280	1789	775	548	5	3.58
Outside	89	89	865	567	281	5	3

Notes:
Based on CVRWQCB data for 2018-19.
Priority 2 dairies and those outside defined NMZs are included in the all dairies category

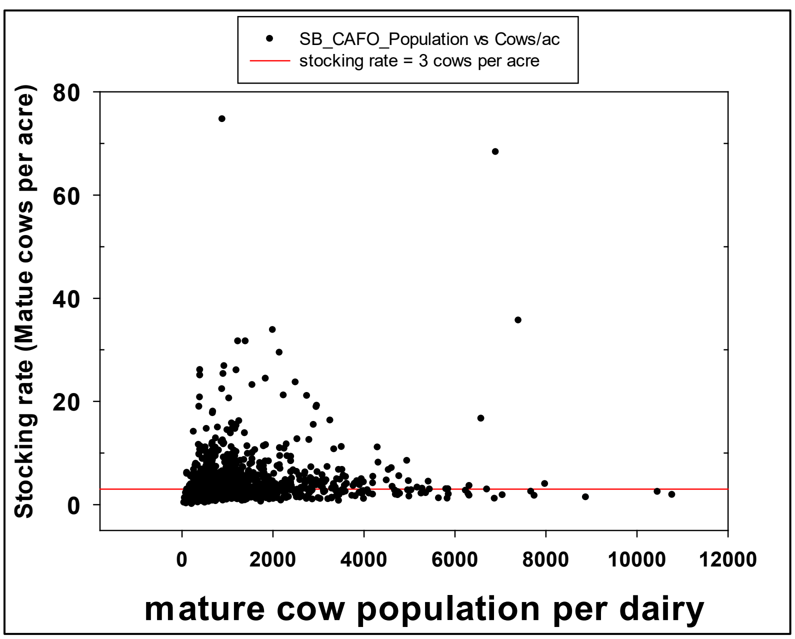


Figure 1.8. Stocking rate of mature cows per dairy versus total numbers of mature cows. Based on CVRWQCB mature cow data for 2018-2019**.** The red horizontal line indicates 3 mature cows per acre of land reported receiving manure. Each dot is a single dairy.

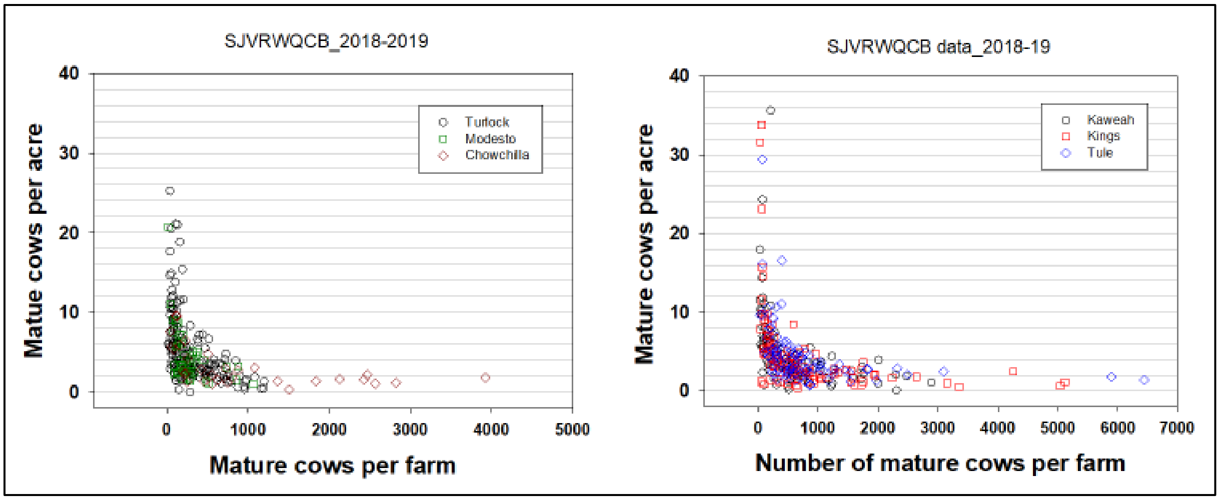


Figure 1.9. Stocking rates in the northern (left panel) and southern (right panel) San Joaquin Valley by farm size within priority 1 NMZs. The highest stocking rates tend to be on the smaller dairy farms in terms of acres.

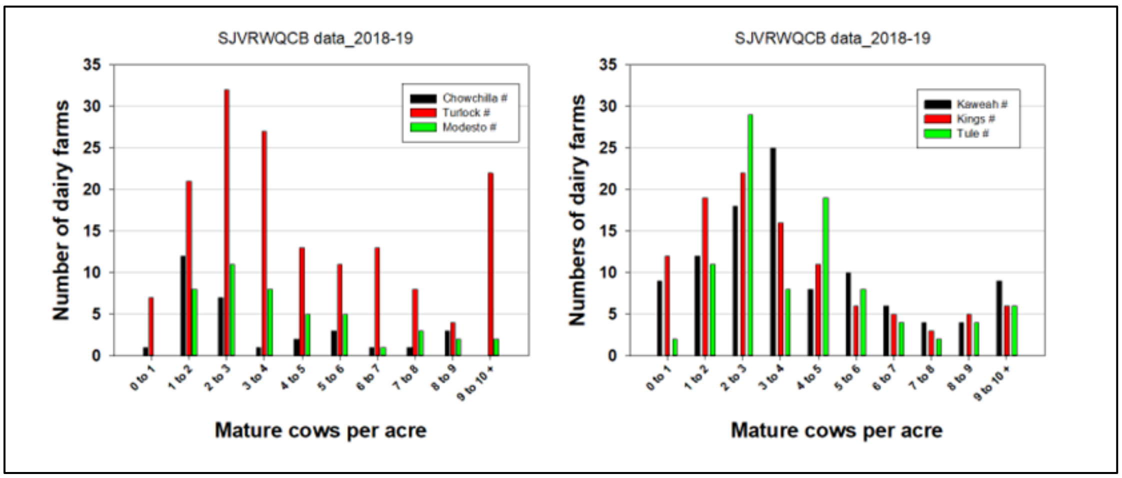


Figure 1.10. Numbers of dairies versus mature cows per acre (stocking rates) within Priority 1 NMZs. Data are grouped within the northern and southern portions of the San Joaquin Valley.

In fig. 1.10, all dairy data is sorted by NMZ and grouped by the northern and southern regions of the San Joaquin Valley. Notably, the Turlock NMZ has the largest total number of dairy farms, and the largest number of dairies (by number and percent) with larger stocking rates (Fig. 1.10). This indicates that this region has a greater challenge in meeting nutrient application limits and is likely to be where alternative manure management practices and new technologies may be required. To the degree that economies of scale apply to the adoption of such technologies, higher stocking rates on smaller dairies may present a challenge. This is discussed in greater detail below and in Tasks 2 and 5.

Co-location of dairies is another indicator of the potential need for alternative manure management technologies. This is especially the case when several dairies with large stocking rates are located near each other. Dairy co-location is depicted in Fig. 1.11 for the six NMZs. There are areas within each NMZ that have many dairies near each other. The Turlock NMZ has the largest number of dairies, and the largest proportion of dairies with higher stocking rates compared to other Priority 1 NMZ areas. It is also the case that many farms with higher stocking rates in this NMZ are among the smaller farms (Fig. 1.10). This could affect the ability of these enterprises to adopt expensive systems for nutrient recovery, where economy of scale is a factor. Several smaller, co-located farms with higher stocking rates, however, may be able to find creative ways to collaborate as a group, cluster, or cooperative on a technology-based solution with the help of supportive policies. This is also discussed in Task 3.

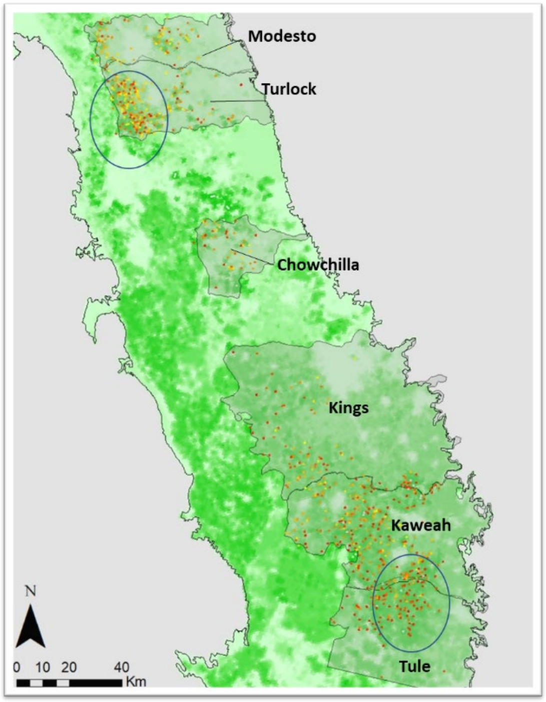
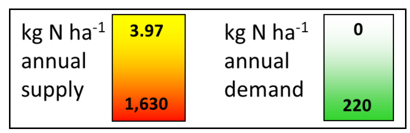


Figure 1.11. Dairy nutrient concentration and potential demand for surplus nutrients.

The dairy farm locations in the San Joaquin Valley are mapped by estimated supplied N amounts per 1 km^2 hexagonal grid (in yellow and red). Areas with dense clusters of farms are likely to be targets for nutrient recovery and removal systems. Cropland on non-dairy farms is also indicated with estimated approximative N demand. Adjacent non-dairy farmland is a potential market for fertilizer equivalent N and P nutrients derived from dairies, and for organic amendments from dried solid manure and composts.



1.4.2 Estimating manure surpluses available for recovery, removal and reuse.

A multi-stage approach to assessing N surpluses is needed. Five steps are outlined in Table 1.7. Steps 1 and 2 constitute the majority of this analysis. Steps 3 to 5 must be completed by individual farms to be accurate since farms can and do vary widely and differ from average characterizations. The SRMR provides a methodology useful for these later stages of assessment that are dairy specific (Cativiela et al., 2019). The distribution of farms by stocking rates and NMZs is included in Table 1.8. Calculations supporting steps 1 and 2 are included in Tables 1.9 (A and B).

Table 1.7. Protocol proposed to estimate nutrient surpluses on dairy farms.				
Step	**Level**	**Description**	**Use**	**Limits**
1	*NMZ*	Calculate stocking rates, manure available for application to fields, and potential crop uptake and removal, above a chosen regulatory threshold for nutrient application to crops: N basis, P basis.	Identifies farms with nutrient surpluses needing additional management. Identifies approximate scale (maximum) of surplus nutrient accumulation on each farm and in each NMZ.	Farms vary in ways that affect nutrient surpluses. Otherwise, similar farms may have significant differences in nutrient surpluses and vary in their need for additional management. (estimated error: ± 20 - 40 % at the NMZ scale)
2	*NMZ*	How many high stocking rate farms (≥ 4 cows/ac) are co-located. (Are there regions within the NMZs with collectively especially large numbers of cows per acre?)	Further identifies areas within NMZs where manure management within the farm and among neighboring farms requires additional management.	May require cooperation among farms for regionalized solutions. (estimated error: ± 20 - 40 % at the NMZ scale)
3	*Farm level*	Carry out Summary Representative Monitoring Report (SRMR) calculations to evaluate potential N surpluses on an individual farm, accounting for the type of manure handling system(s), number of cows and replacements, amount of manure collected from concrete and stored in lagoons or collected in solid form, the amount of land available for manure application, crops grown and crop uptake and removal, and other details.	More exactly quantifies manure surpluses for recovery and removal at the farm level. Helps clarify what types of changes in manure and crop management are needed.	Useful for assessment at the level of the individual farm and within subregions (including neighboring farms). Supports incremental improvement. (goal is reducing error to ± 10% for crop removal and the solid manure fraction, measurements most subject to error).
4	*Farm level*	For farms with large, calculated surpluses (from Step 3), evaluate conventional strategies and incremental improvements to adjust surpluses. (These may include improved measurement and management of manure nutrients; an improved and enlarged manure distribution system for lagoon materials; reductions in manure collected on concrete and stored in lagoons; increased off-farm sales or distribution; other steps suggested in the SRMR report. See Task 3	Identifies which conventional strategies and incremental improvements are most likely to be useful at the farm level to help adjust nutrient balances and improve on-farm management. These strategies will be beneficial for most farms.	Conventional strategies and incremental solutions will take time to adopt and may not be sufficient. (error: ± 10 - 20 %)
5	*Farm level*	For farms with persistent surpluses and limits on the conventional alternatives mentioned, evaluate new manure treatment technologies (composting and off-farm sales, ammonia stripping, polymer treatments, denitrification technologies (vermiculture), etc.).	Guides the adoption of technical nutrient recovery and removal solutions for farmers and technology providers. Provides the regulatory community guidance on costs and potential for advanced technical solutions. (Tasks 2-5)	Identifies which farms require additional technology and investment to manage nutrient surpluses. Quantifies the scale of the problem with reasonable certainty (goal: error = ± 5 to 10%)

Table 1.8. Numbers and percent of dairies by different stocking rates and NMZ												
	Chowchilla		Turlock		Modesto		Kaweah		Kings		Tule	
Stocking rate (Cows ac^{-1})	Dairies		Dairies		Dairies		Dairies		Dairies		Dairies	
	(n)	%	(n)	%	(n)	%	(n)	%	(n)	%	(n)	%
1	1	3	7	*4*	0	0	9	9	12	11	2	2
2	12	39	21	*13*	8	18	12	11	19	18	11	12
3	7	23	32	*20*	11	24	18	17	22	21	29	31
4 (3.5 to 4.4)	1	3	27	*17*	8	18	25	24	16	15	8	9
5	2	6	13	*8*	5	11	8	8	11	10	19	20
6	3	10	11	*7*	5	11	10	10	6	6	8	9
7	1	3	13	*8*	1	2	6	6	5	5	4	4
8	1	3	8	*5*	3	7	4	4	3	3	2	2
9	3	10	4	*3*	2	4	4	4	5	5	4	4
10	0	0	22	*14*	2	4	9	9	6	6	6	6
SUM	31		158		45		105		105		93	
Dairies with a SR of cows/ac >3	10	*32*	98	62	26	*58*	66	*63*	52	*50*	51	55

At the NMZ level (Steps 1 and 2), we have used stocking rates calculated from data reported to the CVRWQCB and assembled from 2018-19 by the CVDRMP to identify the distribution of stocking rates within NMZs and across the SJV region (Table 1.8; Figs. 1.9-1.11). Stocking rates (SR) are calculated by dividing the number of mature cows reported by the reported land available for manure application. For the sake of clarity of presentation, stocking rates have been rounded to the nearest whole number in the tables. In actuality, the set of dairies evaluated here have stocking rates that vary continuously. For example, due to rounding, dairies with 4 cows per acre include dairies that range between 3.5 and 4.4 cows per acre.

Dairies with stocking rates of 4 mature cows or greater per acre have been chosen for the calculations of surplus nutrients[21]. These dairies accumulate nutrients in amounts much greater than the amount that can be recovered by crops in an average crop year, even when producing three high-yielding crops per

[21] Since the goal of this report is to identify the amount of surplus nutrients on dairies that will require additional management, including increased manure exports or advanced nutrient recovery and removal, all dairies with these stocking rates on average will have exportable surpluses and provide a reasonable basis for initial estimates. Dairies with smaller stocking rates (especially in the range of 2.5 to 3.4 cows per acre or less) will also have some surplus manure nutrients, but in lesser amounts, depending on manure handling systems and cropping practices. We assume that these dairies can more easily adopt conventional strategies (TASK 3) to better align manure application rates with crop uptake and/or export relatively smaller additional amounts of solid manure or manure composts. This will bring farms into approximate balance between N in manure available for application and crop uptake and removal.

To come into approximate balance between manure N available for land application and crop uptake and removal, they may require export of large amounts of manure off the farm or new technology to recover and remove surplus nutrients (Table 1.7-Steps 4 and 5; Fig. 1.7). All the NMZs analyzed except Chowchilla include more than 50 % of all dairies with > 3 cows per acre (Table 1.8). The Turlock NMZ has the largest absolute number of such dairies and along with the Kaweah NMZ, the largest proportion of dairies with high stocking rates among the Priority 1 NMZs (Fig 1.9 and 1.10).

The amount of manure that falls on concrete versus in corrals and pens influences the amount of N available for land application after volatilization and other losses from raw manure during handling and storage. More N potentially is conserved in lagoons as liquid manure (LM) than in solid manures (SM) falling in corrals due to larger (but variable) N losses in corrals. Solid manure N content is also more variable due to a large range of conditions and management practices that can influence the amount of N in that source. Free stall farms, which collect more of the total manure excreted on concrete, are estimated to conserve more manure N in LM than open lot farms or farms with both free stalls and open lots combined. An attempt was made to distinguish between LM and SM and the amounts on free stall dairies and open lot dairies. Meyer et al. (2019) reported that approximately 62 % of dairies in the SJV are free stalls, 32 % are open lot dairies, and 6 % are mixed (Fig. 1.6). Here, mixed dairies are treated as free stalls in these calculations, slightly overestimating LM collection for those dairies.

Manure surpluses depend on the stocking rate, how manure is handled, including losses (largely to the atmosphere) during collection and storage, and crop uptake and removal of applied manure N. Variables, units, values and methods for calculating manure nitrogen surpluses within the six NMZs analyzed are presented in tables 1.9A&B. Results of these calculations are reported in the subsequent tables. After losses during collection and storage are accounted, the amount of N that is surplus on a farm is thus dependent on the dairy farm's cropping systems. Growing three crops a year compared to two allows for larger amounts of manure N to be recovered by crops, reducing surplus N accumulated in manure. Crop choices, crop yields and the number of crops produced per year thereby affect uptake (Fig. 1.3; Chang et al., 2006). These vary among farms, but a standard set of choices is assumed here. Higher crop yields remove more nutrients in harvested biomass. Values for crop uptake and removal reported in the literature for typical crops produced on dairies (cereal silages, corn silage, and Sudan grass hay) are used to estimate crop removal per year (Chang et al., 2006; Pettygrove et al., 2009; Miller et al., 2017). Chang et al.'s values (400 and 500 lbs per acre for a two and three crop system respectively) are lower than later estimates, were the basis for the choice of protective application ratios for manure use and are conservative with respect to manure application rates. Alfalfa is also produced on some dairy farms but is not considered for manure application since as a legume it fixes N from the atmosphere and does not require N fertilization of any kind, including from manure. Not all farms produce alfalfa, and acres are declining and likely will decline further due to water limitations under SGMA. As discussed above (1.3.2), manure N can be applied at an application rate of 1.4 times the estimated crop recovery rate, (560 and 700 lbs per acre respectively) and this AR is used to calculate the amount of manure N that can be applied to crops based on estimated crop uptake and removal.

These calculations are based on average estimated manure and crop nutrient contents from diverse sources and represent our best judgment for average values based on these sources (Table 1.9A).

Table 1. 9.A. Variables, units, and values used for calculating manure N surpluses				
Variable	**Units**	**Symbol**	**value**	**Source(s)**
Manure N excreted per matue cow + replacements	lb N/yr	MN	**440**	Harter et al, 2012; Pettygrove et al, 2009; Chang et al.,2006; others
Stocking rate	# of mature cows per farm per acre receiving manure	SR	**1 to 36**	Calculated from data from CVRWQCB
Free stall farm (FS): fraction of MN falling on concrete (= liquid manure (LM))	unitless	FS_{LM}	**0.6**	Meyer et al., 2019; Davidyan, 2021, Harter et al., 2017; Lorimor,et al., 2005, other sources
Fraction of LM conserved	unitless	LMcon	**0.7**	Meyer et al., 2019; Davidyan, 2021, Harter et al., 2017; Lorimor,et al., 2005 other sources
FS fraction of manue N falling in corrals as solid manure (SM)	unitless	FS_{sm}	**0.4**	by difference and similar to above
Open lot farm (OL): fraction of LM	unitless	OL_{LM}	**0.35**	Meyer et al., 2019; Davidyan, 2021, Harter et al., 2017; Lorimor,et al., 2005 other sources
OL: fraction falling in corrals as solid manure	unitless	OL_{SM}	**0.65**	Meyer et al., 2019; Davidyan, 2021, Harter et al., 2017; Lorimor,et al., 2005 other sources
MN sold off farm	unitless	MN_{sold}	**0.2**	Parsons and Harter , 2018
Acres receiving MN per farm	acres	ac	**from data**	CVRWQCB data
N removed by crops (cereal+corn silage)	lb N/ac/yr	CR_{2crop}	**400**	Chang et al., 2006, Miller etal., 2017
N removed by crops (cereal+corn silage+ sudan grass hay)	lb N/ac/yr	CR_{3crop}	**560**	Chang et al., 2006, Miller etal., 2017
Application ratio of MN to crop uptake	unitless	AR	**1.4**	Chang et al, 2006; CVRWQCB
Fertilizer N applied to fields (corn silage)	lb N/ac/yr	Fert N	**50**	Diverse sources

Table 1.9.B. Calculations for surplus manure N per dairy farm		
Variable	**Equation**	**Purpose**
MN	440*SR	Total raw manure N per acre for cows + replacements (lbs) based on the stocking rate on each farm in the data base
FS_MN_{cons}	$MN*(FS_{LM} * LM_{cons}) + MN*(FS_{SM} * SM_{cons})$	Calculates MN available (conserved) after volatilization losses on a free stall (FS) dairy, per cow equivalent
OL_MN_{cons}	$MN*(OL_{LM} * LM_{cons}) + MN*(OL_{SM} * SM_{cons})$	Calculates MN available after volatilization losses on an open lot dairy, per cow equivalent
FS_MN_{sold}	$FS\_MN_{cons} *0.2$	Assumes 20 % of total manure N (after volatilization losses) is sold
OL_MN_{sold}	$OL\_MN_{cons} *0.2$	Assumes 20 % of total manure N (after volatilization losses) on an open lot dairy is sold
FS_MN_{net}	$FS_{LM} *LM_{cons} + (FS_{SM} * SM_{cons} – FS\_MN_{sold})$	Assumes only SM is sold. Deducts total MN_{sold} only from the SM fraction on a free stall farm.
OL_MN_{net}	$OL_{LM} *LM_{cons} + (FS_{SM} * SM_{cons} – FS\_MN_{sold})$	Assumes only solid manure is sold on an open lot dairy. Deducts total MN_{sold} only from the SM fraction on an open lot farm.
$CROP\_N$	$CR_{xcrops} *AR$	MN recovered by crops (x = either a 2 or 3 crop system)
$FS\_MN_{surplus}$	$(FS\_MN_{net} + FertN – CROP\_N)*ac$	MN left after volatilizations losses, sales and crop removal based on the number of cows per acre and the number of acres per farm on a free stall dairy.
$OL\_MN_{surplus}$	$(OL\_MN_{net} + FertN – CROP\_N)*ac$	MN left on an open lot dairy after volatilization losses, sales and crop removal based on the number of cows per acre and the number of acres per farm on an open lot dairy.

There are differences among farms in the amount of manure N that is sold or otherwise distributed off the farm. Parsons and Harter (2018) estimated that approximately 20% of (primarily solid) manure was sold off-farm on California dairies on average (Fig. 1.4). Attributing this average amount of manure sales to all farms implies a large amount of uncertainty. Average values do not reflect actual conditions on individual dairy farms. It is likely that off-farm sales are not uniformly distributed. High stocking rate farms in general have larger surpluses and may be responsible for a larger portion of off-farm manure sales and distribution, especially if they have large amounts of SM to manage. For example, there are many smaller acreage dairy farms that report limited land available for manure application. If these farms also report high stocking rates, it seems likely that these farms sell or remove large amounts of solid manures from the farm, simply to be able to maintain their facilities and the physical capacity to operate. But this assumption is speculative.

Reducing manure N through off-farm distribution increases the stocking rate that is in theoretical balance with crop uptake. Even small farms with very high stocking rates may not have a large surplus of N if most of their manure is used off the farm for non-dairy crops. But the data available for this analysis do not indicate which farms sell manure nor how much they sell or distribute off-farm, so we have used the value proposed by Parsons and Harter (2018) of 20% for off-farm distribution for all farms. We have also assumed that the SM fraction is distributed off-farm, rather than the liquid manure fraction (Table 1.9B).

Fertilizer is sometimes added to crops on dairy farms, particularly corn silage, to correct perceived deficiencies in N availability resulting from inadequate mineralization of organic N in manures compared to the needs of corn crops for sufficient N during a relatively short period of crop uptake and development. Not all farms do, and the amounts purchased are uncertain from farm to farm and year to year. Purchased N decreases the stocking rate level that can be balanced with crop uptake on a total N basis. We have included a small amount of fertilizer use applied to corn silage crops for all farms (50 lb N ac^{-1}) because reports in the literature (e.g., Chang et al., 2006; Pettygrove et al., 2009) and discussions with farmers and dairy consultants indicate this is common practice.

Results of surplus nutrient calculations

Table 1.10 reports estimated N surpluses based on SR. Table 1.11 includes estimates of surplus N in the Priority 1 NMZs as LM and SM. These estimates account for differences in manure management systems between free stall and open lot dairies, (including differences in estimated volatilization losses of N during collection and storage), cropping system intensity, fertilizer use and off-farm sales (Table 1.9B). The average values for amount, type, and location of potential manure N surpluses on each farm within the Priority 1 NMZs and sums with the each NMZ and presented in Table 1.11.

Table 1.10 differs from Table 1.11. In Table 1.11 values for N surpluses are multiplied by the acres of land available for manure application reported for each farm within each NMZ with a stocking rate of 4 mature cows per acre or greater, derived from the CVDRMP data set, while Table 1.10 uses only average values. The manure amounts include manure generated by dry cows and replacements as well. (For 1 cow plus replacements this is estimated as 440 lb N per year (Table 1.9B and Table 1.10). Estimated LM and SM are reported separately, and the range within each manure type by NMZ is included.

The estimates in Tables 1.10 and 1.11 rely on average values that include significant variance among farms classified as free stalls and open lot dairies. That means that there are large uncertainties for each value. More accurate accounting, however, can only come from careful estimates for each farm, (Table 1.7, Steps 3 to 5), which then can be summed up within each NMZ or other sub-regional level as needed. That is why each farm must carefully account for its manure nutrient supply, especially N. The SRMR report (Cativiela et al., 2019) provides a well-designed model for calculating a manure N balance at the farm level.

Table1. 10. Estimated surplus N in manure based on stocking rates, collection system, estimated crop uptake, AR 1.4, accounting for manure export of SM and fertilizer use for corn silage

Cows/ac	Manure N (lb/ac/yr/coweq) (excreted)	Forage crops/yr			
		2	3	2	3
		Free stall dairy		Open Lot Dairy	
1	**440**	**-253**	**-393**	**-276**	**-416**
2	**880**	**-17**	**-157**	**-63**	**-203**
3	**1320**	220	80	151	11
4	**1760**	456	316	364	224
5	**2200**	693	553	578	438
6	**2640**	929	789	792	652
7	**3080**	1166	1026	1005	865
8	**3520**	1402	1262	1219	1079
9	**3960**	1639	1499	1433	1293
10	**4400**	1875	1735	1646	1506

Notes: Cows + replacements; Manure per cow equivalent (lactating cows + replacements = 440 lbs N/yr
2 crops/yr: cereal silage and corn silage, N uptake = 400 lb N/ac
3 crops/yr: cereal silage, corn silage, Sudan grass hay; N uptake = 500 lb N /ac
AR = 1.4 times manure N available for application
N application: 2 crop system =490 lb N/ac/yr after adjusting for 50 lb N/ac fertilizer use per acre;
N application: 3 crop system = 650 lb N/ac/yr after adjusting for 50 lbs N fertilizer use per acre
Free stall: 60% on concrete (70% recovery of N); 40 % in corrals (63% recovery of N)
Open lot: 35% on concrete (60 % recovery), 65 % on corrals.
50 lbs fertilizer N per acre per year assumed for corn silage. This reduces the amount applied at an AR of 1.4 to to 490 and 650 lb N equivalent respectively.

Table 1.11. Dairies reporting a stocking rate ≥ 4 mature cows per acre.

	Chowchilla	Modesto	Turlock	Kaweah	Kings	Tule
Number of dairies	10	20	81	44	43	44
% of dairies	32	52	58	63	50	55
Acres receiving manure (total per NMZ)	1660	4230	13660	10350	10830	16290
Lagoon manure N (t yr^{-1})	330	700	3430	2150	2810	2980
Range by dairy type (FS-OL)	440-160	950-350	4320-1590	2850-915	2780-960	4060-1430
Solid manure N (t yr^{-1})	270	610	2690	980	1810	2580
Range by dairy type (FS-OL)	215-370	670-780	2495-3740	2180-3540	1570-2250	2230-3380

Notes:
FS: Free stall; OL: Open Lot.
Averages are the mean of 2 and 3 crop systems (Manure N application rate of 490 or 630 lb manure N acre respectively at an AR ratio = 1.4.
Lagoon manure (LM) is from FS and OL farms combined. Similarly for Solid Manure (SM).

The estimates reported here are indicators of the level of surplus manure N within each Priority 1 NMZ[22] if the data reported to the regional board in the 2018-19 period and used here used for cow populations and land receiving manure are accurate, and given the assumptions made about collections and losses in LM and SM management systems (Tables 1.9A-B). Manure N on farms with stocking rates less than or equal to 3 cows per acre are approximately in balance with crop requirements, assuming volatilization or other losses before manure is applied to fields. Averaging the surpluses in this class between 2 and 3 crop systems (equal to high yielding crops in a 2-crop system), yields a surplus of 150 lb N per acre on FS farms and 80 lb N per acre on OL farms. This assumption has the effect of reducing total N surpluses within the NMZs compared to an undifferentiated calculation including all farms (Fig. 1.4). For those farms with this stocking rate that might still be somewhat in surplus, conventional or currently available strategies are available for helping to bring these farms closer to N balance (discussed in TASK 3).

Differences between LM and SM within each NMZ are more uncertain but are included because different approaches to surplus manure nutrient recovery, removal, and reuse will be needed for these two general types of housing and manure management systems (TASK 2, 5). Even accounting for the uncertainties in these estimates, however, it is clear that large amounts of manure N are in surplus, a result reported by all other authors focusing on this issue and cited above, and that a large portion of all dairy surplus N is included in the SM fraction. This is important because the size of a farm and type of manure available on a farm affects the types of solutions available for surplus nutrient management. Consequently, different approaches to surplus N management will be needed and different supportive policies. The proximity of farms also will influence the kind of solutions adopted. If a farm with a large surplus N supply is surrounded by other dairy farms, off-farm distribution opportunities in the surrounding area may be limited, requiring longer transport distances for SM or manure composts.

Differences among NMZs.

There are large differences among the NMZs analyzed here with respect to the distribution of farm sizes, manure types and surplus N amounts. Two NMZs are compared in Tables 1.12 to 1.15 that reflect the contrasting sets of conditions and constraints affecting manure management that characterize the dairy industry in the state, and differences between the northern and southern SJV. The Turlock NMZ has the largest number of farms among the 6 NMZs, and a larger proportion of smaller farms than the NMZs in the southern SJV. Discussions with representatives of the dairy industry, farmers and cooperative extension personnel also suggest that most of these farms are free stall farms or include free stall barns, at least for parts of the herd. Open lot farms reportedly are more common in the southern SJV.

The Turlock NMZ has the largest calculated N surplus. This increases marginally if it is assumed most farms use free stall structures with larger levels of N conserved in manure. In contrast, the Tule NMZ has nearly the same number of cows but on many fewer and mostly larger farms, and a larger reported amount of cropland acres receiving manure. Dairies developed earlier in time in the Turlock region for the most part than in the Tule region and reflect different development pathways and constraints. Many smaller dairies expanded herd size without being able to add additional crop land. Stocking rates are very high on a large proportion of the farms in this NMZ and smaller farms (by acres) account for a majority of the surplus N. There are 23 dairies with reported stocking rates of 10 or more cows per acre

[22] Dairies not included in priority 1 NMZs also are not included in calculated N surpluses (approximately 150 dairies). There is also a small number of dairies in the data available that did not report cropland and were excluded.

that account for an estimated 38 % of all the surplus manure N in the NMZ. All these dairies have less than 200 acres of land receiving manure, and more than half report less than 100 acres.

In contrast, the Tule NMZ has half as many total farms with stocking rates greater than 4 cows per acre, very few are small, none report less than 200 acres receiving cropland, and only 4 farms have stocking rates greater than 10 cows per acre. Half of the 81 farms in the high stocking rate group (≥ 4 cows plus replacements per acre) report cow populations of approximately 3000 cows or greater. These differences, when combined with farm characteristics (more open lot dairies) and proximity to non-dairy farmland, will affect the pathways and technology available for treating manure N and transferring it to non-dairy croplands, the costs of these technologies, and their GHG consequences (TASK 2/TASK 4).

Table 1.12. Turlock NMZ; surplus N by farm size (available acres) for farms with ≥ 4 cows per acre

Available acres (ac)	Dairies (#)	Acres Sum (ac)	Stocking rate Average (cow ac^{-1})	Cows Sum (cows)	SURPLUS N (tons N yr^{-1}) Free stall, Crops per year 2	Free stall 3	Open Lot 2	Open Lot 3	Contribution % Farms (%)	Acres (%)	Cows (%)	N (%)
<100	37	2211	9.5 (5 to 25)	20341	1858	1703	1626	1471	46	16	21	24
100-200	21	3100	9.6 (4 to 21)	29894	2780	2563	2423	2206	26	23	32	36
200-300	12	2916	5.2 (4 to 8)	15372	1087	883	912	708	15	21	16	13
300-400	3	1149	6.7	7696	625	544	537	456	4	8	8	8
400-500	3	908	6.4	5783	474	410	406	343	4	7	6	6
500-600	2	1096	5.4	5810	433	356	365	288	2	8	6	5
600-700	0											
700-800	2	1439	4.5	6430	414	313	339	239	2	11	7	5
800-900	1	843	4.0	3340	192	133	154	94	1	6	4	2
Total	81	13661		94666	7863	6905	6761	5805	100	100	100	100
AVERAGE N SURPLUS					7384		6283					

SURPLUS Weighted average (67% FS: 33% OL) = 7021 tons N yr^{-1}

SURPLUS Weighted average (90% FS: 10% OL) = 7274 tons N yr^{-1}

Table 1.13. Turlock NMZ; surplus N by stocking rate for farms with ≥ 4 cows per acre												
Stocking rate	Dairies	Acres	Cows	SURPLUS N (tons N yr^{-1})				Contribution %				
				Free stall		Open Lot						
		Sum	Sum	Crops per year				Farms	Acres	Cows	N	
(Coweq ac^{-1})	(#)	(ac)	(cows)	2	3	2	3	(%)	(%)	(%)	(%)	
4 to 5	17	5136	22250	1368	1008	1112	753	21	38	24	16	
5 to 6	12	1885	10477	818	686	694	562	15	14	11	10	
6 to 7	14	2432	15859	1303	1133	1119	949	17	18	17	16	
7 to 8	7	1267	9363	781	693	675	587	9	9	10	10	
8 to 9	5	650	5378	465	419	405	359	6	5	6	6	
9 to 10	4	272	2533	228	209	199	180	5	2	3	3	
10 to 11	5	344	3567	327	301	287	263	6	3	4	4	
11 to 12	6	648	7423	733	688	647	601	7	5	8	10	
12 or more	12	1028	17816	1841	1769	1624	1552	15	8	19	25	
Total	82	13662	94666	7863	6905	6761	5805	100	100	100	100	

Table 1.14. Tule NMZ; surplus N by farm size (available acres) for farms with ≥ 4 cows per acre													
					SURPLUS N (tons N yr^{-1})								
vailable acre	Dairies	Acres	Stocking rate	Cows	Free stall		Open Lot		Contribution %				
					Crops per year								
		Sum	Average	Sum	2	3	2	3	Farms	Acres	Cows	N	
(ac)	(#)	(ac)	(cow ac^{-1})	(cow $farm^{-1}$)					(%)	(%)	(%)	(%)	
<100	4	261	16.2	4470	465	446	413	395	9	2	5	7	
100-200	6	940	6.6	6296	517	451	445	379	14	6	6	7	
200-300	6	1533	7	10519	850	742	731	624	14	9	11	11	
300-400	10	3311	7.4	25539	2243	2011	1947	1715	23	20	26	31	
400-500	5	2308	5.3	12238	853	691	716	554	11	14	12	11	
500-600	4	2248	4.9	11077	777	619	648	491	9	13	11	10	
600-700	6	3926	4.6	17941	1196	921	986	721	14	23	18	15	
700-800	2	1540	4.5	7095	447	339	367	259	5	9	7	5	
800-900	1	854	5	3850	296	236	247	187	2	5	4	4	
Total	44	16921		99025	7644	6456	6500	5325	100	100	100	100	

Table 1.15. Tule NMZ; surplus N by stocking rate for farms with ≥ 4 cows per acre.											
Stocking rate	Dairies	Acres	Cows	SURPLUS N (tons N yr^{-1})				Contribution %			
				Free stall		Open Lot					
		Sum	Sum	Crops per year				Farms	Acres	Cows	N
(Coweq ac^{-1})	(#)	(ac)	(cows)	2	3	2	3	(%)	(%)	(%)	(%)
4 to 5	18	9244	40987	2644	1997	2167	1520	41	57	44	33
5 to 6	10	3866	20584	1532	1260	1291	1020	23	24	22	20
6 to 7	4	1380	8894	697	600	596	500	9	8	10	9
7 to 8											0
8 to 9	2	407	3263	285	257	248	219	5	2	3	4
9 to 10	4	619	477	520	412	365	329	9	4	1	6
10 to 11	3	856	9255	904	844	796	736		5	10	13
11 to 12											0
12 or more	3	548	9990	1062	1023	946	908	7	3	11	15
Total	44	16920	93450	7644	6393	6409	5232	100	100	100	100

Ultimately, the adoption of additional nutrient recovery, removal, and reuse practices and technologies will occur at the farm level, or among clusters of farms, based on careful assessments of nutrient surpluses for each farm needed to guide investment in new technologies or changes in manure management systems. Accurate assessment will be much more important for commercial success (or failure) for engineered systems that perform more efficiently and predictably with uniform substrates supplied at a constant rate (Task 2). Where such technologies are needed (Step 5 in Table 1.7), arrangements between technology providers and farmers will occur in response to incentives created by a combination of markets and regulation.

Surplus manure N can replace some of the N added to non-dairy farmland as commercial fertilizer. If the average total amounts of estimated surplus manure N as LM and SM manure are summed for all priority 1 NMZs, they equal approximately 25,300 tons of N per year. This is a large amount of N but much less than estimated total N fertilizer use on California crops annually, and less than previous estimates for the entire dairy sector in the state cited above. The amount of fertilizer N used annually reported in the *California Nitrogen Assessment* from 2014, was 514,000 tons per year (Tomich et al., 2016)[23]. Surplus dairy manure N in these NMZs is thus approximately 5% of total fertilizer inputs. If the larger amounts of the ranges reported are assumed (~34,000 t/yr), then surplus N in these 6 NMZs equals approximately 7% of total fertilizer use. Farms omitted from other NMZs or priority two groups would increase this amount further. While these percentages are small, overuse of reactive N (as fertilizer) is an important environmental and climate problem worldwide. Any prudent steps to reduce the synthesis and use of new N fertilizer without adverse consequences for food production should be considered. Additional benefits for food production systems could come from the use of SM or SM products like compost from dairies due to their generally positive effects as a soil amendment on soil

[23] https://www.google.com/search?client=firefox-b-1-e&q=How+much+fertilizer+N+is+used+in+California+each+year%3F

structure, soil carbon storage, and correlated agronomic benefits, in addition to supplying nutrients (Task 4).

1.5. Other approaches to assessing manure N surpluses

The level of manure application and the stocking rates associated with surplus calculations are dependent upon the application ratio used for crop uptake, and whether it is based on N, P or some other standard. Regulatory guidelines limit manure N application to 1.4 times crop uptake. Since manure is biologically active and N in manure is subject to transformation and loss (Fig. 1.2), Pettygrove et al., (2009) in California, and policy makers elsewhere (for example in The Netherlands, a major dairy producing country in Europe; World Bank, 2017[24]) have suggested using P amounts in manure as a guide for application rates, using crop P requirements rather than crop N requirements. P does not volatilize, so is easier to measure and quantify when applying manure to fields. Dairy manure is relatively rich in P compared to N (Pettygrove et al., 2009). Using estimates made by Pettygrove et al (2009) as a first approximation, if manure were applied based on the phosphorus requirements of common forage crops, rather than on their N requirement, less manure would be applied to crops on average. The effective stocking rate after applying a P constraint based on current feeding practices and common manure P levels is well below the average observed on all dairies in the San Joaquin Valley (4.67 mature cows per acre-Table 1.6) and below the median value (3.3 cows per acre) observed (Table 1.6). Stocking rates below those observed currently are uneconomic.

Some dietary adjustments to limit surplus P in feeds might occur. Perhaps as a first response, a P -based standard would encourage dairy nutritionists to constrain P levels in total mixed rations (TMRs). To the degree this were economically viable, manure application rates and effective stocking rates could then increase over those estimated in Table 1.16 by an unknown amount. However, the AR appropriate for manure P application rates is not will characterized and requires research (see, for example, Jenkins et al, 1998). Additionally, if manure is applied at rates that limit crop growth (especially corn silage), using a P basis for manure application may cause farmers to use more fertilizer N in response. Fertilizer N use can be more precise than manure N for crops like corn silage, but its use increases the amount of nutrients brought onto dairy farms.

From the perspective of recoverable N and P surpluses on dairy farms, the use of a P-based standard, would result in a lower threshold stocking rate and larger amounts of manure N than those estimated in Table 1.11 at current stocking rates (Fig. 1.12). These additional surplus nutrients likely would be available for recovery and removal, potentially making investments in practices and technologies that recover and remove surplus N more important and more feasible economically, though this is uncertain. Since a P-based constraint currently is uneconomic, its use also implies using public subsidies to support

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[24] This report describes the gradual development of regulations affecting manure application in The Netherlands, a country with very large numbers of intensive livestock operations. Over time, standards and subsidies were developed to help farms gradually reduce the amount of manure applied to land and export more manure and manure nutrients to non-livestock farmers. Many of these regulations were P based and were successful in reducing application rates across the country over a time frame of several decades. But public subsidies were required. Many farms, largely smaller farms, went out of business in The Netherlands during this period. The increased costs of manure management imposed by regulation were a contributing factor to the loss of farms.

technology on dairies that would recover surplus N (and P) in an agronomically useful form for use on non-dairy farms (World Bank Group, 2017).

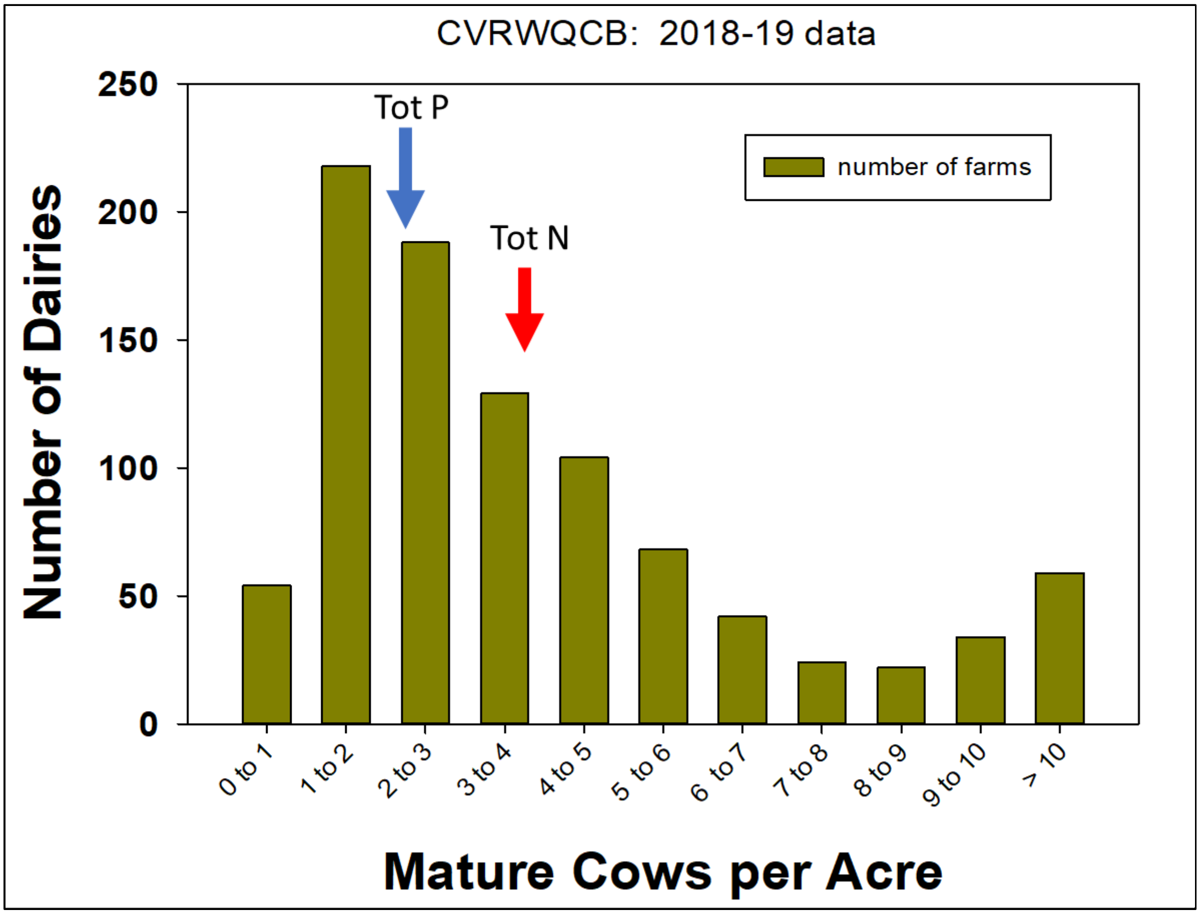

Figure 1.12. Approximate stocking rate thresholds associated with P or N based standards for manure applications (Tot N is based on this study; Tot P based on Pettygrove et al, 2009**).**[25]

The loss of crop production acres under SGMA

SGMA is affecting the amount of water available for irrigation on farms in the San Joaquin Valley and elsewhere in the state by limiting the amount of water that can be withdrawn from wells on farms, without offsets from additional supplies from surface water sources. Current drought conditions also concurrently limit the amount of surface water delivered to farms in canals by irrigation districts and the state and federal governments. This regulation will limit the production of forage crops on farms, effectively increasing the amounts of manure N and P that are surplus. If increased amounts of purchased feeds are used to replace lost crop production, surpluses increase accordingly. In effect,

[25] A commonly recommended N:P ratio for corn crops is five to one. But manure is enriched in P relative to N compared to common fertilizers. Samples in California collected and analyzed by Pettygrove et al., (2009) reported N:P ratios of 2.3 to 3.0. Using these values, the allowable N amount applied as manure would decline to ≈ 60 % or less than the amount that can be applied using a N basis for application and reduce threshold stocking rates as calculated here by approximately that amount.

these circumstances combined act as standard limiting manure application to fields. We have not attempted to estimate the effects of SGMA and drought on dairy manure management because policies are still being implemented and also due to time constraints for this report.

1.5.1. Dairy farm co-location

The climate benefits of using manure and manure composts on non-dairy farms depend on more than their values as fertilizer and organic amendments. Solid manure and manure composts contain some moisture and have relatively low bulk density. They require over-the-road transportation to off-farm locations. The greater the amounts moved and the longer the distances, the more energy is needed to transport them, with associated climate related emissions. In addition, solid manure must be spread on fields, an additional cost requiring machinery and fuels. These costs are accounted in TASK 5, focusing on Life Cycle Assessment.

Dairy co-location is a factor that constrains, but may also support manure nutrient recovery, removal and reuse. Co-location constrains export of surplus manure over short distances to neighbors' farms when many neighboring farms also are dairies. At the same time, this challenge also increases the need for treatment technologies that recover surplus N (and/or P) from manures in usable form for export to non-dairy farms. Geospatial analysis can be used to visualize areas where large numbers of dairies or large surpluses on N and P occur within each NMZ and across NMZ boundaries. Fig 1.13 maps N surpluses and Fig. 1.14 maps P surpluses in the northern SJV and southern SJV, based on dairies within the NMZs analyzed. Data used are the same as all the analyses presented here. N surpluses are based on stocking rates greater than 3.3 cows per acre, the median value of dairies in the data analyzed (Table 1.3) and P surpluses are based on using 2.3 cows per acre as the manure application threshold.[26] These geospatial visualizations reinforce the localized nature of dairy-related nutrient surpluses, particularly overloading in a few important subregions in the Turlock NMZ in the northern San Joaquin Valley (northern SJV) and the Kaweah/Tule NMZs in the southern SJV. The occurrence of P nutrient surpluses is like N, except challenging due to the lower application threshold estimated for manure P.

Surplus N and potentially surplus P in manure in these areas is still much less than overall fertilizer application in the northern SJV and southern SJV. Fig. 1.15 indicates areas in the larger region where fertilizer N and P could be transported and applied to non-dairy crops that might otherwise use nutrients recovered from manures, if using those nutrients were cost-effective. Crop nutrient demand was evaluated based on UC Davis cost and return studies produced by the Agriculture and Resource Economics Department, which estimate fertilizer demand on a per acre basis for all of California's major cropping systems (UC Davis ARE, 2021. These are based on grower interviews, focus groups, statewide economic datasets, modeling and expert judgement. Annual N and P demand by crops was linked with land cover spatial data from the USDA NASS *Cropscape* dataset[27], mapped to 1-km hexagonal grids covering the central valley.

Most P is in the SM fraction. N tends to be more concentrated in the LM fraction, though SM also is a N source. P distribution will rely on off-farm sales of dry manure or manure composts, or as struvite, while

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[26] In our analysis, we estimate that all farms distribute 20 % of total manure N available for application as solid manure. While 4 cows per acre were used to calculate surpluses, using the median value for dairy size within the NMZs to assess manure transport off-farm more completely reflects the scale of the distribution problem.
[27] https://nassgeodata.gmu.edu/CropScape/

N may be removed as a concentrated fertilizer product after treatment (Task 2) or as dried SM and composts. Based on these maps, there appear to be large areas of croplands capable of receiving surplus dairy manure nutrients in the SJV, especially in the southern and western portions of the valley. Distribution will depend on the form and quality of the manure materials and manure products developed to recover, remove and reuse surplus nutrients form dairy manures, and other properties as fertilizers and as soil amendments. This is discussed in greater detail in Task 2 and 4.

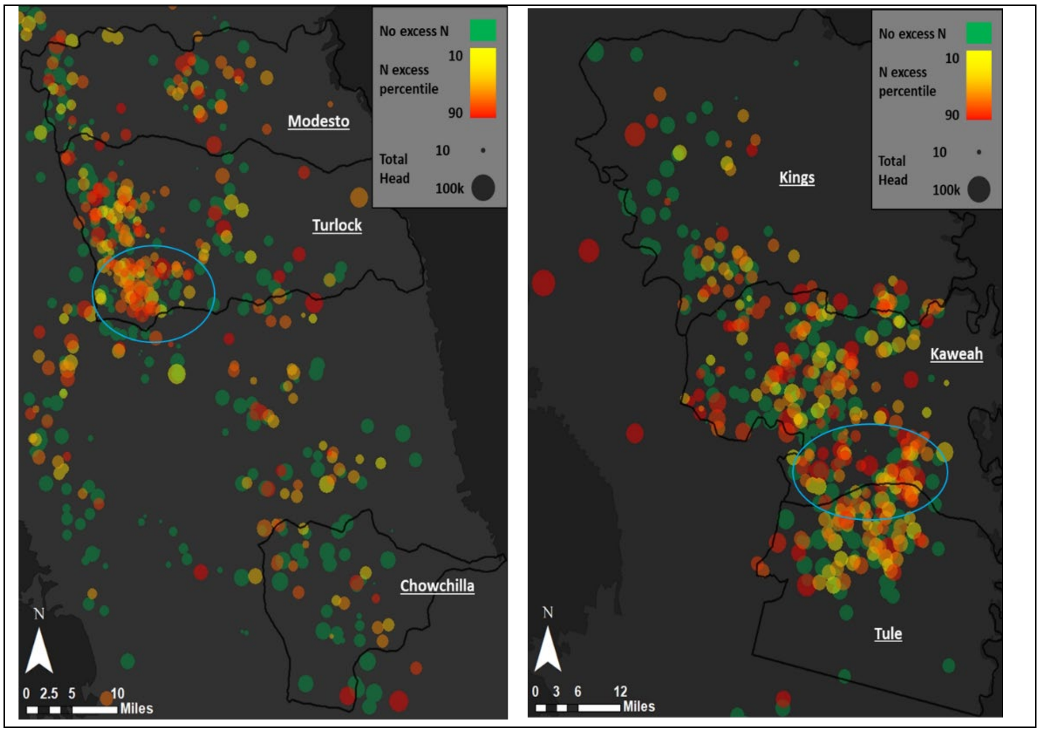

Figure 1.13. Areas within priority 1 NMZs with dairy manure N surpluses.

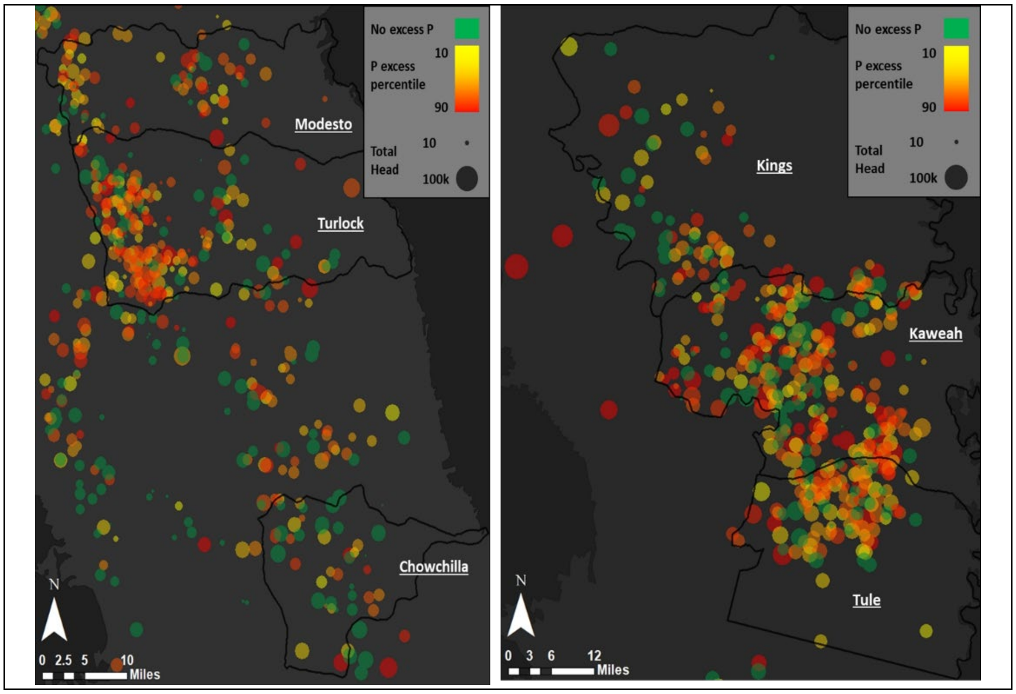

Figure 1.14. Areas within priority 1 NMZs with potential dairy manure P surpluses

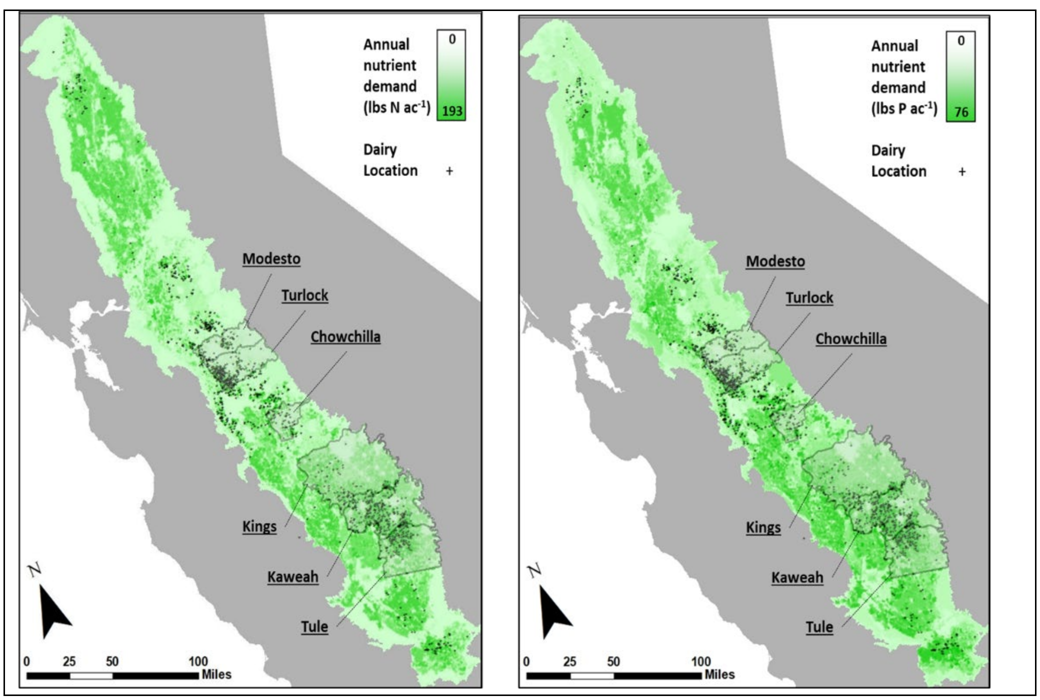

Figure 1.15. Potential crop nutrient demand for surplus dairy farm N and P.

1.6. Research questions and data needs

This report is an initial attempt to estimate manure nutrient surpluses within each of the priority 1 NMZs in the SJV. The goal was to identify the potential for adoption of manure nutrient recovery, removal and reuse systems on dairies with surplus nutrients, especially N. The character of individual dairies (free stall, open lot or mixed) was not identified in the data available and was estimated using reported proportions of each type (Meyer et al., 2019).

(1) Additional data collection about dairy type and better characterization of manure deposition on concrete or corrals and pens on each dairy would improve the estimates of the liquid and solid manure amounts in surplus per farm within each NMZ. It would also help align different alternative management technologies with individual farms and subregions of each NMZ with concentrated manure nutrient surpluses. The SRMR report provides a well-developed methodology for farm nutrient balance estimation.
(2) Solid manure is managed variably, and nutrient contents available for application to crop fields vary accordingly. A range of nutrient values is reported in the technical literature. Better characterization of solid manure N contents at the individual farm level as it is actually managed are needed to assess more accurately the amount of N available in this form, and amounts of nutrients available for recovery and reuse, to support improved management on the farm and adoption of new, advanced treatment technology. Ways to more accurately and cheaply characterize and/or predict manure N content (especially solid manure) would be helpful.
(3) Optimum solutions to manure surpluses will be affected by differing circumstances within each NMZ. In some areas of each NMZ, dairies are densely co-located. These areas should be identified and analyzed carefully for the opportunity to transport solid manures out of the region, and for the treatment of liquid manures on individual farms or in groups or clusters of farms. Creative, entrepreneurial activity in such areas is needed to devise effective solutions to regional manure nutrient surpluses through projects adapted to individual farms or to groups or clusters of farms.
(4) Nutrient surpluses exist within both liquid and solid manure materials on diaries. The proportions vary by farm. Transporting solid manures to non-dairy farms occurs but is limited economically and environmentally as distance increases. Finding ways to overcome the limitation on solid manure (or manure compost) distribution by distance is needed.
(5) Research on the value of solid manure, solid manure composts and novel manure products for a wide range of annual and perennial crops grown on non-dairy farms is needed to support wider use of these materials (See TASK 4).
(6) Pending reductions in the availability of irrigation water in the SJV under SGMA will alter the results presented. Any reduction in the amount of land used for crop production and manure disposal, and reductions in crop yields and nutrient removal due to decreased amounts of water available for irrigation will increase manure nutrient surpluses. If dairies respond to lost on-farm production of forages by purchasing more feeds, nutrient loading relative to land area will increase. It is not clear how individual farms will respond to these changes. Modeling is possible to predict the consequences of decreasing water availability for irrigation and its consequences for manure nutrient management.

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TASK 2:

Nutrient Recovery Systems

Manure nutrient recovery methods include so called "advanced solids separation" (or fine solids removal), nitrification/denitrification, evaporation, and others. There are many ways to manage surplus nutrients in manures. These are listed and discussed on a useful website created by the *Newtrient Group*[28]. Some of these technologies are listed in Figure 2.1, organized by primarily solid manure (SM) or liquid manure (LM) systems. A subset of these, marked by an "*" is evaluated in this report. Many of the technologies listed on the *Newtrient Group* website are in early stages of development or not yet commercially demonstrated. The ones evaluated here are either in commercial use, or demonstrated on dairies, or commonly available in California or elsewhere. Algal raceways and duckweed (Lemna sp.) production systems fit under this description but are not evaluated here due to time and resource limitations. They are described in Timmermann and Hoving (2016), and in Rude et al., (2022).

How and where manure is collected influences adoption of potential nutrient recovery systems. These systems focus on raw manure or liquid manure (LM) primarily collected on concrete. Solid manure (SM) deposited in corrals and other soil surfaces is managed variably and generally conserves less than manure falling on concrete. Manure in a solid form is less useful for the systems evaluated here and would have to be re-wetted or otherwise prepared to be useful and have reduced levels of recovery. LMs are more suitable for nutrient recovery systems due to greater uniformity of the material and the collection of urine, the form in which most N is shed by cows. Liquid Manure (LM) collection systems commonly are structural elements of farms, designed and integrated with freestall barns and other concrete surfaces. They are not easily altered, but lend themselves to post collection secondary treatments, such as those considered here.

[28] https://www.newtrient.com/Catalog/Dairy-Manure-101

Manure Treatment Technologies

Solid Manure	Surplus Nutrient Reduction, Recovery and Reuse
Active solids drying **Solids separation**: Screens, centrifuges, screw presses, weeping walls, sand separation	Sale of dry solids Composting* and sale Pyrolysis and gasification Struvite crystalization Torrefaction
Liquid Manure	
Aeration **Anaerobic Digestion*** **Evaporation**	Algal raceways Duckweed based systems Ammonia stripping* Chemical flocculation* Membrane systems Nitrification/denitrification (vermiculture*)

Figure 2.1. Manure treatment technologies categorized by type. Those evaluated in this report are indicated with an *.

Solid separation: Primary, or course solids screening removes only small portions of nutrients from the effluent flow (Jensen et al., 2016). Phosphorous and much of the organic N is contained in the suspended fine solids remaining after primary screening (Frear et al., 2018). Advanced, or fine solids separation is therefore effective for P and organic N recovery. Centrifuges, flocculation systems and high-pressure membrane filters are commonly used for fine solids removal in industrial and wastewater treatment applications.

Nitrification/denitrification (NDN) is a microbial process converting ammonia to nitrite and then nitrate (nitrification) followed by nitrate reduction to gaseous N (denitrification) (TASK 1). This process is used extensively in municipal wastewater treatment systems to reduce effluent ammonia amounts. Dairy manure is problematic for use in standard wastewater treatment NDN systems because of high ammoniac N and solids (Frear et al., 2018).

Evaporation systems concentrate nutrients through volume reduction and can produce a relatively clean water fraction via condensation. The nutrients are mostly retained in the thickened slurry (12-25% solids), or a solid product if enough moisture is evaporated.

In this task, three nutrient recovery systems applicable to dairy manure are described:

1. The *Trident Nutrient Recovery System* which uses a flocculant followed by dissolved air flotation to separate and recover fine solids ("advanced solids separation"). This system is operating on several dairies in the U.S.

2. The *BioFiltro BIDA System* which is a trickling vermifilter that removes ammoniac N through NDN and retains much of the P and organic N in the organic filter media. This system is being piloted at several dairies in the US (including at least one in California).
3. The *Sedron Varcor* process which uses evaporation by mechanical vapor recompression (to reduce energy consumption) to concentrate the nutrients in dried manure solids ((≤ 10% % moisture) and an aqueous ammonia stream. Relatively clean water is a byproduct. This system is being demonstrated at a 3000+ cow dairy in the Midwest and is being considered for at least one dairy in California.

There are many potential dairy manure treatment technologies that recover nutrients from manure at some level of concentration and facilitate the use of recovered nutrients on non-dairy farms. These are summarized usefully in Frear et al., 2018 and on the *Newtrient* website. Many are still developmental or lack demonstration under farm conditions. These three technologies were selected because they are currently in use in one or more dairies, including in California.

2.1. Trident Nutrient Recovery System

The Trident Nutrient Recovery System treats liquid or slurry manure using a dissolved air flotation system (DAF) to recover the majority of P and smaller amounts of N and potassium (K) in the separated fine solids. The system is modular and typically consists of course solids removal followed by a standard flocculant (typically polyacrylamide) and DAF system for fine solids removal. The flocs or coagulated fine particles float to the surface in the DAF vessel assisted by small air bubbles. The floating sludge-like material is skimmed and passed through a disc press dewatering the material to about 20% dry matter (sometimes called "fine solids cake"). The combined effluent from the DAF and the disc press, with relatively low solids content, flows to storage for reuse as flush water and eventual irrigation (Figure 2.2).

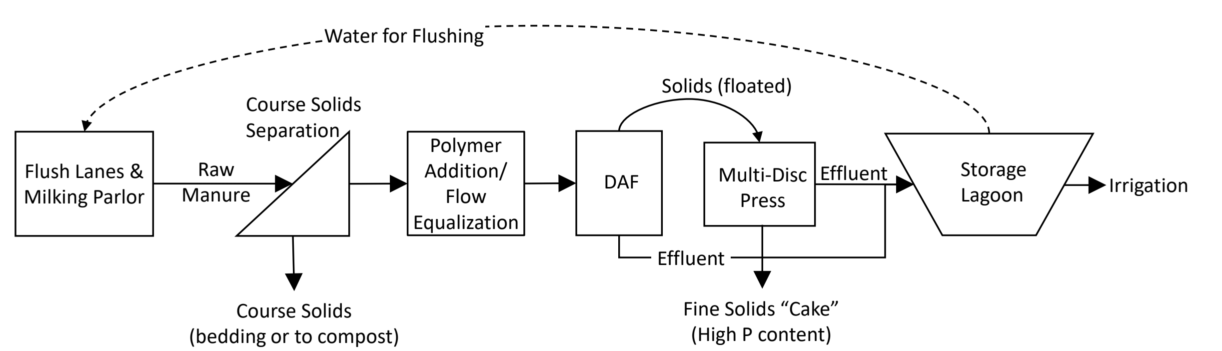


Figure 2.2. **Typical layout of the Trident system at a flush dairy.**

DAF was developed in Sweden in 1965 for use in clarifying drinking water (Crossley & Valade, 2006) and is used primarily in the drinking water and pulp and paper industries. Because of its ability remove fine solids and partition nutrients, more than 20 DAF systems have been installed on dairies in the U.S. (Stacey et al., 2021).

Nutrient Recovery (Trident DAF)

DAF systems can recover up to 90% of the P and smaller amounts of N and K (Table 2.1). Roughly half of the N (organic N and nearly all the ammoniac N) and more than 80%+ of the K remains in the liquid effluent.

Table 2. 1. Nutrient recovery fractions in fine solids from DAF systems

Nutrient	Fraction Recovered in Fine Solids (%)
N	15 - 55
P	45 - 90
K	10 - 20

Notes:
Sources: Canter et al., (2021), Porterfield et al., (2020), Newtrient (2022), and Frear et al., (2018).

Canter et al., (2021) measured flows and analyzed grab samples at a dairy in the Midwest with an operating Trident Nutrient Recovery System. Table 2.2 shows the distribution (or partition) of nutrients and solids they measured across the three main product flows: Course Solids, Fine Solids Cake, and Liquid Effluent.

Table 2. 2. Distribution of nutrients and solids measured at a Trident Nutrient Recovery System Installation

Constituent	Distribution Fraction (% of input)		
	Course Solids	Fine Solids Cake	Liquid Effluent
Total N	8	38	52
Ammonia N	4	12	76
P	10	70	20
K	3	13	80
Solids	22	43	31

Notes:
Source: Canter et al., (2021).

Trident Costs

Installation cost at a 7,000-cow dairy farm was approximately $2.5 million (Angerman, 2019). Assuming operation and maintenance costs of approximately $391,000/year (including electricity consumption) and amortizing the installation cost over ten years at 8% annual interest, the total annual cost of the Trident system is nearly $764,000 or $109 $/cow/year (Table 2.3).

Table 2. 3. Trident Nutrient Recovery System Cost Estimate for a 7000 cow dairy				
Adult Cows	Total Capital ($) [a]	O&M ($/y) [a, b]	Annual Cost ($, 10 year 8% loan) [c]	$/cow/y
7000	2,500,000	390,990	763,563	109

Notes:
[a] Angerman, (2019).
[b] Includes $164,000 (892,000 kWh/y) electricity consumption.
[c] Capital cost is amortized for 10 years at 8% interest.

2.2. BioFiltro Vermifiltration

The BioFiltro BIDA system is a vermifiltration wastewater biotreatment system consisting of a layer of wood chips or shavings inoculated with earthworms in the upper portion. Beneath the woodchips is a porous layer of gravel or river cobble. The bottom of the system is a catchment or drainage basin (Figure 2.3). Wastewater is applied to the top surface and trickles down through the media where it is degraded by symbiotic activities of earthworms and microorganisms (Zhou et al., 2010). The Biofiltro system is primarily an aerobic bioreactor, maintained by tunneling activities of the earthworms, with anaerobic conditions inside the worm gut and small non-aerated pockets in the media (Lai et al., 2018). Periodically (i.e., every twelve to eighteen months), the organic media along with accumulated worm castings and retained influent solids are removed and can be used as fertilizer or compost. Vermifiltration was added to CDFA's AMMP program in 2021.

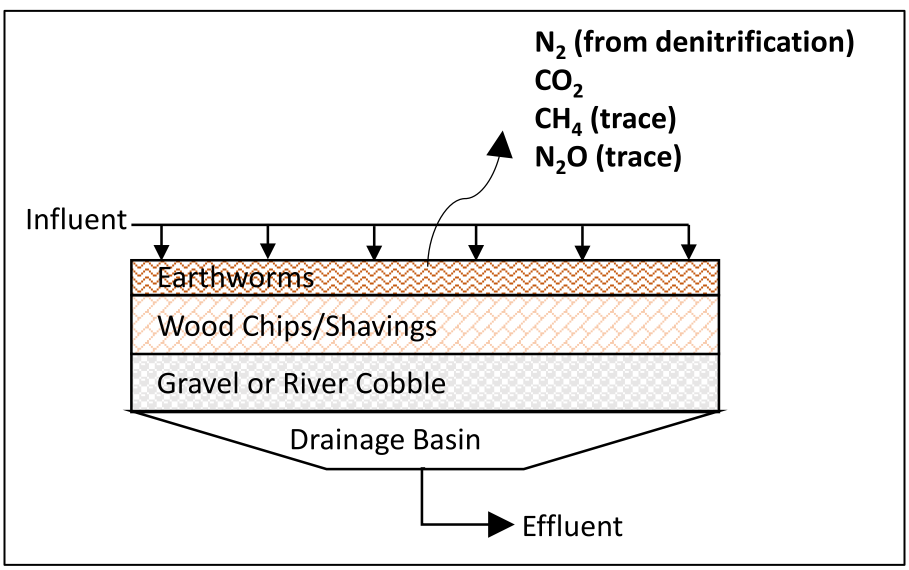


Figure 2.3. Schematic of the BioFiltro BIDA vermifilter.

With vermifiltration, ammonia N is reduced via biological nitrification/denitrification producing mainly N gas (N_2) with trace amounts of N_2O (Frear et al., 2018, Lai et al., 2019). A portion of the influent P and K remains in the media in captured solids, worm castings and adsorbed onto the wood chips. Solids and volatile solids in the effluent are reduced by biological activity and/or trapped in the media.

Nutrient and Solids Reduction

For systems treating dairy manure, total N in the effluent is reduced 40%-90% compared to that in the influent. Phosphorous (P) and potassium (K) reduction range from 20%-80% and 0-25%, respectively. Total solids reduction is 30%-80% while volatile solids are reduced 80%-90% (Table 2.4).

This fairly large range in nutrient and solids reduction is likely due to differences in manure management and flush rates, placement of the vermifilter within the manure management system (before or after a wastewater storage lagoon), amount of course solids removal prior to the vermifilter, scale (pilot or full flow treatment), climate, etc. among the systems in the cited literature.

Table 2.4. Nutrient and solids reduction by vermifiltration of dairy manure*.

Component	Reduction (%)*
Total N	40-90
NH4-N	70-97
P	20 - 80
K	0 - 25
TS	30-80
VS	80-90

Notes:
*mass in Effluent/mass in Influent.
Sources: Pasha et al., (2018), Lai et al., (2018), Miito et al., (2021), Dore et al., (2019), Dore et al., (2022), and Frear et al., (2018).

System Layout

For treating flush dairy manure, coarse solids need to be removed from the flush stream prior to entering the vermifilter. The liquid effluent from the vermifilter would be sent to a storage lagoon for reuse as flush water and/or eventual irrigation. The preferred placement of a vermifilter at a flush dairy is shown in Figure 2.4. Some installations put the vermifilter after the primary storage lagoon and upstream of a second (or effluent) lagoon.

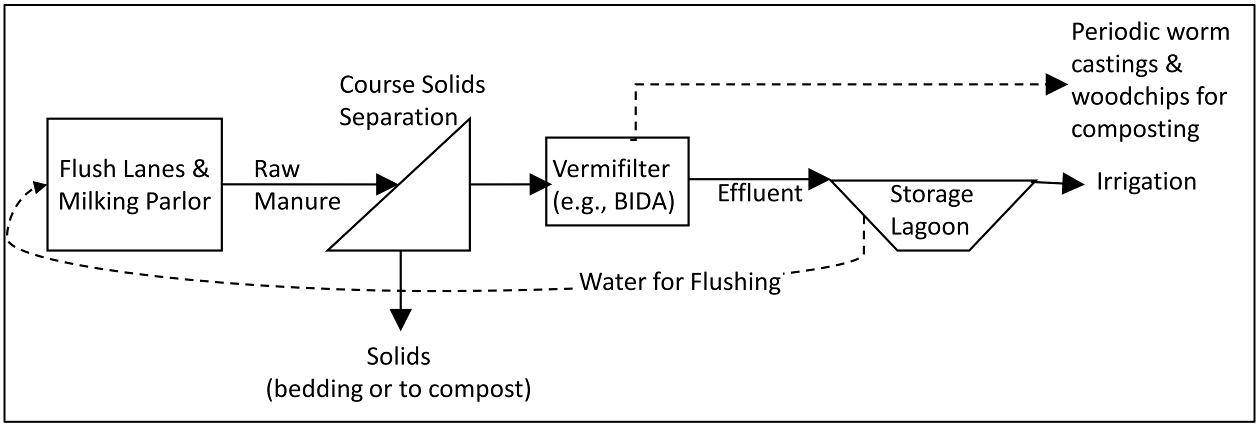


Figure 2.4. **Schematic showing manure flow at a flush dairy with a vermifilter.**

Size and Cost

A BioFiltro vermifilter for a dairy would require about 0.9 – 1.2 ft^2 surface area per gallon-per-day (GPD) of flow with less than 3% total suspended solids in the inlet (BioFiltro 2022). Therefore, land area required for a vermifilter would vary from about 0.6 acre for a 500-cow flush dairy to 12.5 acres for a 10,000 cow dairy (Table 2.5).

Table 2. 5. Vermifilter size vs. dairy size

Adult Cows	Vermifilter size*	
	Square Feet	Acre
500	27,260	0.6
1,000	54,520	1.3
3,000	163,559	3.8
5,000	272,598	6.3
10,000	545,196	12.5

Notes:
*Assumes vermifilter surface area requirement is 1 ft^2 GPD^{-1} of flow, 60% of excreted manure falls on concrete and is flushed. TS before and after course solids separation is 3% and 2.2%, respectively.

BioFiltro system costs \$200-\$300 per cow to install and approximately \$40-\$50 per cow per year to operate (Frear et al., 2018; and Dore et al., 2019), (Table 2.6).

Table 2. 6. BioFiltro Costs

Capital Cost (\$ cow^{-1})	Operation & Maintenance (\$ cow^{-1} $year^{-1}$)
180 - 280	40 - 50

Biofiltro offers agreements with dairy operators where CAPEX is potentially paid by carbon credits and costs funded by selling of vermicompost. BioFiltro purports that the system can be installed with relatively little money from the dairy (Dore 2022).

Methane Emissions

Lai et al. 2018 measured methane emissions of about 0.8 kg/day from a BioFiltro vermifilter at a California dairy. The vermifilter was 539 m^2 in size and designed to process manure from about 150 adult cows (after coarse solids separation). Assuming 60% of total manure is collected in the flush system, and 30% solids removal in the separator, the BioFiltro unit has a methane emission factor of approximately~0.0019 kg CH_4/kg VS which is about 98% lower than the emissions factor for anaerobic lagoons (Table 2.7). Dore et al., 2022 measured methane emissions at the same vermifilter and found the emission factor was approximately 99% lower for the vermifilter compared to an anaerobic lagoon.

Table 2. 7. Methane emission factors for a BioFiltro vermifilter and an anaerobic lagoon using dairy manure.

	Emission Factor (kg CH_4 kg^{-1} VS)	**Notes**
BioFiltro	0.0019	Derived from Lai et al. 2018 measurements
Anaerobic Lagoon	0.119	Based on ultimate methane yield (B_0) = .24 m^3 kg^{-1} VS and lagoon methane conversion factor (MCF) of 0.748 (CARB Livestock Protocol)

Overall system methane emissions for a BioFiltro vermifilter that discharges into a storage lagoon (anaerobic lagoon), see Figure 2.4, is about 0.026 kg CH4 per kg of VS that enters the vermifilter (Table 2.8). This is about 78% less methane emitted than the system without the vermifilter (i.e., anaerobic lagoon only).

Table 2. 8. System methane emissions per kg VS.

Technology	System methane emissions (kg CH_4 kg^{-1} VS)	Reduction compared to Lagoon Only*
BioFiltro + Effluent to Storage Lagoon	0.026	78%
Lagoon Only	0.119	-

Notes:
*Assumes 80% VS removal by the BioFiltro vermifilter, 20% od VS flows to lagoon (Table 2.4)

2.3. Sedron Varcor

The Sedron Technologies Varcor™ system separates solids from a liquid or slurry input producing an aqueous ammonia stream (~80 g NH_4 /L^{-1}), relatively clean water (~30 mg NH_4 L^{-1}) and low moisture solids.

The solid and liquid fractions of the input stream are separated by thermal evaporation and the resulting vapor is sent to a compressor, where it undergoes Mechanical Vapor Recompression (MVR). The latent heat in the compressed vapor is then used as the heat source for the evaporation process (Figure 2.5). The compressed vapor condenses to a liquid after transferring its latent heat to the dryer. The liquid flows through the ammonia distillation system where an aqueous ammonia distillate stream is produced separate from the main condensate flow. MVR is used widely in applications that require concentrating or thickening a liquid (i.e., food, beverage, pharmaceutical, chemical industries, and zero liquid discharge wastewater treatment). Energy inputs include electricity, mainly for the compressor and, after initial start-up, a relatively small amount of natural gas to make up for equipment heat loss.

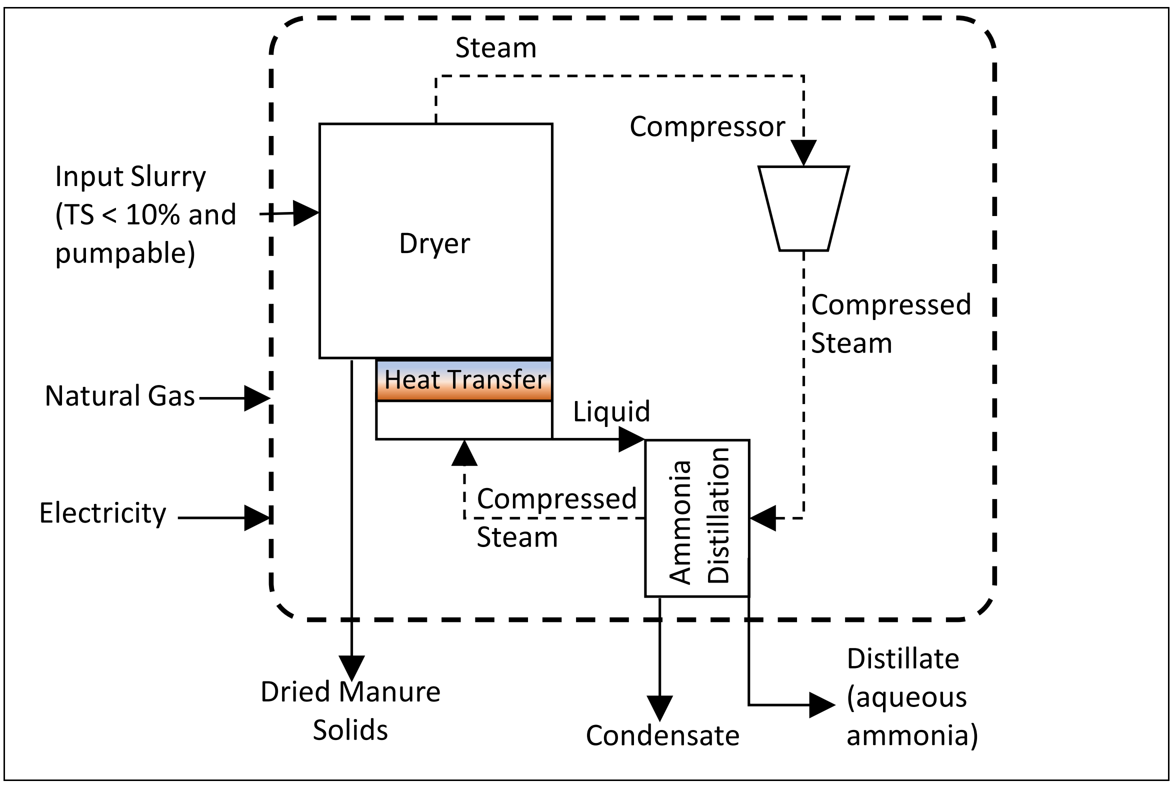


Figure 2.5. Sedron Varcor Schematic

The Varcor system can treat pumpable slurries with solids content less than about 10%. For application at dairies, the system is best suited for those that use scrape or vacuum manure collection and/or have effluent from a high solids digester (e.g., plug flow or continuously stirred tank design).

Flush manure management produces low solids, comparatively dilute, manure streams. Sedron Technologies is currently working with a California flush dairy on initial diligence and simple water optimizations for a Varcor system installation and would work with any interested dairy on a case-by-case basis to evaluate feasibility.

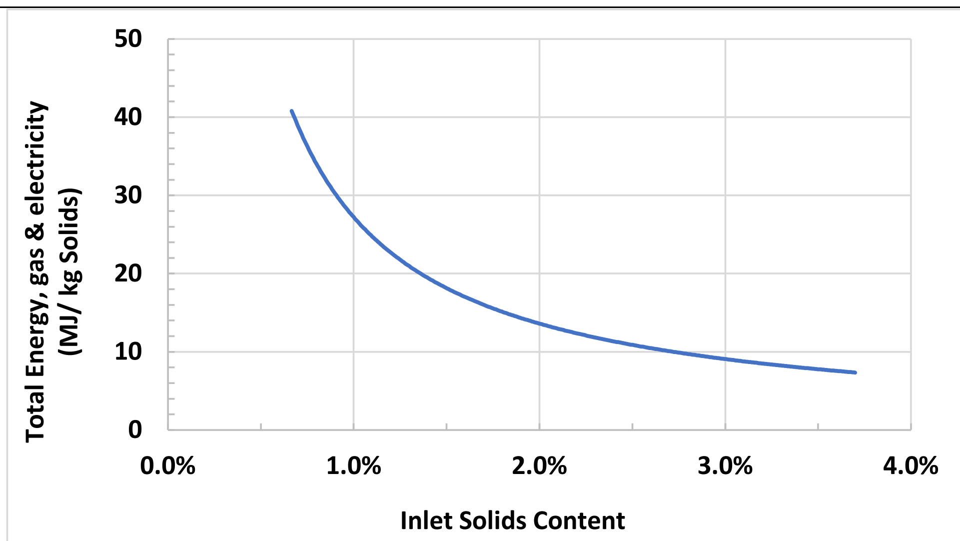
Nutrient Distribution

Ninety percent or more of the inlet ammonia is recovered in the aqueous ammonia distillate output stream. This could be used as a pathogen-free ammonium liquid fertilizer with about 10% N concentration and a pH of 7. The dried solids output retains essentially all of the inlet organic N as well as all of the inlet P and K. This could be used as weed and pathogen-free solid fertilizer. Finally, the relatively clean water (condensate) output could be recycled at the point of use. The solids output product has been certified "organic" by the Organic Materials Review Institute (OMRI). Sedron is presently pursuing organic certification for the ammonia distillate product through OMRI (Sedron 2022).

Energy Requirement

The Varcor system is treating effluent from a plug-flow digester at a 3500-cow dairy in the Midwest that utilizes vacuum manure collection. It processes 90 gallons per minute at approximately 3.7% solids. The energy to operate the system is about 80 MMBtu/day (84,400 MJ/day) of natural gas and 14 MWh/day of electricity (Sedron 2022). This is about 1/8th of the energy needed for a dryer with no latent heat recovery (i.e., without MVR).[29]

On a per-kg solids basis, the energy required to separate solids climbs steeply as the influent solids content decreases (Figures 2.6 and 2.7).



Note: Based on energy requirement for 90 gpm constant liquid volume flow.

Figure 2.6. **Approximate total energy requirement vs. inlet solids content for the Varcor system.**

[29] Energy to evaporate w/o MVR: 2.26 MJ/kg-water x 475,596 kg-water/day = 1,075,000 MJ/day

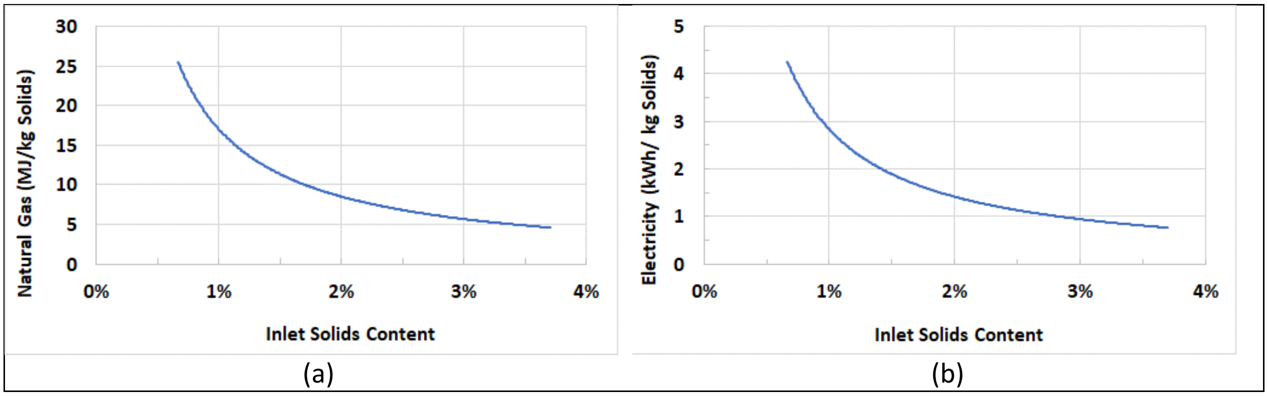


Figure 2.7. Approximate natural gas requirement (a) and electricity requirement (b) vs. inlet solids content for the Varcor system.

Sedron business model for Varcor

Sedron would establish manure supply and land use agreements with an individual dairy or group of dairies and then design, build, own, operate, and maintain a Varcor system. Sedron would operate the system at no cost to the dairy and market the fertilizer products for revenue.

Evaluating the feasibility of a Varcor system is conducted on a case-by-case basis with the interested dairy(ies).

2.4. Potential Application to Farms in California

The systems discussed above are suitable for treating liquid manure, and/or digester effluent at California dairies, with varying degree of nutrient recovery.

The BioFiltro vermifilter system is relatively simple to operate but installation cost appears high (though BioFiltro purports that the system can be installed with relatively little money from the dairy through carbon credits). The footprint requirement is rather large and scales with the amount of manure or dairy size. This could be a drawback, especially at large dairies, though a system is currently operating at scale on a large Washington State dairy[30]. The system has the potential to reduce a large amount of N in the effluent (by de-nitrification) and significantly lower the CH_4 emissions from a storage lagoon if it directly treats fresh flushed manure. Because it is an NDN process, a large of amount of N in excreted manure is lost to the atmosphere as N_2 gas, negating its further use on non-dairy farms as a N fertilizer replacement. But it also reduces NH3 losses from liquid manures, the major pathway for reactive N loss (Rotz et al., 2021).

The Trident Nutrient Recovery System can remove most of the fine solids and recover nearly all the P, and moderate amounts of N, in the manure flow. It may be attractive at larger dairies, or dairy clusters, due to economies of scale.

The Sedron Technologies evaporation system appears highly effective at recovering nearly all the N, P, and K in treated manure for use as potential fertilizer products. Since the largest losses of reactive N

[30] https://jofnm.com/article-106-Worms-do-the-dirty-work.html

from dairy farms in California are from NH_3 emissions to the atmosphere (Rotz et al. 2021), and likely are the most difficult to manage under the agroecological conditions of the Central Valley, this technology also has the benefit of reducing losses through this pathway, while capturing and recycling N. It seems better suited for higher solids manure flows because of the energy required to remove water. Sedron claims costs to the dairy would be minimal, depending on the manure supply agreement with Sedron. Sedron would own and operate the system and sell the output fertilizer products.

2.5 Additional Research and Demonstration Requirements

All these systems are relatively or completely new to California dairy farmers and have not been demonstrated and evaluated at commercial scale in the state. All technologies in the early stages of development undergo refinement and improvement.

There is a large range of values for nutrient recovery reported in the literature for vermifiltration and uncertainty in the recovery values for the DAF and evaporation systems is likely higher than reported since there are fewer publicly available data. Research to understand variability in vermifiltration performance (or verify performance) at full scale for typical California dairies is recommended. In fact, any opportunity to closely monitor and verify performance of commercial scale operations for these three technologies should be utilized before setting policy or incentivizing installation with state funds.

The ongoing Manure Recycling and Innovative Products Taskforce (MRIP**)** advising the Secretary of the California Department of Food and Agriculture (CDFA) supports establishing on-farm demonstrations of likely manure nutrient recovery technologies to both adapt them to California dairy conditions, and to provide publicly available data for further analysis of the performance of these systems. This recommendation should be supported by CDFA and the state's dairy industry.

2.6 References Task 2

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Task 3:

Effects on dairy farms of surplus nutrient removal

Dairy farms in California are very diverse in size, organization, cow numbers, age, economic condition, history, and many other characteristics that affect the way manure is managed and used. All dairies must operate under a permit under the state's General Order[31]. The General Order requires reporting data on manure and crop management and restricts dairies to applying more manure to fields than can be recovered by crops, accounting for unavoidable losses and incomplete plant-availability of manure N. The application ratio of 1.4 times crop N uptake was judged to be adequately protective against losses of nitrates to groundwater. Nevertheless, nitrate pollution of groundwater is common in the Central Valley of California, and especially in areas with large numbers of dairy farms (Harter et al., 2017).

Different reviewers and analysts of dairy manure management over the years have identified discrepancies between reports to the regional board and calculated N contents in manure (Cativiela et al., 2019[32]; Parsons and Harter, 2018; Miller et al., 2017; Chang et al., 2006). These deficiencies explain in part the occurrence of nitrate exceedances in groundwater in the Central Valley. But like all human activities, there are large differences among farms with respect to manure management practices and risks of excessive loss of nitrates to groundwater. This variation was characterized in Task 1 in this report for dairies located in the Priority 1 nitrogen management zones (NMZs) in the San Joaquin Valley (SJV). These NMZs include farms that must provide alternative sources of nitrate-free drinking water to groundwater users affected by nitrate exceedances in their domestic water supplies. The six Priority 1 NMZs start in the Modesto area in the northern SJV and extend to Kern County in the southern SJV (Task 1: Fig. 1.1) and include a majority of California's commercial dairy farms.

In Task 1, we estimated surplus N in manure based on (1) estimated average values for N conserved in solid and liquid manure handling systems, (2) differences in animal housing (free stall and open lot dairies) and associated manure management systems, (3) estimated crop N uptake for typical forage cropping systems on California dairies based on cereal and corn silage crops, and (4) stocking rates derived from data reported to the CVRWQCB in the 2018-19 period. Significant yearly accumulations of

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[31] https://www.waterboards.ca.gov/centralvalley/water_issues/confined_animal_facilities/program_regs_requirements/dairy/

[32] "Evidence garnered from annual reports to the Regional Board by individual dairies suggests a substantial amount of "unaccounted-for" manure N exists on many dairies. This unaccounted-for portion is essentially the difference between N excreted by cows (supply) and what is reported as being applied to agricultural fields to fertilize crops (demand) and/or exported from the dairy. Some of the unaccounted-for portion of N can be attributed to volatilization of N as ammonia and other gases, but those pathways don't fully explain the difference between excreted N and applied N. Large amounts of unaccounted-for N, combined with imprecision in measurement of applied N and irrigation water, can result in overapplication of N to crops and reduced NUE." SRMR page 23 (Cativiela et al., 2019).

surplus N greater than the amounts lost from manure conservation systems plus amounts recovered by crops were estimated for farms with ≥ 4 mature cows plus replacements per acre. Surpluses increase with stocking rates (cows ac^{-1}). Surpluses occurred in both liquid and solid manure fractions. Farm size based on total cow numbers was not correlated uniformly with surplus N. In the Turlock NMZ, smaller farms (in acres) with higher stocking rates (due to limited acres of land available for manure application) were the most important locations for surplus N. In other NMZs, surpluses were more evenly distributed across farm sizes (Task 1).

On farms with higher stocking rates and large surpluses, manure or manure nutrients must be exported off the farm to avoid groundwater pollution problems from manure application to crop land. Excess manure must be exported off the farm, or alternatively, treatment technologies that remove nutrients from manure through denitrification, or which capture and concentrate nutrients for use off the farm on non-dairy enterprises. Selected technologies for manure N and P recovery, removal and reuse are evaluated in Tasks 2 and 5, including the GHG emissions associated with each technology. The fertilizer value of treated manure products from some of these technologies and the benefits of manure application to soils and crops are discussed in Task 4.

For the most part, new types of engineered treatment systems are expensive (Task 2) and may involve structural changes to manure collection and treatment systems. To be economic, engineered systems may be limited to larger dairies or require larger supplies of suitable types of manure assembled from a set or cluster of dairies, perhaps organized as a coop. Supportive public policies could help offset initial investments in new technology in ways like policies supporting the adoption of anaerobic digesters or alternative manure management practices on dairy farms in the state, including supporting demonstrations of new technologies under farm conditions. For example, the Dairy Digester Research and Development Program[33] integrates public with private capital for construction of anaerobic digestion facilities that become a significant portion of a farm's total capital investment. Policy stability and cost sharing are essential to support the adoption of new management technologies when significant capital and operating costs are involved (Lee and Sumner, 2018).

Farmers are aware of these costs and risks, so they will favor lower cost solutions under most circumstances that can be adopted without substantial modification of farm operations and structures. These are referred to here and in a companion report by an advisory committee to Secretary Ross (MRIP, 2022) as **conventional strategies**. For dairy farms at or near farm nutrient balance, these strategies will improve overall efficiency and better align nutrient production in manure with crop fertility requirements. This would help reduce the use of supplemental N fertilizers commonly used and improve farm nutrient balances. These methods collectively help reduce the risk of nutrient losses to groundwater or via other pathways. For farms with substantial nutrient surpluses, these strategies also can help improve nutrient use efficiency within the farm but not eliminate the need to recover and export surplus nutrients off the farm.

[33] https://www.cdfa.ca.gov/oefi/ddrdp/

3.1. Conventional strategies

To evaluate the responses of leading dairy producers to stricter requirements for balancing manure N with crop uptake, we met with farmer-members of the Central Valley Dairy Representative Monitoring Program (CVDRMP). The CVDRMP had recently published a comprehensive assessment of manure management issues and potential methods to improve accounting and management of nutrient surpluses on dairies in the state called the Summary Representative Monitoring Report (SRMR) (Cativiela et al., 2019). This report proposes a range of recommended short-term changes to dairy manure management and its measurement[34]. All dairy farmer participants in the CVDRMP participated in creating these recommendations. Participants in the discussion understood that surplus nutrients are a problem on some dairies, but also that other dairies had worked successfully to manage manure nutrients effectively.

A diverse set of conventional strategies were discussed by the CVDRMP members. These are improvments in current practices that would result in closer alignment between manure applied and crop nutrient recovery, and be better protective of groundwater, without requiring the adoption of new forms of technology or significant alterations in manure management practices. In themselves, they would not address surplus nutrient accumulation resulting from large stocking rates but nevertheless could help improve nutrient management in fields belonging to a dairy of any size. The discussion with CVDRMP members is summarized and discussed qualitatively here. Cativiela et al (2019; Chapter 3) have estimated the costs of a diverse set of conventional and engineered solutions to manure management, including these conventional approaches.

3.1.1. Improving measurement and accounting of manure nutrients

Conventional alternative practices can be grouped in a few larger categories. The first involves improving measurement of manure nutrient content, application rates, irrigation practices and crop nutrient removal. What isn't measured can't be managed well. But measuring manure nutrient contents is difficult since manure is alive with micro-organisms which constantly change its character and produce emissions (Miller et al. 2017; Task 1, Fig. 1.2). Nutrient contents are inconsistent, especially in solid manures. Since manure is a variable material, some error in applying nutrient amounts quantitatively is unavoidable, and measurement errors are commonly greater than 10% (Task 1: Table. 1.7). Current requirements for sampling and measurement are insufficient to accurately account for actual nutrient contents as applied (Cativiela et al., 2019). Consistent, improved methods of sampling solid and liquid manures near in time to manure application, is a conventional strategy improvement.

Measuring liquid and solid manure application rates to fields also is challenging. Flow meters can and have been installed to measure lagoon water and manure slurry applications. They provide more

[34] SRMR specific short-term actions: Install flow meters on liquid manure systems to better measure application of lagoon water; Improve manure nutrient testing and crop nutrient recovery testing; Collect data on all manure applications and crop yields by field or zone; Improve data management; Collect less manure in the lagoon system by diverting some manure into solid management (vacuuming, less time on concrete, other); Export raw manures or minimally processed manures (windrow dried) to non-dairy sites; Extend the lagoon irrigation pipeline system to additional fields on the dairy; Haul liquid manure to non-dairy locations for surface application; Line lagoons (Cativiela et al., Chapter 2).

accurate estimates of LM transported to fields. But farmers commented that meters become a maintenance issue, have measurement errors, and may not perform uniformly when measuring variable materials like manure slurries.

Manure N is lost when applied to fields due to NH_3 volatilization, denitrification or leaching, but the amounts lost typically can only be estimated and vary with meteorological conditions, soil chemical and physical properties, and crop factors. Estimates are subject to uncertainty and error (Miller et al., 2017; Task 1: Table 1.7). Burt et al. (2014) recommend not relying on modeling manure N behavior in fields for regulatory purposes due to these large uncertainties.

Applying nutrients as manure uniformly across fields also is challenging. Solid manure is applied using trucks or manure spreaders attached to tractors. It can vary in nutrient and moisture content, sometimes from pile to pile, requiring sampling to account for differences. If there are differences in solid manure quality and moisture content, each truckload will transfer different amounts of material. Evenness of application depends on the machinery used, uniformity of speed, overlap, and variance within the manure source itself. On some farms, improvements in record keeping may be needed to better track manure use on fields over time. This may require use of truck scales (or their more consistent use) for solid manure loads going to fields and for crop loads harvested. More frequent sampling of manure and crops may be necessary. This adds time, effort, and expense. Improvements require trade-offs.

Liquid manure in California is applied commonly using surface irrigation systems. Surface irrigation commonly is non-uniform (Hanson, 1989). Within a field, when irrigating with lagoon water, water sources may be blended (to dilute or supplement lagoon water), with uneven mixing and nutrient distribution at the field scale. Settling of manure solids near the head end of fields is commonly observed. Blending of lagoon water with fresh water supplies may be controlled by irrigators and be based on their judgement and field level constraints. Accurate accounting of LM nutrient content may be especially difficult in practice when solid separation of LM is managed using a series of holding ponds, rather than using screening systems. Pipeline distribution systems for liquid manures may not reach all fields producing crops, resulting in excess concentration on some fields, and inadequate amounts on others. Extending pipelines to more fields, or all fields owned or used by the farm where possible would improve distribution of LM materials and reduce concentration on nearby fields.

Better management of manure application rates relative to crop uptake and removal was the primary recommendation of the Committee of Experts Report (Burt et al., 2014) that reviewed the issue of surplus nutrients on dairies up to that point in time in California and the recommendation of the SRMR. They emphasized the close relationship between irrigation practices and technology, and manure application. Irrigation systems that combine the ability to deliver lagoon water and N with greater precision and uniformity than surface irrigation systems can more precisely manage manure N. Recent research on the use of drip irrigation systems[35] and on automated surface irrigation systems[36] suggests that improvements are possible. Additional research is required.

[35] https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=31237
[36] https://cdrf.org/research-projects/automation-of-surface-irrigation-systems-in-dairy-production-systems-in-the-central-valley/

Automated irrigation systems are linked to improved methods of measuring irrigation water (and LM) applications and to crop water use in real time, resulting in improvements in irrigation efficiency and more precise control and measurement of lagoon water application timed to crop demand. Research and demonstration on such systems are on-going. Capital investments are needed, but these are potentially less expensive than some of the more highly engineered manure treatment systems discussed in Task 2. For farms closer to achieving a whole farm N balance, improved irrigation methods have the additional benefit of saving scarce irrigation water. New systems for automated surface irrigation require investment in infrastructure for automated gates and additional delivery structures, but reduce irrigation amounts and tailwater runoff and eliminate most of the labor needed for irrigation (Koech and Langat, 2018). They support a more precise estimation of the amount of water (and nutrients) applied. Automated systems are untested with the use of lagoon water on dairy farms in California currently but are a current topic of research and demonstration in the SJV.

Problems with manure use for crops are not new and have been the subject of substantial research effort aimed at improving crop recovery of manure N and reducing losses to the environment, both in California and wherever dairy farming has been an important agricultural activity (Burt et al., 2014; Harter et al., 2017; Task 4). Cativiela et al (2019) emphasized more precisely recommendations for improved testing, accounting and reporting of manure N and crop N uptake on dairies in California that are like those recommended by the farmer participants interviewed. These included the use of flowmeters for measuring lagoon water use, more accurate irrigation and management plans, new reporting formats for nutrient management, modified sampling and testing requirements, and the export of additional manure N amounts to non-dairy farmlands. Costs for increasing measurement frequency and accuracy of manures, crops, and water also are estimated in Cativiela et al., (2019, Chapter 3).

In general, farmers perceive a unavoidable tradeoff between increased cost of measurement and errors in measurement. This is an area for further research, development, and producer education. The solution for the uneven application of manure nutrients and uncertainty about the adequacy of manure N in meeting crop needs adopted by many farmers is the supplemental use of conventional fertilizer N, but this increases surplus N levels on farms when added to total N already present in manure (TASK 1).

3.1.2. Other conventional strategies[37]

Different breeds of cattle produce different amounts of manure. Many dairies have Jersey cows or other colored breeds. Jerseys produce approximately 40% less manure per cow plus replacements than Holsteins, the dominant dairy type (Knowlton et al., 2010). Despite lower levels of milk production, Jerseys tend to have higher fat and protein contents in their milk, so revenue per hundredweight (cwt) of milk can compensate for lower production levels. There is then less manure N per cwt of milk sales produced on the farm.

Most N imported in feed is in the form of protein. Balancing the protein, fiber and energy needs of different cow classes and production groups on a dairy farm is the job of dairy nutritionists.

[37] Suggestions from discussions with Nathan Heeringa, Innovative Ag Services, and Peter Robinson, Department of Animal Sciences, UC Davis.

Nutritionists can include as a goal in their feed optimization strategies to minimize excess protein in total mixed rations.

Many dairy farms raise their own mature cow replacements from calves to first lactation heifers. Some dairies, however, have separate facilities for this purpose or contract with others to raise their replacements. This moves some manure N generation off the main dairy. However, depending on circumstances associated with replacement operations, the surplus manure N problem may simply be moved to a different location.

Lastly, increasing crop yields through a combination of management improvements already discussed will increase the amount of manure nutrients that can be successfully recycled within a dairy farm.

3.1.3. Infrastructure improvements

Farmers commented that extending pipelines that distribute liquid manure to more fields may be possible in some circumstances but not in others. For example, pipelines may have to cross beneath public roads, or cross other's property. Some farmers have arrangements with neighbors to apply manure to their property. In some instances, this may include liquid manure distributed by pipeline. But the ability to extend pipelines or move liquid or solid manure to neighbors' farms is limited if there are many dairies in near proximity. In addition, an estimated 20 % of manure N collected already is sold or distributed off-farm according to estimates made from CVRWQCB data by Parsons and Harter (2018). Prices for dried solid manure (most sales) are low, indicating limited demand (Cativiela et al, 2019). So new sales would be additional to current sales or distribution arrangements and may require longer transport distances and/or improvements in the quality of solid manure products. Manure transport costs are evaluated in TASK 5 as part of life cycle assessment of manure treatment technologies.

Liquid manure distribution by truck is common in some other dairy states. But this is an energy intensive and potentially costly practice given the large amounts of water involved, depending on distance. One potential way mentioned to reduce the cost of liquid manure distribution to outlying or neighbors' fields suggested by the CVDRMP group was to extend a pipeline to a point closer to outlying fields or the farm's edge and then use trucks for the final distances and field applications required. The cost would vary with individual farm circumstances. As discussed above (Section 3.1.1), changes to irrigation systems including the adoption of pressurized systems like drip irrigation or controlled surface irrigation technology can improve the distribution and use of LM materials for irrigation.

The state's Alternative Manure Management Program[38] supports conversion of some manure management practices on dairy farms that collect large amounts of manure using flush systems and lagoons to others that divert manure from lagoon storage. These practices help reduce CH_4 emissions by reducing the quantity of fermentable materials (fine solids) reaching lagoons. Scrapping equipment, some barn modifications, and/or vacuum trucks are supported as well. Installation of screens or other solid/liquid separation devices are supported. Vermifiltration systems are eligible for support (TASK 2 and 5). These changes reduce the amount of methane produced in lagoons by the amount of manure feedstock (volatile fine solids) diverted (Kaffka e t al., 2015). But the manure collected must then be off-loaded and dried somewhere before additional piling for storage or recycled for use as bedding. This is

[38] https://www.cdfa.ca.gov/oefi/AMMP/

more easily accomplished in summer than winter when temperatures are lower, and rainfall occurs. It requires land for drying and storing the fresh, wet manures diverted from the concrete surfaces otherwise managed using flush methods. Alternatively, a weeping wall system can be created for manure management (Meyer et al., 2019). Emissions from weeping wall systems are not well characterized (Williams et al., 2020).

These recommendations collectively are likely to have the largest near-term effects on whole farm nutrient balances and the efficiency of manure nutrient use on farms with lower stocking rates closer to N balance than for farms with larger stocking rates and for those in areas with large numbers of nearby dairy farms.

3.1.4. Farm size, stocking rates and conventional strategies

In TASK 1, it was determined that farms with 3 cows plus replacements per acre were in N balance or close to balance (TASK 1: Table 1.11). The number of farms within the priority 1 NMZs with approximately 3 or less cows per acre is reported in Table 3.1. Depending on the NMZ, a large number and percentage of farms could achieve approximate overall farm nutrient balance by adopting available conventional methods.

Table 3.1. Number of farms at or near N balance (≤ 3 cow_{eq} ac^{-1}) in the different NMZs

	Chowchilla	Modesto	Turlock	Kaweah	Kings	Tule
Number of farms	18	19	60	39	54	42
Percentage of farms	58%	42%	38%	37%	51%	45%

Most other farms will require more aggressive efforts to manage surplus nutrients. Highly overstocked farms (stocking rates >> 4) would need to remove some or most of their manure N (depending on stocking rate). Clusters of small farms or cooperating groups of farms could provide sufficient scale to potentially support engineered technologies that recover surplus N for removal and reuse (Task 2). These clusters may also be able to support cooperative commercial composting operations that meet regulatory specifications, including enclosed composting facilities, or other treatment technologies that make solid manure fractions more widely useful and valued in California's food-focused cropping systems. Alternatively, denitrification systems like vermiculture may be useful if the economic and GHG costs of nutrient recovery prove to be too expensive for dairy producers (Task 2). Solid manure applied to fields supplies nutrients like N, P and K and adds carbon to soils as an organic amendment. Adding C in the form of organic fractions in manure helps overcome fundamental limitations on increasing soil organic carbon storage that occurs when relying on cover crops or crop residues alone (Janzen et al., 2022; Task 4), especially if water is increasingly restricted for irrigation, limiting cover crop production. This will become increasingly important as lands become fallow in the SJV under SGMA, leading to losses in soil organic matter from those fields (TASK 4).

3.2. Adopt a certification system to support continuous improvement over time on each farm

The accumulation of excess manure nutrients on dairies over time is unsustainable and a difficult regulatory challenge (Miller et al., 2017; Harter et al., 2017, 2012). The notion of agricultural sustainability can be and is defined variously. One way to avoid subjectivity is to remember that fundamentally, the term sustainability implies the capacity to persist over time. Commonly in places like California, only those farms that have been able to improve their performance economically over time have survived, and commonly these farms have increased stocking rates and otherwise grown in size (Njuki, 2022). Those that have not been able to do so have gone out of business or left the state.

The dairy industry could consider creating and adopting a more formal process of self-assessment focused on specific goals and guidelines for improvement over time at the farm scale. This resembles the overall recommendation found in the SRMR report (Cativiela et al., 2019). Sustainable dairy farms would be those that measure their performance across several cattle, crop and manure management categories and make progress over time towards improving performance in measured categories. In the area of whole farm nutrient management, a goal would be to bring the farm into balance between manure application and crop nutrient uptake.

There are multiple pathways to achieve this goal. For farms with very large stocking rates, adoption of nutrient recovery and removal systems, or manure denitrification systems may be necessary. For farms already closer to nutrient balance, the conventional strategies discussed above may be sufficient to advance those dairies towards that goal. Many farms would benefit from improving irrigation and management plans, improvements in irrigation systems, and better measurement and accounting of manure nutrients included under the category of conventional strategies.

There may be a way for the dairy industry to formalize the process of continuous improvement measured against quantifiable benchmarks unique for each farm. The goal would be continuous self-improvement over time, recognizing that progress may vary from year to year for reasons unrelated to farm planning. If financial incentives were tied to continuous improvement, then these changes would align more directly with the economic interests of farmers. Many dairy processors and dairy foods companies have sustainability programs that might support a system of financial incentives. A process of this type would also align with the long-term public policy goals of the state's CV Salts and Nitrate Program.

There are some examples of current certification programs that focus on environmental and livestock stewardship in California and elsewhere. One is the *California Dairy Quality Assurance Program*'s Environmental Stewardship Certification[39]. Producers attend classroom or online education to learn about environmental regulations from the Central Valley Water Quality Control Board, other Regional Boards, and San Joaquin Valley Air Pollution Control District. Third-party evaluators from CDQAP visit farms every five years to evaluate compliance using a standardized checklist. Certified dairies receive a 50 percent discount on their annual Waste Discharge Permit Fund fees and a roadside sign proclaiming the dairy as Environmentally Certified. In 2021, 772 farms in California had participated[40].

[39] https://cdqap.org/environmental-stewardship/

[40] Denise Mullinax, California Dairy Research Foundation, personal communication.

Other examples are the *Farmers Assuring Responsible Management (FARM) and FARM Environmental Stewardship* (FARM ES) program. These programs are voluntary and were created by the National Milk Producers Association and Dairy Management, Inc., a national dairy advocacy organization[41]. The FARM animal welfare program sends second-party (from the co-op) or third-party (independent) evaluators to dairies who use a standardized checklist to evaluate animal welfare practices and outcomes on dairies. They typically sample a third of each co-op's dairies annually so that each dairy is evaluated once every three years. The FARM ES program[42] surveys one dairy at a time to gather data on manure management, herd size, animal diet, energy use, water use and other key information. The FARM ES Tool then allows each individual farm and the cooperative to estimate their greenhouse gas emissions, carbon footprint (total and per kilogram of milk produced) and a few other key metrics[43]. Data is shared with the Innovation Center for U.S. Dairy[44] to report on progress in the dairy industry overall.

An example of an annual approach to improving farm management applicable across a range of farming systems is provided by the Sustainability Index for Specialty Crops (**SISC**). SISC provides an example of a measurement-based process for continual self-improvement, used as a basis for recognizing improvements in sustainability.[45] Farms measure improvement against their own past performance, but can also anonymously compare their performance against other farms participating. Farm data is preserved confidentially by the certification system. Importantly, SISC is performance based, allowing for creativity and individual pathways to improve farm performance rather than specifying particular pathways. Certification based on such a process seems congruent with the corporate sustainability goals of milk processers and food companies responding to public concerns about the consequences of food production. It also reflects the current approach and methods of those innovative dairy managers who are currently adopting creative strategies to better manage manure assets and other beneficial dairy farm management practices[46].

The CVDRMP has suggested assuming a role of this type for the California dairy industry (Cativiela et al., 2019). Farms in California must already collect and report some of the data needed for such a system. The SRMR report notes the inadequacy of current data collection and reporting methods and suggests improved measurement and accounting techniques that lend themselves to a certification system

[41] https://www.nmpf.org/year-in-review-spotlights-farm-programs-growth/
[42] https://nationaldairyfarm.com/dairy-farm-standards/environmental-stewardship/
[43] https://nationaldairyfarm.com/dairy-farm-standards/animal-care/

[44] https://www.usdairy.com/about-us/innovation-center
[45] The SISC website provides the following description of the benefits to farmers of their measure to manage approach to sustainability and certification: "Quantitative performance metrics, developed collaboratively, offer significant potential benefits, including: Providing a standardized system for measuring and reporting performance, thus reducing the potential for duplicative systems; Allowing individual operators to engage in the sustainability journey starting at (and regardless of) their current level of performance; Addressing the unique needs of the specialty crop industry while demonstrably improving environmental and social impacts; Helping operators identify opportunities for increasing efficiency and reducing costs; Enabling verifiable marketing claims (i.e., backed by measurable performance data); Reducing the likelihood of future industry regulation by solving problems and demonstrating improved performance to regulators; and freeing users to innovate best practices-by focusing their sights on performance outcomes rather than specific processes." https://www.stewardshipindex.org/

[46] An example: https://www.youtube.com/watch?v=Bfc8EkFWlpw ;

similar to the one described in SISC. These methods were the collaborative outcome of work by the CVDRMP (Cativiela et al., 2019).

Regulatory measures might be integrated with a self-assessment and benchmarking approach to improvement. California's Low Carbon Fuel Standard (LCFS) is a performance-based measure and stimulates innovation in the alternative fuel and transportation sectors. A performance-based standard with gradually increasing goals would support improvements in surplus manure nutrient management on dairies in the state.

Despite the existence of these and other well intentioned and resource rich certification programs, California still has well-documented problems with groundwater degradation related (in part) to dairy farming, and many dairy farms with significant nutrient surpluses (TASK 1). Yet there are also farms that have actively improved their manure management methods and continue to investigate new approaches suitable to their farms[47]. Not all farms are as aggressive at adopting innovative practices, but broadening participation in such efforts could help sustain the dairy industry in California.

3.3. Attrition

Dairy farming is an economically challenging business. Over time in California and the United States as a whole, fewer dairy cows have been kept on farms in successive years, but total milk production has steadily increased (Njuki, 2022; Matthews and Sumner, 2018). Farm size (number of cows per farm) has also steadily increased due to economic pressures, which tend to force increases in stocking rates and overall farm size (Fig. 3.1A). Where expansion in farm size is not possible, increases in cow numbers occur without corresponding increases in farmland for manure application. Under these circumstances, surplus manure accumulates and becomes a limiting factor for further intensification of cow numbers. The NMZs in the northern SJV have a larger number of farms on smaller acreages, and many of these have very high stocking rates (TASK, 1: Tables 1.9 and Table 1.12 to 1.14). In the Turlock NMZ, 25 % of calculated N surpluses were generated by mostly smaller farms (in acres) with very high stocking rates. If economic forces continue to pressure smaller farms, some portion of regional N surpluses may be eliminated through attrition, resulting in less overall surplus N within that region. This assumes that neighboring farms do not adjust by adding the cows from farms going out of business or leaving the state. Other farms may find the costs of meeting groundwater protection standards linked to additional manure processing and export too great. That was a result of increasingly strict manure management standards in The Netherlands and resulted in the loss of some farms (World Bank Group, 2017). More recent regulatory proposals in The Netherlands have aroused and continue to arouse significant opposition from the farming community[48].

Anything that reduces cropping intensity and crop yields on SJV dairy farms will increase the amount of manure nutrients that are in surplus by reducing crop uptake and removal. A related consequence is an

[47] An example: https://www.nmpf.org/focus/medeiros-holsteins/ ; https://californiadairymagazine.com/2022/06/10/cas-bar-20-dairy-among-2022-innovation-center-for-u-s-dairy-sustainability-award-winners/

[48] https://www.theguardian.com/environment/2021/sep/09/netherlands-proposes-radical-plans-to-cut-livestock-numbers-by-almost-a-third

increased reliance on imported forages and feeds, further increasing the amount of nutrients brought onto farms (Fig 3.2). Current and projected policies seem likely to cause attrition in the dairy industry. Attrition, however, may not just affect smaller, overstocked farms. Attrition seems likely to occur from recent public policy decisions affecting water use. This is not necessarily congruent with the kind of attrition that would occur from market forces alone. For example, SGMA limits water available for irrigation on many farms in the SJV, but unevenly, depending on the location of the farm and its access to water resources. It can and likely will occur that well-managed, efficient dairies may be forced out of business by SGMA due to their location and access to water, while less well-managed or poorly balanced farming operations survive in others. It is not clear how different and potentially conflicting state policies focused on improved nutrient management can be reconciled with reduced water use for crop production on dairy farms in the San Joaquin Valley. This is an area for further research and demonstration.

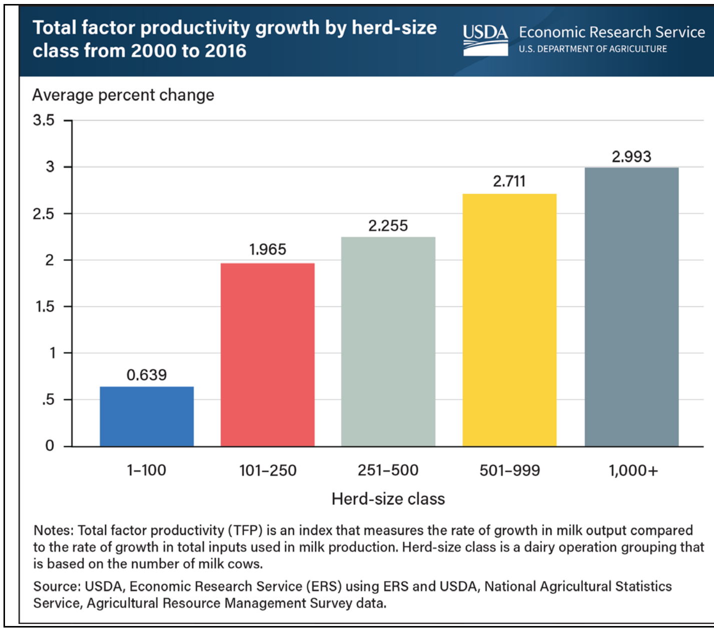

Figure 3.1. Milk productivity growth by herd-size class from 2000 to 2016. Economic and agroecological efficiency have increased with herd size in the dairy sector over time, but intensification may make nutrient management more difficult, especially for farms that have limited land area for crop production and manure use, or limited manure export options.

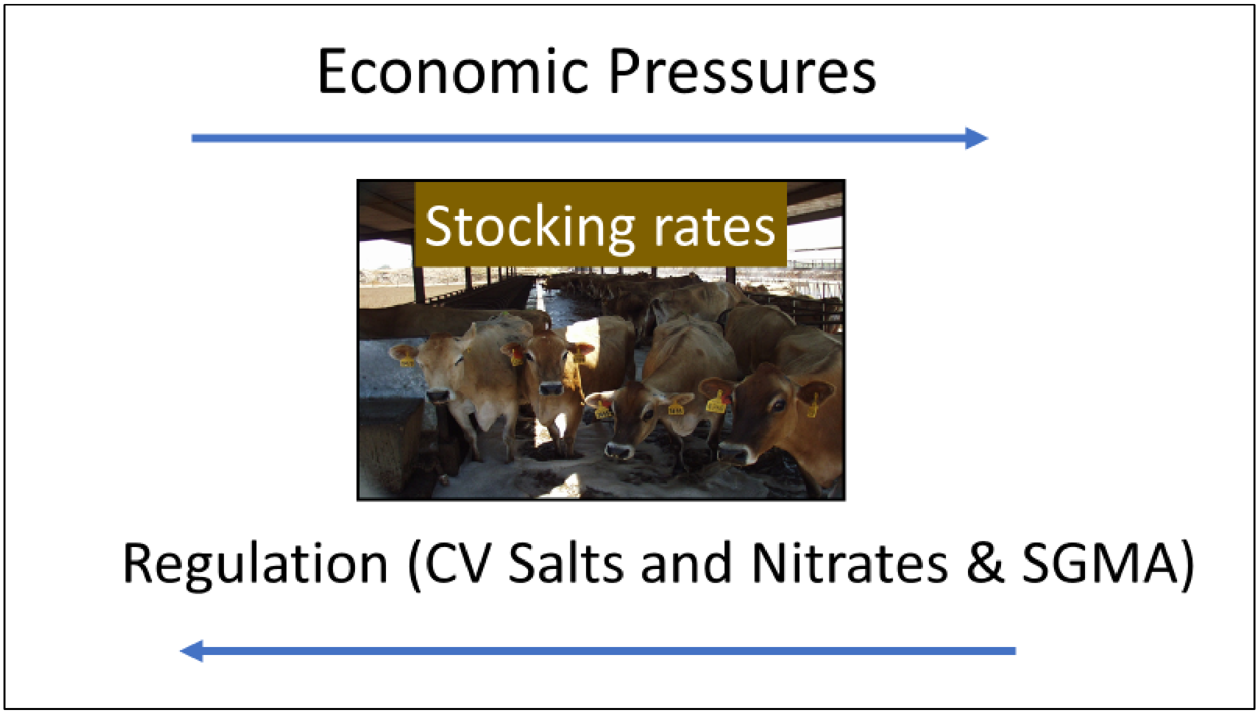

Figure 3.2. Conflicting pressures affect dairy operators: the need to increase herd size but simultaneously reduce the effects of increasing manure accumulation that result.

3.4. Important research needs and potential projects to address important barriers to adoption

Research that helps improve the recovery by crops of N applied as manure will reduce losses of N to the environment and help balance N produced on dairy farms with crop uptake. Improving irrigation systems, especially with respect to their use in conjunction with liquid manure application is an important subject for research. Research on better linking manure N availability with crop uptake would improve farm N balances and increase in some cases surpluses available for nutrient recovery.

There are notable examples in California and elsewhere of dairy farms that have improved their manure management practices through innovation. Some successful dairy farms likely already use a program of self-assessment, benchmarking and improvement, even if not formalized.

To most effectively address the problem of surplus nutrient accumulation on many dairy farms in California, a creative process is needed that aligns the interests of dairy producers, food companies and consumers with the state's regulatory goals. This approach need not be limited to nutrient management alone but could include other important areas of dairy management.

Creating a certification system based on measurement of performance at the individual farm level that supports improvement over time compared to each farm's individual baseline, could form the basis for a successful approach. It would elicit diverse, creative responses to the challenge of nutrient management on modern dairy farms at the individual farm level. A well-designed program needs to be gradual enough to allow farms to evolve but sufficient to achieve longer term regulatory targets to prevent additional degradation of groundwater.

A precedent for a performance-based standard is the state's Low Carbon fuel Standard[49], which encourages innovation in the alternative transportation fuel sector and is widely regarded as successful. If financial incentives could be provided in some combination by the dairy foods industry and by the state through subsidies or favorable fee and tax policies, such a system would align the interests of dairy farmers with consumers and regulators.

Creative policy making is needed to find the right balance between incentives and mandates. The dairy program might be managed Initially by the dairy community to preserve the confidentiality of data, while enabling individual farmers to compare their performance against averages for neighboring farms. This should help support the broader adoption of a quantitative self-improvement program within the dairy community.

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TASK 4:

Fertilization value, climate impacts, and effects on soil organic matter of selected manure products.

4.1. Dairy Manure Management Technologies for Nutrient Recovery

4.1.1. Impacts of Manure Collection and Separation Processes on Nitrogen Partitioning

Treating manure in ways that aim to recycle nutrients for use in agriculture has multiple potential benefits, including reduced use of synthetic fertilizers, reduced nutrient losses on dairy farms, and potentially lowered greenhouse gas emissions. Farm-scale nutrient balances are important tools to help determine which component of dairy operations are leading to excessive nutrient accumulation. Manure nutrient recovery and whole farm N balances on dairy farms have been analyzed extensively in California and elsewhere[50]. Surplus nutrient accumulation is common on many modern, intensive dairy farms. A study conducted by Spears et al. (2003) found that for western dairies the ability of farmers to apply manure to crops was an important factor in determining the overall N balance of the farm. An additional estimate was created by Castillo (2009) who calculated that for all California dairies collectively to balance whole farm N accumulation with crop uptake, manure exports need to increase from 15 to 19 tons of manure-N per farm per year. Using data from individual farms reporting manure amounts, stocking rates, and land available for manure application, surplus quantities of manure N were estimated in Task 1 for priority 1 Nitrogen Management Zones (NMZs) in the San Joaquin Valley, the region with the most dairies in the state. Results indicated that approximately 25,000 to 33,000 tons of surplus N a year above estimated crop uptake were generated on farms in this region, in both liquid and solid manures (Task 1: Table 1.12). These studies highlighted the need, but also the opportunity for California dairy farms to develop stabilized, useful fertilizer products to export off farm.

Dairy manure handling, separation, processing, and storage alters the nutrient content of the various fractions, leading to different optimal end uses for the material (Gangwer, 1995). Improving nutrient recovery by crops fertilized with manures remains challenging due to the difficulties of managing manure, variability in manure types and quality, and incomplete mineralization of organic N during periods of crop demand. There is an ongoing need for research to improve nutrient recovery and further our understanding of value-added fertilizer products (Bernal, 2017).

Different post-separation treatments are beginning to receive attention, including vermicomposting, pelletization, high solids Anaerobic Digestion (AD) and ammonium stripping (Vanotti et al., 2020) but other new technologies such as mechanical vapor recompression and dissolved aerated flotation, for example, have received little to none. Here we evaluate selected, novel nutrient recovery technologies that can support additional nutrient exports from California dairies.

[50] See Task 1 for an overview of this research.

Many forms of manure separation technologies exist, all with varying degrees of nutrient recovery efficiencies (Dong et al., 2022).[51] Manure separation technologies are generally categorized by the way in which the solid portion is separated from the liquid. These include mechanical separation, filtration, sedimentation, or gravity filtration (Burton, 2007). Each technology is limited in different ways, impacting their feasibility for on-farm use as nutrient recovery technologies. To develop novel fertilizer products from manure, it is important to understand how different separation systems influence the partitioning of nutrients such as nitrogen into solid or liquid fractions. Each manure portion (liquid or solid), after separation, can contain different concentrations of nutrients. The liquid portion after separation is often higher in N content, whereas the solid component can be higher in P (Powell and Wu, 1999; Meyer et al., 2007). This reduces the value of the solid portion of manure as a mineral N fertilizer replacement.

Several novel systems for solid and liquid manure processing with potential application to California dairies were chosen for technical and life cycle assessment in this report (Tasks 2 and 5). These are assessed here based on N and other nutrient recovery and the fertilizer equivalent value of selected primary and secondary products was estimated. Mineralization rates were measured under controlled conditions for primary or secondary solid manure products. Their role as fertilizer substitutes is reviewed and discussed.

4.1.2. Mechanical and chemical separation systems

Screen separation. Screen separation is the most common method for manure separation in California (Williams et al., 2020). Generally, screened solids are dried and used for bedding or composted. This method is not considered as an effective N recovery technology due to low rates (5-10% TN), rather a management strategy for removing total solids (Powers et al., 1995; Meyer et al., 2007). Combining screen separation with other techniques, such as chemical coagulation, has shown to increase the N retained in the solid fraction, but more research is necessary (Hjorth et al., 2010). This is needed due to the wide adoption of this separation technology in California.

Centrifuges. The use of centrifuges to separate the solid matter from liquids is a common method in other states but has seen limited adoption in California. Although this method is remarkably efficient, it has high capital costs. Even so, Lyons et al. (2021) found that the nutrient recovery efficiencies of centrifuge technologies can vary considerably due to the initial dry matter content of the influent. In reviewing the literature, they showed that N recovery efficiencies can be as high as 40% for centrifuge separation. Much N is excreted as urine by cattle, so the liquid fraction of manure tends to contain more N than coarse separated solids. Although the cost is a considerable barrier to adoption, centrifuge separation has promise as a first step in novel fertilizer manufacturing due to its larger N recovery efficiency in the solid manure fraction.

Mechanical press separation. Screw-presses are a common method for separation of liquid and solid manure constituents (Burns, 2005). Previous work evaluating N losses from manure following a screw

[51] A large, current catalogue of alternative manure treatment technologies is found at: www.newtrient.com

press has found that the C/N ratio of the liquid portion can be very low (high N content) and differs considerably from the solid portion (Pereira et al., 2010). This reduces the potential for screw pressed solids to be made into N supplying fertilizer products but may increase the efficiency of systems that treat the liquid fraction.

Chemical separation. Chemical separation using flocculants can be added to solid separation systems to improve nutrient recovery efficiency and to reduce methane emissions from liquid manure (LM) storage (Ellison and Horwath, 2021). Flocculants can consist of natural materials, such as chitin derivatives, or manufactured synthetic materials like polyacrylamide (PAM), or chemical additives (Shewa and Dagnew, 2020). Iron salts can be added to remove solids from LM and stabilize nutrients in manure, allowing for off farm transport (Barrow et al., 1997). Flocculant can be applied before mechanical separation as well as after, whichever is a better stage to recover nutrients. The use of natural flocculants, such as chitin, has been shown to recover nearly 75% of the total N in dairy manure effluent (Garcia et al., 2009). The fact that these are organic materials allows for the use of separated solids in certified organic production systems, increases the market value of these novel fertilizer products. The use of flocculant materials, however, becomes an on-going expense and can result in materials handling difficulties on dairies. It has not been widely adopted to date in California.

4.1.3. Post-separation Treatments

Composting. After solid separation, the fraction can be treated further to retain nutrient value. The most common methods include aerobic composting of separated solids and lagoon storage or anaerobic digestion of separated liquids. On open lot dairies, manure falling in corrals can be collected, dried and sold or further composted. Retaining high levels of N in compost requires intensive management of the oxygen and moisture levels in the pile (Shi et al., 1999). Static storage reduces N retention making this handling method a denitrification pathway. High quality compost used as a soil amendment adds limited amounts of immediately available crop nutrients to soils but importantly can improve long-term fertility by changing soil physical and chemical properties (Martínez-Blanco et al., 2013).

Anerobic digestion (AD). AD is another widely accepted post-separation treatment technology. The use of AD systems is encouraged by the state's DDRDP program and the use of the biogas produced through the state's LCFS. Over half of the N in manure can be recovered using this manure management practice, with further biogas gains being shown from acidifying manure before digestion or combining the practice with other methods such as centrifuge separation (Hou et al., 2017). There is considerable experience and research supporting the use of AD systems for dairy manure and its use is growing in California and more broadly across the nation.

4.1.4. Next Generation Technologies (NGT)

Several new manure management technologies are becoming available and may provide opportunities for California dairy producers (Task 2 and (Meyer et al., 2019). For example, dissolved aerated flotation (DAF) can be combined with other systems such as screw presses or anaerobic digestion, to enhance nutrient recovery, specifically of the fine solids. Yet, for N, this system has only shown to capture a third of the total N within the solid fraction from dairy manure effluent, but 85% of the P (Porterfield et al., 2020). This method is more effective at exporting P off farm than N (see TASKS 2 and 5).

Another relatively new technology is vermifiltration. This method uses earthworms, supported in a woodchip base to process liquid dairy effluent (Tasks 2, 5). Woodchips are an input to the system. Vermiculture is considered a denitrification technology, similar to woodchip bioreactors used to intercept nitrate flows from fields to surface waters. There are diverse reports of N balances in the literature (Task 2), but large amounts of soluble and some organic N is converted to N_2 gas through vermiculture and lost to the atmosphere. Residuals may be of high value. For example, Singh and Sharma (2002) reported that the presence of the worms can enhance the plant availability of the remaining N in the solid compost end-product often with a lower C:N ratio than the original feedstock.

Nitrogen recovery from manure using NGT is often dependent on the physical and chemical characteristics of the manure and the temperature of the environment in which these systems operate (Pandey and Chen, 2021), potentially resulting in inconsistent final products. The wide range in technology types, combined with the variability in N recovery efficiencies, calls attention to the need for more research before the optimal system for an individual dairy farm can be determined. Specifically, the soil health and crop fertility effects from amendments and biofertilizers generated by NGT systems need to be assessed. Medium-term aerobic incubations (80 days) carried out during this study allow for the estimation of potentially available mineral N.

Figure 4.1 depicts the complex, multiple stage separation and handling pathways for raw manure to become solid amendment products. Additional nutrients are left in separated liquid manure residuals. The manure products tested are indicated in the diagram and were chosen to conform to technologies analyzed in Tasks 2 and 5, or similar to those technologies such as in the case of livestock water recycling (LWR). The LWR technology is a post-collection membrane based solid separator that produces an N-rich solid material similar to DAF.

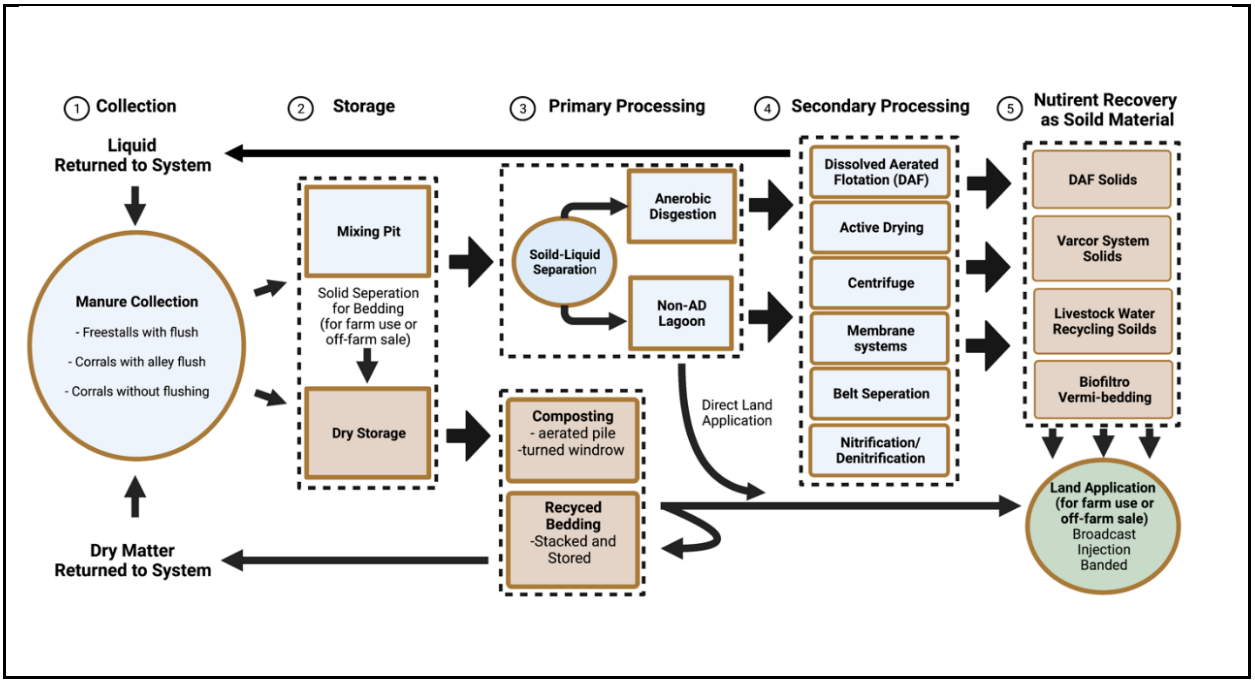

Figure 4.1. Schematic diagram representing the flow of dairy manure from collection to final processing as novel fertilizer products.

4.2. Fertilizer Value of Manure and Manure Derived Products

Recycling manure in agricultural systems is an historic practice has been shown repeatedly to boost crop yields and improve soil health (Xia et al., 2017). Nitrogen availability from manure can be highly variable and therefore uncertain, ranging from immobilization of over a quarter of the total applied N to 50% released as plant available N (Eghball et al., 2002; Van Kessel and Reeves, 2002). Recent work has shown that uncertainty in measurements of N concentrations in dairy solid and liquid waste can lead to widely divergent predictions of N discharge to groundwater sources (Miller et al., 2020). An important factor in determining the value of manure or manure derived products as mineral fertilizer replacements is chemical composition (Schröder 2004). Understanding the nutrient availability to crops of novel stabilized products derived from manure, however, is not well researched, but necessary to accurately quantify their value as substitutes for synthetic fertilizers. As novel manure products begin to be introduced to California, standardized metrics for chemical analysis and quality are needed to characterize their fertilizer potential more accurately.

Nutrient release is further complicated by climate and soil type (Watts et al., 2007). Temperature changes (Cassity-Duffey et al., 2018) and soil water status (Al-Ismaily and Walworth, 2008) significantly affect the release of plant available N. Temperature can also increase the ratios of inorganic to organic N as manure mineralizes (Chodak et al., 2001). This makes predicting the amount of soluble N released from manures applied and leached to groundwater, based on the amendment chemical composition alone, highly uncertain (Burt et al., 2014~~).~~

Manure solid/liquid separation procedures can also influence the total amount of N available to crops after soil application. Pratt et al. (1973) tested common dairy manures and estimated rates of N availability to crops, including dried dairy manure. But in 1973 they were unable to consider materials derived from newer manure treatment technologies. Sørensen and Thomsen (2005) found that for pig manure, the dry matter fraction provided nearly twice the amount of available manure N in the second year after application as the liquid fraction. Earlier work estimated the N availability for different manure fractions as 50% in the inorganic mineral form, 25% available as easily degraded organic N and 25% available in a slow pool of organic N which can become available in following years (Sluijsmans and Kolenbrander, 1977). Heinrich and Pettygrove (2012) showed that when the organic fraction is removed from the liquid stream, the predictability of N availability to crops from the liquid stream increases. This is an important outcome given land application of minimally treated raw manure is a common method of manure disposal in California, with over 40% of dairy producers reporting applications throughout the year (Meyer et al., 2011).

Research on the repeated applications of organic amendments have shown that multi-year mineral fertilizer replacement values increase after repeated annual applications (Gutser et al., 2005) due to the changes in soil organic N pools. Solid manures are higher in dry matter content than liquid manures. Schröder et al. (2007) found that for solid manures with low first year fertilizer replacement values, multiyear N availability is often higher than from liquids and increase in value over time. Up to half of the total N applied as compost can become available during a 10-year period after application (Martínez-Blanco et al., 2013). Importantly, Hijbeek et al. (2018) highlighted the need to use these long-term, higher replacement values when offsetting mineral fertilizer, as the use of lower N availability rates can lead to over application of mineral fertilizers. This phenomenon is rarely factored into nutrient management plans that include organic amendments and needs further research in California growing conditions to better understand the crop N availability of this pool, especially for newer manure products.

Data available on crop responses to manure-based products generally focuses on compost or anaerobic digestates. Limited data is available on other, more novel products. The development of stabilized, carbon rich, manure amendment products derived from nutrient recovery technologies has the potential to provide many benefits, but predicting the N available to crops is challenging.

Recent studies investigating the agricultural application of digestate from anaerobic digestion of manure have shown improved crop performance. Ai et al. (2020) found that crop yield can be increased by more than 20% after application of treated digestate when compared to application in raw form from a lagoon. For separation technologies such as screw presses and centrifuges, research has shown that screw press separated solids perform similarly, but centrifuged material can increase crop nitrogen recovery by over 20% compared to raw manure (Pantelopoulos and Aronsson, 2021). Centrifuges increase fine solid separation and collection compared to screens. Other technologies such as ammonium stripping have not been shown to improve yield outcomes compared with synthetic fertilizers, but the process can increase N concentration to make export more affordable (Sigurnjak et al., 2019).

Limited literature exists on the N replacement values of novel manure products, which require further soil and agronomic research. Novel manure technologies have been shown to be highly variable in retaining plant available N, resulting in both reductions and increases, depending on the treatment. For example, when dairy manure was treated with organic versus inorganic flocculants, results varied with the flocculant material. Mineralizable N was either decreased or slightly increased with respect to the raw material (Ellison and Horwath, 2021). Porterfield et al. (2021) also found, for DAF separated solids, total plant available N content decreased by the addition of additives that increased pH.

4.3. Environmental Impacts of Applying Manure Products to California Soils

4.3.1. Effects of manure application on soil organic carbon

Dairy manure amendments that are rich in complex C can mitigate climate change in California agricultural systems through storing organic C in the soil. The application of dairy manure to California soils has the potential to increase soil carbon reserves, leading to many positive soil health benefits. Generally, manure application rates are considered the most dominate factor regulating soil C increases, as opposed to land use type or soil physical properties (Maillard and Angers, 2014). Compared with rates of application, the effects of timing and frequency have not been shown to be important controls affecting soil organic matter accumulation (Bierer et al., 2021). The cropping system can also significantly influence soil C sequestration. For example, Maillard et al. (2016) found that more soil carbon was accumulated at the soil surface (0-20 cm) under perennial-annual crop rotations versus single crops when liquid dairy manure was applied. This highlights the need for comprehensive recommendations that include information about application strategies within specific cropping systems.

In a meta-analysis of 141 studies evaluating manure applications to soils, Xia et al. (2017) found that overall soil C can be increased by 33% per year when manure substituted synthetic fertilizer but used at a 75% N fertilizer replacement rate significantly decreased crop yields. Soil C increases from dairy manure are due to shifts in microbial populations in the long-term through increasing total microbial biomass size and community composition that favors soil C accrual (Peacock et al., 2001). Min et al. (2003) showed that after repeated applications of dairy manure, microbial metabolism of C was altered, leading to increase C accumulation and soil aggregation.

Long-term modeling studies that have included dairy manure have shown that soil C can accumulate for many decades when applied yearly (Abrahamson et al., 2009). Recent research within a no-till orchard system has shown that the application of dairy manure compost significantly increases soil organic carbon (Khalsa et al., 2022), aligning with previous studies using manure compost in rangelands (Ryals et al., 2014). Annual cropping systems in California have also been shown to accrue considerable amounts of soil C after chicken manure compost application, particularly when soil profile depth (~2 m) is included in the accounting (Tautges et al., 2019). These treatments also included winter cover crops, which increased total C additions to soils beyond what was supplied by manure compost. These outcomes support manure products being used to meet soil C sequestration goals as part of larger climate change initiatives.

Increasing long-term C sequestration, however, will be challenging. Generally, it has been estimated that C inputs into agriculture must increase by more than a quarter, relative to current practices, if positive gains are to be made (Wiesmeier et al., 2016). The potential use of cover crops to increase SOC, especially in water limited regions like California's San Joaquin Valley, is limited. As water supplies for irrigation decline, the amount of biomass C from crop residues and from cover crops returned to agricultural soils will become increasingly limited, emphasizing the importance of manure as a vital source for the re-carbonization of agricultural soils (Janzen et al., 2022). The novel manure products investigated in Task 4 have the potential to find a role in California agriculture's climate-smart future.

4.3.2. Manure application and greenhouse gas (GHG) emissions

Applying manure to soils has the potential to affect GHG emissions, due to its N content, soil application of manure can lead to increased N_2O emissions (Reddy and Crohn, 2019). The form of manure applied, liquid or solid, can have a significant impact of the total N_2O emissions, with liquid manure reported to have a four times higher emissions factor than solid manure and mixed organics compost. This effect was increased in fine textured soils under high precipitation (Charles et al., 2017). Although data is limited, some research has been carried out on the GHG effects of separation treatments and byproducts. For example, Pereira et al. (2010) found that the application of screw press separated byproducts did not lead to a difference in soil N_2O emissions when compared to the non-separated control. This result would be expected as pressed cakes from manure solids often have low total N contents. Assessment of the N_2O emissions resulting from soil application of novel manure products is needed for a complete accounting of GHG effects from the use of these products.

4.4. Estimating the Fertilizer Equivalent Values of selected manure products

To optimize the use of manure-derived fertilizers and amendments, it is important that growers understand the amount of crop available N coming from the applied materials. Having this knowledge allows growers to increase the value of these inputs through improvements in N application timing with crop uptake, or synchrony. Determining this value is complicated and it is hard to characterize crop N availability based entirely on material characteristics. Determining how both variability in materials as well as climate conditions influence plant N availability from these materials, will improve nutrient management planning. Various water holding methods exist for estimating the fertilizer equivalence from organic amendments, all with different degrees of accuracy (Delin et al., 2012). A very reliable method for estimating potentially available N that has long been used is aerobic incubation (Hadas and Portnoy, 1994). This technique employs laboratory microcosms without plants to track the evolution of inorganic N as a combination of ammonium (NH_4^+) and nitrate (NO_3^-). As the inorganic N pool changes over time, the assumption is that this change is related directly to either the release (mineralization) or the uptake (immobilization) of crop available N. Based on the time interval, an estimation of total fertilizer equivalent N can be determined.

4.4.1 Methods: Aerobic incubation protocol

A randomized, full factorial design aerobic incubation experiment is being carried out using two representative soil types collected in the San Joaquin Valley (one fine textured clay type, one coarse textured, sandy type). Incubations were maintained at three temperatures (10°C, 20°C and 30°C), with 5 different manure derived organic amendments (dairy manure compost (COM), vermifiltration bedding (VER), Dissolved Aerated Flotation (DAF) solids, Livestock Water Recovery (LWR)[52] solids and Sedron (SED) solids), each treatment was replicated three times. Bio-fertilizers were selected to support technology assessments and comparisons in Tasks 2 and 5, as well as the selection of other N-rich products derived from similar processes as in the LWR material. These materials are by-products of manure nutrient recovery and treatment systems likely to be tested and adopted on California dairies in the future.

Table 4.1. Chemical characteristics of select manure derived products

Parameter	Unit	COM	VER	DAF	LWR	SED
Total C	%	21.6	96.6	22.6	18.3	34.5
Total N	%	2.6	6.6	3.0	2.0	3.3
NH_4^+	mg g^{-1}	0.98	1.89	0.84	1.16	1.35
NO_3^-	mg g^{-1}	0.27	0.39	1.64	0.37	0.25
C / N Ratio		8.5	14.5	7.4	9.4	10.4
NH_4^+ */ TN Ratio*		0.04	0.03	0.03	0.06	0.04
pH		9.3	8.3	6.8	8.5	8.2
EC	mS/m	7.3	2.1	4.5	0.8	17.9

Notes:
COM – Dairy manure compost; VER – Dairy manure from vermifiltration bedding; DAF – Dissolved aerated flotation solids; LWR – Livestock Water Recycling solids; SED – Varcor system (Sedron) solids

The selected materials ranged in C:N ratios, from a low of 8.5 in the COM and a high of 14.5 in the VER. The pH values of the materials were all neutral to alkaline, with the COM having a considerably high value of 9.3. In most amendments, the initial inorganic N pool is in the form of NH_4^+, except for DAF which contained a majority as NO_3^-. Notably, the SED material contained high levels of salt, over twice as high as any of the other amendments.

Organic amendments were added at a rate of 500 mg N kg^{-1} soil. One week before the onset of the incubation, soils were brought up to 40% water holding capacity (WHC) and pre-incubated for 7 days. After pre-incubation, soil moisture was reduced, and soils were weighed (25 g dry mass equivalent) into standard 120-mL specimen cups and mixed with bio-fertilizers. The soil-amendment mixtures were then transferred to 50-mL falcon tubes and the final soil moisture content was adjusted to 40 or 60% WHC by

[52] This technology uses membranes as part of its treatment technology. It was not included in systems evaluated in Tasks 2 and 5, but materials were provided for this part of the analysis. https://www.livestockwaterrecycling.com/

spraying deionized water onto the soil. All falcon tubes were then placed in 1-L Mason jars containing 2 mL of water to maintain sample soil moisture throughout the incubation. Each Mason jar contained 5 falcon tubes. The lid of the jar contained a 5-mm diameter hole with a foam sponge inserted, allowing for even gas exchange. Individual tubes within the jar were not capped. Samples were incubated for 80 days, with subsamples being taken on select days. The incubation was carried out in a 10°, 20°, and 30°C temperature-controlled room. Soil moisture was kept constant throughout the entire incubation period by weighing the soil every other day and subsequently adding water to replace water lost through evaporation.

Figure 4.2. Aerobic incubation system followed by K_2SO_4 extraction and colorimetric analysis for nitrate and ammonium.

Inorganic Nitrogen Measurements

Soil samples were taken from falcon tubes at day 3, 7, 14, 28, 60 and 80 days after the onset of the incubation. At each sampling day, one of the five falcon tubes in a Mason jar was harvested and 6.0 grams of soil was sampled and extracted with 0.5 M K_2SO_4 and shaken for 1 hour. The supernatant was subsequently filtered through Whatman 40 filters and analyzed for nitrate ($NO3^-$-N) and ammonium

(NH_4^+-N) concentrations using the colorimetric method (Verdouw et al., 1978; Doane and Horwáth, 2003).

Inorganic Nitrogen Calculations

Net mineralized N from the amendments was assessed according to Sims (1986).

$$N_{min}\left(\frac{\text{mg N}}{\text{kg soil}}\right) = \Delta N_{\,t} - \Delta N_{t=0}$$

$$\Delta N_{\,t}\left(\frac{\text{mg N}}{\text{kg soil}}\right) = (N_{min\,t})_{trt} - (N_{min\,t})_{con}$$

$$\Delta N_{t=0}\left(\frac{\text{mg N}}{\text{kg soil}}\right) = (N_{min\,t=0})_{trt} - (N_{min\,t=0})_{con}$$

Organic Nitrogen Calculations

Total added organic nitrogen (N_{org}) was calculated by subtracting the initial inorganic nitrogen value from the total applied N amount of 500 mg N kg-1 soil. The total percentage of organic N mineralized (% N_{org}) at time t was then calculated as the amount of mineralized N over the total amount of organic N added at time zero.

$$N_{org}\left(\frac{\text{mg N}}{\text{kg soil}}\right) = 500 - \Delta N_{t=0}$$

$$\%N_{org} = \left(\frac{N_{min}}{N_{org}}\right) * 100$$

Results from Short-term Aerobic Incubation

Results are reported in Fig. 4.3. Overall, organic N in dairy manure compost and vermiculture compost mineralized slowly over the 28 days reported here and were largely unaffected by increasing temperatures or clay or sand soil textures. Mineralization from the other amendments tested from more intensively treated manure materials were affected by increasing temperature, and generally released more N in soluble form in sandy soils compared to clay soils.

Amendment Type

Amendments can be grouped by N mineralization responses, with COM and VER (indicated as composted) exhibiting low to no N release, and LWR, DAF, and SED all exhibiting similarly larger inorganic N release. Soil texture affected mineralization variably across the different amendments. For example, there were differences among amendments in the sandy soil. All high N materials (LWR, DAF, SED) were all significantly different than the low N materials ($p<.05$). Yet, in the clay textured soil, only SED was significantly different than COM ($p=.007$) and VER ($p=0.02$).

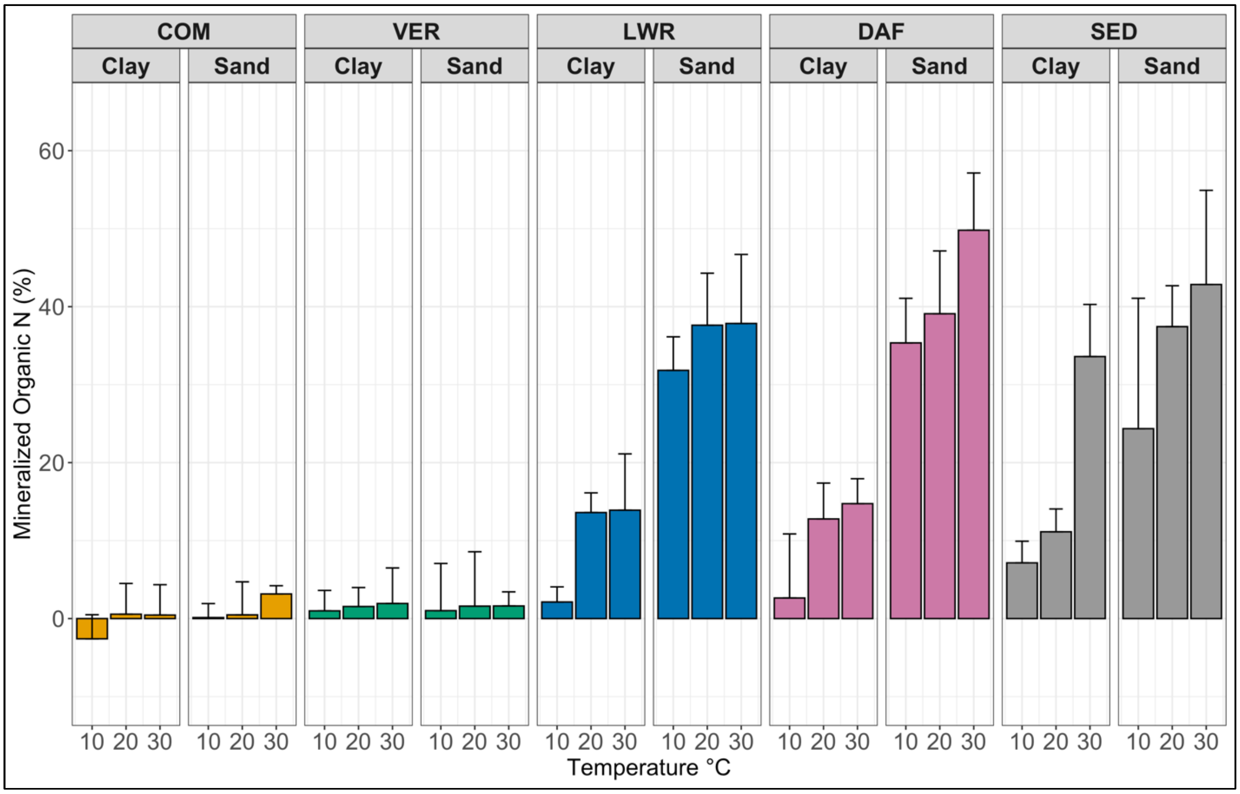

Figure 4.3. Total mineralized N for the 5 amendments (COM, VER, LWR, DAF, SED) shown as a percentage of added organic N incubated at 3 temperatures (10°C, 20°C, 30°C) in two soil textures (Clay and Sand) for 28 days.

Temperature

Temperature influenced the mineralization of organic N from amendments differently across soil and amendment types. SED material was significantly affected by temperature, especially at the highest temperature tested, in clay soil (ranges 10 °C to 30 °C, $p = 0.0006$; 20 °C to 30 °C: $p =0.003$). Although not always statistically significant, mean % org N mineralized tended to increase for the highly treated manure byproducts as temperature increased, but not for composted materials. The COM appeared to immobilize inorganic N (-2.6 % N) at the lowest temperature in clay but mineralized 3.16 % N at the highest temperature in sand. The VER varied less than COM, mineralizing 0.99 % at the lowest and 1.9 % N at the highest temperature, both in the sand and clay soil. The VER material contains woodchips, a highly lignified material.

Soil Texture

The effect of soil texture on mineralization varied among the amendments tested. Composted materials had much lower rates of mineralization in both soil types compared to more intensively treated manure products and were not significantly different across soil textures, (COM ($p =0.72$) and VER ($p=0.98$)).

Mineral N availability was greater in sandy soil compared to clay soil for the LWR, DAF and SED materials. The differences in total mineralized N between soil textures were similar across the range of temperatures evaluated. For example, the LWR material mineralized 20-30% and the DAF material approximately 25-35% less N in clay than in sandy soils for each temperature. More N mineralized in sandy soil for each highly treated amendment. SED was affected by temperature the least. Interestingly, the difference in % N mineralized was less than 10% between the clay and sandy soils at 30°C, and 26% at 20°C.

4.5. Fertilizer Replacement Value of Novel Soil Amendments

The value of each amendment as a N fertilizer replacement differed, and was high for LWR, DAF and SED materials. Applied at a rate of 500 mg N kg^{-1}, N after 28 days was over 200 mg N kg^{-1} soil for both DAF and SED materials, and 185 mg N kg^{-1} soil for LWR. Notably, soil type affected plant available N and amendments applied to sandy soil mineralized nearly 20% more total applied organic N compared to clay for the LWR, DAF and SED amendments. Although this short-term incubation was not designed to elucidate the mechanisms responsible for the differences among soil textures, previous studies have shown that decomposition can be directly influenced by clay mineralogy (Vogel et al., 2015), with increased mineral N accumulation in soils with higher sand content after application of organic materials (Chae and Tabatabai, 1986; Griffin et al., 2002).

Recommendations for use of these high mineralization solid amendments should be considered with the understanding that this experiment reflects only short-term N release dynamics. Generally, medium term aerobic incubations have shown to estimate crop N availability under field conditions well (Gale et al., 2006), yet can be dependent on amendment type (Pinto et al., 2020). In the long-term, N availability can be dictated by soil environmental conditions in combination with amendment chemical characteristics (Ige et al., 2015). This can lead to either an under or overestimate from the lab. Using only lab estimates may lead to reduced crop available N or increased N loss. Our results show that when applied to sandy soil, managers can expect plant N to be readily available regardless of the temperature. If soils contain larger amounts of clay, growers should expect a slower release of plant available N, and that release will be affected by soil temperatures. With these considerations, this work has shown that novel soil amendments derived from dairy manure can serve as an important synthetic N fertilizer replacement, with the co-benefits of recycling organic waste, positive effects on soil health and the potential reduced N loss to the environment through leaching (Wei et al., 2021) if amendments are used on non-dairy farms as a strategy to reduce N surpluses on dairies. Although, more information is needed concerning N loss as soluble organic N (Wang et al., 2018) and through different dentification pathways as impacted by amendments (Wei et al., 2014).The use of all these materials can have positive effects on SOC accumulation which will support climate-smart agriculture initiatives on California dairies. Farm-scale carbon footprint, however, will also depend on the amount of fertilizer displaced and the carbon costs associated with transportation (Task 5).

4.6. Future Research Needs

Although manure use has been studied in California for many years, novel management and nutrient recovery technologies generate new materials aimed at recycling surplus nutrients from dairies to non-dairy farms. Their mineralization properties and nutrient concentrations require evaluation before recommendations can be made. At the lab scale, short to medium term aerobic laboratory N mineralization assays that evaluate nutrient release characteristics under different climate and soil types have been used here for a select set of materials. This approach can be used to quantify the fertilizer equivalent values of new manure products. The use and further development of standardized protocols for field and lab validation of mineralization rates will help these procedures become implemented in commercial soil testing labs and provide better guidance for use of organic amendments and fertilizers by farmers. The limitations of lab testing also require that N availability is empirically evaluated under real-world farming conditions for diverse crops. Field level N mineralization can be highly variable highlighting the need for the development of techniques to determine the spatial resolution of N availability across landscapes after application of organic amendments. By integrating N data gathered on the ground with data gathered via remote sensing such as the Normalized Vegetation Difference Index (NDVI) and Landsat satellite, managers will be able to optimize applications for crop needs while reducing N losses as groundwater pollution or GHGs. This information will allow for the development of a tool to help growers make use of organic amendments, such as highly treated manure byproducts, with more precision. With increased grower confidence in N availability, more N can be exported off California dairies as the different solid products discussed in this task.

4.7. References Task 4

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TASK 5:

Comparison of greenhouse gas emission effects of selected manure nutrient recovery, removal and reuse systems.

5.1. Introduction

The motivation for adoption of nutrient recovery technologies in the California dairy context is primarily to reduce N loss to sensitive aquifers and other potentially uncontrolled N emission pathways, including NH_3, especially in the priority one nutrient management zones evaluated here. However, the state of California has also prioritized greenhouse gas impact reductions in service of climate goals laid out in AB32, the Global Warming Solutions Act of 2006. Therefore, any evaluation of technological solutions to the problem of excess nutrient loading must also be sensitive to potential GHG effects.

Life cycle assessment (LCA) uses a methodological toolset defined by the International Standards Organization (ISO 2006) for evaluation of environmental impacts of industrial processes, including industrial-scale agricultural production. More than most industrial processes, agricultural processes are highly dependent on regional and local factors such as climate, water availability for irrigation and a host of locally mediated crop and livestock production factors. In the agricultural landscape of California's Central Valley, large-scale dairy production is subject to regulations which significantly affect nutrient management in feed and waste streams and water available for irrigation. These limitations may require development of alternative systems for recovery and redistribution of nutrients – primarily N and P – found in surplus on many dairy farms (TASK 1). The concentration of nutrients in livestock feeding operations, including dairy farms, can lead to losses to groundwater (primarily NO_3) and other undesirable emissions when nutrients in manure accumulate in amounts surplus to crop recovery.

Here, we make use of a previously developed *Scalable, Process-based, Agronomic-Responsive Cropping System LCA (SPARCS-LCA)* model framework (Marvinney & Kendall 2021) to conduct a process-based, consequential LCA of three alternative manure nutrient recovery technologies currently of interest to the California dairy industry. This LCA is process-based. It examines the input demands and environmental flow outputs of a technology's processes and sub-processes within the system in question (dairy manure management and nutrient recovery). It does not use estimated impacts based on secondary indicators such as sector-specific economic data.

A consequential LCA uses counterfactual scenarios to determine the consequences of various potential technological pathways or management options on system impacts, rather than simply characterizing an existing system by itself, called attributional LCA. Thus, the technologies evaluated are compared with a baseline or counterfactual scenario representing business-as-usual manure management: an uncovered, lagoon-based storage of liquid waste and effluent delivery to on-site forage and silage crops. Composting solid manure waste streams (i.e., solids separated from flushed manure and dried manure from corrals) and the export of the resulting materials to regional, non-dairy cropping systems based on estimated N or P demand for crops is considered separately.

Although these nutrient recovery technologies produce useful products, we treat these products as waste streams in a strict sense for purposes of LCA. Essentially, a product that incurs net handling/

disposal costs to the producer, as opposed to generating an income stream, is treated as a waste by-product of the system, rather than a valued co-product. This methodological choice avoids the need to calculate full dairy system impacts and allocate them between primary products (primarily milk, meat, and animal by-products) and then including traditional or novel manure nutrient products.

The three nutrient recovery technologies examined, Trident Dissolved Air Flotation (DAF), Sedron Vapor Recompression Distillation (VarCor), and Biofiltro vermifiltration systems (TASK 2), accept liquid waste streams as input – essentially those wastes falling on concrete surfaces and traditionally subsequently flushed into anaerobic storage lagoons. Furthermore, each of these technologies can function in series with lagoon storage or anaerobic digestion systems and can produce solid nutrient products comparable with windrow-composted solid manure. Therefore, the *baseline scenario for comparison* to each of these technologies is defined as an uncovered lagoon used for storage of the liquid waste stream, and windrow composting of solid waste streams with assumed export to croplands with displacement of N fertilizer. Composting is assumed because it reduces weed seed populations and potential pathogens, compared to scrapped and piled solid manure, making it more readily distributed to non-dairy farms for use on food crops. The three nutrient recovery technologies assessed here are treated as add-ons to business-as-usual lagoon storage, with results reported by quantity of manure dry matter (DM) input.

5.2. Methods

In order to quantify the impacts associated with each of these technologies, the SPARCS-LCA model was parametrized using data from the literature and publicly available datasets (USDA 2021) as well as direct interviews with technology company representatives. The dairy nutrient recovery LCA model system boundary includes three major components: technology operation, product distribution, and fertilizer displacement (Fig. 5.1-5.3).

Treatment system operation is treated as a black box system, in which energy and material inputs as well as recovered nutrient outputs are quantified, but the various operations or sub-systems are not analyzed separately. Mass balance data describing quantities and nutrient content of influent and effluent for each of these systems was obtained from supporting literature and interviews with company representatives (described in TASK 2) and converted to a per kg manure dry matter input basis (Table 5.1). Manure dry matter input was chosen as the functional unit for reporting, as it is easily converted to total input mass, cattle numbers, and acreage functional units.

Life Cycle Inventory (LCI) data were obtained from *Ecoinvent* and US Professional databases accessed through *GaBi* LCA modeling software (PE International 2019). These data characterize and quantify the various energy, material and chemical flows to and from the environment associated with various products and processes contributing to the dairy nutrient recovery system. After being assigned to the various system processes under examination, these flows were converted to global warming potential over 20- and 100-year time horizons (GWP_{20} and GWP_{100}) and pollutant emissions (Particulate Matter and Smog Formation Potential) using TRACI3.1 impact characterization factors (CFs). These CFs, based on empirical data and modeling efforts undertaken by the US Environmental Protection Agency (USEPA 2017), provide the means to convert individual chemical flows to the environment (for example, individual GHGs such as CO_2, CH_4, and N_2O) into generalized environmental impacts such as Global Warming Potential, based on their relative effect as compared to a reference substance. In the case of

GWP, the mass of individual GHGs released to the atmosphere are multiplied by their individual conversion factors and then summed to calculate their effect on radiative forcing or “warming” reported relative to carbon dioxide – that is, as carbon dioxide equivalents.

Table 5. 1. Nutrient product mass balance by waste treatment system.

Per kg manure dry matter input (kg)	Trident DAF System	Sedron VarCor System		Biofiltro Vermifiltration System	Anaerobic Digestion	Compost/ Windrow
		Aqueous ammonia distillate	Solid to compost			
Product dry matter (kg)	0.55	0.066*	0.98	1.24**	--	0.618
N output (kg)	0.0043	0.054	0.029	0.019	0.036	0.049
P output (kg)	0.0013	--	0.013	--	0.042	0.023
K output (kg)	0.0009	--	0.028	--	0.255	--
N replacement value	0.62	1	0.62	0.62	--	0.53

Notes:
*Solute mass reported for liquid nutrient product
**Includes addition of woodchips at an assumed 1:1 mass ratio

5.2.1. Modeling Technology Operation

In order to establish a baseline for consequential analysis of alternative technologies for dairy liquid waste management, lagoon storage was chosen as a business-as-usual (**BAU**) scenario, with each alternative technology scenario considered additively. The most common alternative currently is anaerobic digestion (**AD**). California supports the development of AD on dairy farms using anaerobic lagoon storage, and the number of systems is anticipated to continue to increase. AD systems in California most commonly use a covered liquid manure storage lagoon to collect biogas consisting mainly of methane and carbon dioxide produced under low-oxygen conditions. Liquid waste influents are pumped or flows by gravity into the lagoon following collection from concrete areas in free stall barns, feeding areas, and milk houses after solids are separated (TASK 4). Separated solids are commonly used for bedding or spread on fields.

Effluent pumping is excluded from comparative analysis as energy demand is assumed to be identical for each of the technology alternatives and the AD baseline. The biogas produced in AD systems for simplicity is assumed to displace fossil energy use in electricity generation. Currently, most new dairy biogas is committed to transportation fuel uses for economic reasons. While N and P containing effluent is utilized for fertigation of on-site forage crops, this use of effluent as fertilizer is not assumed to displace fertilizer production, as it is applied on-site as a waste management practice under BAU and its nutrient content is calculated relative to crop uptake (TASK 1), rather than moved off-site to replace other N and P sources on non-dairy fields. Manure storage, including residual materials from the AD process, also results in on-site emission of methane, nitrous oxide and carbon dioxide as fugitive emissions from the lagoon, calculated as 5% of methane yield (CARB 2014). The carbon dioxide emissions, derived from biogenic sources, are here treated as carbon neutral in keeping with ISO14040 guidelines (ISO 2016).

Manure treatment technologies

The three recovery technology scenarios are represented graphically to compare processes and the framework for calculation of environmental impacts measured per unit mass of manure dry matter input. The diagrams used to represent each treatment technology illustrate different types of manure storage on dairy farms. They include manure flows before and after treatment by each selected technology, and subsequent distribution and potential use pathways. In the SPARCS-LCA model, the three recovery technology scenarios are defined by a unique set of state variables, inputs, and outputs. Each process component represented in the scenario-specific system diagram is associated with a particular set of input and output flows (that is, energy and material demand, manure input, nutrient and waste output). These flows are quantified at each stage in the nutrient recovery process and subsequently summed. The process-based SPARCS-LCA model outputs flow and impact data for each process component and for the system as a whole.

The **Trident Dissolved Air Flotation system** (Fig. 5.1) separates coarse and fine solids from the liquid fraction using drum press and chemical flocculant with dissolved air flotation components, respectively. The system outputs coarse fiber which is directed to bedding (nutrient cake) which is assumed to be utilized for off-site crop fertilization, and a low-P effluent which is used for on-site forage crop fertigation. This system requires the addition of a flocculation polymer for fine solids separation. This analysis assumes the use of polyacrylamide at a rate of 25 mg per L influent, or $1.17X10^{-4}$ kg per kg dry matter input. Electricity is used by the Trident system for primary solids separation, fine particle separation, and dewatering operations at a total rate of 0.113 MJ per kg dry matter input. Diesel fuel is used for management and loading of nutrient cake and fiber bedding products at a rate of $4.31X10^{-4}$ L per kg dry matter input, calculated based on fuel consumption rates for loading of other agricultural products on a per kg basis (Marvinney and Kendall 2021).

The **Sedron Varcor Recompression Distillation system** (Fig. 5.2) separates manure solids from the liquid waste input through heating and evaporation/distillation of the vapor component. The process requires electricity for vapor recompression and natural gas to compensate for component heat loss and produces aqueous ammonia with a N content of approximately 8% by mass, assumed to displace ammonia produced by the Haber-Bosch process in off-site cropping systems. Diesel fuel is used for management of the solid component, which is assumed to be composted and delivered to cropping systems, also displacing N fertilizer. This system also produces a solid product containing organic N, which is assumed to be directed to on-site windrow composting.

The **Biofiltro BIDA Vermifiltration system** (Fig. 5.3) directs liquid waste into a sprayer system to distribute the input over a trickling biofilter with woodchip substrate hosting earth worms. The woodchips are assumed to be derived from local or regional perennial cropping systems (orchard removal wood chips) as a waste product. Worm activity breaks down the liquid waste and substrate, producing dilute effluent for on-site forage crop irrigation and nutrient and carbon dense Vermifiltration, which can be utilized off-site to displace fertilizer in annual and perennial cropping systems. Diesel fuel is used in management of this nutrient product, including loading and windrowing. The Biofiltro system also reduces on-site methane and N_2O emissions to the atmosphere (Table 5.2), as well as NH_3, which was not specifically examined in this analysis.

Table 5.2. Emission factors for methane and nitrous oxide for manure treatment processes.				
Emission kg per kg manure DM	**Anaerobic Digestion**	**Biofiltro Vermicomposting**	**Lagoon**	**Windrow Composting**
CH_4	0.0019	0.0016	0.101	0.037
N_2O	0.00024	0.00024	0.00028	--
*CH_4 post-Biofiltro**	0.00038	--	0.02	--

Notes:

*Based on volatile solids (VS) reduction as described in section 2. These values are used to calculate the direct emissions component of the LCA results, converting input DM to CH_4 and N_2O emissions.

5.2.2. Nutrient Product Distribution

Delivery of dairy nutrient products to regional cropping systems, where they can displace conventional fertilizers, entails significant freight transport costs and inputs. These impacts were estimated using a source-sink distribution model developed in the R coding environment. This model accepts a near distance table produced in ArcGIS as input. In this analysis, the near table input was produced from a 1-km hexagonal (hex) grid overlay of the Central Valley, to which were mapped dairy cattle population based on reported data and farm location, manure production using assumptions from TASK 1, nitrogen management zone (NMZ), and crop nutrient demand. Use of a hex grid anonymizes crop acreage and dairy population, as well as significantly reducing computational demand.

The model sequentially distributes nutrient products from dairy hexes to crop hexes outside of the Priority 1 Nutrient Management Zones, in order of near rank (closest to farthest) and in packets proportional to the percentage of total Central Valley nutrient demand represented by the destination 1-km hex. This process is iterated over each source-sink hex pair by near distance rank, and repeated until 99% of estimated nutrient supply is delivered. Crop hexes are removed from the calculation matrix when their nutrient demand is filled. This process was run using both N and P as demand-limited nutrients.

Product transport mass was calculated based on the nutrient mass percentage (N or P) and moisture content of each specific nutrient product, and transport impact. Metric tonne-kilometers (tkm) per kg nutrient product was calculated by multiplying transport mass by distance from dairy nutrient source to cropland nutrient sink. The tonne-kilometer impact is then converted to tons CO_2eq as GWP_{100} using life cycle inventory (LCI) data from EcoInvent database and TRACI 3.1 impact characterization factors. These transport model output values are driven by dairy herd size and corresponding manure nutrient output, as well as by the spatial and supply-demand relationships between nutrient sources (dairies) and non-dairy cropland nutrient sinks. Both dairy manure/recovered N production and crop nutrient demand were determined on an annual basis.

Figure 5.4 illustrates the results of transport impact estimation, using a generic composite recovered N product with N and moisture content set as the average of Sedron, Trident, and BioFiltro nutrient recovery products. In addition to demonstrating the reduction in transport impacts associated with recovered nutrient products (red) as compared to composted manure (brown), this figure illustrates the low correlation between dairy herd size (grey) and nutrient product or manure compost transport emissions – a potentially counterintuitive finding. All transport distances being equal, the primary driver of transport impacts on a per dairy basis would be the total mass of manure or recovered N product exported. This lack of correlation between nutrient transport impacts and herd size/annual manure production demonstrates that the local distribution of non-dairy cropland relative to the dairy is a much greater driver of nutrient product transport impacts.

Thus, the variability in cropland distribution and nutrient demand as determined by crop type translates to significant overall differences in nutrient product distribution impacts among the NMZs examined. Figure 5.5 uses Trident technology and manure composting as examples. As identified in TASK 1 (Figs. 1.10, 1.11), a set of dairy operations in the Turlock NMZ represent a significant nutrient surplus hotspot. However, this nutrient excess does not correspond to equivalently large nutrient product distribution emissions due to the large potential cropland N-demand located nearby, providing a sink for exported nutrient products within a relatively small transport distance (TASK 1; Fig. 1.12). Effectively, the large surplus nutrient amounts in the Turlock NMZ are potentially offset to some degree by nearer cropland access. Similarly, other NMZs with relatively fewer surplus nutrients may have larger emissions costs associated with manure distribution.

5.2.3. Fertilizer Displacement

Displacement quantity of chemical fertilizers by recovered nutrient products was calculated as the N content of system outputs multiplied by fertilizer replacement values obtained from literature (Table 5.1). This quantity was then multiplied by the chemical input and output flows defined by a US generic N fertilizer LCI dataset, converted to impacts using TRACI3.1 impact factors, and subtracted from the total impacts calculated for each nutrient recovery process.

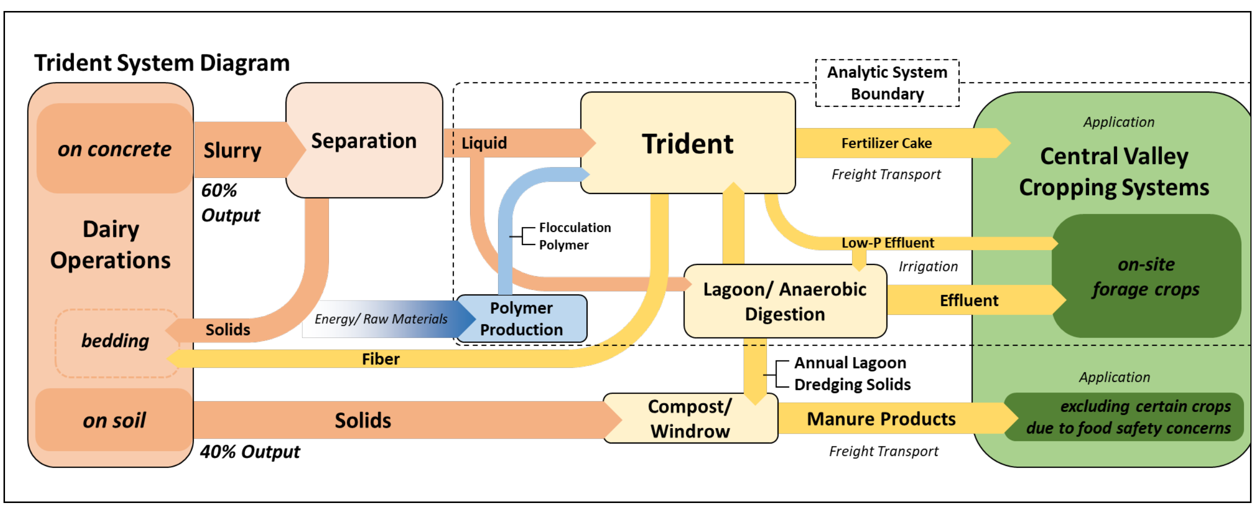

Figure 5.1. Trident LCA system diagram.

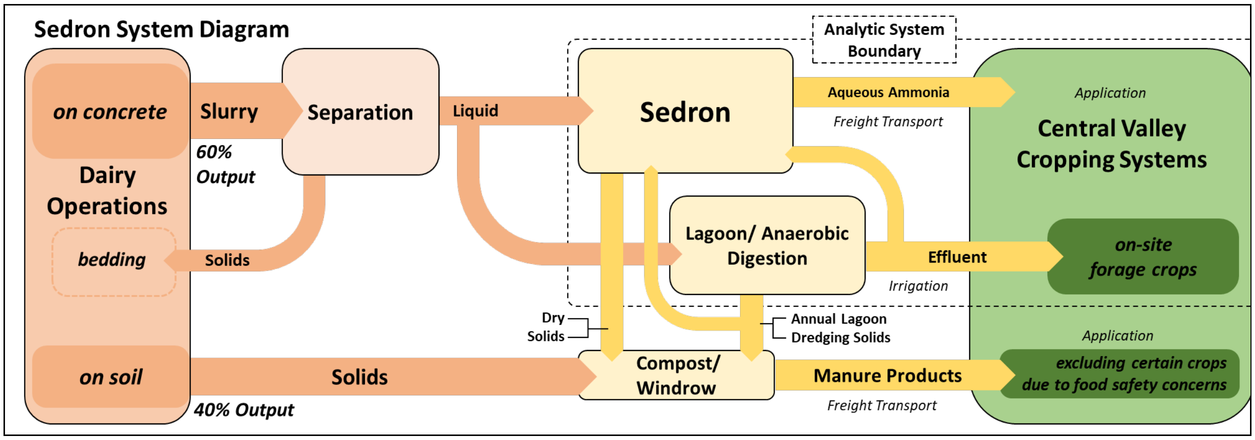

Figure 5.2. Sedron LCA system diagram.

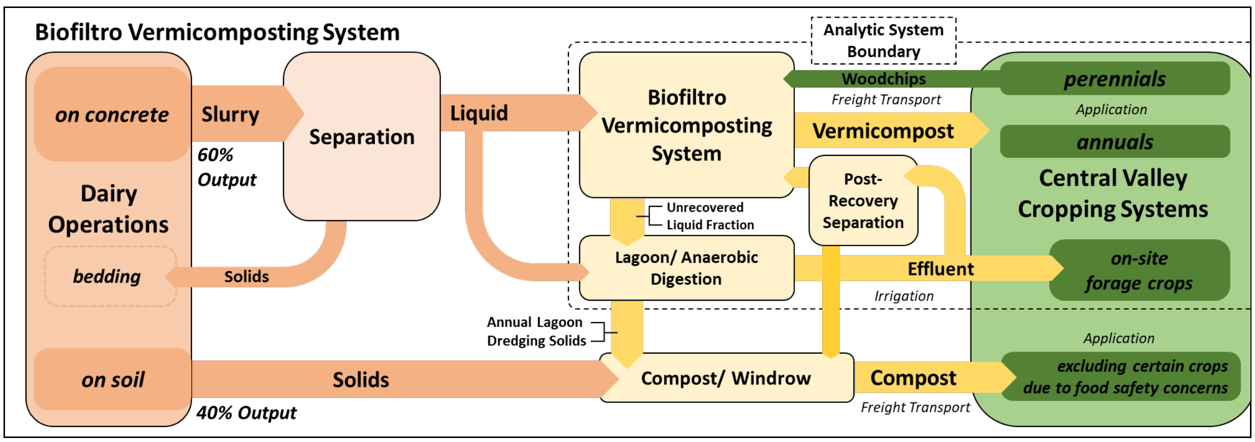

Figure 5.3. Biofiltro Vermicompost LCA system diagram.

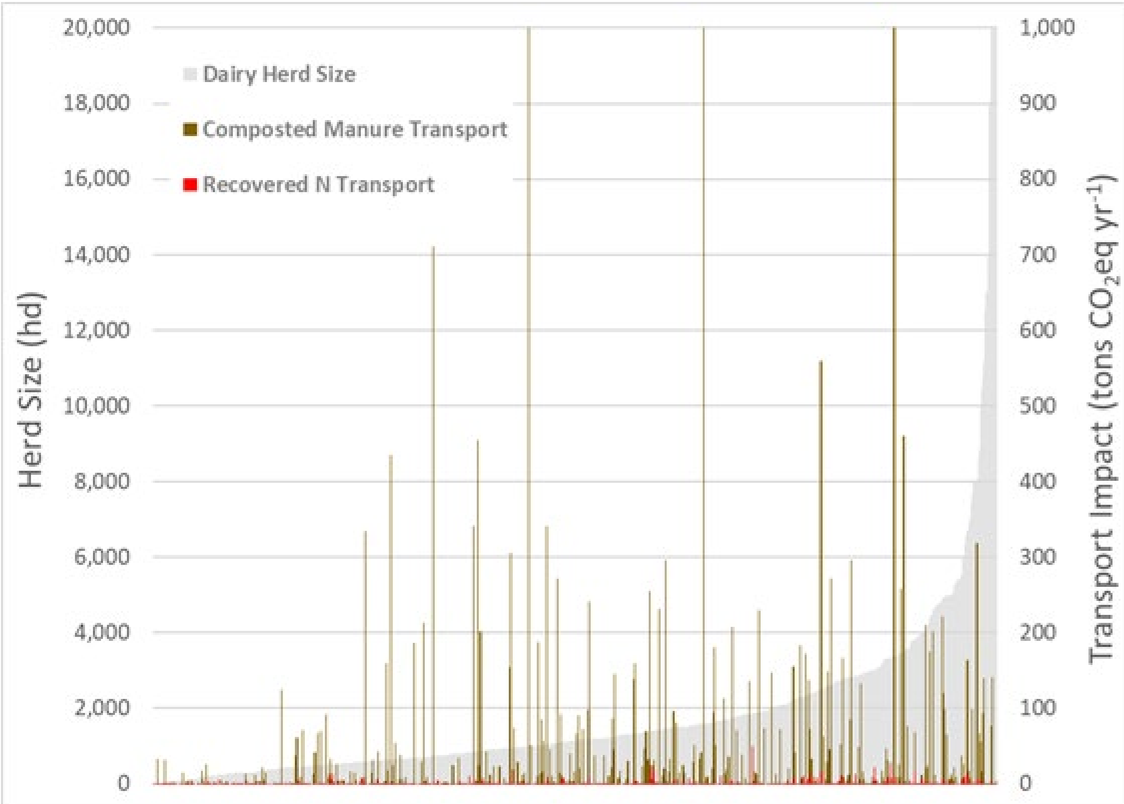

Figure 5.4. Freight transport requirement for delivery of generic recovered N products or composted manure from dairies to non-dairy cropping systems. Calculated by multiplying annual product mass (I.E., metric tonnes produced at each dairy) by transport distance (kilometers) to produce tonne-kilometer (tkm) freight transport impact values on a per-trip basis. Tkm values are then converted to tons CO_2eq using life cycle inventory data (from EcoInvent LCI database) and GWP_{100} impact characterization factors (from USEPA TRACI 3.1). The x-axis is ordered by increasing dairy herd size (grey fill). Red lines indicate GWP_{100} impact of delivery of generic recovered nutrient product to cropland, while brown lines indicate GWP_{100} impact for delivery of composted manure to cropland. Transport requirements are determined by the distances between dairy sources and crop fields available to accept nutrients, specific to crop type and annual nutrient demand

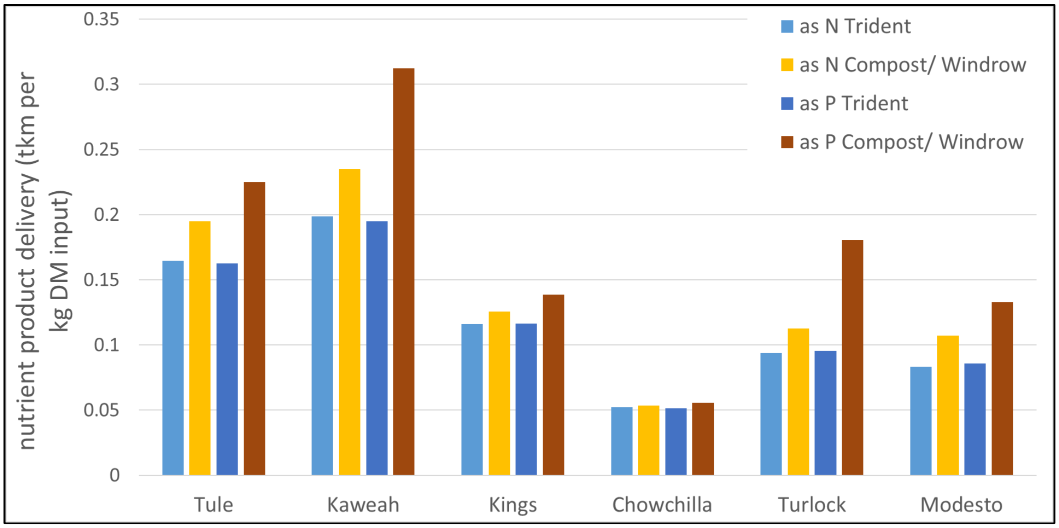

Figure 5.5. Freight transport requirement by nitrogen management zone, nutrient (N or P), and technology, using the Trident technology and composting as examples**.**

5.3. Results and Discussion

Results are presented in two ways: first as stand-alone technologies (Fig. 5.6), and then as used in sequence with lagoon storage or AD systems (Fig. 5.7). This is intended to reflect and illustrate modeling assumptions about how these technologies might be deployed in the context of California dairy operations. The baseline scenario against which each nutrient recovery technology is compared is open lagoon storage. In each case, technologies are compared on the basis of GHG emissions per kg manure dry matter input to the nutrient recovery pathway. The LCA methodology used is expressly designed to account for off-site impacts and benefits. In the case of dairy nutrient recovery and removal, the potential for displacement of N fertilizer production by manure-derived N sources for non-dairy cropland is especially relevant.

Analysis of the Trident system indicates that GHG emissions can be avoided by displacement of fossil fuel-based N fertilizer production the use of the system's nutrient cake. This displacement benefit slightly outweighs the emissions from system operation and distribution of the nutrient cake. This results in a net negative GHG footprint for the Trident system (Fig. 5.6d) and leads to a reduction of GHG emissions when this nutrient recovery technology is utilized as an added process to the baseline anaerobic digestion system (Fig 5.7b).

The Sedron VarCor system uses significantly more energy as electricity and natural gas compared to the Trident system, as well as the direct emission of methane resulting from assumed composting of the solid product (Fig. 5.2). Although these emissions are offset by fertilizer displacement from use of the aqueous ammonia distillate product as well as organic N in the composted solids, the net GHG footprint of this system is positive (Fig. 5.6e). This results in a slight increase in total GHG emissions with the addition of the Sedron VarCor system to lagoon and AD processes (Fig. 5.7d).

The Biofiltro Vermicomposting system requires low energy inputs other than fuel for woodchip and compost management but produces some direct methane and nitrous oxide emissions that outweigh the fertilizer displacement benefits (Fig 5.6f). However, the reduction of volatile solids (VS) and subsequent reduction of methane emissions from effluent directed to a storage lagoon or to anaerobic digestion creates a significant reduction in methane emissions (Fig. 5.7e&f) – here calculated using an 80% VS reduction as described in Section 5.2.1 and Table 5.2.

The recovery processes are considered equivalent in different regions, except for emissions from distribution of products – a relatively small contributor compared to direct emissions. Figure 5.8 illustrates regional differences in total manure nutrient management GHG emissions among the priority one NMZs. The observed differences result largely from total cattle populations and stocking rates by NMZ – the determinants of manure surpluses and amounts directed to nutrient recovery processes.

For each of these systems, significant uncertainty remains regarding several key factors determining overall emissions estimates. Generic data from literature sources is used for calculation of fertilizer replacement value – a measure of the ability of a given nutrient product to provide nutrition to crops, expressed as a value relative to a mineral N source. This value provides the basis for calculation of emissions avoided from fossil fuel displacement, and these calculated results may change significantly when product-specific fertilizer replacement values become available with further analysis. TASK 4 presents preliminary fertilizer-replacement values but were not concluded in time for this modeling effort.

Uncertainty also arises when calculating direct emissions based on emission factors from literature sources (Table 5.2) – in particular those associated with composting operations for solid products (especially, the Sedron Varcor solids output). While we consider these emissions factors to be a reasonable first approximation estimate, the Sedron Varcor product has initial characteristics significantly different from manure solids and thus may be expected to behave differently in terms of compost-related emissions. There may also be both dairy operation and regionally specific differences in direct emissions based on climate and management factors. This uncertainty may have a significant effect on the outcome of these analyses, given that direct emissions are by far the largest component of the total GHG footprint of each process examined (Fig. 5.7). These factors can be accounted when evaluating the use of nutrient recovery systems on a per dairy or dairy cluster basis (TASK 1, TASK 3).

Similarly, the functional behavior of these nutrient products when applied to various annual and perennial crops, (each with differing management, tillage, and irrigation practices) should be evaluated. Organic amendments may result in significant carbon sequestration benefits in agricultural soils and include diverse effects on potential GHG emissions (TASK 4). A full assessment of nutrient recovery technologies must take these in-field dynamics into account to some extent, though collection of data necessary for this level of analysis was beyond the scope of this study.

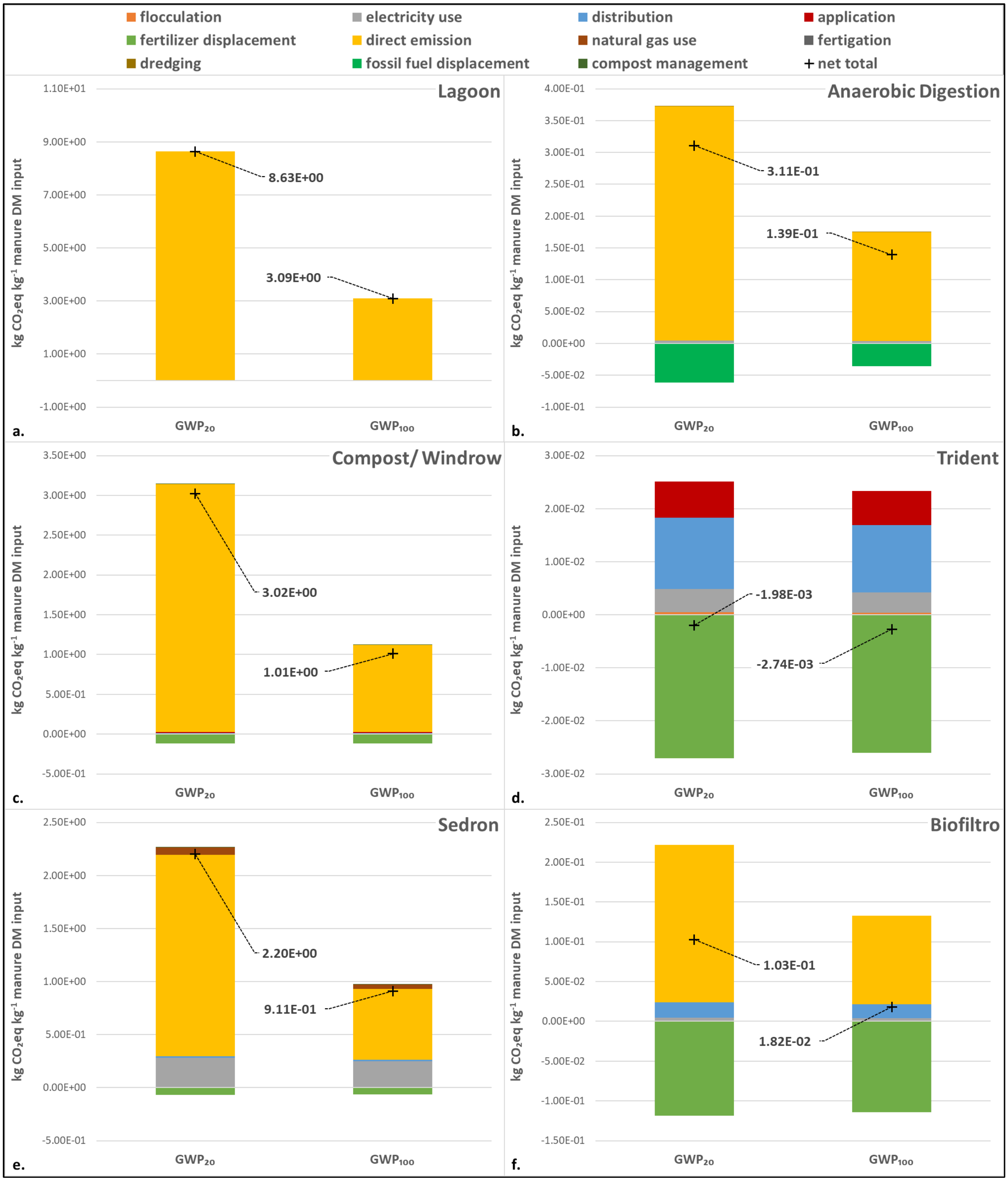

Figure 5. 6. Individual waste-management process GHG emissions expressed per unit input waste dry matter. a) Baseline or "business-as-usual" (BAU) scenario: uncovered storage lagoon. b) Covered lagoon with anaerobic digestion. c) default on-site composting for solid waste streams, including manure falling on soil or solid product from Sedron VarCor system. d) Trident DAF e) Sedron VarCor. f) Biofiltro vermifiltration. *Note: scales on the y-axis vary.*

Figure 5. 7. Combined (sequential) waste-management process GHG emissions per unit input waste dry matter. a) lagoon effluent to Trident DAF. b) post-digester effluent to Trident DAF. c) lagoon effluent to Sedron Varcor, with solid output to composting. d) post-digester effluent to Sedron Varcor, with solid output to composting. e) Pre-lagoon liquid waste to Biofiltro vermicomposting with reduced volatile solid (VS) effluent to storage lagoon. f) Post AD effluent too storage lagoon.

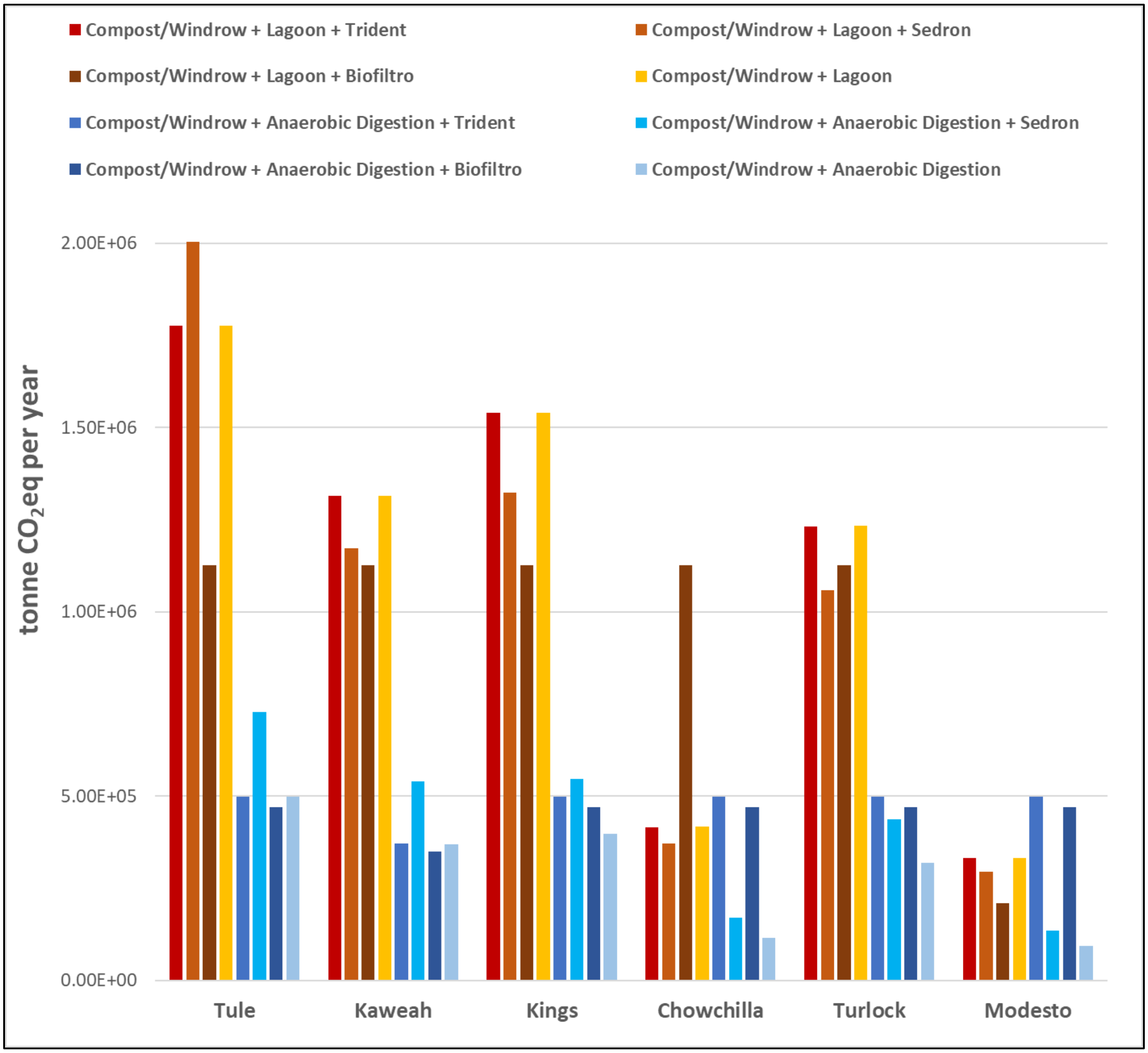

Figure 5.8. Total estimated GHG emission as tonnes CO2eq emission under different dairy waste management-nutrient recovery scenarios by nitrogen management zone (NMZ), assuming a distribution of manure dry matter of 48.75% in solid and 51.25% in liquid waste streams. The first 4 columns in each NMZ category represent uncovered lagoon-based processes, while the second 4 columns include anaerobic digestion systems with the treatment technologies, as in figure 5.7. Regional differences among NMZs are driven primarily by total dairy nutrient surpluses, with variability in nutrient product distribution playing a minor role in the total GHG footprint. From a GHG emissions standpoint, the addition of Trident and Biofiltro processes to lagoon or AD produces an additional nutrient product while correspondingly reducing potential nutrient loading to fields and aquifers, but with no significant effect on GHG emissions. Note: 1 metric tonne is equal to 1.1 US tons.

5.4. System comparisons

The BioFiltro Vermifiltration system best fulfills the combined goals of reduced nutrient loading to aquifers without significant GHG emissions increases (Fig. 5.7, Table 5.3) when used upstream of storage lagoons, mainly by virtue of removing volatile solids from treated influent, reducing methane emissions from downstream storage lagoons. It also requires relatively low energy inputs and relies on a waste stream from woody perennial crops – woodchips – as a primary material input. This reduction in downstream emissions is the most important contributor to net emissions, significantly greater than the contribution of displaced emissions from avoided fertilizer production, which are limited. Vermifiltration results in the largest total N losses from the manure system through denitrification, reducing the chance to recycle N. But it also reduces N_2O and NH_3 emissions in the process, illustrating that tradeoffs occur. These losses are primarily in the form of N_2. However, all the systems examined involve tradeoffs among the forms of N emitted.

The Trident DAF system also fulfills these criteria, creating a small reduction in GHG impacts over the baseline scenario of lagoon storage for liquid manure wastes (Fig. 5.7, Table 5.3). This comes about through consideration of nutrient products produced by the Trident system and the other technologies evaluated here as a fertilizer substitute, resulting in avoided emissions through displaced fertilizer production. In the case of Trident DAF system, the fertilizer displacement benefits modestly outweigh the impacts of the energy and material demand of the system, resulting in a net negative GHG impact. Therefore, the use of this process to recover nutrients from lagoon effluent can protect groundwater from nutrient overloading while also reducing net GHG emissions. The Trident system performed best when used in conjunction with AD systems, since it reduces overall GHG footprint via fertilizer displacement without interfering with AD biogas production.

The Sedron-Varcor system performs less well from a GHG standpoint. This process requires significantly larger energy inputs as electricity and natural gas, while producing a relatively low nutrient density primary product such as aqueous ammonia. This system also produces a solid byproduct which is assumed to be directed to composting, with some associated GHG emission. This direct emission from composting plus emissions from fossil energy use results in a considerably larger GHG footprint for nutrient recovery as compared to the Trident and BioFiltro systems. The impacts for the Sedron-Varcor system's N recovery on a per kg dry matter input basis depend greatly on the solids content of the system's influent, exhibiting increases of 32% and 63% for GWP_{20} and GWP_{100}, respectively, when influent solids are reduced from the assumed value of 3.7% to 0.6% by mass (Table 5.3).

Anaerobic digestion (AD) is well understood to be a major reducer of dairy waste-stream emissions, especially when compared to open lagoon storage. This analysis finds that AD reduces GHG emissions far more than any of the nutrient recovery technologies assessed. However, it must be noted that the primary purpose of these technologies is not GHG reduction per se but rather recovery and utilization of excess nutrients in dairy waste streams. Table 5.3 indicates the change in GHG impacts incurred by use of each of these technologies for this purpose.

Table 5.3. Life cycle greenhouse gas impacts of various dairy waste management processes generated using the SPARCS LCA model (Marvinney and Kendall 2021).				
Process	**GWP_{20} (kg CO_2eq kg input DM^{-1-})**	**GWP_{100} (kg CO_2eq kg^{-1} input DM)**	**% lagoon baseline (GWP_{20})**	**% lagoon baseline (GWP_{100})**
*Compost/ Windrow**	3.02	1.01	--	--
*Trident***	-0.002	-0.003	--	--
*Sedron (3.7% influent solids)***	2.20	0.91	--	--
*Sedron (0.6% influent solids)***	2.89	1.48	--	--
*Biofiltro***	0.10	0.02	--	--
Lagoon[†]	**8.63**	**3.09**	**100.00%**	**100.00%**
Trident + Lagoon	8.63	3.09	99.98%	99.91%
Sedron (3.7% influent solids) + Lagoon	10.83	4.01	125.49%	129.43%
Sedron (0.6% influent solids) + Lagoon	11.53	4.58	133.53%	147.86%
Biofiltro + Lagoon	1.56	0.57	101.19%	100.59%
Anaerobic Digestion	0.31	0.14	3.60%	4.51%
Trident + Anaerobic Digestion	0.31	0.14	3.58%	4.42%
Sedron (3.7% influent solids) + Anaerobic Digestion	2.51	1.05	29.09%	33.94%
Sedron (0.6% influent solids) + Anaerobic Digestion	3.20	1.62	37.08%	52.24%
Biofiltro + Anaerobic Digestion	0.22	0.10	2.49%	3.12%

Notes:
*Solid waste stream process - not directly comparable with lagoon liquid waste stream baseline.
**Assumed to be used only in combination with lagoon storage or anaerobic digestion - not directly comparable with lagoon baseline.
[†]Baseline, "business-as-usual" scenario.

5.5. Further research questions

This analysis is incomplete. In order to account for the benefits of fertilizer displacement, we have expanded the system boundary of the LCA to include transport and application of the nutrient product on regional croplands. In order to completely characterize the expanded system and fully capture the environmental benefits of the technology, a number of unanswered questions must be addressed:

- Further characterization of the nutrient products of the Trident, Sedron and Biofiltro systems is needed. The fertilizer replacement value of these products determines the quantity of displaced fertilizer and associated benefits, as well as the dynamics of distribution to regional cropland and associated freight transport impacts. This value was not experimentally determined in time to inform these LCA modeling efforts, warranting further study and model updates.

- These nutrient products contain both labile and stabile carbon species. Some of this carbon may be sequestered in agricultural soils with application as a nutrient source, while some may be emitted from soils as carbon dioxide or methane. Some of the N contained in these products will be released as nitrous oxide (N_2O). These dynamics are driven by management practices as well as local soil, climate and environmental conditions, and may have a significant effect on overall evaluation of the GHG performance of these nutrient recovery processes. They are a subject for further research.

- The chemical characteristics of the Sedron-Varcor solid manure product and its potential utility and further processing demands must be characterized. Without product-specific data[53] this analysis used literature values for manure composting to account for direct emissions from composting of the Varcor solid product. However, the altered characteristics likely change the emissions profile. Additionally, the material may potentially be used as a soil amendment directly, without an additional composting step. This may provide significant emissions reduction from carbon storage, but potential increases in soil methane or N_2O emissions. Determination of the net effects of soil application with this nutrient product requires further investigation.

- Each of these systems may potentially be used to recover nutrients either upstream or downstream of lagoon storage or anaerobic digestion. This analysis assumes that Sedron and Trident systems operate downstream while Biofiltro operates upstream. With additional data on volatile solids removal and other transformations of system influent, additional environmental benefits may be revealed for various process combinations.

- To achieve whole farm nutrient balances on an individual farm, especially those with stocking rates of 4 or less, only a portion of the nutrient flow may need to be treated. This may be especially suited for a vermiculture system which can be scaled variably. Research evaluating such possibilities would be beneficial.

- Only GHG impacts were examined for this analysis. Given the importance of air quality and water use in the Central Valley, quantification of smog formation, particulate matter, and freshwater use impacts in addition to GHG emission is warranted. Potential tradeoffs between impact categories for each of these technologies can serve to further refine recommendations on which options are appropriate and maximize overall environmental performance on a regionally specific basis.

- The geographic and technological scope of this work was limited to dairy farms in the priority 1 NMZs in the San Joaquin Valley. Expansion of this analysis to include other technological processes, as well as additional production regions within the state of California may identify

[53] Available from the research supported under TASK 4 when published and from further research on their fertilizer replacement value under empirical conditions.

additional pathways for optimization for managing surplus nutrients in the dairy industry to reduce nutrient losses to groundwater, GHG emissions, and other environmental impacts.

5.6. References Task 5.

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Summary and Conclusions.

Task1. Estimates of surplus manure nutrients, types, and locations on San Joaquin Valley Dairy Farms

Since crops are never completely efficient at recovering the nutrients applied as fertilizer or especially as manure, some losses and emissions from agriculture are both necessary and unavoidable. Manure N, however, is present on a large portion of dairy farms in the San Joaquin Valley (SJV) in amounts that exceed the recovery of manure nutrients by common forage crops, (especially N), leading to losses of nitrate to groundwater. This conclusion has been reported many times in reviews of manure management in California.

Stocking rates are the numbers of mature cows plus replacements per acre of cropland reported receiving manure applications. These are useful proxies for estimating surplus manure N and P on individual farms and regionally within Priority 1 Nitrogen Management Zones (NMZs) in the SJV.

Based on stocking rates and estimated manure nutrient amounts after losses during collection, storage, and crop removal, surplus nutrients in Priority 1 NMZs are estimated to occur primarily on farms with stocking rates greater than 4 cows per acre. Overall, more than half the dairies within these NMZs have stocking rates leading to surpluses, though the proportion varies with NMZ.

Small surpluses may still exist on farms with lower stocking rates (Table 1.10) but arguably can be better managed largely with improvements currently available to farmers.

Larger stocking rates are not a function of dairy size measured simply by the number of cattle or by the area of land available for manure application. Many of the farms with the largest stocking rates are smaller farms in terms of land area, especially in the northern SJV.

All Priority 1 NMZs have surplus nutrients, with the Turlock and Tule NMZs reporting the largest absolute surpluses (Table 1.11). Estimated average total amounts of manure N considered surplus in both solid and liquid manure summed in all six priority 1 NMZs are approximately 25,300 tons of N per year when calculated for dairies with stocking rates ≥ 4 cows per acre. This total amount represents approximately 6 % of all fertilizer N applied to farms in California based on a 2015 estimate of total fertilizer use. This surplus estimate accounts for crop uptake, N losses through volatilization and other gaseous pathways, and accounts for differences between free stall and open lot dairies in terms of how manure is handled and used. Estimates are based on several assumptions and averages reported for California dairies by diverse authors, so have a large amount of uncertainty.

More precise estimates can only be carried out at the level of the individual dairy. Since farms vary widely, accurate assessment of actual N surpluses sufficient to support changes in manure management or adoption of new management technologies must be carried out at the individual farm level. The methods proposed by Cativiela et al. (2019) in the SRMR provide a basis for improved assessment of surpluses.

Stocking rates indicate which farms are likely to accumulate surplus nutrients. But dairy farms vary significantly from each other, reflecting diverse local conditions, the history of each region and farm, management choices and preferences over time. Such differences are important from the perspective of manure nutrient management and constrain potential choices about future technology adoption.

Depending on the character of an individual farm, surplus N will be present primarily in liquid manure in lagoons on free stall dairies or in solid manure from corral scrappings on Open Lot dairies. Surpluses occur in both forms of manure. The form of manure and amounts will affect the types of solutions needed to manage surplus nutrients and require different management solutions.

Under current conditions, only a portion of all farms with surpluses likely will require or be able to support some of the new technologies and engineered solutions evaluated here for managing manure surpluses.

Task 2. Selected Nutrient Recovery Systems

Three new nutrient recovery systems were evaluated for the treatment of liquid manure and anaerobic digester effluents at California dairies. They vary in the amount of nutrients recovered.

The *BioFiltro* vermifilter system is relatively simple to operate, but installation cost appears high. The footprint requirement is comparatively large and scales with the amount of manure and dairy size. This could be a barrier, especially for large dairies. The system reduces N in the effluent (by denitrification) and significantly lowers the GHG emissions from a storage lagoon if it directly treats fresh flushed manure. The amount lost is a function of the amount treated. If a dairy has a relatively small surplus of manure N, a small, supplementary system may be sufficient to achieve a whole farm nutrient balance (Task 1). However, because it is a Nitrification-Denitrification (NDN) process, a large of amount of N in excreted manure is lost to the atmosphere as N_2 gas, eliminating its further use on non-dairy farms as a N fertilizer replacement.

The *Trident Nutrient Recovery System* can remove most of the fine solids and recover nearly all the phosphorous, and moderate amounts of N, in the manure flow. It may be attractive to larger dairies, or dairy clusters, due to potential economies of scale.

The *Sedron Technologies* evaporation system appears highly effective at recovering nearly all the N, phosphorous (P), and potassium (K) in treated manure for use as potential fertilizer products. It seems better suited for higher solids manure flows because of the energy required to remove water. Costs to the dairy are projected to be minimal, depending on the farm's manure supply agreement with Sedron. Sedron would own and operate the system and sell the output fertilizer products. High values for recovered nutrient products in the organic farming market are likely required for economic viability.

Task 3. Effects on dairy farms of surplus nutrient removal

Faced with increasingly restrictive manure nutrient management requirements, farmers will first adopt approaches that are less costly and easiest to integrate with their current farm management system.

On dairies in California, *conventional strategies* that better align the nutrients available in manure with crop uptake and removal include: improved measurement of manure quantities in storage and during application to fields, better accounting of and wider, more even distribution of manure nutrients to all fields on the farm, better integration of manure nutrient application with irrigation (including improvements to irrigation systems), and export of larger amounts of manure off the farm to near neighbor sites where possible.

Farms with larger stocking rates and fewer opportunities to sell or transfer manure off their farms may need to adopt new manure nutrient recovery and reuse technologies, such as those reviewed in TASKS 2 and 5. Significant capital and operating costs for some of these systems will be a barrier to adoption, absent policy support.

Attrition may affect some dairies that are unable to sufficiently improve nutrient management. Attrition may reduce the scale of the surplus nutrient problem within each NMZ by an unknown amount. The SGMA regulation may also cause attrition among dairies by an unknown amount.

Policy certainty and stability will influence the choices farmers make with respect to improved nutrient management. To most effectively address the problem of surplus nutrient accumulation on many dairy farms in California, a creative process is needed that aligns the interests of dairy producers, food companies and consumers with the state's regulatory goals. This approach need not be limited to nutrient management alone but could include other important areas of dairy management.

Creating a certification system based on measurement of performance at the individual farm level which supports improvement over time compared to each farm's individual baseline, could form the basis for a successful approach. It would elicit diverse, creative responses to the challenge of nutrient management on modern dairy farms at the individual farm level. A well-designed program needs to be gradual enough to allow farms to evolve but sufficient to achieve longer term regulatory targets to prevent additional degradation of groundwater.

Task 4. Fertilization value, climate impacts, and effects on soil organic matter of selected manure products

Although manure use has been studied in California for many years, novel management and nutrient recovery technologies will generate new materials aimed at recycling surplus nutrients from dairies to non-dairy farms. Their mineralization properties and nutrient concentrations require evaluation before recommendations can be made for their use. At the lab scale, short to medium term aerobic N mineralization assays that evaluate nutrient release characteristics under different climate and soil types were used for a select set of materials to compare and quantify the fertilizer equivalent values of new manure products.

Four products were tested (COM: composted manure; DAF: Dissolved Air Flotation solids; LWR: Livestock Water Recycling Solids, approximately similar to DAF; SED (Sedron Varcor fine solids; and VER: Biofiltro Vermifiltration bedding material). They were tested for rates of mineralization at three soil temperatures and using both a course textured and fine textured soil base. These products were derived from manure treatment systems analyzed in Tasks 2 and 5, or from composted manure treatment methods used here for comparison (COM). These products differed in % C and % N, C:N ratios and other characteristics (Table 4.1). C:N ratio varied from a low of 8.5 in the COM and a high of 14.5 in the VER. The pH values of the materials were all neutral to alkaline, with the COM having a considerably high value of 9.3. In most amendments, the initial inorganic N pool is in the form of NH_4^+, except for DAF which contained a majority as NO_3^-. Notably, the SED material contained high levels of salt, over twice as high as any of the other amendments.

COM and VER mineralized minimally during the 28-day test period in both soil types and at all three temperatures (10, 20 and 30^0 C). In contrast, DAF, LWR and SED solids mineralized faster with temperature, and more rapidly in sandy soils than clay-textured soils (Fig. 4.3). These initial data suggest that these three products would provide a larger amount of soluble N to crops more quickly that standard composts and VER bedding with residual wood chip materials.

The use and further development of standardized protocols for field and lab validation of mineralization rates will help these procedures become implemented in commercial soil testing labs and provide better guidance for use of organic amendments and fertilizers by farmers. Tests in labs, however, do not include many factors that could influence performance under farming conditions. Materials evaluated here and others to be developed will also require empirical evaluation under real-world farming conditions for diverse crops, possibly including spatial data at the field scale. This information will allow growers to make more precise use of novel organic amendments, such as highly treated manure byproducts. Support for the use of advanced manure treatment technologies should also include support for research of this type testing novel manure products. With increased grower confidence in N availability, more N can be exported off California dairies in the form of different solid manure products discussed in this task, and others that might be developed.

Task 5. Comparison of greenhouse gas emission effects of selected manure nutrient recovery, removal and reuse systems.

The motivation for adoption of nutrient recovery technologies on California dairy farms is to reduce N losses to sensitive aquifers, particularly those in the NMZs evaluated here. However, the state of California has prioritized GHG emission reductions as part of the climate goals laid out in AB32, the Global Warming Solutions Act of 2006. Therefore, any evaluation of technological solutions to the problem of excess nutrient accumulation on dairy farms must also be sensitive to potential GHG effects. These were estimated using Life Cycle Assessment (LCA) methods.

Different technologies have varying effects on GHG emissions, but also variously influence the form of N emitted by the manure management system. Tradeoffs among emission forms are always involved.

The *BioFiltro vermicomposting system* best integrates the goals of reducing N surpluses in manure and minimizing GHG emissions (Fig. 5.7, Table 5.3). By removing volatile solids from treated influent, this system also greatly reduces methane emissions from downstream storage lagoons. It also requires relatively low energy inputs and relies on a waste stream from woody perennial crops or other sources – woodchips – as a primary material input. This reduction in downstream emissions is the most important factor reducing net GHG emissions and outweighs the potential climate benefits of displaced emissions from avoided fertilizer production via the use of vermiculture compost, which are small quantitatively. This is because vermiculture results in the largest total N losses from the manure system through denitrification compared with other nutrient recovery technologies analyzed here.

The *Trident DAF system* also reduces nutrient surpluses and lowers GHG emissions from manure treatment and storage. (Fig. 5.7, Table 5.3). In the case of the Trident DAF system, the fertilizer displacement benefits modestly outweigh the energy and material requirements of the system, resulting in a net negative GHG impact. Therefore, this process can simultaneously reduce the total system GHG footprint while reducing N nutrient surpluses on dairy farms.

The *Sedron Varcor* system is less effective from a GHG standpoint. This process requires significantly larger energy inputs as electricity and natural gas, while producing a relatively low nutrient density primary product as aqueous ammonia. This system also produces a solid byproduct which is assumed to be directed to composting or perhaps to direct field application, with some associated GHG emissions. The direct emission from composting plus emissions from fossil energy use in the recovery system itself result in a considerably larger GHG footprint compared to the Trident and BioFiltro systems. The GHG emissions from the Sedron-Varcor system's N recovery per kg dry matter input depend greatly on the solids content of system influent, exhibiting increases of 32% and 63% for GWP_{20} and GWP_{100}, respectively, when influent solids are reduced from the assumed value of 3.7% to 0.6% by mass (Table 5.3).