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Nitrogen Cycling on Dairies in California's Central Valley

Efficient use of nitrogen, more than for any other nutrient, is the key to profitability for dairy-forage production in California's Central Valley. Nitrogen also has the most potential of any nutrient to harm air and water quality, and therefore it is the target of government regulations. Although other nutrients in the crop-animal-soil system take on different chemical forms, the nitrogen cycle is the most complicated. Throughout the cycle, there are opportunities for gains and losses of N, many of which have the potential to cost money (by increasing fertilizer or feed costs) or degrade air and water quality (e.g., ammonium volatilization and nitrate leaching). A good understanding of N cycling can help farmers and other practitioners choose management techniques that will improve the whole-farm nutrient balance, by conserving nutrients and reducing losses.

Key Points

- *Typical N losses on Central Valley dairies range from 42 to 69% of total N excreted*
- *Reducing losses by 20% of excreted N could save $34,600/yr for an average sized Central Valley dairy*
- *The ONLY way to meet regulatory requirements and prevent crop N deficiency is to minimize field N losses.*
- *The N cycle is complex, with transformations into different forms and various points for N loss or gain*
- *Excess N in surface and groundwater can seriously impact human and environmental health*

NITROGEN TRANSFORMATIONS

A dairy farm is best seen as a system whose components all are linked, with nitrogen flowing between constituent parts and leaving or entering at various points (see Fig. 1). Feed N is transformed into milk protein (and meat protein in growing animals), with the remainder excreted as urine and manure. Approximately 35% of excreted N is urea[1] with the rest in more complex organic forms. Urea is converted very quickly (within hours) into ammonium by the enzyme urease, which is ubiquitous in soil and manure. The ammonium (NH_4^+) and remaining organic N then enters manure treatment and/or storage, with some losses along the way. Depending on its form, organic N is mineralized into NH_4^+ over a period of days to years. From manure storage, where the N is in both inorganic and organic forms, it is applied to fields on the dairy or exported from the farm.

Ammonium, either already present in the manure or as it is produced during mineralization of organic N, is available for plant uptake. However, it is more likely to be converted into nitrate (NO_3^-) by nitrifying bacteria in the soil before absorption by plants. Field losses of N can occur through volatilization of NH_4^+ and denitrification or leaching of NO_3^-. Nitrogen utilized by forage crops then completes the cycle when harvested for animal feed.

WHY MINIMIZE N LOSSES?

From a whole-farm perspective, minimizing N losses is associated with lower feed and fertilizer expenditures. N conserved on the facility or in the fields directly reduces the need for imports to the system. Feed N conversion to milk and N excretions depend on feed characteristics, milk production level, and animal health, with an average excretion rate for lactating cows in California of 1.0 lb N/head/day [1, 2][2]. Prior to any losses, a typical Central Valley dairy of 1000 cows[3] will generate 337,000 lbs of manure N each year. If recycled and used by crops with the same efficiency as commercial fertilizer N, it has a value (early 2009 prices) of approximately $173,000[4]. Reducing losses by 20% of excreted N therefore has a potential value of $34,600/yr[5]. For the same size dairy, over 62,000 lbs of phosphorus

($142,000$ lbs P_2O_5) are also excreted, although the full fertilizer value is not generally realized because N is more limiting in most cases. Potassium (K) and other nutrients in the manure may further increase the fertilizer value of the manure, if needed for the specific field or crop. Therefore, even if air and water quality were not environmental concerns, these benefits alone should warrant management changes to reduce nutrient losses. Obviously, where manure nutrients are applied to cropland beyond the point of agronomic benefit, the actual economic value will be non-existent; however some future benefit may be obtained if nutrients are "banked" in the soil.

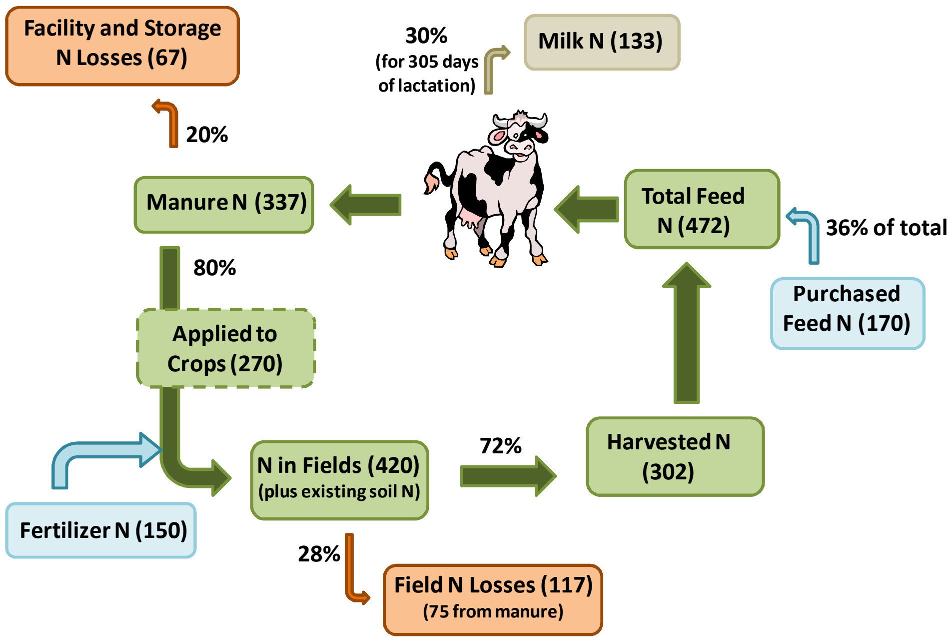

Figure 1. Hypothetical nitrogen cycle for a Central Valley dairy herd[6]. Units are lbs N/yr/cow.

Note: The indicated values assume high feed N conversion efficiency to milk as well as low facility, storage, and field losses. For simplification, the following flow pathways are not illustrated: imports or exports of animals and manure, legume associated N fixation, atmospheric N deposition, crop exports, changes in soil N reserves, and N in irrigation water.

On the other hand, regulations controlling N applications to fields receiving dairy manure are primarily in response to concerns over the public and environmental health effects of N losses to ground- and surface-water. Human health and quality of life is adversely affected by elevated N in drinking water. High ammonium (NH_4^+) concentrations in drinking water interfere with disinfection processes, and elevated nitrate and nitrite (NO_3^- and NO_2^-) concentrations are a potential health hazard for infants and pregnant women. When nitrate is transformed into nitrite and taken into the bloodstream, it prevents proper oxygen absorption, causing methemoglobinemia or "blue baby" disease. Excessive amounts of N and other nutrients in surface water also increase aquatic weed and algae growth, killing fish, causing offensive odors, and otherwise damaging natural ecosystems. While the main product of denitrification is nitrogen gas, it can also release nitrous oxide (N_2O), a key greenhouse gas that has 300 times the warming capacity of CO_2. Therefore, reducing N losses from the dairy/forage system can have diverse benefits – to the dairy's financial balance, drinking water, broader air quality, climate change, and wetland health.

WHOLE FARM N EFFICIENCY

The largest inputs of N to the dairy N cycle are purchased feed and fertilizer (see Fig. 1), with additional contributions from atmospheric deposition (rain), irrigation water, imports of bedding and animals, and biological N fixation by microbes in root nodules of alfalfa and other legumes. Unless a large proportion of manure or feed is transferred off the dairy, milk constitutes the single greatest intentional export of N (amounting to 25–30% of feed N). However, when feed production is out of balance with ration requirements or exceeds animal needs or (on the other hand) if crop acreage is insufficient for recycling of manure, dairy producers may transfer significant amounts of N off the dairy in the form of manure or feed/forage. Unplanned or unintentional losses of N to air and water can be considerable and are significantly impacted by management decisions.

Table 1 contrasts the N balance for four hypothetical dairies, including the example from Figure 1. All harvested N is assumed to be fed to animals, though in reality some losses can occur here as well. For purposes of simplicity, legume N additions and animal exports are not included, although in many cases legumes can significantly reduce the need for imports of feed or fertilizer N. Dairy A is the base case, with efficient feed N conversion, low N loss rates and sufficient land availability. The other three dairies demonstrate the impact of reduced feed N efficiency (Dairy B), higher N losses from facility and the land (Dairy C), and insufficient land for manure application and forage production (Dairy D). All of these issues require additional purchases of N, as fertilizer or as feed components. Feed N conversion varies from 25% to 30%, facility N losses vary from 20% to 40% of that excreted, and field N losses vary from 28% to 48% of that applied [2, pp. 20, 34, 48]. The land limitation of 0.28 acres/cow in Dairy D is the median non-alfalfa forage land availability for a sample of dairies in the Central Valley in 2002. At 2008 prices, Farms B, C, and D face additional N purchase costs of approximately $165, $117, and $330/cow/yr, respectively.

TYPICAL LOSS RATES AND INFLUENTIAL FACTORS

Dairy operations in the Central Valley differ significantly in animal housing, feed ration composition, manure treatment and storage, irrigation water flow rates, and manure distribution and application methods. All of these factors influence the variation in whole-farm N losses that typically range from 42% to 69% of the total N excreted in manure [2]. Table 2 summarizes current research on the range of N losses at different points and the impacts of different controlling factors.

Table 1. Nitrogen cycling on four hypothetical dairy farms with equal levels of milk and forage production, assuming 305 days lactating and 60 days dry. Dairy A is as shown in Figure 1.

	Dairy A	**Dairy B (↓feed efficiency)**	**Dairy C (↑losses)**	**Dairy D (↓land available)**
N in Cycle (lbs N/cow/yr)				
Feed N	472	561	472	472
Excreted N	337	426	337	337
Manure N applied to fields	270	341	202	170
Harvested N	302	302	302	123
Exports and losses (lbs N/cow/yr)				
Milk N	133	133	133	133
Calves born[a]	1	1	1	1
Manure exported	0	0	0	100
Facility losses	67	85	135	67
Field losses – from manure	75	95	97	48
Field losses – from fertilizer	42	22	182	0
Total N exported or lost	**320**	**337**	**548**	**349**
N imports (lbs N/cow/yr)				
Feed purchases	**170**	259	170	349
Fertilizer purchases	**150**	79	378	0
Total N imported [cost[b]]	**320 [$462]**	**337 [$628]**	**548 [$580]**	**349 [$793]**
Applied N : Harvested N Ratio	**1.4**	**1.4**	**1.9**	**1.4**
Assumptions[c]				
Feed N conversion efficiency (% feed N converted to milk in lactating cows)	30	25	30	30
Facility N losses (% of excreted N)	20	20	40	20
Field N losses (% of all applied N)	28	28	48	28
Feed N purchased (% of total)[d]	36	46	36	74
Forage land (acres/cow)[e]	0.69	0.69	0.69	0.28

[a] Assumes calves are exported from dairy directly after birth. Actual practice may impact feed and manure N.

[b] Cost of N imports is based on feed N of $2.27/lb and fertilizer N of $0.513/lb – calculated from available fertilizer and feed cost reports for 2008.

[c] The ranges used in N efficiency assumptions are based on ANR publication 9004 [2].

[d] Assumed and set at 36% for Dairy A [see 8]. Dairies B and C are assumed to have same amount of cropland and crop productivity and Dairy D has limited land – % of feed N purchased is then calculated.

[e] Calculated based on total annual harvested N removed of 440 lbs N/acre (average from BIFS project). Set at lower value for Dairy D.

Facility and Storage Losses

Up to 60% of excreted N can be lost by ammonia volatilization before the manure is even removed from the animal living quarters [9, 10], with highest loss rates observed where cattle are in dry corrals or large loafing areas and manure is left on the ground for days or weeks. However, research in California suggests that for a dairy with all manure entering an uncovered storage pond via flush lanes, the facility and storage N losses range from 20 to 40% [2].

Losses are also influenced by the design and operation of manure treatment and storage systems. More N is conserved when using manure water ponds – rather than solid systems – to handle the majority of manure. Under Central Valley conditions, within the commonly used freestalls and flushlanes, the maximum atmospheric N loss rate is approximately 35% [2, p. 31]. Estimated ammonia (NH_3) volatilization rates from storage ponds range between 2% (pH = 7.0, 25 ft depth) and 38% (pH=7.8, 10 ft depth) of total N excreted [2, p. 32], and are also impacted by the proportion of N in ammonia versus organic forms. Composting of manure can release large amounts of N (up to 50%) as volatilized NH_3 [11], and carbon-rich materials are sometimes added to immobilize N and reduce losses. Where nutrient recycling using nearby cropped fields is severely limited, systems have been designed to remove N by conversion into N_2 gas through alternating aerobic and anaerobic treatment reactors [12]. However, most anaerobic biogas reactors have negligible losses of N and convert much of the organic N into mineralized – and thus plant-available – forms [13].

Field Losses

Sufficient dilution of manure water reduces volatilization losses during field application, and experts suggest that NH_4^+ concentrations below 100 ppm in the irrigation water will result in minimal losses [2]. When applied to a field with a closed crop canopy, the crop can also absorb much of the NH_3 gas that does escape. Although NH_4^+ is adsorbed to soil and organic matter particles during infiltration, much of it does enter the soil profile, where it is converted into NO_3^- over a period of days. This initial adsorption prevents immediate leaching with excess irrigation water.

A greater concern is NO_3^--N leaching, since after conversion to NO_3^-, the N is readily soluble in the soil solution and susceptible to leaching with subsequent irrigation events. In the gravity flow irrigation systems common to the Central Valley, the best achievable irrigation application efficiency (amount of water that remains available to the crop) is 70 to 85%; the remaining 15 to 30% of the water leaches beyond the root zone [2, p. 43], taking soluble NO_3^- and other salts with it. Some leaching is necessary to move excess non-nitrate salts below the root zone and prevent crop damage. Rain may achieve this in some locations and in some years. Intentional leaching for the purpose of salt removal should be timed for periods when soil nitrate is low.

While some build-up of organic N in the soil can occur with regular manure additions, most fields on or near dairies are already at an equilibrium condition, with a constant level of organic N. This means that total N applied equals crop removal plus losses (denitrification and leaching). The proportion of losses due to leaching versus denitrification varies with soil characteristics, amount of irrigation water, amount of carbon in the soil, and other factors [14]. Studies in other regions have found total leaching losses to be 5 to 35 times greater than denitrification losses of N [15, 16]. In well-drained soils with relatively low organic matter content (typical of the Central Valley), leaching losses are the main concern. The timing of these nitrate-N losses is directly related to irrigation and precipitation and when NO_3^- is present in the soil solution, and applications targeted to crop uptake needs reduce losses. Cooler weather also slows mineralization and volatilization rates, reducing losses.

FARM-LEVEL ACTIONS TO REDUCE LOSSES

While producers cannot eliminate N losses, adaptations in facility design and operation can improve efficiency, save money, and reduce the transfer of N to air and water. Table 2 outlines the typical range of losses at various points in the dairy-forage system and the main factors that affect loss rates. Dairies will generally wish to address losses from facilities and losses from fields for different reasons. Attention to losses from the animal production and manure storage facilities will primarily impact the need for imports of N in feed and fertilizer and thus have a considerable financial impact. However, with the Central Valley regulatory limit on N applications, losses in the field are more critical. If field losses are not addressed, complying with the regulatory N loading limits will lead to crop N deficiencies and yield loss.

Farm-level actions to reduce N losses vary according to cost and efficacy (see Table 3). Nitrogen losses in animal housing facilities are significantly reduced when cattle spend the majority of their time in free stalls and the manure is flushed regularly into storage ponds. Most experts assume that manure excretion is distributed according to the amount of time cattle spend in each location. Therefore, increasing the time animals spend in areas where manure can be quickly removed will conserve N in the system. Loss rates in manure water storage ponds can be significantly reduced with dilution (lower NH_4^+-N concentrations), increased pond depth (reducing surface area to volume ratio), and lower pH (acidification).

Effective control of N losses in the field is essential in order to achieve good environmental stewardship, regulatory compliance, and healthy crop production. Field N losses can be most effectively controlled through measurement and control of manure application (again, see Table 3). The lessons learned by pioneering farmers and researchers suggest that applications should be spread out through the growing season where possible, especially in irrigated conditions and coarse-textured soils (e.g. sandy loam). Solid manure applications between crops can be used to bring nutrients further from the manure storage than is possible through the irrigation system. Timing and controlling manure water application during the growing season to coincide with crop N uptake needs can prevent build-up of excess NO_3^- in the soil and significantly reduce N leaching losses. Even distribution of manure nutrients is also essential to prevent crop nutrient deficiency.[7] While not directly related to loss prevention, both improvements in feed N utilization efficiency and increasing on-farm N production with legumes can also reduce N input costs.

Table 2. Nitrogen losses in dairy/forage system and factors impacting loss rates

Location in System	Range of Losses	Factors Impacting N Loss
Facility and Storage Losses of N to atmosphere		
Manure in corral/feedlot	Can lose 15 to 60% of total N [9, 10]	Temperature – N loss (mostly volatilization of NH_4^+) up to 60% higher with temp increase from 10°C to 25°C [9]
		Sprinkling with water to remove and dilute urine can reduce volatilization [17]
		Regular removal of manure from corral reduces losses: daily scrape and haul – 15 to 35% loss, versus open lot scraped quarterly – 40 to 60% loss [10]
Manure in freestalls, flush lanes and storage ponds	20 to 40% lost to atmosphere (primarily as NH_3) [2]	Increased flushing frequency and increased depth of storage pond reduces surface area for NH_3 volatilization [2, p. 30]
		Fresh water used for flushing and dilution in storage reduces NH_3 concentration and volatilization rates [2, 17]
		Inlet/loading system – ponds loaded from the bottom have significantly lower losses (3-8% of total N) than those loaded from top (29-39% of total N) [18]
		Lower pH in storage – losses can be reduced by six times when pH lowered from 7.8 to 7.0 [2, 17]
		Reduced residence time in storage pond reduces losses [2, p. 30]
Manure treatment systems	Up to 50% loss of total N with composting [11]	Low intensity (very little mixing) and anaerobic composting methods experience lower N loss than their alternatives. Total N losses in aerobic or high intensity manure composting reached 50%, while anaerobic and low intensity composting losses were only 26% and 5%, respectively [19] [11].
		Reduced pH and a higher C:N ratio are also associated with fewer losses [11, 19]
	Up to 95% of NH_4^+-N loss by conversion to nitrogen gas in batch reactors [12]	
Field Losses		
Ammonia volatilization after field application of manure water	Range from 3% to 33% of NH_4^+-N volatilized [2, 20, 21]. With typical diluted manure water in Central Valley, losses are near lower end of range.	Soil water content – greater losses in dry soil, e.g. NZ study with similar manure water to Calif. found 32% N loss in dry soil and 22% N loss in wet soil [22]
		Soil and air temperature – lower temperatures are associated with less volatilization
		pH – lower soil and manure water pH reduced volatilization rates [2]
		Nutrient concentration – dilution with fresh water significantly reduces losses [2, 23], e.g. less than 10% losses if diluted below 100 ppm NH_4^+-N [2], versus 24% to 33% lost with manure application of 2800 to 3100 ppm Total N [20]
		Increased frequency of applications – effectively the same as dilution
		Low wind conditions reduces volatilization
		Crop canopy can absorb gaseous NH_3 [2, p. 41]

Nitrate N in fields – leaching	Range from 10-15% loss to more than 50% of total N applied (all of excess N)	Volume of irrigation water – increased irrigation water application by 33% over that required by crop resulted in 3% to 8% increase in proportion of excess N lost by leaching, for liquid manure applications 400 to 1250 lbs N/acre in excess of crop needs [14] Improved irrigation efficiency (shorten check length, use torpedoes to speed water flow in furrows) and delayed introduction of manure into long irrigation times results in even distribution and reduced overall losses – useful where irrigation set times are at least four hours. Manure application frequency – more frequent applications with lower N concentrations results in less NO_3^--N in the soil, less to leach [2, p. 9] Time applications to meet crop N uptake needs – less NO_3^--N remains in the soil for leaching during following irrigation event
Nitrate N in fields - denitrification	Negligible in recent Central Valley experiments [2] 11 to 25% of applied manure N in other in year-round irrigated forage systems [14, 24-26]	Amount of N in excess of crop uptake – more excess N results in greater proportion lost to denitrification (versus leaching), e.g. up to 62% of excess N when applications were more than 1200 lbs N/acre greater than crop uptake [14] and from 32 to 114% of excess N with applications up to 230 lbs N/acre greater than crop uptake [25] Soil type – clay soil will have more denitrification than sandy soil, sandy soil will have higher leaching rates Soil moisture content – higher soil moisture increases denitrification [25] ; soil with high water table showed more denitrification than a well-drained soil [26] Available carbon – Central Valley soils have low C content and thus little energy source for denitrifying microbes

Table 3. Farm-level actions that may reduce N losses and N purchases/inputs for California dairies

Action	Comments
Animal Feeding and Housing	
Adjust feed composition	For dairies with excess feed N, reducing N intake to NRC recommendations can significantly decrease N excretion. Protein level reduction of 7 to 11% in a typical dairy cow diet can lower total N excretion by 5 to 18% without impacting milk production [27, 28]. Costs can be minimal, because of reduced feed purchases.
Bovine growth hormones, 3X/day milking or artificial light	While controversial for animal health and other reasons, rBGH/rBST, 3X/day milking or artificial light to extend photoperiod can improve feed N use efficiency by up to 8% (15% with all three actions combined) [27, 29].
Convert from corrals to free stalls with flush lanes	This can reduce N losses in animal housing facilities by 20 to 40%. Construction costs may be justified if the fertilizer N savings are sufficient (assuming land is available for nutrient application).
Manure Storage	
Increase depth of storage pond	An increase in depth from 10 to 25 ft can prevent the losses of from 1 to 15% of the N excreted [2], with greater impact at higher pH levels. Costs are significant, but could fit into already planned improvements or storage expansions.
Line storage ponds to limit leaching	This generally has minimal impact, and is quite costly or not practical with established ponds.
Reduce pH level of pond	Treatment to reduce pH from 7.8 to 7.0 could prevent losses of 9 to 31% of the N excreted [2].
Forage Fields	
Install flow meter and control valve, collect and analyze samples, control manure water application rates.	While also helping dairies to fulfill regulatory requirements, monitoring (and adjusting) manure N applications can improve distribution and reduce field losses by 20 – 70%. Costs include flow meter and valve installation, sample collection and analysis, and management; these are quite quickly covered by fertilizer cost savings.
Change timing of manure N application	Apply manure N to coincide with crop needs (i.e., pay attention to high growth periods). This likely requires dilution of manure water and increased application frequency.
Shorten check length, use torpedoes, or increase flow rates	These methods may improve irrigation efficiency and provide more even distribution of manure nutrients. Impact is greater in sandy texture soils, with possible reductions in deep percolation of up to 77% for shorter furrow lengths [30]. Increasing water flow rates or using torpedoes have less effect.
Delay manure injection into irrigation flows	Provides more even distribution of manure nutrients, fewer losses at the head of the field. This may be useful when it takes more than four hours for one irrigation set. Main cost is management of irrigation system.
Increase N fixation by legumes	Allows on-farm production of more high protein and N fixing forages such as alfalfa; deep roots of alfalfa also serve to “catch” nitrate that has leached downward [31]

TERMS

Absorption – Taken up, e.g., by plants

Adsorption – Retention of atoms, molecules or ions (e.g., on soil organic or mineral surfaces) by chemical or physical binding

Denitrification – Microbial process that converts nitrate (NO_3^-) or nitrite (NO_2-) into gaseous nitrogen (N_2) or oxides of nitrogen. Generally occurs in flooded or other low oxygen conditions

Eutrophication – aging (and "death") of surface waters at a more-rapid-than-natural pace due to elevated nutrient concentrations. Generally involves high algae populations that die and use up oxygen, leading to death of fish and other aquatic organisms.

Leaching – process by which soluble compounds (including nitrate) are transported by water from the surface of the soil to greater depths, potentially reaching groundwater aquifers or surface waters.

Mineralization – process by which microbes break down organic products such as manure into inorganic forms, releasing plant nutrients and other elements. For example, organic N in proteins is converted to ammonium (NH_4^+)

Oxidation – process by which microbes add oxygen to a reduced form of a molecule, often changing the charge and thus susceptibility to leaching; for example, ammonium (NH_4^+) is changed into nitrate (NO_3^-)

Volatilization – process by which ammonium N (NH_4^+) and other molecules pass from aqueous (in water) solution into gaseous phase, entering the air (NH_3 in this case).

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Footnotes

[1] Approximately 50% of excreted N is in urine and 50% in feces. In the urine, 70% of the N is in urea [1, p.30].

[2] The excretion rate of 1.0 lbs/head/day assumes milk production of 88 lb/day. To calculate N excretion associated with different milk production rates, see ASABE Standards equations [1].

[3] In 2007, California's Central Valley had 1.59 million dairy cows (75% of state total), with an average of 1084 cows/dairy facility [3]

[4] 2008 UCCE costs studies indicated N cost of $0.55/lb N as aqua ammonia[4] and $0.745/lb N for UN-32[5]; in 2001 UCCE cost studies, costs for aqua ammonia (on rice) and anhydrous ammonia (on corn silage) were $0.30 and $0.28 per lb N, respectively[6, 7]. Using the same cost ratio, we assume 2008 anhydrous ammonia cost of $0.513/lb N.

[5] These calculations assume that fertilizer is the main purchase of N on the farm; this value increases with increasing proportions of purchased N in feed and feed supplements.

[6] Assumptions for Figure 1: (1) Average of 305 days lactating and 60 days dry, (2) Some feed purchases necessary to balance ration, assume 36% of total feed N as concentrate, consistent with James et al. [8], (3) Cows are 1400 lb Holsteins, (4) No replacement stock included in calculations, and (5) N excretion values based on ANR Publication 9004 [2].

[7] See bulletin on irrigation system design and performance

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