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Agriculture and Natural Resources

Efficient Nitrogen and Irrigation Management of Corn Grown on California Dairies

In responce to evidence of agricultural impact on increased groundwater nitrate levels, the Central Valley Region Water Quality Control Board has adopted a regulatory program that requires growers to track and report nitrogen (N) inputs. This information will be used to estimate an N balance, N removed from fields as grain or silage. The more that the N applied exceeds the N removed in the harvested crop, the greater the potential for N loss to the environment. This publication provides information on how to calculate an N budget for corn and also discusses the timing of N applications and leaching losses.

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Corn Growth, Nitrogen Accumulation, and Timing of Nitrogen Applications

When a corn seed germinates, the initial (seminal) roots grow out at an angle from the seed. Banded starter fertilizer is generally placed 2 in. to the side and below the seed to increase the probability that the roots will come in contact with it quickly while minimizing the risk of root damage by high ammonia and salt concentrations around the seed.

Secondary roots require moisture in the soil in order to develop. While this is only occasionally an issue with surface-irrigated corn, it must be taken into consideration when using subsurface drip irrigation: supplemental surface irrigation may be necessary at this stage to ensure surface moisture. However, large applications of water on small corn plants may move existing nitrate past the developing roots, resulting in severe nutrient deficiencies and yield losses.

Corn growth stages are referred to by a standardized scale based on the number of leaves before tasseling and the development of the grain after tasseling (table 1). When corn first emerges, a leaf is counted once the blade has expanded and the line at the collar can be seen. The VT stage begins when the last branch of the tassel is fully emerged. At this point the plant switches from vegetative to reproductive growth. The first reproductive stage, silking (R1), begins as soon as the silks on the primary ear are visible, regardless of whether the tassel is fully emerged. During the reproductive stages, kernels are formed and grain fill occurs.

Table 1. Corn growth stages

Vegetative stages	Reproductive stages
VE emergence	R1 silking
V1 first leaf	R2 blister
V2 second leaf	R3 milk
V3 third leaf	R4 dough
V(n) nth leaf	R5 dent
VT tasseling	R6 physiological maturity

Corn plants take up little N until they reach the V6 stage (fig. 1; see also fig. 3). Generally, a moderate starter N application and residual soil nitrate supply enough N during early growth. Between V6 and tasseling, however, N uptake rates are high. During this period, 60% or more of the total N for the entire season is taken up; it is especially critical to supply these large amounts of N during this period. Immediately after tasseling, for a period of 7 to 10 days, new nitrogen uptake from the soil essentially ceases while the crop shifts from accumulating dry matter during the vegetative phase to a reproductive phase. Nitrogen accumulation resumes again during grain fill.

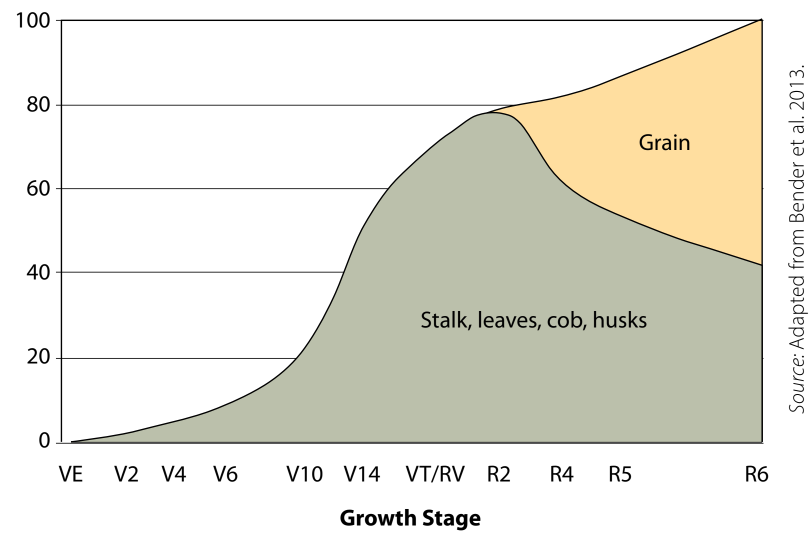


Figure 1. Seasonal N uptake and partitioning of corn.

During the reproductive stages, some N is remobilized from the stalk and leaves into grain. Of the total N in the grain, about two-thirds is new N coming from the soil and one-third is from remobilized N from other parts of the plant. At maturity, 50 to 60% of the total N is in the grain, while the stover contains 40 to 50%.

When producing corn for silage, keep the lower leaves green to achieve maximum tonnage and quality. It may be necessary to apply some N after tasseling to accommodate late-season uptake. Silage hybrids are usually bred with a "stay green" trait that helps keep N in the lower leaves. It is likely that more N will need to be applied after tasseling to silage corn than to grain corn.

In addition to N in the aboveground crop, additional N is contained in the roots. Most of the roots are grown prior to tasseling. Usually the N needed to grow the roots is ignored because it is presumed that this amount is recycled back into the soil and will supply the next crop. Under conditions of highly deficient N, however, it may be necessary to take the amount of N needed to grow the roots into account when determining application rates.

The total amount of N contained in the roots is 15 to 20% of the total amount of N in the aboveground portions.

Determining Site-Specific Nitrogen Application Rates

The amount of N required by corn plants can be determined from N rate trials or by an N budget approach. Because little data is available from N rate trials carried out in California, this section focuses on the N budget approach. Nitrogen budgets are calculated in four steps that will be discussed below.

Step 1. Determine the amount of N removed by the corn plants based on the amount of N removed at harvest.

Step 2. Adjust the fertilizer application rate to account for residual soil nitrate and nitrate in the irrigation water.

Step 3. Estimate the availability of N from organic amendments.

Step 4. Take into account expected losses and inefficiencies (most losses come from leaching and denitrification).

Corn N Removal

Most crop N budgets start with the amount of N removed from the field in the crop. Table values for crop nutrient removal may be useful where actual values do not exist. However, actual field data from previous years measured when the crop is harvested may be more accurate because N concentration in the grain and stover depends on the N status of the plant, especially near harvest. Corn silage yield is usually corrected to 70% moisture as a basis for determining the price and harvest costs, and the silage is usually analyzed for protein content before it is fed. Since protein is calculated from analyzing for total N, the yield and N concentration data needed to estimate site-specific N removal can often be obtained from existing records from the buyer or nutritionist without the need for additional sampling and analysis.

If no data are available, use a value of 7.56 lb N/ton in silage at 70% moisture. This value, which corresponds to an N content of 1.26% in the dry matter, is the average N concentration of more than seventy silage corn samples taken on California dairies. In this dataset, values ranged from 5 to 10.4 lb N/ton (Geisseler 2016).

Similarly, grain corn is sold on the basis of protein content and is yield-corrected to 15.5% moisture. This data can be used to calculate nutrient removal and estimate the total N needed for the crop. Little information is available on N in corn grain in California. A global analysis of modern varieties found an average of 24 lb N/ton at 15.5% moisture (Ciampitti and Vyn 2012). The N content can be calculated by dividing the protein content of the kernels by 6.25. For example, for corn with a kernel protein content (CP) of 9.4%,

$$9.4 \div 6.25 = 1.5\% \text{ N.}$$

Calculating Nitrogen Removal in Corn Silage

For corn grown for silage, almost the entire aerial portion of the crop is harvested, and the yield and N content can be used to calculate crop removal (table 2). As the crop is being harvested and weights recorded, take representative samples and analyze them for moisture and percent total N. It is especially important to measure moisture content accurately since small errors in moisture content can result in large errors in N removal (Miller et al. 2018).

Method 1: Calculating N Removal from a Whole Field Based on Dry Matter and Percent N

Table 2. Effect of moisture content on calculated N removal

Yield as harvested	Moisture	Yield corrected to 70% moisture	N removed at 1.5% N
ton/ac	*%*	*ton/ac*	*lb/ac*
30	67	33	297
30	70	30	270
30	73	27	243

1. Calculate the dry matter of the harvested forage.
   a. Subtract the percent moisture from 100 to calculate the percent dry matter.

b. Divide the percent dry matter by 100 to express the percentage as a decimal.
c. Multiply the tons of silage harvested from a whole field by the dry matter fraction.
d. Multiply the tons per field by 2,000 to get pounds per field.

2. Determine the amount of N removed in the silage.
   a. Obtain the N fraction by dividing the percent N by 100 to express the percentage as a decimal.
   b. Multiply the tons of dry matter by the N fraction.
   c. Divide the amount of N by the acreage of the field.

Example: 1,945 tons of corn silage is harvested from a 56-ac field at a moisture content of 72% and a total N of 1.5%.

1.a. **100% – 72% = 28%**

1.b. **28% ÷ 100 = 0.28**

1.c. **1,945 tons x 0.28 = 544.6 tons**

1.d. **544.6 tons x 2,000 lb/ton = 1,089,200 lb**

2.a. **1.5% ÷ 100 = 0.015**

2.b. **1,089,200 lb x 0.015 = 16,338 lb N**

2.c. **16,339 lb N ÷ 56 ac = 292 lb N/ac**

Method 2: Calculating N Removal from Tons of Silage at 70% Moisture and 8.5% Protein

A shortcut method to calculate final N uptake of silage is to multiply the tons per acre of silage at 70% moisture by the percentage of crude protein (CP), then multiply by a conversion factor of 0.96 to get the pounds of N removed.

Example: Corn silage, 31 tons/ac with 8.5% CP content

31 x 8.5 x 0.96 = 253 lb/ac N removal

How to obtain the conversion factor of 0.96:

- Multiply by 0.3 to convert tons at 70% moisture to tons of dry matter.
- Multiply by 2,000 to convert tons of yield to pounds.
- Divide by 100 to convert the percentage to a fraction.
- Divide by 6.25 to convert CP to N.

0.3 x 2,000 ÷ 100 ÷ 6.25 = 0.96

Calculating Nitrogen Removal for Grain Corn

Grain corn N removal can similarly be calculated using N or protein content and yield harvested.

Method 1: Calculating N Removal from Dry Matter and Percent N

1. Calculate the dry matter of the harvested grain.
   a. Subtract the percent moisture from 100 to obtain the percent dry matter.
   b. Divide the percent dry matter by 100 to express the percentage as a decimal.
   c. Multiply the tons of grain harvested by the dry matter fraction.
   d. Multiply tons per acre by 2,000 to get pounds per acre.
2. Calculate the percent N from the percent protein.
3. Calculate the pounds per acre of N removed in grain.

Example: 6.5 tons/ac of corn grain was harvested with a moisture content of 15.5% and 9% protein.

1.a. **100% – 15.5% moisture = 84.5% dry matter**

1.b. **84.5% ÷ 100 = 0.845**

1.c. **6.5 tons x 0.845 = 5.49 tons dry matter**

1.d. **5.49 tons/ac x 2,000 lb/ton = 10,985 lb/ac**

2. **9% protein ÷ 6.25 = 1.44% N**

1. **44% ÷ 100 = 0.0144**

3. **10,985 x 0.0144 = 159 lb N/ac removed**

Method 2: Calculating N Removal from Tons at 15.5% Moisture and Protein

If you know that the grain yield per acre is reported on the basis of the standard 15.5% moisture, you can use the shortcut method shown here to calculate N removal.

Example: 6.5 tons/ac of corn grain is harvested with a moisture content of 15.5% and 9% protein.

6.5 tons/ac x 9% protein x 1.13 = 159 lb N/ac removed

This method calculates N removed in the harvested (grain) portion of the crop. The grain accounts for about 50 to 60% of the total amount of N in the plant. To calculate the amount of N taken up by the crop, divide the removal by the proportion of N in the grain (0.5 to 0.6).

Example: 159 lb N/ac removed with grain; 60% of the total N is in the grain.

159 lb N/ac ÷ 0.6 = 264 lb N/ac in the aboveground biomass.

Accounting for Nonfertilizer Nitrogen

Nitrogen fertilization rates should be adjusted by the nitrate-N present in the soil profile before the first major N application: 1 ppm of nitrate-N in the top 2 ft of the profile corresponds to 7 to 8 lb/ac (3.5 to 4 lb/ac/ft of soil). During the growing season, more N will be made available by soil microorganisms that mineralize N; the amount of N mineralized depends among other factors on soil organic matter content and recent applications of organic material. Currently, no University of California recommendations exist for application rates based on preplant soil nitrate levels.

Soil Nitrate Tests

Nitrate is a form of N that is directly available to plants; therefore, soil nitrate tests measure the plant-available N at the time of sampling. The nitrate level depends on a number of factors related to soil properties, weather, and crop management. For this reason, the test is field-specific and must be carried out every year. Due to the variability of nitrate in the soil, care must be taken that the sample is representative of the field. It is generally recommended to take at least twenty cores and composite them to represent a field or management area. Take cores at random locations within the field unless the field has obvious strong or weak areas, in which case it may be desirable to sample these areas separately.

Soil samples for nitrate analysis should be collected before the first major N application of the season. Depending on the fertilization program, soil samples should be collected either prior to the preplant N application (this test is generally called the preplant nitrate test, or PPNT) or before the first sidedress N application (the presidedress nitrate test, or PSNT). The PPNT measures the N carried over from the previous crop plus N released from soil organic matter, crop residues, and manure applications. Samples are generally taken to a depth of at least 2 ft. High irrigation application rates between soil sampling and the time of peak N uptake by corn may leach nitrate below the root zone, making it unavailable for the plants. In this case, the PPNT overestimates the available soil N. Therefore, PPNT and high preplant N applications are an efficient fertilization strategy only when leaching during the early stages of corn growth is minimal. When most N is applied during the growing season, the PSNT is the better option. When corn is produced with mineral fertilizer, the PSNT sample is generally taken when the corn plants are 6 to 12 in tall, corresponding to the 4- to 6-leaf stage. When corn is fertilized with lagoon water, the sample is best taken before the first lagoon water application. As the sample is taken just prior to the period of high N uptake, the PSNT more accurately determines available residual N than the PPNT:

concentration of nitrate-N in soil (mg/L or ppm) x 3.5 = l b N/ac in 1 ft of soil.

Nitrate in the Irrigation Water

Irrigation water from wells can be a significant source of N. If the irrigation water contains 10 ppm nitrate-N, 2.26 lb N/ac are applied with each acre-inch; 40 ac-in of this water would apply 90 lb of N. When irrigation water is applied in excess of plant needs, much

The Three Main Forms of Nitrogen in Soil and Manure

Organic form (Org-N)

Nitrogen that is part of proteins and other organic molecules in undigested feed, bacteria bodies, etc., is eventually broken down by soil microorganisms and ultimately excreted by them as ammonia. Plants cannot use this form of N, and it usually does not move very far through the soil.

Ammonium form (NH_4-N)

Ammonium is the same molecule as commercial fertilizer. It has a positive charge and sticks to soil particles when it is applied in irrigation water. It does not leach but can be lost to volatilization if left on the surface of the soil such as when spreading dry manure or applying commercial fertilizer. Microorganisms convert this form to nitrate within a few days in warm soils.

Nitrate form (NO_3-N)

Nitrate has a negative charge and does not adhere well to soil particles. It moves with water through the soil and can contaminate groundwater if it moves beyond the reach of the crop roots. It is converted to N gas by soil microorganisms in the absence of oxygen, such as in flooded or poorly drained soils, a process called denitrification. A byproduct of denitrification is nitrous oxide, a greenhouse gas that is of far greater concern than carbon dioxide.

of the nitrate in the water moves with the water past the roots and beyond the reach of the crop. A way to avoid overestimating available N from irrigation water is to calculate the nitrate in the amount of water that is used by the plant, which corresponds to evapotranspiration (ET).

N concentration (mg/L or ppm) x 0.008345 = lb N/1,000 gal

N concentration (mg/L or ppm) x 0.22625 = lb N/ac-in

Example: Evapotranspiration (ET) of a corn crop is 26 in. and the irrigation water contains 8 ppm nitrate-N.

Calculation:

8 mg/L x 0.22625 = 1.81 lb N/ac-in

26 ac-in x 1.81 lb N/ac-in = 47.1 lb N/ac

Nitrogen Budget Example

The goal of an N budget is to determine how much N the crops need to take up from mineral or organic fertilizer.

Example: Silage corn yields 35 t/ac at 70% moisture with 8.7% CP.

Soil nitrate-N concentration is 16 and 8 mg/L in the first and second foot of the profile, respectively.

26 in of irrigation water with a nitrate-N concentration of 8 mg/L is applied.

Calculation:

N removed = 35 x 8.7 x 0.96 = 292 lb/ac

N credits:
Residual soil nitrate in first foot = 3.5 x 16 = 56 lb/ac
Residual soil nitrate in second foot = 3.5 x 8 = 28 lb/ac
N in irrigation water = 26 x 8 x 0.226 = 47 lb/ac
Total N credits = 131 lb/ac
Corn fertilizer N requirement (292–129) = 161 lb/ac

When organic fertilizers are applied, not all the N will become crop available during the current season. Extra N to compensate for unavoidable N losses must be added. Nitrogen availability from organic sources and unavoidable N losses are highly site specific. A general discussion is included in the following sections.

Availability of Nitrogen from Organic Sources

Nitrogen in manure occurs mainly in organic forms and as ammonium. The ammonium is directly available to plants provided it is not lost to the atmosphere in the form of ammonia (see sidebar). Manure ammonium content varies widely depending on the source and its handling. Samples of solid manure, including corral scrapings, composted manure, lagoon sludge, and mechanical screen solids, taken from dairies in the San Joaquin Valley were found to have an ammonium-N proportion ranging from 0 to 6% of the total N (Pettygrove 2009). Ammonium makes up a much higher proportion of lagoon water; Pettygrove (2009) found that on average two-thirds of the total N was in ammonium form. Lagoon water that is drawn from the bottom of lagoons where more solids are present may have a higher total N content, but only about one-third of it is in ammonium form (Campbell-Mathews et al. 2001).

Table 3. Estimated availability of organic N in manures

Manure type	Amount of applied organic N mineralized		
	Initial 4 to 8 weeks	Year 1	Year 2
	%	%	%
Dairy lagoon water	15 – 35	40 – 50	15
Dairy lagoon sludge and slurry; corral manure	10 – 20	20 – 30	15
Dairy mechanical screen solids	5 – 15	10 – 20	5
Aerobically composted cattle or horse manure (finished or mature)	0 – 7	0 – 10	5
Solid poultry manure	20 – 35	50	15

Source: Pettygrove et al. 2009.

The organic forms of N are not directly available to plants but must first be mineralized by soil microorganisms. How quickly organic N is mineralized depends on manure properties, temperature, soil moisture, placement of the manure, and other soil-related factors. For these reasons it is difficult to predict the amount and time when N becomes available to crops (table 3). Some of the N is incorporated into soil organic matter and does not become available during the growing season in which is applied From 40 to 70% of the expected mineralization occurs within the first 2 months after application; for material applied in late fall or winter, the amount is probably closer to 40%. Lagoon water N mineralization will be slowed if solid particles do not infiltrate into the soil and remain on the surface, which may happen when lagoon water with high levels of solids is not sufficiently diluted.

Manure applications may contribute to N mineralization for multiple years. In fields that have been manured continuously for many years, the annual amount of N mineralized from recent and past manure applications may roughly equal the total amount of N added with manure the present year. Therefore, in fields with a long-term history of regular manure additions, the manure application rates can be reduced to the point that the total manure N applied is approximately equal to the projected crop demand. However, during periods of high crop N demand, mineral fertilizers or manures with high ammonium concentrations may be needed to supplement N mineralization. This strategy should be used cautiously where N leaching losses during irrigation are high.

Compensating for Expected Losses and Inefficiencies

A N budget method for determining fertilizer application rates based on N removal or crop demand as a starting point must add extra N to compensate for unavoidable N losses such as denitrification, inefficiencies in application, and imprecision in application measurement.

Denitrification

Denitrification is the reduction of nitrate to nitrous oxide (N_2O) or dinitrogen (N_2) by soil microorganisms. Nitrous oxide and dinitrogen are gases that are lost to the atmosphere. The denitrification rate depends on soil water saturation, soil nitrate concentration, soluble organic carbon (C) availability, and temperature (Rolston et al. 1982). The denitrification rate is increased in wet or compacted soil when the proportion of soil pores filled with water increases above field capacity and aeration is reduced. High nitrate concentration, high temperature, and the availability of C from manure, crop residues, or root exudates also increase denitrification rates.

In a study on a Yolo loam, total denitrification losses ranged from 0.7 to 5% of the nitrate fertilizer applied (Rolston et al. 1978). More-frequent low-volume irrigations tended to lower losses, while the availability of C from incorporated straw increased losses.

However, when the soil moisture was constantly above field capacity, denitrification losses from plots cropped with ryegrass reached 14% during the summer. Under the same conditions, losses exceeded 70% of the applied nitrate-N in a manure-amended plot (Rolston et al. 1978). Keep soil nitrate concentrations low by matching N supply with demand and adjusting irrigation rates to crop needs to greatly reduce the risk of denitrification and the risk of nitrate leaching. These practices are discussed in the following sections.

Leaching Losses

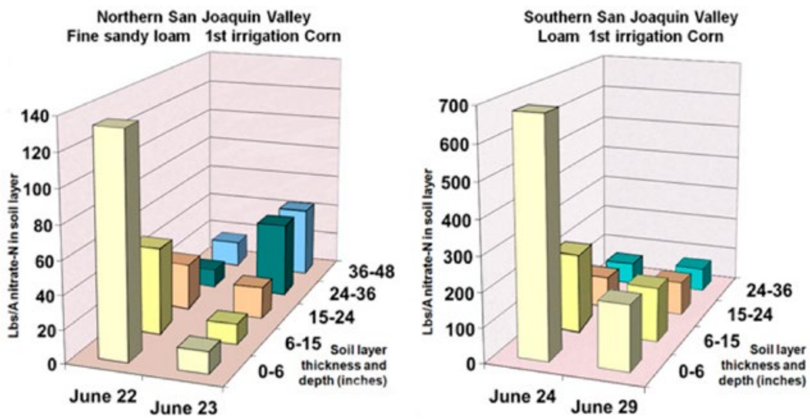
The amount of leaching that will occur is determined by the soil nitrate concentration and by the amount of water that is applied in relation to the amount that can be retained by the soil. Nitrate is the form of N that is most susceptible to being lost through leaching because it does not adhere well to soil particles and moves though the soil with the water. The more water passes through the soil, the more nitrate moves with it. In contrast, ammonium is much less mobile in the soil and is not easily leached (see sidebar). However, ammonium is converted to nitrate by soil microorganisms. Once in the form of nitrate, it is prone to leaching. In a typical surface irrigation system (flood or furrow), application rates are often determined by the amount of water necessary to move water from the head to the end of the field rather than by how much is needed to refill the soil profile. Applying less water in a given irrigation is not usually a practical option, although all efforts should be made

Table 4. Nitrate concentration before and after freshwater irrigation at 9 sites in the San Joaquin Valley, CA

Site	Soil type	Sampling season	Freshwater applied	Irrigation date	Nitrate-N in top 2 ft		Nitrate-N lost from top 2 ft
					before	after	
			ac/in		*lb/ac*	*lb/ac*	*%*
1	Madera sandy loam	1st corn irrigation	12.8	Jun 18	186	86	54
2	Hanford sandy loam	1st corn irrigation	3.8	Jun 18	255	55	78
5	Dinuba fine sandy loam	1st corn irrigation	6.7	Jun 22	189	45	76
6	Delhi sand	1st corn irrigation	6.3	Jun 24	105	73	30
3	Dinuba loamy sand	2nd corn irrigation	6.8	Jun 12	202	97	52
4	Colpien loam	2nd corn irrigation	5.0 (est.)	Jun 25	895	444	50
6	Delhi sand	8th corn irrigation	6.5	Sep 2	167	52	69
7	Delhi sand	8th corn irrigation*	5.6	Sep 2	205	66	68
8	Delhi sand	8th corn irrigation*	4.8	Sep 4	191	135	29
6	Delhi sand	preirrigation for winter crop	6.8	Oct 17	112	83	26
7	Delhi sand	preirrigation for winter crop	6.9	Oct 18	142	85	40
9	Tujunga loamy sand	1st winter crop irrigation	5.5	Oct 19	125	58	54

Source: Campbell, Mathews, Pettygrove, and Eagle 2001; Campbell and Geisseler unpublished data.
Note: *There was a maturing corn crop on the site at this time, and some unmeasured N uptake occurred.

Figure 2. Pounds per acre of nitrate-N in each layer of soil just before and just after a single freshwater irrigation. The axis on the bottom represents the date of the irrigation. The height of the bar shows the pounds per acre N present in the soil layer. The front bars are the surface layers; the back bars are deeper layers. The left bars on each graph are the amount in the soil before the irrigation, and the bars on the right show what remained after the irrigation was over.



to do this if possible. Pre- and first irrigations are usually more difficult than later applications because the surface is rough and the infiltration rate is high. Since these irrigations occur when there is the least amount of crop uptake and often follow long periods in which mineralization has been occurring in the absence of a crop, significant nitrate losses are possible if large amounts of nitrate are present in the soil at this time.

In a study where soil was sampled at 1-foot increments just before a freshwater irrigation and again as soon as possible afterward at twelve locations or irrigation events, an average of 177 lb/ac of the nitrate-N in the top 3 ft of soil was lost during a single freshwater irrigation (table 4; fig. 2), which corresponded to 52% of the nitrate present in the top 2 ft of the soil profile before the irrigations. An average of 123 lb/ac of nitrate-N was lost from the top 1 ft. The soil types ranged from loam to loamy sand, and the irrigation amounts were typical for the areas tested. Losses occurred in each of the locations sampled regardless of the time of year. A mature corn plant usually takes up much of its water and nutrients from the first and second foot of soil. Roots that extend to the fourth foot seldom account for a significant portion of the total uptake. Therefore, much of the nitrate leached below the second foot may not be taken up by the plant.

Not all fields are subject to these kinds of losses, and some fields are prone to losses only with irrigations that are applied to freshly tilled soil. Leaching losses can be expected to be minimal on fields where only the amount of irrigation water that is needed to refill the root zone is applied.

Assessing the Risk of Leaching Losses

Leaching risk can be assessed by comparing the amount of water in acre-inches that is usually applied in each irrigation event with the amount that would have been needed to replenish the root zone. The most accurate way to determine this amount is to calculate how much water the crop actually used since the last irrigation. This method is explained in detail in the publication *Determining Whether Nutrients are Leaching from Your Fields (Schwankl et al. 2008). The crop water use method is recommended when the soil is not likely to be fully depleted of water before the next irrigation is applied, which is common for heavier soils.*

Table 5. Usable water storage in different soil types

Soil type	Water-holding capacity	Depletion	Inches of usable water in			
	in/ft	*%*	*1 ft*	*2 ft*	*3 ft*	*4 ft*
sand	0.7	60%	0.4	0.8	1.1	1.3
loamy sand	1.0	59%	0.6	1.2	1.5	1.8
sandy loam	1.3	58%	0.8	1.5	1.9	2.3
loam	1.8	57%	1.0	2.1	2.6	3.1
silt loam	2.0	56%	1.1	2.2	2.8	3.4
sandy clay loam	1.2	55%	0.7	1.3	1.7	2.0
sandy clay	1.1	54%	0.6	1.2	1.5	1.8
clay loam	1.5	53%	0.8	1.6	2.0	2.4
silty clay loam	1.9	52%	1.0	2.0	2.5	3.0
silty clay	1.7	51%	0.9	1.7	2.2	2.6
clay	1.6	50%	0.8	1.6	2.0	2.4

Source: Adapted from Hanson et al. 1999.

For lighter soils that are usually allowed to dry between irrigations, the amount of water needed to refill the soil profile can be estimated using table 5. Some of the water in the soil is bound so closely to the soil particles that the roots cannot use it, so only a percentage of the total water amount in the soil can be accessed by the plant, and only the amount actually used by the plant needs to be replenished with irrigation water. In some cases, however, the amount of water needed to refill the profile may be higher because the upper few inches of a sandy soil can dry nearly completely through evaporation, resulting in a depletion even of water that is not plant available. The amount of water needed to bring a soil from the permanent wilting point to field capacity is provided in table 5 in as the water-holding capacity. Using table 5, the actual applied water can be compared with the amount of water that can be stored according to the soil type and the estimated rooting depth for the crop during the period prior to the irrigation. If the difference between the applied water and the amount that can potentially be stored is large, water will percolate below the root zone, taking soil nitrate with it.

Table 6. Estimated nitrogen accumulation in aboveground biomass by silage corn with a protein content of 8.5% at selected yield levels based on N accumulation data in grain corn

Stage	N uptake per period								
	% of total	*25 tons/ac (lb/ac)*	Subtotal	*30 tons/ac (lb/ac)*	Subtotal	*35 tons/ac (lb/ac)*	Subtotal	*40 tons/ac (lb/ac)*	Subtotal
V4	4	7		9		10		12	
V8	6	11		14		16		18	
V12	15	30	133	37	162	43	188	49	215
VT	42	85		102		119		136	
R1	–5	–10		–12		–14		–16	
R2	5	11		13		15		17	
R5	34	69	81	83	97	96	112	110	128
R6	0.2	1		1		1		1	
Entire season	100	204		245		286		327	

Source: Karlen et al. 1988.

Optimizing Nitrogen Application Rates and Timing to Minimize Leaching Losses

Under conditions where most or all irrigations can leach nitrate, movement of nitrate to the groundwater can be minimized if large quantities of nitrate are not present in the soil during irrigation where deep percolation is occurring. This is accomplished by scheduling N applications so that N availability just meets a crop's evolving needs (table 6). This approach avoids yield losses while reducing the amount of excess nitrate in the soil profile that is prone to leaching. In this synchronized-rate nutrient application system, typically about 50 lb N/ac, but no more than 65 lb N/ac, is applied in each of five to six corn irrigations. The irrigations in which the N is applied are selected to coincide with periods of peak N uptake by the corn crop. If dairy liquid manure is used, this equates to a fresh water to nutrient water dilution that varies but is commonly around 10:1. At these dilutions, crop growth inhibition from excess salts would not be expected to occur unless the dilution water has a high salt content. Also, because the concentration of ammonium in the irrigation water is relatively low at these application rates, volatilization of ammonia to the atmosphere during irrigation is expected to be minimal. Lower amounts of N, around 30 lb of available N/ac, may be necessary if the water is to be applied to very young corn (shorter than 15 in.) to avoid ammonia toxicity to the leaves and salt damage.

Table 6 gives approximate amounts of N taken up by a well-fertilized silage corn crop at selected yield levels. In general, for silage corn, roughly two-thirds of the N is taken up before tasseling and one-third during grain fill. During tasseling and for a short time thereafter, the crop stops taking up N. The daily N uptake rates are shown in figure 3.

Exact timing of N applications is complicated by the fact that the exact rate of N mineralization from organic sources is not known (see the section "Nitrogen Budget Example," above). While synchronizing N application rates with corn N uptake is an efficient

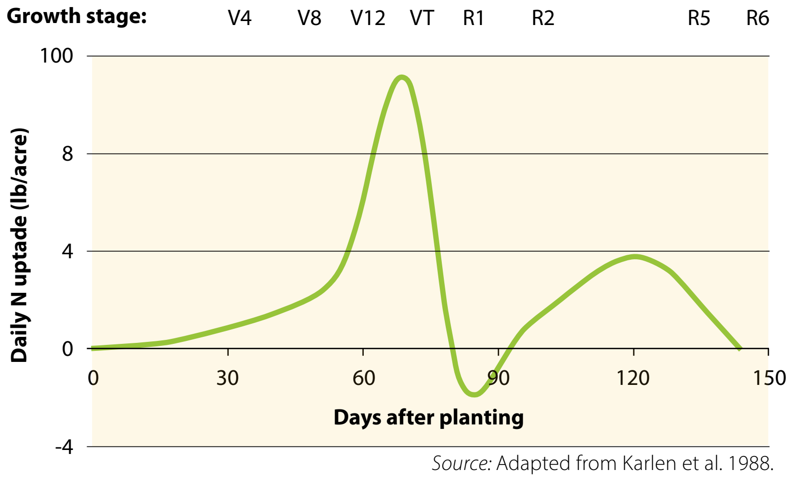


Figure 3. Daily nitrogen accumulation in the aboveground biomass of corn with a total uptake of 320 lb/ac.

approach to reduce leaching losses during the growing season, considerable amounts of nitrate may still be leached early in the season, when residual soil nitrate levels may be high. Adjusting the fertilization of winter forage crops using the same budget approach discussed here for corn may help reduce residual soil nitrate levels in spring.

If leaching losses are so high that it is not possible to make a workable N budget, consider methods of reducing the amount of water that is applied. Methods to consider include reduce field length

- increase the flow rate so the water moves faster
- irrigate sooner or, in the case of winter applications, when the soil is already wet so that the water moves faster
- increase slope
- make the soil surface smoother
- use pulsed or surge irrigation
- install a sprinkler system

Some of these methods can be difficult to implement and may have limited effectiveness. Sprinkler systems are being considered more seriously for dairies despite their expense because limiting leaching losses allows flexibility in types and timings of manure that can be applied. The installation expense of the system may be offset by the availability of cost-share funding, and the operating expense may be offset by decreased irrigation labor costs. Sprinkler systems may not be a viable option on smaller parcels.

If leaching conditions do not exist because irrigation water application rates are appropriate and rainfall rates are not excessive, it is feasible to apply N in advance of crop uptake. Under these conditions, a large single application of liquid manure N in the second or third irrigation that provides over half of the total available N needed for the crop may give reasonable yields at acceptable application-to-uptake ratios. This can be an advantageous strategy in situations where it can be difficult to apply small amounts of liquid manure through the existing infrastructure. These situations also make it easier to use more dry manure in the N budget, as the mineralizing N can be "banked" in the soil for use later in the year. Note, however, that this approach may increase denitrification losses, which occur following irrigation and heavy rains. These losses are also usually higher in soils fertilized with organic fertilizers, such as manure, than in conventionally fertilized soils.

In-Season Monitoring of Corn Nitrogen Status

Even when using the best data available, an N budget is an estimate of N demand and availability. Considerable uncertainties about N uptake, N losses, and N mineralization exist. Plant analyses can be useful in diagnosing nutrient limitations before deficiency symptoms become visible and in determining whether current fertility programs are adequate or need corrections. Plant tissue nutrient concentrations are somewhat variable. Yield and plant tissue concentrations from previous years, as well as N and irrigation water budgets, help interpret the results.

Leaf Analysis

The nutrient concentration in plants changes over time and varies between plant parts. In order to be able to interpret the results correctly, care must be taken to sample the correct plant parts at a specific growth stage (table 7). When N concentrations are below the sufficiency range, yield may be decreased even in the absence of deficiency symptoms. Concentrations above the sufficiency range may indicate excess N availability.

Leaf Greenness

The N status of corn plants is reflected in the leaf color: a light green color indicates low N availability, and a dark green color indicates N sufficiency. The leaf greenness of corn plants can be determined using a hand-held device, such as the SPAD Chlorophyll Meter, or a canopy reflectance meter.

Leaf chlorophyll readings should be averaged from 20 to 30 plants. Before tassels appear, take readings from the most recent leaf with a fully visible collar. The values are more consistent when the reading is taken at approximately the same position on the leaf blade.

Leaf greenness readings can be used for real-time N management decisions. Currently, no functions relating absolute leaf greenness readings at a specific growth stage to N fertilizer requirements are available for California. However, relative values can be used to assess the N status of a field. The relative leaf greenness, often referred to as N sufficiency index, is the average leaf greenness of a field relative to the average leaf greenness of a well-fertilized strip in the same field with identical management and variety. Studies found that N fertilization is required to prevent yield loss when the relative leaf greenness drops below 90 to 96% of the well-fertilized strip (Samborski et al. 2009).

Cornstalk Nitrate Test

To review and evaluate the N fertilization program and to make adjustments for the following years, a stalk nitrate test at corn maturity can be performed. Take samples just before silage harvest when the milk line is one-fourth of the way down the kernel and through about 3 weeks after black layer formation. During this period, the nitrate concentration in the lower part of the stalk remains relatively stable. Cut an 8-inch-long section of the stalk, with the lower cut being about 6 in. above the soil surface. Remove the leaves from the stalk. Take ten to twenty samples from a field. Submit the samples immediately to a laboratory for nitrate-N analysis.

An optimal range of 700 to 2,000 ppm nitrate-N has been reported. Optimal stalk nitrate-N concentrations in fields where manure was applied in fall are generally higher, possibly because a larger proportion of the manure N becomes available later in the season. This N often cannot offset the potential yield loss from early or midseason N deficiency. The Oregon State University Extension Service recommends an optimal range of 3,500 to 5,500 ppm nitrate-N (Hart et al. 2009).

General Considerations in Developing a Nitrogen Budget

The key to designing an efficient N management plan is to ensure that the crop needs are met while at the same time minimizing the amount of nitrate present in the soil when losses can occur. Nitrogen losses are closely linked to irrigation management. Therefore, N management and irrigation management must be adjusted in tandem. Minimizing leaching losses is a crucial step in achieving high yields and low N losses. An effective N management plan needs to address the following issues.

- How much and what kinds of manure materials do you have, and when is it feasible to apply them?
- What concentration and forms of N are in the materials you have?
- What crops do you want to grow, and how much N will they remove at harvest?
- What times during the season does the crop need the N, and how much is needed?
- When will the organic N in the manure become crop available?
- How much of the crop-available N present in the soil at any given time will be lost before the crop will actually use it?
- How can irrigation management be improved to reduce leaching?
- Will there be enough crop-available N in the soil to supply the crop when needed?

- Do you need to apply extra N to account for expected losses so you can be assured that the crop will have what it needs?

In a dairy system, once the N budget is developed, review the planned application rates to ensure that the pumps and pipelines will be able to deliver the desired amount of lagoon water. Also, make sure there is sufficient storage capacity for liquid and solid materials to accommodate the planned rates and timings. An N budget that ignores the physical limitations to what can be applied and stored will not succeed.

Remember that maintaining good yields is essential for meeting crop removal targets. If N is applied according to the plan but the yield is less than what the plan was based on, the field will still be out of compliance. Higher yields increase N removal and allow more manure N to be applied.

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