Community Forum Comments

Submitted in Response to:

California Department of Food and Agriculture Nitrogen Tracking & Reporting Task Force Final Report (December 2013)

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Prepared by:

LAND IQ

Prepared for:

Kern River Watershed Coalition Authority

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1 INTRODUCTION AND PURPOSE

The Nitrogen Tracking & Reporting System Task Force (Task Force) was convened by the California Department of Food and Agriculture (CDFA) as a requirement of the State Legislature to implement Recommendation 11 of the Recommendations Addressing Nitrate in Groundwater (SWRCB, 2013). The Task Force was charged with identifying an appropriate nitrogen (N) tracking and reporting system. The objective of the Task Force was to provide meaningful and high quality data to help CDFA, the State Water Resources Control Board (SWQCB) and the Regional Water Quality Control Boards (RWQCB) address groundwater quality in nitrate high-risk areas in California.

The Final Report of the Task Force ([Final Report] December, 2013) included recommendations for certain data to be tracked and reported by growers and third parties (aggregators). These data include information related to crop type and characteristics, N fertilizer use and consumption by crop, and irrigation system. The Task Force did not specify how each of these data types would be used for the purpose of protecting groundwater; however, the data types were selected in response to the recommendation from the State Water Board Report to the Legislature (January 2013) that a N mass balance approach be pursued as a starting point. The Final Report of the Task Force acknowledged limitations of this approach as follows:

> *"The benefits of the recommended nitrogen tracking and reporting system are intended, but not proven. Limitations can also be anticipated. Primary among these is the fact that the scientific knowledge currently available for understanding nitrogen's movement beyond the root zone for the many crops growing in California is limited and in some cases non-existent, particularly in terms of calculating exact amounts of nitrogen lost to air and groundwater. Additionally, it is recognized that the timing and amount of water applied can be critical to water/nitrogen moving below the root zone and is not tracked as part of these recommendations."*

The impact and weight of these limitations were not clearly described. This document is submitted in response to the request by CDFA during the January 13, 2014 Community Forum to submit written comments. Its purpose is to clarify that the impact and weight of the limitations were not clearly described. These comments also seek to illuminate why an N mass balance approach, while appropriate for large-scale modeling applications, will have limited effectiveness in achieving the ultimate purpose of the Irrigated Lands Regulatory Program (ILRP), and how its limitations can be addressed.

It should be noted that some of the conclusions of the Task Force were unable to be fully defined during the limited time-frame allowed. As such, some of the more technical components were referred to the upcoming Expert Panel, as established by the SWRCB and as required by the State Legislature (Recommendation 14). During the community forums, CDFA stated that the Final Report is considered one component of a broader analysis that includes work done by the SWRCB and the Expert Panel specifically and therefore may be modified. Similarly, some of the comments in this document may also need to be forwarded on to the SWRCB Expert Panel and are not defined within the scope of the Task Force work and subsequent report.

2 SUMMARY

A quantitative approach of tracking and reporting N depends on the measurement of numerous components of the N cycle, and/or making assumptions about other components that are impossible or very difficult to measure because of their spatial and temporal variability. The N cycle has been studied for decades in agricultural systems, is very complex and dynamic, and N in any form can transform and change within the N cycle according to a variety of environmental and human-induced factors transient. Therefore, the mass of N in an agricultural system can only be "balanced" with great expense, time and effort to determine all the components of a complete N balance. Such mass balance requires rigorous monitoring that is impractical over large landscapes. Nitrogen "balances", as described in the Final Report, are actually partial N balances and are inherently incomplete. Though an incomplete N balance might represent what is potentially available for leaching, it does not does not truly represent and account for the variable, unmeasured pools of agricultural N that influence the amount of N available for actual leaching.

In a practical sense, partial N balances (or N budgeting) cannot accurately capture the variability of N dynamics in California agriculture at the field scale across the wide range of geography, climate and cultural practices throughout the state in a timely manner that will be useful for the regulatory purpose of the ILRP. More importantly, N budgeting can neither provide information on what is contributing to, or causing high or low nitrates in groundwater in any given scenario, because the assumption that applied N fertilizer alone correlates to groundwater nitrate concentration is only valid under certain circumstances. The key factor that links nitrate concentration in groundwater to N in soil (not only N applied) is water volume passing through the root zone, which can be measured, but has great spatial and temporal variability. Therefore, no amount of tracking, reporting and/or "balancing" N can account for or encapsulate the influence of this key factor and in turn, provide meaningful information that can be used to decrease N leaching to groundwater in agricultural systems.

Because of the great complexity and variability of the N cycle in the highly diverse agricultural systems in California, the results of N budgeting will be uncertain (as proven by numerous examples from scientific literature, described in this report), as with any attempt to quantify a natural, biologically mediated system. In addition, these results will have little use without a means to interpret their underlying cause.

This means of interpretation can be provided by using other factors known to influence N leaching, such as irrigation system type, to improve N management and immediately decrease N migration. Management factors, specifically irrigation, crop, and soil types should be documented and used in the Nitrogen Groundwater Pollution Hazard Index (NHI) or a modified version of the NHI, which might include other factors related to leaching such as effective precipitation or irrigation distribution uniformity, and those identified by the Task Force. The NHI was developed and validated specifically for California agriculture to track both management factors and crop type changes. This tool and its supporting documentation, rationale, and scientific underpinnings were developed by a team of experts in the mid-90s, convened by the SWRCB to determine the best way to assess and address nitrate leaching potential on agricultural land. The main conclusion of this expert team was that a qualitative (not quantitative) approach was the most effective and immediate way to address agricultural nitrate contamination identification, characterization, and minimization. In other words, the NHI can be used to identify: 1) where nitrate contamination is likely; 2) what is likely causing it; and 3) how to minimize it.

Though the shortcomings of an N budgeting approach cannot be entirely mitigated by using NHI, their impact can certainly be reduced. The NHI can use the same information that the Task Force identified as important, but in a more informed and educational way. Growers have no control over intrinsic site factors (e.g. soil type) that influence N leaching, but they do have control over specific vulnerability, which refers to the specific management factors such as fertilizer N and irrigation management that impact N leaching. Therefore, strategies intended to reduce nitrate in groundwater that do not consider specific vulnerability (management factors) in combination with intrinsic variables are likely to be unsuccessful.

At best, the N tracking and reporting approach should be modified with a system that addresses what growers can control and improve – N management, irrigation management, specifically irrigation uniformity – through BMPs, improvements in crop production (to allow for more uptake) and improved N application management. An inaccurate partial N balance will serve as a poor approximation of N status in agricultural systems, potentially erroneous regulatory requirements, and thus, inappropriate management decisions. At the least, the quantitative approach to N tracking should be supplemented with a methodical system that focuses on collecting information that can be used to make decisions that will successfully manage agricultural N to protect groundwater statewide.

3 OVERVIEW OF NITROGEN MASS BALANCE APPLICATIONS

Approaches proposed in the ILRP have been made in the context of guiding documents, specifically:

1. The UC Davis Report for the SWRCB SBX2 1 Report to the Legislature (Harter and Lund, 2012); and
2. Recommendations based on the UC Davis report from the SWRCB to the legislature, Recommendations Addressing Nitrate in Groundwater (SWRCB, 2013).

The purpose of the former document was to provide insight into the extent and status of nitrate contamination in groundwater, and identify ways to address it. The purpose of the latter document was to make specific recommendations, based on the former, on how to address nitrate contamination through specific regulatory processes.

The Harter and Lund (2012) report determined groundwater nitrate loading from agriculture using the cropland inputs and outputs in the context of a N mass balance, where the sum total of all inputs (one of many being synthetic fertilizer) equals the sum total of all outputs (one of many being leaching of N below the root zone). This approach was also used in the California Nitrogen Assessment (CNA), an effort to compile data and analyze trends for the purpose of informing policy and agricultural practice (http://nitrogen.ucdavis.edu). This approach is useful in developing a gross inventory of relative N pools in a particular agricultural system to gain understanding of how N flows between components, and the relative proportion of each component. The N mass balance is also a convenient and easily understandable way to portray the N cycle as it relates to a particular activity, in this case farming. It is depicted in Harter and Lund (2012) as an orderly, logical, mathematical set of relationships that can be determined with a combination of data and assumptions. Although simplified relative to a more detailed N mass balance approach, this method of determining and portraying groundwater nitrate in relation to other pools of N at a gross scale was an appropriate use of the N balance approach for these purposes.

The SWRCB (2013) report then recommended the N mass balance approach as a framework and methodology to track and report N in farming systems, for the ultimate purpose of decreasing groundwater nitrate contamination and preventing further degradation. This step in the process, from identifying and characterizing the problem to recommending how to solve the problem, is where the detailed field-scale N dynamics were overlooked.

In actuality, the N cycle is not a neat, orderly, set of mathematical relationships; it is a highly variable, transient cycle of ever-changing interactive relationships that are exceedingly difficult to quantify. An N balance is a model that is only as accurate as the data that informs it. Conducting an N balance requires large amounts of frequently measured data, for which accurate sources are not necessarily available, and the variability many times unpredictable. To achieve true balance, assumptions must be made about certain elements which are highly variable. For this reason, conducting N balances to determine farm- or regional-scale agricultural N pools over the large and diverse agricultural area in California has high potential for error.

In addition, conducting an N balance alone, even with good data, does not provide information on what management change is needed to alter the N cycle in a way that decreases N leaching. In fact, the N balance approach promotes the idea that decreasing N inputs of a certain variety will necessarily decrease N outputs of a certain variety (e.g. decreasing N fertilizer inputs will decrease N leaching). This assumption is only valid under certain circumstances, largely because of the interaction of N with water via irrigation, as well as differences in plant vigor and subsequent plant uptake mechanisms. Therefore, interpreting the results of an N balance, for the purposes of managing (not describing) N requires the methodical collection and application of other information such as cropping systems, management and irrigation practices, N management, and soil physical, chemical and biological attributes that have a major influence on N leaching.

For these reasons, the N balance approach, though appropriate for other purposes, namely a more gross understanding of the pools of N in a larger system (e.g. agriculture in general), is not an effective tool for achieving the goals of the ILRP which is to regulate at a much more refined level. This document includes:

- a general summary of the findings of numerous scientific studies that support this rationale,
- a detailed review of these findings,
- and an alternative method for further understanding, supplementing, modifying and/or selectively using the N balance approach.

4 DESCRIPTION AND EVALUATION OF THE N BALANCE APPROACH IN REGULATING AGRICULTURAL SYSTEMS

The quantitative approach of tracking, reporting and budgeting N for the purpose of developing an N balance depends on the measurement of one or more components of the N cycle. The result of this type of assessment, such as nitrate concentration in groundwater, which is what is generally used to determine the status of leached N, is a measurement that is assumed to be an accurate indicator of the N status of a particular scenario. This value is then categorized as being over or under a threshold, and is also used as a benchmark to compare future measurements and determine whether N leaching potential has decreased after steps are taken to reduce N leaching potential. Evaluating this approach requires an understanding of the N cycle in the context of agricultural systems.

COMPONENTS OF A NITROGEN MASS BALANCE

Nitrogen in the soil is found in several forms, including:

1. Organic N in soil humus;

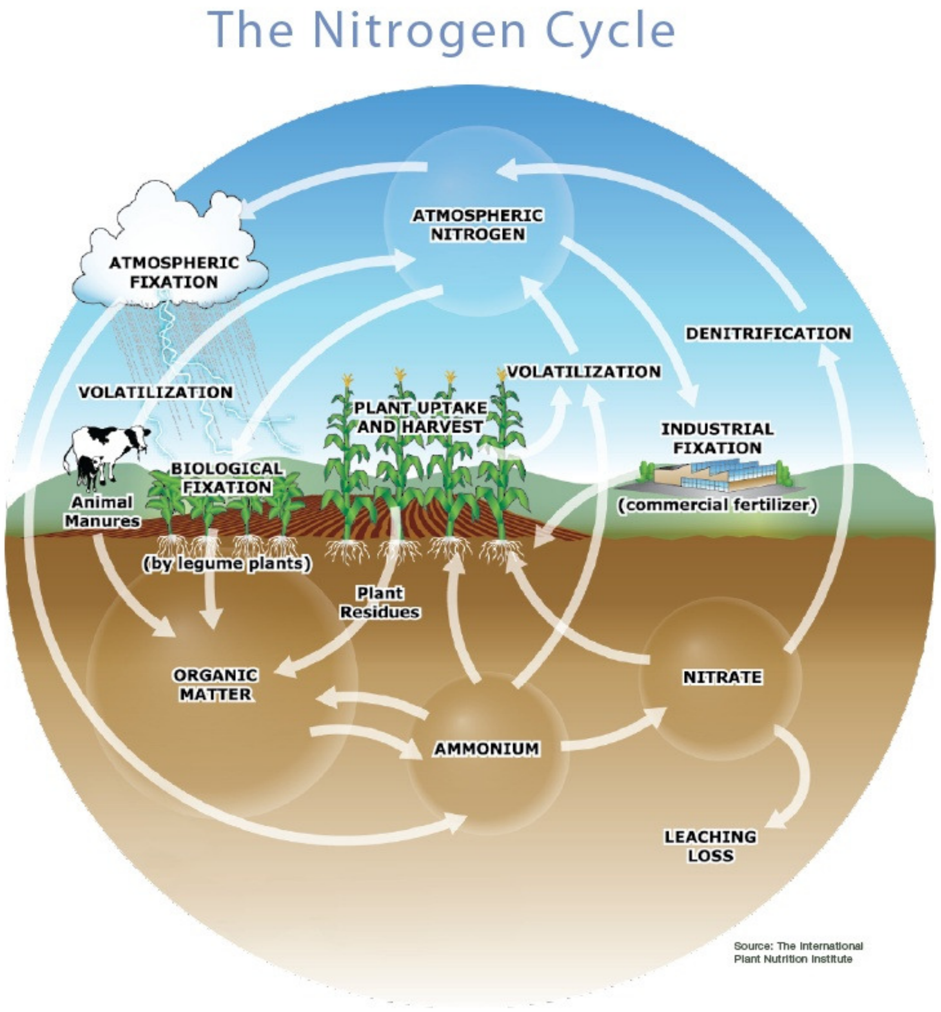
2. Inorganic N, such as ammonium, nitrite and nitrate; and,

3. Gaseous forms (such as ammonia and NO_x forms).

Mineralization is a combination of two biological process that convert organic N to ammonium (ammonification), which can then be converted to nitrate by another biological process called nitrification. Plants use both nitrate and ammonium. The rate at which these transformations occur depends on many factors, including moisture, temperature and biological activity, which are interdependent of soil type and management as well as environmental conditions. All fertilizer N, whether it is organic or inorganic, can be transformed into nitrate, which is the form of N that is mobile in water. **The only way that N reaches groundwater is by water through leaching.**

Nitrogen is otherwise lost from the soil-plant system through volatilization and denitrification, processes that convert N to gaseous forms, which are also biologically mediated and highly variable between sites, seasons, and years. Nitrate is leached when water moves beyond the root zone and transports the nitrate in the soil solution at that time. The N cycle in agricultural systems is illustrated in Figure 1.

One concept that has been used as an indicator of N management is N use efficiency (NUE). Though it has several definitions, it is generally understood as the ratio of N consumed and exported by the crop to the amount of N applied. NUE greater than 100% is not ever sustainable over an extended period of time because one must account for N losses described previously. NUE can be greater than 100% for one or more years if the amount of mineralized organic N is substantial as compared to the amount of N applied. Because NUE is a ratio of N taken up by the crop to the amount applied, the numerical value is also affected by yield that controls the amount of uptake. Applying low amounts of N that causes a low yield frequently causes an increase in the NUE number. Indeed, some yield commonly can be achieved without applying any N for a year or two. This results in a NUE value of infinity. So every value from much less than 100% to infinity are possible making it an imperfect indicator of the effectiveness of N management.



Source: The International Plant Nutrition Institute

Figure 1. The N cycle in an agricultural system

LIMITATIONS OF THE N BUDGET APPROACH

It would appear in Figure 1 that the N cycle in agricultural systems is similar to a bank account; if all the credits (or N inputs) and debits (or N outputs) could be quantified then we could know with certainty how much N resides in the system and where. Unfortunately, that is not a valid comparison due to the dynamic nature with the "account" itself and the many variables that affect it. It could also be assumed that N must reach equilibrium or "balance" at some point. However, N in agricultural systems is unique because its behavior is affected by both natural biological interactions and imposed management. Therefore, N in agricultural systems:

- Exists in several pools, many of which are poorly understood (such as organic N);
- Is biologically mediated, and is therefore affected by environmental factors as well as management;
- Is extremely variable; and,

- Is constantly involved in transformations (additions and losses) and always seeking equilibrium but not achieving it.

In other words, the N cycle in an agricultural system is very complex and dynamic, and N in any form is transient. Therefore, the mass of N in an agricultural system can never truly be "balanced" without assuming the size of N pools, and the rate and nature of how these pools transform. An N budget, which estimates how much N is in each form and where it is in the system, can be used to estimate certain components of the N cycle. However, it cannot be used to describe the entire N cycle in any system at any given point in time, make assumptions about other parts of the N cycle that are not measured, or, in the case of the ILRP, be used in an attempt to make inputs and outputs of N equal each other in this type of system.

The N cycle as illustrated in Figure 1 contains many N pools with connecting arrows. A very complex network is portrayed. However, the cycle is even more complex than shown. The following provides examples of the extreme complexity of the actual N cycle.

Organic matter is listed in one pool. However, there are several different organic chemicals and each should have their designated pool. There is an arrow directed from the organic pool to ammonium that may be extended to nitrate. The arrows merely depict the directions of flow and not the rate of flow. The rate of conversion of organic N to inorganic N decreases exponentially with time. Each pool has its unique rate of conversion. Also the conversion is very temperature dependent and soil temperatures vary with time of year. A complete depiction of mineralization of organic N would contain several pools, each with different rates of mineralization.

There are arrows from ammonium and nitrate to plants. The rate of flow depends on plant uptake which varies greatly with time as well as the growing conditions of the crop. If the N supply at any time is not adequate to supply the full crop demand, yield is reduced. Any factor that affects plant growth such as weather, disease, pest damage, drought etc. will modify the crop demand at any time and can vary widely.

An arrow is from the nitrate pool labeled as leaching loss. Water flow through the soil is the transporting medium and thus, the controlling factor in leaching nitrate. One could illustrate a water cycle on an agricultural field in a manner that the nitrogen cycle is depicted in Figure 1. Computing the leaching loss would require interconnecting the water cycle with the nitrogen cycle. The water cycle contains components that are rate dependent and interactive with plant growth. A true depiction of leaching loss would entail the overlay of the water and nitrogen cycles and results even more complexity.

Nitrogen is a "moving target"; for this reason, it is difficult, if not impossible to quantify N in any given form. For this reason, N balances are widely used in scientific studies to isolate, quantify, or predict specific N pools and acquire relative understanding of the N cycle; however, they are seldom successful in quantifying or characterizing a complete agricultural N system on which to base management decisions or institute regulatory restrictions or requirements.

The limitations of a quantitative N balance approach outweigh the potential advantages, which include the following:

1. Absolute values provide benchmarks that in time, can provide useful comparisons in helping to understand the fate of N in agricultural systems;
2. Measurements provide valuable information about status of N groundwater contamination; and,
3. The relative proportions of N pools can be portrayed at a gross scale to improve general understanding of N in the environment.

The first advantage is thwarted by the lack of data requirements proposed in the Task Force Report to achieve an accurate N balance; absolute values are only useful if they are accurate and reflect the true status of N but are not useful if they are “precisely wrong.” The second and third advantages can only be realized at much larger scales, as have been evidenced by statewide efforts such as the CNA and Harter and Lund (2012).

5 RESULTS OF N BALANCE STUDIES

Because of the complexities of the N cycle in agricultural systems, many studies have attempted to quantify the many pathways, pools and forms of N in agricultural systems. The results of these studies have two important commonalities:

1. The results are extremely variable from year to year, from site to site, and within seasons; and,
2. They do not provide any information, from a management perspective, about *why* particular N parameters (such as groundwater nitrate) are what they are and therefore cannot be used to make management decisions.

A detailed review of these studies is provided in the literature review at the end of this document. Because N is and has always been the most studied agricultural nutrient, experiments focused on N research number far too many to include here. The studies included in this review were selected because of their focus on one or both of the following research objectives:

- Using an N balance approach to describe N flows; and,
- Measuring specific inputs and/or outputs of N in specific agricultural systems

The high variability exhibited in N studies means that there is great potential for error when assumptions from one scenario are applied to others, which must be done when N is tracked and reported on a statewide scale. Considering that N needs to be tracked and reported on approximately 10+ million acres across a wide range of soils, climates, and practice regimes, the amount of data required to apply an N budget approach is unreasonable and would likely produce erroneous results. Conclusions from the literature review are summarized below.

SUMMARY OF CONCLUSIONS

1. Nitrogen *cannot* be budgeted so that N fertilizer input is equivalent to crop consumption.
2. Cropping systems necessarily accumulate residual N at the end of the growing season because of the nature of plant physiology and optimizing resource efficiency.
3. Residual N and/or N fertilizer applied is *not* necessarily related to amount of N leached.
4. Reducing N fertilizer application rates does *not* necessarily minimize N leaching.
5. No individual factor on its own (soils, crop types, irrigation methods, climatic conditions or N management) can account for the potential of a site to leach nitrate.
6. Of farm management practices, the amount of nitrogen leached *primarily* depends on the amount of water percolating through the root zone and the nitrate concentration in the soil profile.
7. Irrigation system management, maintenance, and uniformity are key factors, not accounted for in N balance approaches, in minimizing leaching.
8. Quantification by assumption of certain N cycle processes (i.e. mineralization, denitrification, etc.) is not a valid approach to completing N balances at the field scale.
9. The N balance approach is *not* an adequate tool for minimizing N leaching at the field scale.

ASSUMPTIONS AND SCIENTIFIC FINDINGS RELATED TO N BALANCE APPROACHES

The N balance approach implies numerous assumptions that are largely associated with the use of N concentration in soil water and/or groundwater as an indicator of how N is managed on the surface of an agricultural field, and how surface applied N should be managed to reduce N leaching risk. Many of these assumptions are not scientifically valid because they have been disproven by agricultural studies in California and elsewhere. Although the Task Force Report states the Recommendation is not intended to provide scientific analysis, as stated above, SWRCB, 2013 Recommendation 11 directs the Task Force to, "…identify appropriate nitrogen tracking and reporting systems, and potential alternatives, that would provide meaningful and high quality data to help better protect groundwater quality."

The scientific limitations of the recommendation to provide "high quality data" should be covered in the limitations section of the Task Force Report. The assumptions and the scientific findings that disprove them are listed and described as follows:

1. **Assumption:** The concentration of N in soil water and/or groundwater is correlated with the amount of N fertilizer applied, and can be used with an N mass balance to manage N fertilizer applied.

   Scientific Finding: The amount of N leached to groundwater does not correlate well with the amount of N applied alone, though it does correlate well with the drainage volume, and with drainage volume *and* N applied as co-factors.

   Typically, the concentration of nitrate in groundwater or soil water is measured without measuring the rate of water flow. The reason the rate of water flow is not measured is because it is impossible to measure it accurately at any given time because of its spatial and temporal variability (Letey and Vaughan, 2013; Broadbent and Rauschkolb, 1977). Therefore, the discharge load is difficult, if not impossible, to determine. The measure of N concentration has little meaning by itself, because N concentration in groundwater is not directly related to N fertilizer applications. Studies show unequivocally that the best correlation with leached N is a combination of drainage volume and amount of N fertilizer applied, indicating that both of these causal factors are important in assessing and improving N leaching risk (Letey and Vaughan, 2013; Wang et al, 2013; De Vos et al., 2000;)

   For example, very efficient systems result in high N concentrations in soil water, but these high concentrations may never reach the aquifer because of low downward movement of water. Conversely, inefficient irrigation systems or high water duties result in low N concentrations in soil water; however, over time high drainage volume would result in a high amount of N being leached to the aquifer. In this case, N concentrations by themselves would lead to incorrect conclusions about N leaching risk potential, and in turn, changes in management that would not serve to reduce N leaching risk.

   Additional studies that support this finding are reviewed in the Literature Review and include: Feaga et al. (2004); Randall and Iragavarapu (1995); Gaines and Gaines (1994); and Tindall et al. (1995); Wang et al. (2013); Burrow et al. (1998).

2. **Assumption:** Reducing N fertilizer application reduces N leaching.

   Scientific Finding: Reducing N applied does not necessarily result in a corresponding reduction in N leached, and may lead to *increased* leaching. Nitrogen leaching is only reduced if the N applied is over what is needed for maximum yield, and then is reduced to equal or below what is needed for maximum yield. Except for conditions of maximum yield, a reduction in the amount of N applied does not induce an equal reduction in the amount of N leached

(Rosenstock, 2013; Letey and Vaughan, 2013; Broadbent and Rauschkolb, 1977). This results from the relationship between N uptake and crop vigor. As more and more fertilizer N is applied, the rate of increase in yield decreases and reaches a point where further N application does not result in additional yield. This reduction in N uptake leaves more N available for N leaching. Conversely, reducing N fertilizer applications below a rate needed for maximum yield in hopes of reducing N leaching can lead to reduced crop vigor, poor N uptake, poor yield, and resulting reduction in evapotranspiration, which results in greater probability of over-irrigation increased deep percolation, and hence, more leaching. Therefore, reducing N fertilizer applications can sometimes result in *more* N leaching because of adverse impacts on plant vigor and N uptake.

Additional studies that support this finding are reviewed in the Literature Review and include: Pang et al. (1997); Altman et al. (1995); Fix and Piekielek (1983).

3. **Assumption:** The concentration of N in groundwater and soil water represents current N status on the surface of the overlying field and correspondingly, current management practices.

   Scientific Finding: There are temporal and spatial components that must be considered. The transport time between nitrate leaving the root zone and reaching first-encountered groundwater can be anywhere from days to decades, depending not only on depth to groundwater, but soil heterogeneity in the root zone, vadose zone, deep vadose zone; and also on irrigation management practices (Harter and Lund, 2012; Pratt et al. 1972; Fogg et al., 1995). Also, groundwater contamination is not a one-dimensional phenomenon and is influenced by vertical and horizontal water movement. Therefore, assessing the N status of an agricultural system using an indicator such as groundwater does not represent the current N status of the fields directly above or the many factors that influence it that are currently in use in many cases. In addition, studies show soils may retain more fertilizer N over the long term (up to 15 percent) than previously assumed (Sebilo et al., 2013).

4. **Assumption:** Irrigation management is less important than N fertilizer management in reducing N leaching risk.

   Scientific Finding: In California, irrigation is one of two key factors that determine how much N leaches to groundwater – 1) residual nitrate in the soil profile, and 2) volume of water that passes through the root zone. If nitrate can only reach groundwater through the movement of water, then it is reasonable that the amount of water that leaches through the root zone is not just a contributing factor to N leaching risk, but is an *essential* factor. Growers have applied what might be considered "excessive" irrigation water for numerous reasons (salinity management, lack of irrigation uniformity, poor irrigation management, etc.), all of which are significant management concerns in agricultural production and cannot be ignored in addressing N leaching risk factors.

   In addition, excessive drainage resulting from excessive irrigation has been found to be the cause of N fertilizer over-application, not the other way around. In other words, growers have been found to over-apply N because excessive/inefficient irrigation causes greater losses of N, and this reduces crop yield (Letey and Vaughan, 2013). This finding underscores the importance of irrigation management, because it can be used to minimize leaching losses, and in turn minimize over-application of fertilizer N.

   Studies that support the finding that irrigation factors (specifically, uniformity) is equally important as applied or residual N in soil include Waskom (1994); Feaga et al. (2004); Barragan et al. (2010); Pang et al. (1997), Allaire-Leung et al. (2001); Wang et al. (2013); Letey et al. (1979).

5. **Assumption:** The N balance approach is an adequate tool for characterizing agricultural N losses to leaching at the field scale, and ultimately minimizing N leaching at the field scale.

   Scientific Finding: The uncertainties associated with the N balance approach result in a broad range of "results" which are not ultimately useful in minimizing N leaching to groundwater in agricultural systems. The great variability in N leaching and the processes that influence it not only between cropping systems but within them, have been documented numerous times in scientific literature (including but not limited to Randall and Iragavarapu, 1995; Altman et al., 1995; Aschmann et al.,1992; Denton et al., 2004). N balance approaches have been rejected by numerous initiatives intended to effect change at the field scale (Waskom, 1994, Feaga et al. 2004, Gross et al., 2010). Attempts at using the N balance approach to quantify leaching are generally limited to simulation modeling, and are not always successful when their results are compared to field data. Uncertainties include the temporal and spatial variability of N losses such as volatilization and denitrification, and long term soil retention of applied N (Sebilo, 2013).

   One example of the limited success of using an N balance approach to predict nitrate in groundwater is that of **Botros et al. (2011)**. These authors used various approaches in conjunction with standard hydrologic modeling techniques to estimate groundwater nitrate at the UC Kearney agricultural experimentation site. They concluded that the simple root zone mass balance model was limited in its ability to predict the low total nitrate mass measured in the deep vadose zone or the large variability of nitrate observed in the deep vadose zone at the field site. They further concluded that the results of their study raised questions about our understanding of the fate of nitrate in the vadose zone. Additionally, they suggest that not all vadose zone water can be modeled with current techniques, yet needs to be considered for "*simulating nitrate transport under conditions of cyclical infiltration with gravity dominated convective flux*". In other words, downward movement of irrigation water cannot be described accurately. If downward movement of irrigation water is key in determining the amount of N that leaches to groundwater, but we have no means to describe it, then it is unlikely that attempts to balance N in this complicated system will yield meaningful results.

   Additional studies that support this finding are reviewed in the Literature Review and include Burrow et al. (1998); Delgado (2008); and Nolan 2001.

The main reason why these assumptions do not hold true for many agricultural systems is because they do not consider the complex interactions between plant response to yield, plant response to water, plant response to N, and interactions of N with water, which are not inherent in the N budget approach.

CONCLUSIONS

The current approach commonly used in hydrogeological studies to minimizing the impact of agricultural N on groundwater quality, as described by Denton et al. (2004), is to evaluate nitrate leaching by monitoring root zone nitrate levels up to a 6-foot depth. Nitrogen balance models are then used to estimate the impact of N fertilizer on groundwater quality. The same authors state, "*The common assumption is that nitrate losses to below approximately six feet represent the amount of nitrate leached into ground water. This assumption is justified for many areas in the US, where ground water is found at depths <u>of less than 10 to 20 feet</u>*". In conclusion, the authors state, "*Our current understanding of the spatial variability of hydraulic properties and their impact on nitrate fate and transport below the root zone is therefore limited and based on greatly simplified models.*"

The National Research Council (1993) determined that groundwater vulnerability depends on both *intrinsic vulnerability* and *specific vulnerability*. Intrinsic vulnerability is the result of soil and hydrogeologic factors that cannot be controlled by a grower. Specific vulnerability consists of the vulnerability that results from crop type, irrigation system, and other management factors. Growers have no control over intrinsic vulnerability, but they do have control over specific vulnerability. Therefore, strategies intended to reduce nitrate in groundwater that do not consider specific vulnerability (management factors) *at the field scale* are likely to be unsuccessful. This is largely because groundwater/soil water N concentration measurements taken out of context of management practices can easily lead to erroneous conclusions, reflected in the assumptions listed above.

If the ILRP is underpinned by these assumptions, it will not necessarily be successful at protecting groundwater and will likely waste financial, human and natural resources. The N tracking and reporting approach should employ a system that addresses what growers can control, such as N fertilizer management (form, placement, and timing) and irrigation management (time and amount of application). At a minimum, the quantitative approach to N tracking should be supplemented with a methodical system that can track management practices and use them as interpretive tools to make decisions that will successfully manage agricultural N to protect groundwater statewide.

6 AN ALTERNATIVE/COMPLEMENT TO THE N BALANCE APPROACH

Because numerous studies have shown that there is little correlation between groundwater nitrate concentration and N fertilizer applied alone, the values of N cycle components derived from N balance approaches have little meaning if they are not coupled with information about what intrinsic factors (such as soil type and depth to groundwater) and/or how management factors contribute to the cause of the level of nitrate contamination. And since management is the only thing that growers can control, *modifying management practices and choices at the field scale is the only way growers can decrease groundwater nitrate contamination overall.*

Therefore, it is imperative that the N tracking and reporting protocol, which will be used state-wide for the purposes of protecting and preventing further degradation of groundwater for beneficial uses, incorporate a method for compensating for the two main shortcomings of the N budgeting approach, namely:

1. **N budgeting alone cannot accurately capture the variability of N dynamics in California agriculture** across the wide range of geography, climate and cultural practices throughout the state in a timely manner that will be useful for the purpose of the ILRP.
2. **N budgeting cannot necessarily provide information on what is contributing to or causing high or low nitrates in groundwater** in any given scenario, because the assumption that N fertilizer applied correlates to groundwater nitrate concentration has been shown to be invalid in many cases.

In other words, tracking and reporting N for the purpose of conducting an N balance alone will not completely protect groundwater from degradation because it does not account for or include the impacts of management practices, which are key factors in nitrate leaching. The influence of management factors on leaching has been documented in numerous studies, specifically in California (see Literature Review at the end of this document). Management factors must also be tracked and reported to determine the source of nitrate, and used to provide context for quantitative, inherently uncertain N budgeting. Management factors must also be tracked and reported to determine if strategies to better manage N and reduce leaching are successful.

The Nitrogen Tracking and Reporting Task Force included several components of agricultural systems in their recommendations on what to monitor for purposes of implementing the ILRP. Clearly, the intent of including components such as N fertilizer applied, N in irrigation water, and N removed in crop yield is to use them in a partial N balance. However, the data needs specified in the Final Report in no way provide the necessary data for a complete N balance. Because of the great complexity and variability of the N cycle in the highly diverse agricultural systems in California, the results of an N balance approach will be uncertain, as with any attempt to quantify a natural, biologically mediated system, especially with poor and/or incomplete input data**.** A farm-gate N mass balance that only measures N fertilizer going in and estimates crop consumption N going out does not account for the N cycle within, the dynamics of which significantly influence leaching. **In addition, these results will have little meaning without a means to interpret their underlying cause.**

This means of interpretation can be provided by tracking other factors known to influence N leaching, such as irrigation system type. Though it has not been specified how these factors will be used in the tracking and reporting system in the Final Report, they would serve as meaningful data if they were used in a scientifically valid methodology to identify the localized, underlying causes of groundwater nitrate concentrations. If they are not used this way, but merely reported as part of a comprehensive tracking strategy without defined purpose or analysis approach in mind, they will result in wasted time, effort and resources.

Management factors, specifically irrigation practices and type, should be documented along with crop type and soil type (at a minimum) and used in the NHI, which was developed (University of California Agriculture and Natural Resources) and validated (Wu et al., 2005) specifically for California agriculture, to track both management factors and crop type changes. The NHI tool was developed as a first step in a Best Management Practice (BMP) approach. The NHI provides a field-scale rating of the potential for nitrate leaching, but it also identifies the major factor that is contributing to this potential. It can be used in its simplest form with basic on-farm information, or can be refined for regions with common irrigation systems, soil types, etc. Paired with GIS resources and landscape information, it is a powerful tool for assessing groundwater pollution vulnerability specifically for N and for guiding BMPs. Using the NHI as a way to track, assess, and modify management factors would serve two purposes:

1. **The NHI could be used to provide insight into the causative factors of N budget results.** Without such an interpretive tool, there is no way to determine what is causing N concentrations that are either measured or determined through an N budget. For example, crop type has a major influence on N budgeting because different crops have different rooting depths and uptake patterns. A change in irrigation system type from surface flood to micro-irrigation would dramatically change the potential for nitrate leaching. This may not be observed immediately in groundwater monitoring results and reflected in an N budget if groundwater is at great depth; however, an NHI assessment would capture the change in nitrate leaching risk beneath the root zone. The NHI serves as a built-in education tool that provides meaningful and practical information to growers, who will ultimately effect positive change towards decreasing groundwater nitrate contamination.
2. **The NHI would serve as a means of validating, verifying, and providing context for N budgeting results,** which are likely to be highly uncertain (and potentially inaccurate) given the high variability and unknown dynamics of N cycles in wide-ranging California agricultural systems. For example, if the N budget and NHI approaches yield dissimilar results for a particular site, this would indicate that more investigation into site-specific factors must be considered. In this way, the NHI can be used to verify the results of the N balance, given the latter's expected variability in accuracy.

The SWRCB accepted this approach when this work was developed (Plant Nutrient Management TAC Report, http://www.waterboards.ca.gov/water_issues/programs/nps/tacrpts.shtml), as part of the SWRCB Initiatives in Nonpoint Source Management program, but it could not be implemented at the time because the indexing information for the factors that determine N leaching potential (soils, crop types, and irrigation system types) was not completely available. However, this information is now available and this constraint no longer exists.

Though the shortcomings of an N budgeting approach cannot be entirely mitigated by using NHI, the impacts can certainly be reduced. Specifically, one of the factors that directly determines amount of N leached below the root zone is volume of water that passes through the root zone. This factor is excluded from N budget approaches because it is not part of the N cycle per se. Most importantly though, it cannot be measured on a large scale. Therefore, no amount of tracking, reporting and/or budgeting N can account for or encapsulate the influence of this key factor. However, a methodical system of tracking and relating management factors to groundwater nitrate can provide irrigation management information that would serve as a useful proxy for this important determinant of N leaching.

7 SUMMARY OF ADVANTAGES AND DISADVANTAGES OF N TRACKING AND BUDGETING FOR USE IN THE N BALANCE APPROACH

In summary, the advantages and disadvantages of using a quantitative N balance approach to assess and decrease N leaching are summarized below:

ADVANTAGES

- Measurements of N in any part of the N cycle provide benchmarks that in time, can provide useful comparisons in helping to understand the fate of N in agricultural systems.
- Measurements of N can provide valuable information about status of N groundwater contamination as it currently exists, regardless of how or when it achieved that status.
- The relative proportions of N pools can be portrayed at a gross scale to improve general understanding of N in the environment.

DISADVANTAGES

- When N measurements are not evaluated in context of management practices for the purpose of managing N, erroneous conclusions can result.
- Absolute values of some N status indicators, such as groundwater, do not reflect current N leaching; rather, because of long transport times, they frequently reflect legacy N contamination.
- The N balance approach that usually results from N cycle component tracking is extremely complex and difficult to accomplish, resource intensive and requires major assumptions that call the accuracy of the balance into question.
- Absolute values of N cycle components only provide information about that particular component, and do not necessarily provide information about other components of the N cycle.
- Absolute values of N indicators do not provide any information about the causal factors of that component's status. Further analysis is necessary to make the value useful.
- N tracking and budgeting approaches are data-rich; they require the collection of large amounts of detailed data that is not available at the farm gate.
- These approaches are generally inefficient and do not yield quick results, largely because of the large amounts of data required and the nature and variation of N cycling.
- Scientific uncertainty and potential for erroneous conclusions does not support the Recommendation's use in a regulatory program such as ILRP.

8 LITERATURE REVIEW

The following conclusions represent what is generally known about N leaching in crop systems based on findings in published, scientific literature. This literature represents only a small fraction of the peer-reviewed scientific resources published on N fate in agricultural systems; it has been selected and included because it is particularly relevant to the objective of determining what factors influence N leaching, and how those factors can be measured and controlled to protect groundwater resources in California.

CONCLUSIONS

1. <u>Nitrogen cannot be budgeted so that N fertilizer input is equivalent to crop consumption.</u>

"One fact emerges when one considers the mechanism of N transport to plant roots. It is impossible to extract all the soluble mineral N from soil solution without suffering decreased plant growth. The consequence of this fact is that there will always be some soluble N that can be leached beyond the root zone when "excess" water is applied. The amount and concentration of N leached depends on several dynamic and temporal factors…." **University of Arizona et al. (undated).**

This conclusion is recognized widely in the scientific literature on agricultural N. Biological efficiencies are always less than 100%, largely because of the constant fluctuation in growing conditions that influences a plant's ability to take up nutrients. In other words, optimum growing conditions are never constant. A general rule of thumb is that N fertilizer uptake efficiency is 50 percent, on average, for agricultural crops (**Meyer, 2008**). However, typical fertilizer N uptake efficiencies of major agronomic crops range from less than 30 to greater than 70% because of several factors. First, it is not possible for a plant to deplete the entire inorganic N from the soil solution. As the nitrate and ammonium concentrations decrease in solution, the rate of N uptake also decreases, in a relationship similar to substrate-enzyme reactions.

Harter and Lund (2013) also acknowledged this important conclusion and determined that "*Due to unavoidable N losses, complete crop recovery of all applied inputs is impossible to sustain. Our approach in this report is to identify and describe practices and technologies that are potentially available to growers for achieving high crop N use efficiencies, and for reducing, but not eliminating, nitrate leaching to the groundwater from cropped land.*"

2. <u>Cropping systems necessarily accumulate residual N at the end of the growing season because of the nature of plant physiology and optimizing resource efficiency.</u>

Minimal N concentrations in the soil are required to result in N influx into crop roots. In addition, some N losses (volatilization or leaching) from the root zone are inevitable during the season. As a result, not all of the N supplied will be available for plant uptake. Finally, and perhaps most importantly that to achieve maximum or near maximum yields, N must be supplied at high levels. According to Mitscherlich's Law, as N supply increases, there is a decrease in the incremental yield increase per unit of N input.

As a result, N use efficiency invariably decreases at high levels of N input that are required to achieve maximum yield. On the other hand, if minimal N is supplied so that the soil N is depleted to near zero to minimize nitrate leaching potential, there is an insufficient concentration of soil N to drive maximal rates of N uptake (**Broadbent and Rauchkolb, 1977)**, and crop yield will be limited. For this reason, the presence of residual soil N at the end of a growing season is inevitable in intensively managed cropping systems that are achieving near maximum or maximum economic yields (**Hermanson, et al., Undated**).

3. Residual N and/or N fertilizer applied is not necessarily related to amount of N leached.

The findings of **Broadbent and Rauschkolb (1977)** demonstrate that N application rates alone are not always enough to predict N leaching. **Olson (1982)**, after working on the fate of N applied in the fall using labeled-N and agronomic rates in winter wheat, found that from all the leaching produced during the winter time, only about 10% of it came from the fertilizer nitrogen. **Burrow et al. (1998)** found that nitrate in domestic wells could not be correlated with N fertilizer applications on adjacent farmland. These results are consistent with the results of **Broadbent and Rauschkolb (1977)**, who suggested that the dilution effect of applying more irrigation, which may lower the concentration of nitrate, may also result in more N leached over the long term.

Researchers investigating other forms of N loss, such as nitrous oxide (N_2O) have reported similar results. **Hoben et al. (2011), Linquist et al. (2012),** and **Van Groenigen et al. (2010)** all showed that these losses are not necessarily related to N applied.

Some authors have suggested that N leaching can be better predicted by the amount of residual or surplus N remaining after crop uptake, which is largely a function of N use efficiency. **Rosenstock et al. (2013)** cite the N_2O studies listed above to support their suggestion that "*the best indicator of potential nitrogen loss into the environment is the "surplus" N, which is the difference between the N applied as fertilizer and the N taken up by the crop*." However, the relationship between N applied, residual N, yield and N_2O emissions may not necessarily apply to leachable nitrate. **Hart et al. (1993)**, working with labeled-N in winter wheat, indicated that most of the labeled-N was presumably mineralized during the fall and winter when the losses are high and crop demand is low. They concluded that leaching of NO_3-N from cereals comes predominantly from mineralization of organic N, not from residual unused N. These results call the assumed direct relationship between residual or surplus N and leached N into question.

4. Reducing N fertilizer application rates does not necessarily minimize N leaching.

The findings of a major National Science Foundation Research Applied to National Needs (RANN) Program study conducted on the relationship of N fertilization to water pollution potential in California are summarized in **Broadbent and Rauschkolb (1977)**. This multi-year study demonstrated that addition of N fertilizer beyond that needed for maximum crop yield increases the amount of N that can potentially be leaching. However, at rates of N required for maximum yield, the amount of N remaining in the soil is small, representing little that is available for leaching. Therefore, little can be achieved by reducing N fertilizer applications to below the amount needed for maximum yield; yield is sacrificed and leaching potential is not affected.

Rosenstock et al. (2013) state that applying a greater amount of N fertilizer in and of itself is not necessarily harmful, but the fraction of excess applied is what is harmful. **Pang et al. (1997)** support these findings; in irrigation quantity and uniformity study, concluding that N leaching was very low when the N application was close to crop N uptake and slightly higher when the uniformity coefficient of the irrigation was 90%. When N application exceeded N uptake, N leaching increased dramatically for all uniformity levels. **Rosenstock et al. (2013)** further state that for almost every one of 33 crops evaluated in their study, yields and N uptake increased with greater N supply. They suggested that their findings indicate that growers of the 33 commodities evaluated have become more agronomically N-efficient over the last 40 years and that for most crops, less N is applied per unit of product.

These findings would indicate that optimizing fertilizer application to meet total N crop demand would minimize N leaching. However, **Altman et al. (1995)** reported NO_3-N losses from crops amounting to 24 to 55% of the N applied at economic optimum rates (typically providing for near maximum crop yields). **Jego et al. (2008)** demonstrated that on a high N-uptake crop such as sugar beet, N application rate did not influence the amount of N leached. In Pennsylvania, the apparent recovery of N fertilizer (ammonium nitrate) applied at the economic optimum N rate in 42 experiments averaged 55% (**Fix and Piekielek, 1983**). Therefore, even when using optimum fertilization rates, a potential exists for fertilizer N to accumulate in the soil with subsequent risk of loss through leaching. The missing link that was not addressed in these studies is the amount and timing of water passing through the soil profile and when.

5. **No individual factor on its own (soils, crop types, or irrigation methods) can account for nitrate leaching; leaching potential of a site depends on soil properties, management, irrigation, crop type, and climatic factors.**

This concept provides the foundation for numerous strategies of addressing groundwater N contamination, including that of the **National Research Council Groundwater Vulnerability Assessment (1993)**. Reducing the assessment and management of agricultural N to the result of an N balance is inappropriate in approach, even in consideration of management factors. Management factors must be assessed and given equal weight to N leaching potential in order to determine the true causes, and provide the ability to address those causes.
"While soil, climatic, and geologic characteristics of the site strongly influence leaching potential, management practices finally determine the amount and extent of N leaching. Conscientious management of irrigation water is critical to proper N management." (**Waskom, 2013**)

Increasing irrigation efficiency and uniformity reduces the amount of water drained through the soil, and decreases the amount of NO_3 and other contaminants leached. Proper N rates and good irrigation management are the most critical components of N management. Attempting to minimize leaching by budgeting N fertilizer applications alone will not necessarily ensure the lowest possible leaching if irrigation uniformity and management are not addressed.

6. **The amount of nitrogen leached depends primarily on the amount of water percolating through the root zone and the nitrate concentration in the soil profile, for which there is great spatial and temporal variability.**

"Nitrate-N concentration in groundwater is a function of the quantity of water recharging the aquifer and the rate of N loss from the surface." (**Feaga et al. 2004**)

Concentration data collected over the 5-year study were averaged with respect to flow. Flow-weighted averaging is an appropriate method to represent the average concentration over multiple sampling events, or when more than one sampler is measuring an event. To find a flow-weighted average for a 5-year period, for example, the total mass of nitrate collected divided by the total volume of water collected would be the 5-year flow-weighted average. Flow-weighted averages are better than simply averaging monthly NO_3-N concentrations because the method can prevent misleading data caused when sampling events that collect small volumes have very high concentrations. (**Feaga et al. 2004**)

This nitrate concentration is strongly influenced by N application rates, methods and management. Cropping systems may be a major factor in regulating nitrate movement below the root zone and toward the water table. Rooting depth, water requirement, water-use rate, N-uptake rate, and time of water and N uptake are all factors involved in nitrate leaching that can be affected by choice of cropping system and associated management. For nitrate leaching to occur, appreciable concentrations of nitrates must be present in the root zone at the time that water is percolating.

Perhaps the greatest uncertainty when measuring or predicting deep water percolation and associated nitrate leaching in soil deals with the heterogeneous pore distribution in the root zone where microbial N cycling can greatly alter N availability for leaching. Large pores created by shrinking and swelling of clays, decomposition of roots, and faunal activity can accelerate water movement (two to five times higher for soils without obvious macropores, and as much as twenty times for soils with cracks). This increased water movement will have different effects on nitrate leaching depending on N concentration of those areas of the soil "bypassed" by infiltrating water, the rate of water application, the N concentration of infiltrating water, and other factors. The net result, however, is generally one of increased N amounts being transported beyond the reach of crop roots. **Aschmann et al. (1992)** detected flushes of nitrate and other ions and attributed them to preferential flow through the profile.

Randall and Iragavarapu (1995) also showed that the amount of N leaching is related to the amount of percolating water. They conducted a study on a poorly drained clay loam soil in Minnesota with continuous corn and N fertilization rates of 200 kg N/ha for several years (fertilizer N was applied as one dose in the spring before planting). They found that annual losses of NO_3-N in the tile water ranged from 1.4 to 139 kg/ha. In dry years, losses generally were equivalent to less than 3% of the fertilizer N applied, whereas in the wet years, losses ranged from 25 to 70% of that applied.

Gaines and Gaines (1994) indicated that soil texture affects NO_3-N leaching. In coarser soils, NO_3-N will leach faster than from finer ones. The addition of peat in sandy soils helps in reducing the velocity of N leaching. However, **Tindall et al (1995),** in a laboratory analysis, indicated that leaching of NO_3-N was significant in both clay and sandy soils. They concluded that in clay soils leaching occurred less rapidly than in sandy soils. Nevertheless, after enough time, 60% of the NO_3-N was leached from the clay soils.

These studies highlight the challenge identified by **Broadbent and Rauschkolb (1977)** in assuming that nitrate concentration in the soil profile is related to the nitrate concentration that will reach the aquifer. In the NSF study that evaluated the interaction of N fertilizer treatments and irrigation treatments, they found that higher N concentrations were associated with less irrigation, while lower N concentrations were associated with higher irrigation treatments, because of the dilution effect. The important measure, however, is how much total N mass is transported to groundwater, which clearly cannot be determined from N concentration measurements alone.

La Folie (2000) concluded that it is difficult under non-uniform irrigation to manage either water or N application to achieve high yields without N leaching or water and nitrogen stress, as a consequence of the spatial variability in water and nitrogen fluxes. The authors recognize that farmers commonly apply excess N as insurance against deficiency, or in response to excess deep percolation (**Letey et al,2013)**, but they also state that "*in agricultural practice, irrigation is probably less uniform than under experimental conditions, and more N fertilizer may have to be applied to attain the same yield. Consequently, it remains essential to optimize both mean irrigation depth, and the amount and timing of fertilization*".

7. Irrigation system management and maintenance ensuring high uniformity, not necessarily efficiency, is a key factor in minimizing leaching.

Feaga et al. (2004) describe the influence of irrigation uniformity on nitrate leaching thusly:

> *The effects of an improperly maintained irrigation system on nitrate leaching potential are similar to over-irrigation. An improperly maintained irrigation system will not distribute water evenly throughout the field. Uneven irrigation can set off a chain of events that effectively cause the grower to require additional fertilizer applications. Consider an irrigation system that applies water excessively to certain parts of the field and deficiently in others. Portions of the field receiving the bulk of this water will have higher* NO_3*- leaching rates. Other parts of the field will be under-watered. In response, the grower will increase the irrigation*

> *amount to ensure that the drier areas are receiving enough water. Now the leaching potential in the wetter areas will further increase. Nitrogen-deficient plants in the over-irrigated areas will require additional fertilizer, assuming that the grower is able to realize the problem in time to counteract the deficiency. Crops in the drier areas of the field will have a N surplus.*

Barragan et al. (2010) also suggested that water distribution uniformity in micro-irrigation systems, in addition to irrigation efficiency and other management strategies was influential in achieving environmental quality. Their work did not involve field experiments. **Pang et al. (1997),** as mentioned above, also demonstrated that irrigation system uniformity in sprinkler systems impacted nitrate leaching; specifically, leaching increased as uniformity decreased from 100 to 75 percent. They used a CERES model. **Allaire-Leung et al. (2001)** concluded that irrigation uniformity did not have a significant effect on nitrate leached; however, the irrigation uniformities used in their field study on carrots grown on coarse-textured soil were all above 80 percent. Therefore, their results were not inconsistent with those of Wang et al. (2013). **Wang et al. (2013)** noticed by reviewing the literature that simulation models might tend to over-estimate the significance of irrigation uniformity on nitrate leaching, compared to results from field studies. So they conducted a field experiment on spring corn (in semi-humid conditions) to test the influence of nitrate applied, soil nitrate residual, and irrigation uniformity on nitrate leaching. They reported that all three of these factors contributed to nitrate leaching and recommended that irrigation uniformity remain above 60% to minimize nitrate leaching.

Therefore, the scientific literature to date supports the conclusion that irrigation uniformity, amongst other strategies, is key in minimizing nitrate leaching.

8. Quantification by assumption of certain N cycle processes is not a valid approach at the field scale.

Volatilization is a biologically mediated N loss pathway that is highly variable and cannot be assumed to be constant across sites, seasons, or years. Volatilization can occur whenever free ammonia is present near the surface of the soil. The ammonia concentrations in the soil solution will increase by applying ammonia-based fertilizers or decomposable organic materials to neutral or alkaline soils. The amounts of ammonia volatilized are small when N materials are incorporated into the soil, and ammonia losses are also low (≤15% of applied N) when ammonia-based fertilizers are applied in the surface of acidic or neutral soils.

Ammonia volatilization is a complex process involving chemical and biological reactions within the soil, and physical transport of N out of the soil. The method of N application, N source, soil pH, soil cation exchange capacity (CEC), and weather conditions influence ammonia emissions from applied N. Conditions favoring volatilization are surface applications, N sources containing urea, soil pH above 7, low CEC soils, and weather conditions favoring drying. Precise estimates of ammonia emissions are only possible with direct local measurements. Depending on application conditions, general ranges would be 2 to 50% emissions for soil pH > 7 and 0 to 25% emissions for soil pH < 7. If the N source is mixed into an acid soil, the emissions are usually greatly reduced (0 to 4% lost) (**Meisinger and Randall, 1991**).

Similarly, denitrification can represent significant N loss in agricultural systems, and cannot be assumed to be a constant value. Compared to volatilization, denitrification emissions in agricultural systems are generally lower, however can be significant in some high water table/reduced soil environments. Emissions of N_2O were found to be lower than 5 to 7 % of the applied N, even at high application rates of 680 kg N/ha/year (**Ryden and Lund, 1980**). Similarly, **Mosier et al. (1986)** reported that, on well-drained clay-loam soil sown with corn in 1982, 2.5% of the 200 kg N/ha applied as $(NH_4)_2SO_4$ was lost as N_2O or N_2. The following year, only a loss of 1% could be measured from the same soil sown with barley.

Conversely, considering possible inputs to the N cycle aside from inorganic N fertilizer applications, mineralization is another biologically mediated process where the decomposition of organic matter can contribute up to 50% or more of the plant required N (**Gardner et al., 2009)**. Determining the N contribution from this process is very difficult as climatic and other biological factors can have a significant bearing on the rate of release of N in a plant available form.

9. The N balance approach is an inadequate tool for minimizing N leaching at the field scale.

"If N efficiencies can be estimated, why can't a cookbook approach be used to ensure that crops are being fertilized at a rate to maximize efficiency and minimize N available to leaching? In reality, natural processes and seasonal variation make exact N balances difficult to achieve." (Feaga et al. 2004).

Nitrate leaching is exceedingly difficult to quantify with an N balance and correlate with agricultural fields spatially. **Stenger et al. (2002)** used geospatial statistics to try to characterize NO_3–N at a small plot scale, and found that nitrate and water contents showed a low proportion of structural variance and their distribution patterns were not stable with time. **Delgado (2008)** also stated that "*Agricultural-related nitrogen (N) losses are negatively impacting groundwater, air, and surface water quality. The complexities of the N cycle have made estimating these losses extremely difficult.*"

This fact is implicit and acknowledged in large-scale N balance efforts. For example, the CNA study information states:

> *A mass balance is an efficient and scientifically rigorous method to track the flows of N in a system. The underlying premise of a mass balance is that all of the reactive N entering (i.e., inputs) the study area must be exactly balanced by N leaving (i.e., outputs) and N retained in the study area (i.e., change in storage). A mass balance approach is very useful to compare the size of N flows and also to identify gaps in understanding the size and directions of these flows.* ***Some flows are difficult to quantify -- they are highly variable in time and/or space, or there are simply no methodologies to easily measure or predict the flows.*** *Nevertheless, knowledge of the relative magnitude of the flows is needed to make informed management and policy decisions for targeting N reductions.*

Describing the mass balance approach as "efficient and scientifically rigorous" may be appropriate for large-scale assessments, but is questionable for the purposes of managing field-scale N, and applying regulatory requirements with the aim to modify agriculture to decrease groundwater leaching. Though numerous scientific studies have used N balance approaches to gain understanding of the N cycle, all of these studies identify uncertainties with this approach and acknowledge the use of major assumptions to achieve "balance." Though the high variability of N flux is recognized by the CNA effort, there is no indication of how these uncertainties are addressed. Information from this initiative further states:

> *The range…places nitrate (NO_3) storage in groundwater as one of the major nitrogen sinks in the state, but highlights the uncertainty around some chemical processes, particularly in difficult-to-monitor locations such as aquifers.*

This statement is important because the foundation of the ILRP is to monitor groundwater nitrate concentration *in aquifers* and use it as an indicator of N leaching. Regardless of the accuracy or inaccuracy of N mass balances, their results ultimately do not identify specific causes of nitrate leaching and how to change management practices at the farm scale to address them. Therefore, the N balance approach might be useful for determining gross estimates of N pools and flows, but it is not useful for addressing specific farm management to effect change in real-time or potential N leaching across a wide and varied landscape.

One example of the unsuccessful use of the N balance approach to predict nitrate in groundwater is that of **Botros et al. (2011)**. These authors used various approaches in conjunction with standard hydrologic modeling techniques to estimate groundwater nitrate at the UC Kearney agricultural experimentation site. They concluded that the simple root zone mass balance model was limited in its ability to predict the low total nitrate mass measured in the deep vadose zone or the large variability of nitrate observed in the deep vadose zone at the field site. They further concluded that the results of their study raised questions about our understanding of the fate of nitrate in the vadose zone. Additionally, they suggest that not all vadose zone water can be modeled with current techniques, yet needs to be considered for "*simulating nitrate transport under conditions of cyclical infiltration with gravity dominated convective flux*". In other words, downward movement of irrigation water cannot be described accurately. If downward movement of irrigation water is key in determining the amount of N that leaches to groundwater, but we have no means to describe it, then it is unlikely that attempts to balance N in this complicated system will yield meaningful results.

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