

OPTIMIZATION OF ORGANIC FERTILIZER SCHEDULES

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Budget:

Year	Requested	In-kind support
2012	\$50,000	\$17,750 ¹

¹ In-kind support includes at least 10% time for Crohn and 5% time for Mathews.

Executive Summary

Problem

Most crops need supplemental nitrogen (N) to reach their full potential, but excess N can leach to pollute groundwater. Organic N fertilizers are increasingly used in California for several reasons; organic fertilizer sources are required to market crops as certified organic products; the cost of fertilizers has risen significantly in recent years, and animal agriculture generates high amounts of N-rich manures which should be beneficially disposed.

Organic N can be more difficult to manage than conventional fertilizers, however. (1) Affordable organic fertilizers tend to release their N gradually though most crops have nutrient needs that build, peak and taper as they grow. This means that crops may be over- or under-supplied depending on plant needs. (2) Organic fertilizers continue to release N after harvests and prior to planting. This N is often leached during field preparation operations for subsequent crops. (3) Organic fertilizer N can be lost from the soil through denitrification to a greater extent than N from conventional sources as denitrifying microorganisms use the energy contained in the applied organic material to convert nitrate-N to nitrous oxide (N₂O) and nitrogen (N₂) gas. (4) Mineralization rates from organic N accumulated in soils are difficult to estimate. (5) The availability of N from many fertilizers is affected by many intrinsic and extrinsic factors, such as soil temperatures and textures, which can be challenging to predict.

The dairy industry is coming under pressure to reduce N leaching from forage operations. Operators applying manure in California's Central Valley are limited to 140 percent of the N they remove with their crops. This extra 40 percent must account for leaching and denitrification, as well as other miscellaneous losses. If fertilizer schedules are poorly planned, yields are reduced. Unless corrected, poor scheduling can reduce the amount of manure N permitted for future crops, leading to a steadily decreasing cycle of production and increasing the amount of land needed for safe manure use. Although the dairy industry in California is dramatically impacted by water quality regulations, other crop industries are also facing pressure. Many high-value certified organic crops receive generous fertilizer supplies and groundwater quality can be affected. Management principles affecting these commodities are similar to those affecting dairies, however. Concerns over nitrate pollution and nitrous oxide emissions have created regulatory pressures on Central Valley and Central Coast growers to manage their fertilizers more tightly. Growers are under increasing pressure to balance their nutrient use with their nutrient needs. Many growers make use of cover crops and organic fertilizers but little guidance is available for considering optimal fertilizer strategies throughout the year.

Scheduling of organic N applications must consider the combined influence of each application. An application in August, for example, will continue to release N for several years. Optimal plans will use accepted scientific principles to select from all possible application dates and fertilizer alternatives to find the schedule that best reduces losses while assuring crops of their daily needs. The tool should be flexible, fast and easy to use.

Project Objectives

The object of this project is to develop and extend the **NBOT** (Nutrient Budget Optimization Tool) for use by dairy operators and others to help them to manage their organic N. A workable version of NBOT is already functioning, but several areas of improvement are possible. The model, programmed in Microsoft Excel 2007, finds optimal solutions to N management budgets based on a simple steady-state assumption. Nitrogen uptake curves are available for a variety of forage crops, and others are currently in development. Mineralization rates are based on limited soil incubation studies. NBOT will be improved and extended as part of this project.

- The influence of soil moisture conditions, leaching, and rooting depths will be introduced by incorporating component of a tool such as NLEAP (Delgado *et al.*, 2000).
- The model will be expanded to permit the use of up to 10 different types of fertilizers.
- If desired, users will be able to fix selected application rates within overall optimization solutions.
- Curves will be introduced that include the possibility of temporary N immobilization. Incubation studies of manures and organic fertilizers will be conducted to parameterize this.
- The model will be configured for rapid solution using the mixed-integer linear programming algorithm, *lpsolve*.
- Results will be compared to available data, including recent field measurements of two dairy forage operations.
- The model will be introduced to growers at workshops, and through a narrated web-based presentation.
- Links will be provided to allow other programs to access NBOT.

Audience

Initially, dairy forage growers, but ultimately any grower interested in managing organic N.

Justification

Problem

If organic fertilizers are to be used sustainably, application rates must consider management strategies that apply over the short and long terms. This research project will further develop an existing linear model for optimally scheduling land application rates for an aggrading (or degrading) soil as well as for a system once it has approached steady-state. Improvements will allow multiple fertilizer and amendment types to be included, as well as new objective function forms so that solutions will be optimized by minimizing nitrogen (N) leaching, minimizing cost, or by minimizing cost subject to a tolerable leaching constraint. Mineralization will be represented using first-order decay models. Several compartments can be associated with each type of incorporated material to simulate the behavior of labile and recalcitrant constituents. Immobilization can also be represented. Once the user determines possible application dates, the approach will use linear programming to assign N application rates for each material. Key model parameters will be developed in the laboratory and while the overall suitability of the management strategy will be tested under field conditions where soil N status and crop uptake will be regularly monitored. Results will demonstrate how organic fertilizers can be optimally managed.

CDFA/FREP Goals

This project will further several program goals.

- Fertilizer practices: NBOT allows for more efficient use of N supplied from organic sources, including fertilizers and cover crops.
- Fertilizer and water interactions: NBOT works by matching available soil N to crop needs. By limiting excess available N, less nitrate is available for leaching. Use of the NBOT implicitly coordinates fertilization practices with water management.
- Site-specific fertilizer technologies: NBOT is site specific. It considers soil conditions, local climate, irrigation practices, as well as the different characteristics of the fertilizers employed at the site.
- Education and public information: NBOT is an educational tool. It does not eliminate the need to monitor on-site fertility, but it does allow growers to formulate annual nutrient budgets by considering a variety of different strategies. NBOT quickly illustrates the potential impact of different management choices by presenting numerous numerical and graphical representations of optimal application plans, associated losses, and the soil nutrient status.

Impact

The first implementation of NBOT will focus on dairy forage operations. NBOT will help growers negotiate recent Central Valley water quality regulations restricting fertilizer N use to 140 percent of crop uptake. Organic N is challenging to manage, and growers do not have effective tools for visualizing the relationship between crop demands and N supply. Without good management tools, forage yields are likely to decline increasingly due to N limitation. California is the nation's leading milk producer with cash receipts of almost \$6 billion in 2010 (CDFA 2011). Dairies have already been impacted by declining milk prices and N management poses an additional stress on this industry that depends on forage production for feed and waste management. NBOT determines an annually optimal N budget, something no other fertilizer N management tool can do. Use of NBOT will permit more efficient use of organic N fertilizers, help to assure forage production, assist in regulatory compliance, and educate in N systems management. Although only dairies in the Central Valley are currently subject to the 140 percent application limit, NBOT can also be used by forage production operations in Chino the Imperial Valley, and elsewhere. NBOT prepares a comprehensive annual nutrient management plan based on a steady-state assumption. The steady-state assumption, which automatically determines initial soil N conditions, has proven to be reasonable under most circumstances. In year 3 of this project we will also prepare a non-steady-state version that will allow growers to control initial soil conditions directly.

NBOT will also be capable of supporting the use of organic N fertilizers, common in Certified Organic production, as well as conventional fertilizers and mixture of conventional and organic N supplements. This will help to protect water quality, reduce the cost of fertilizer inputs, save energy, and help assure efficient crop production statewide. We will develop NBOT during the second year of this project for use on the Central Coast using published N demand curves for popular crops. NBOT also permits use of conventional fertilizers and can be used where mixtures of cover crops, composts, organic fertilizers, and conventional fertilizers are applied in an integrated system.

Long-term solutions

NBOT has excellent potential for contribution to solutions to California N management problems. By educating growers, NBOT will improve the capabilities of farmers developing their nutrient plans. Success can be measured in the degree to which NBOT is adopted. Growers confronted by regulations will likely be early adopters. Others faced with increasing fertilizer costs will also benefit. NBOT has been presented previously to farmers in a number of large and small venues, and this project will facilitate modifications needed to make its use more convenient and robust.

Related research

NBOT has been presented to growers, crop advisers, and scholars on many occasions, including the California Plant and Soil Conference, Stanislaus County Cooperative Extension, and international organizations such as the American Society of Biological and Agricultural Engineers. It was recently the subject of an invited talk at the International Symposium on Managing Organic Matter & Using Compost in Horticulture in Adelaide, Australia. Crohn (2006a) described NBOT's central algorithm. Crohn *et al.* (2009) reported on the scalable N uptake curves used by NBOT for forages. A further paper, now in review, describes the mineralization model that will be developed for the proposed NBOT revision. The model also represents N immobilization. NBOT can be accessed using a calendar planning interface (Fig. 1) or through a standard spreadsheet form.

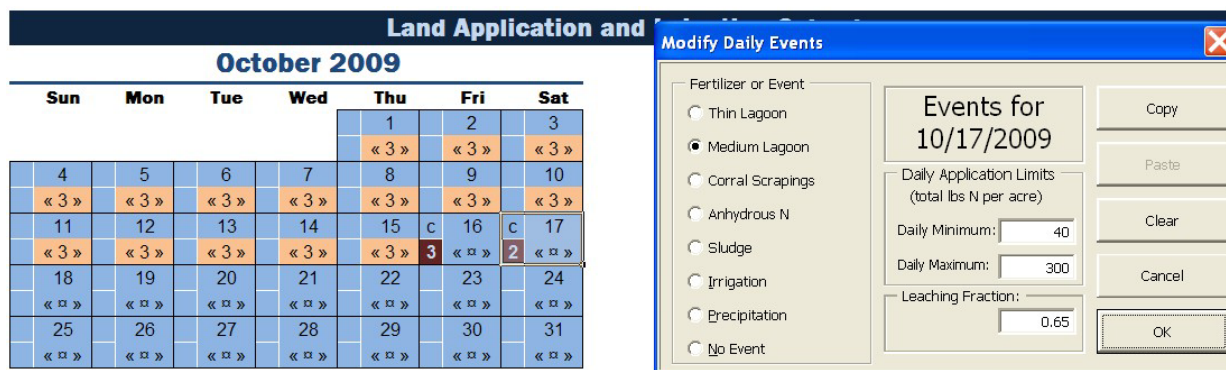


Fig. 1. NBOT Calendar input screen example.

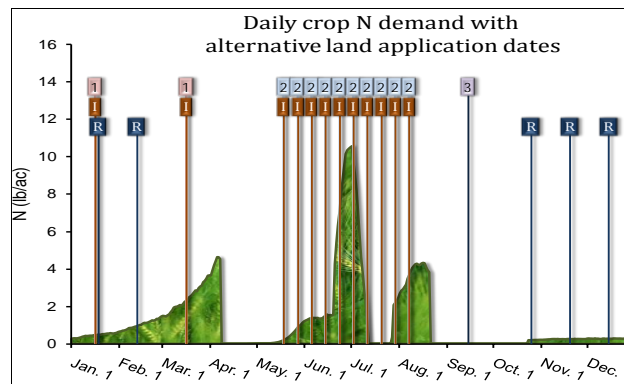
NBOT is a design, rather than a simulation model, that improves on Crohn (2006a). It assumes steady-state, a condition reached quickly in California's warm climate. The model schedules N applications so that target crop meets *in-season* N demand, which is easily customized for local field conditions using functions developed for this purpose (Crohn *et al.* 2009). The model is linear model and therefore solved quickly using the simplex method. This allows for consideration of many different scenarios. NBOT has a daily time step, and allows simultaneous consideration of up to 5 organic or conventional fertilizer types. Nitrogen mineralization (or immobilization) rates derived from CO₂ evolution experiments conducted under laboratory incubations and the initial C:N ratio of the material. N Leaching, denitrification, volatilization are represented in forms that can be reasonably parameterized. Denitrification currently persists for 4 days following a water event. The model also includes heat effects on microbial processes using Arrhenius-adjusted time.

The illustrated example includes 3 manure types; two lagoon waters ("North" and "East") and "Fresh Manure" (Figs. 2 and 3). Model presents an application schedule for each fertilizer type as well as a summary of potential losses (Fig. 4) based on the possibilities and crop needs input by the user (Fig. 1). Denitrification currently accounts for a substantial fraction of total losses. The "Regulatory N supply ratio", which is 1.31, the ratio of total N supplied to the amount removed in the crops and must be less than 1.4.

An earlier version of NBOT was applied to organic fertilizers (Crohn, 2006b). The model planned a three crop rotation near Salinas, California. Broccoli was planted May 4 and harvested on July 23. This was followed by a rye cover crop (*Secale cereale*) planted on August 12 and incorporated without harvest on November 20. Broccoli was again planted on December 20 and harvested on April 29. The organic nutrient sources included in the example were guano and cattle manure compost. Guano could be applied at any of 10 possible dates, while compost had 3 possible application dates. Rye organic N was incorporated on November 30. Application rates were optimized based on cost and on minimizing N. Results were compared to applying N at 25 percent above crop demand without optimization (Table 1).

Fig. 2. Optimized schedule summary.

Fig. 3. Optimized schedule summary.



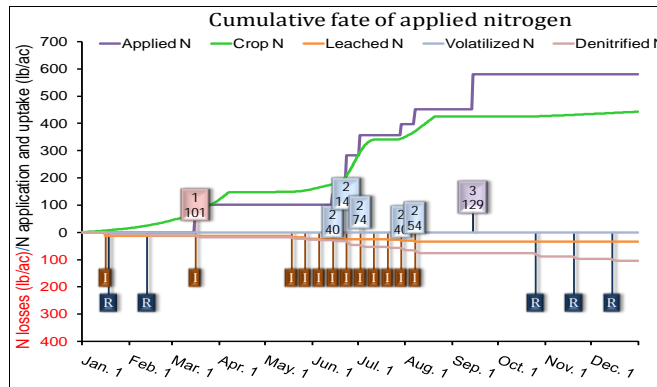


Fig. 4. Optimization result and N fates.

Table 1. Application rates, costs, and N uses associated with different planning methods.

<i>Design Strategies:</i>	<i>Crop demand +25%</i>	<i>Minimize Losses</i>	<i>Minimize Cost</i>	
Date	Guano (kg/ha)	Guano (kg/ha)	Guano (kg/ha)	Compost (kg/ha)
May 4	0.2			1032.2
May 24	2.5			
June 13	34.1			
July 3	300.8	377.8	55.6	
Aug. 2	16.8			
Sept. 11	153.2	83.6		
Dec. 10				
Jan. 9	0.7			
Feb. 8	10.2			
Mar. 10	149.4	160.4		
Apr. 9	152.1	171.9	131.3	
N Subtotals:	820	794	187	1032
Cost Subtotals:	\$5,412	\$5,238	\$1,233	\$3,406
Total N (kg/ha):	820	794	1219	
Total Cost:	\$5,412	\$5,238	\$4,640	
Surplus N:	300	274	699	
Deficit N:	41	0	0	

Contribution to knowledge base

The elements that make up NBOT are established in the scientific literature and the development of NBOT components have been underway for several years. The assembly of these components into a usable whole is what is new. This project combines adds many useful components into a useful tool based on our experiences with growers and their need for simplicity and convenience.

We propose to further develop and extend an organic N management model. Because organic N must be mineralized to ammonium before it can be assimilated by plants, organic nitrogen (N) fertilizers can be more difficult to

manage than conventional alternatives. NBOT optimally schedules organic fertilizer rates once a system has approached steady state. The model uses a daily time-step and up to five different fertilizers can be considered simultaneously. Organic N becomes available gradually over time, although the rate at which this occurs depends on fertilizer properties, soil conditions, and climate. In NBOT, N mineralization and immobilization are represented using a first-order carbon decay model and temperature-adjusted time. To use the model a grower identifies crops, planting dates, harvest dates, harvest N, fertilizer qualities, and possible application dates. Local climate data are used to modify crop development patterns and soil organic N mineralization rates. The model calculates daily crops needs and optimal application rates needed to meet crop demand while minimizing losses. Losses are controlled by reducing the amount of inorganic N present in the soil at times where leaching or denitrification is likely. NBOT has been programmed using Microsoft Excel 2007. We propose to extend NBOT as a producer tool to help with N budget decisions.

Grower use

Forage operations using dairy manure in the Central Valley are heavily regulated. The amount of N they can apply is limited to 40 percent above the amount removed with their crops. Because a substantial amount of N is lost through denitrification and leaching in these flood-irrigated, carbon-rich systems, it is challenging to match the evolving needs of developing crops to gradually released organic N. Regulatory pressures are likely to drive adoption of NBOT by dairy operations. Certified organic growers may adopt NBOT for economic or environmental reasons. Conventional growers can also use NBOT to optimize their operations. It will be particularly useful to growers interested in precision who are also planting cover crops.

Objectives

- The influence of soil moisture conditions, leaching, and rooting depths will be introduced by incorporating components of a tool such as NLEAP (Delgado *et al.*, 2000).
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Work Plans and Methods

Work plan

This project has a three-year duration. Extension will be a component of the project during each year and experiences working with crop advisers and growers will be used to develop a useful and accessible tool.

YEAR 1

1. Incorporation of a water management component, derived from NLEAP or a similar model, to represent leaching, denitrification, and root development.
 - a. Model components, including proposed changes developed mathematically (Crohn)
 - b. Changes to the Excel 2007 program will be coded as necessary and debugged. The program makes extensive use of macros (Crohn).
 - c. Code for *lpsolve*. (Crohn).
 - d. Development of user-friendly interfaces (Campbell-Mathews and Crohn).
2. Generate two-compartment immobilization-mineralization models of organic fertilizers and manures (Crohn).
 - a. Incubate organic fertilizers and manure samples at three temperatures.
 - b. Data analysis and curve fitting.
 - c. Code curve into NBOT.
 - d. Code for *lpsolve*.
3. Development of user-support system (Crohn)
4. Workshop development for Central Valley growers (Campbell-Mathews).

Methods

Crohn (2006a) presented a model for timing application rates throughout the year so that they meet crop needs while minimizing leaching potential. Optimization proved feasible for organic systems. Even if the strategy is not adopted strictly, since operations do vary from year to year, the concepts that emerge by considering steady-state inform farmers interested in sustainable solutions. In addition, it was shown that the optimization approach employed in Crohn (2006a) could be modified and used to schedule applications to a system not yet at steady-state. For systems mainly emphasizing the use of labile and intermediate organic fertilizers, optimizing with a steady-state assumption proved to be an elegant means for planning application rates, even when several different materials are applied throughout the year.

NBOT can potentially be used to manage N in organic fertilizers, composts, manures, and cover crops. Land application rates for organic fertilizers are designed to supply crops with the nitrogen (N) they need while minimizing negative impacts on groundwater. Although certified organic growers in the United States are not permitted to use conventional fertilizers, they have a wide variety of alternatives available to them such as manures and guano, and meals or emulsions derived from bone, feather, fish, alfalfa, and soy. Composts, which are generally used as soil amendments, also contain N (Gaskell et al., 2000). Though compost N concentrations are relatively low, they usually are applied at higher rates than fertilizers. NBOT can also be used with conventional fertilizers and mixtures of organic and conventional N supplements.

Organic N forms must mineralize to ammonium before they are significantly available to plants (Jones et al., 2005). Mineralization rates are affected by temperatures, moisture conditions, and the properties of the fertilizer (Beraud et al., 2005; Flavel, and Murphy, 2006; Hadas, et al. 2004; Hartz and Johnstone, 2006; Leirós et al. 1999), though moisture effects are difficult to predict (Agehara and Warncke, 2005). Over time, soils receiving organic amendments and fertilizers consistently will accumulate N until they reach an approximately steady-state condition. Upon reaching steady-state, the N mineralized annually will equal the amount added and the N will become available according to a predictable pattern. The time required for a newly amended field to approach steady-state is just a few years when moderate-release fertilizers are applied. Previously amended fields require still less time (Crohn, 2006a). Crohn (2006a) described an approach for optimizing dairy manure application schedules under steady-state conditions. This approach was later developed for use by NBOT. Because the equations in the design model are linear the system can be solved quickly and reliably with linear programming. This project will generalize the approach for cases where several different organic amendments are used during the course of a year. It will also develop an approach for incorporating knowledge about denitrification and leaching losses when they can be predicted. Steady-state and non-steady-state conditions will be considered. The changes will allow the model to consider a much wider variety of circumstances than Crohn (2006a). The resulting models will be applicable for certified organic agriculture systems as well as manure land application designs.

To apply the model, a farmer identifies potential application dates, crop planting and harvest dates, and expected yields. A logistic relationship is used to model crop N demand as a function of growing degree-days and to set plant-available N (PAN) targets. It is also possible to select PAN targets manually. Estimates of the fertilizer N content, N inorganic-organic partitioning, and an expected mineralization rate are also needed. If a multiple compartment mineralization model is used, mineralization rates and partition fraction information are needed for each compartment. The model also depends on soil temperature information to modify mineralization rates using the Arrhenius relationship (Crohn and Valenzuela-Solano, 2003). It assumes that soils are irrigated during dry months when low soil moisture levels are most likely to constrain mineralization. Freeze-thaw and drying-rewetting effects are not considered by the model. The system is assumed to be at steady-state in the sense that soil organic N derived from the organic fertilizer varies seasonally, but not from year-to-year.

N MINERALIZATION

Nitrogen mineralization from applied organic fertilizers is currently represented as a first-order process (Fortuna et al. 2003, Gilmour et al. 2003). Decomposition and mineralization are commonly modeled using two compartments, one to represent labile materials and the other to include recalcitrant compounds (Benbi and Richter, 2002; Valenzuela-Solano and Crohn, 2006; Wang et al. 2004). Such models do not represent immobilization, however, and immobilization by dairy manures and cover crops is common. Temperature effects are included by modifying time according to the Arrhenius equation, using an approach described in Crohn and Valenzuela-Solano (2003) and in Crohn (2006a). This approach, called temperature-adjusted time (TAT), is analogous to using growing degree-days, but the Arrhenius relationship has a stronger foundation in biochemistry. TAT, or t° , has an SI unit of d but is given a more informative unit here of d° to indicate days adjusted for temperature (Crohn and Valenzuela-Solano, 2003). It is determined numerically by summing TAT across defined intervals, i ,

$$t^{\circ} = \sum_{\hat{t}_i < t} Q_{10}^{\left(1 + \frac{T_r}{10}\right)\left(1 - \frac{T_r}{T_i}\right)} (\hat{t}_{i+1} - \hat{t}_i), \quad (1)$$

where t_i is the interval i start time, T_i (K) is the mean soil temperature during that interval, T_r (K) is a reference temperature (here $T_r = 298.15$ K, or 25°C), and Q_{10} is the relative proportion by which k_r increases after a 10 K temperature increase from the reference temperature ($Q_{10} = k_{T_r+10}/k_{T_r}$). Experimental determinations of this popular parameter vary, but a frequent assumption is that $Q_{10} \approx 2$. (Andr n and Paustian, 1986; Lloyd and Taylor, 1994). An exact solution to Eq. 1 is found as $i \rightarrow \infty$. Numerical solutions can be calculated easily with a computer and maintained along with temperature and growing degree-days data.

The mineralization of any compartment, m , during a given interval, i , is determined as a first order process in terms of soil TAT,

$$S_{i+1,m} = S_i e^{-k(t_{i+1}^{\circ} - t_i^{\circ})}, \quad (2)$$

where $S_{i,m}$ (kg ha^{-1}) is the compartment m organic N at the beginning of interval i , and where the decay constant, k (d^{-1}), is derived in terms of TAT. Use of TAT both keeps k constant throughout the year and permits the same value to be used in different climates. Organic fertilizer and amendments can be represented using one, two, or more compartments. Unless there is reason to believe that some of the organic N in an amendment will *never* be available, it is important that all of the organic N additions are accounted for.

OPTIMIZATION MODEL:

The Crohn (2006a) model was designed to represent flood irrigated crops fertilized with dairy lagoon water. It divides the year into n planning periods and fertilization can only occur at the beginning of a planning period, j . The linear model schedules fertilizer N applications, A_j (kg ha^{-1}), so that target crop N demand for the same planning period, C_j (kg ha^{-1}), is assured. It depends on the user to predetermine application times, but solutions assign 0 kg ha^{-1} application rates when applications are not needed. Because of the enormous leaching potential associated with each irrigation event, no sharing is permitted between different planning periods. Denitrification losses are not emphasized in the model since field studies had shown such losses to be minor (Harter et al., 2002). Note that no explicit representation of a soil organic N compartment is needed for a steady-state system as this quantity is emerges implicitly from the pattern of organic N applications and associated mineralization rates. The linear optimization model is expressed as,

$$\begin{aligned} & \text{Min} \sum_{j=1}^n A_j \\ & A_j (1 - a_j) (1 - v_j) + \left(e^{kt_f} \sum_{i=1}^j A_i a_i e^{kt_i} + \sum_{i=j+1}^n A_i a_i e^{kt_i} \right) \frac{e^{-kt_j} - e^{-kt_{j+1}}}{e^{kt_f} - 1} \geq C_j; \forall j \\ & A_j \geq 0; \forall j \end{aligned} \quad (3)$$

where k (d^{-1}) is the lagoon water organic N mineralization rate, i and j represent specific planning periods initiating at times t_i and t_j (d°). Additional parameters include v_j , the fraction of fertilizer ammonia volatilized during or following application, a_j , the fraction of fertilizer N that is organic.

NBOT now allows simultaneous consideration of five fertilizer types. To comply with grower requests, this will be expanded to 10 types in the revision. Inorganic N can now be more meaningfully conserved from on planning period to the next. In addition, two new parameters have been added to incorporate leaching and denitrification losses. NBOT has the form,

$$\text{Min} \sum_{j=1}^n \sum_{\forall m} A_{j,m} \quad (4)$$

$$N_j = \sum_{\forall m} \left[A_{j,m} (1 - a_{j,m}) (1 - v_{j,m}) + \left(e^{k_m t_f} \sum_{i=1}^j A_{i,m} a_{i,m} e^{k_m t_i} + \sum_{i=j+1}^n A_{i,m} a_{i,m} e^{k_m t_i} \right) \frac{e^{-k_m t_j} - e^{-k_m t_{j+1}}}{e^{k_m t_f} - 1} \right]; \forall j$$

$$N_j + (1 - q_{j-1}) (1 - d_{j-1}) (N_{j-1} - C_{j-1}) \geq C_j; \forall j$$

$$\sum_{m \in f} A_{j,m} = A_j; \forall j$$

$$A_{j,m} \geq 0; \forall j, m.$$

To allow use of two or more compartments to describe the mineralization of a fertilizer, and to allow applications of different kinds of fertilizers, the revised model adds a compartment subscript, m , to a number of the model parameters and variables, including $A_{j,m}$, $a_{j,m}$, $v_{j,m}$, and k_m . A dependent variable, N_j , represents the total PAN derived during a given interval, j , from organic N mineralization from each of the compartments as well as from any applied inorganic fertilizer N. An additional constraint assures that all compartments associated with a given organic fertilizer, f , are included each time it is applied.

Rather than assuming that all excess N is leached from the system, NBOT assumes that some fraction, q_j , is leached. A denitrification fraction, d_j , is also included. Leaching and denitrification loss fractions values will be developed for the study site by collecting output from well established simulation approaches (Benbi and Nieder, 2003; Delgado et al. 2000; Shaffer et al. 2001).

CROP N DEMAND

Crop demand will be predicted using a logistic expression based on growing degree-days which is indicated using growing degree-days (DD). Its form is

$$C_t = C \left\{ 1 - \left[\frac{D + e^{BM}}{D + e^{B(M-t+t_p)}} \right]^D \right\} \left\{ 1 - \left[\frac{D + e^{BM}}{D + e^{B(M-t_H)}} \right]^D \right\}^{-1} \quad (5)$$

where C (kg ha^{-1}) is the ultimate crop N uptake, t (DD) is time, t_p (DD) is the crop planting time, t_H (DD) is the crop harvest time since planting, and M (DD) locates the time of maximum crop uptake all in degree-days (Crohn et al. 2009). The parameters D and B (DD^{-1}) are shape factors. Degree-days are employed because they are a standard approach for tracking the crops development. This curve has already been successfully applied to small grains. Shape parameters were fitted by minimizing the sum of squared error. Parameters were first developed for a number of considered crops, including Dirkwin Wheat (5 plantings), Swan Oat (6 plantings), T2700 Triticale (9 plantings), Cayuse Oat (5 plantings), Longhorn Wheat (2 plantings), and Ensiler Oat (1 planting). After determining parameters for each crop separately, a general model was also developed by fitting the data from all selected grains simultaneously (Table 2).

The fits with the data were quite reasonable considering the environmental variability associated with measurements. Figure 5 compares selected measurements to predicted curves for four crops. Each curve uses the same set of shape parameters. Local conditions are represented by different values of C , the amount of N harvested with the crop, and t_H , the number of GDD between planting and harvest. This means that the shape of the curve can be determined by its endpoint and that the shape of the curve can be determined by its endpoint so that curves can be customized to conform to historic yields for particular crops.

Table 2. Statistical correlations when (1) the model is parameterized independently for each crop, (2) the model is parameterized simultaneously for all crops, and then applied to particular crops. The overall r^2 for the model parameterized for all crops is 0.91.

Dirkwin Wheat	Longhorn Wheat	Swan Oat	T2700 Trit- icale	Cayuse Oat	Ensiler Oat
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Fitted Plantings:	4	2	6	9	4	1
r^2 custom:	0.96	0.83	0.92	0.92	0.93	0.97
r^2 joint fn:	0.95	0.82	0.92	0.92	0.93	0.97

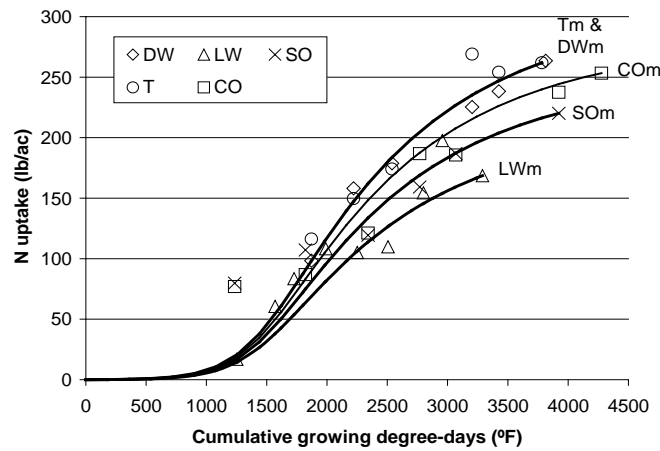


Fig. 5. Observed and model N uptake for selected experiments. Grains include T2700 triticale (T), Dirkwin wheat (DW), Cayuse oats (CO), Swan oats (SO), and Longhorn wheat (LW). Lines represent the model while points represent actual measurements. The T2700 triticale and Dirkwin wheat model lines are superimposed (Crohn and Campbell-Mathews 2009).

Proposed Modifications

LEACHING AND DENITRIFICATION (2012)

NLEAP is an established, widely applied, model representing crop growth and development in a relatively simple manner (Delgado et al., 2000). The model contains simple relationships describing soil water and denitrification components that remain under-developed in NBOT. These components will be adapted for use by NBOT during the first year of this project. NBOT currently relies on user-supplied leaching fractions to determine nitrate leaching rates. Although conceptually straight-forward, these changes represent a substantial revision.

EXPANDING FERTILIZER TYPES AND FIXING RATES (2012)

Currently NBOT allows the use of up to 5 different fertilizers. We will expand this to 10 based on feedback from growers and farm advisors. In addition, there is not currently a mechanism to force NBOT to apply a material on a given date. This revision will allow a user to specify that a material be applied on a given date, regardless of whether such an application is optimal.

MINERALIZATION MODEL AND STUDY (2012)

Mineralization rates represent the greatest area of uncertainty and concern for growers planning their nutrient budgets. Using a recently developed innovation, this proposed revision will permit NBOT to consider both the mineralization and immobilization potential of N supplements (Crohn, 2011). Materials will be assumed to be composed of one or two relatively homogenous organic compartments. At any time, t (days), decomposer microbes are assumed to break down remaining organic carbon, C_t (mg/g), at a fixed rate, k_D (days⁻¹). A fraction of the decayed material, ϵ , is then used by the microbial community to build its tissue while the remainder respire to CO₂-C. This is the substrate conversion efficiency (Gilmour, 1998; Paul, 2007). For any very small time interval, δt (days), this process can be represented as (Crohn, 2011):

$$C_{t+\delta t} = C_t - C_t k_D \delta t + C_t k_D \epsilon \delta t \quad (6)$$

Carbon respiration at time t converts associated organic N, N_t , to inorganic N, a process known as gross mineralization. Gross immobilization occurs simultaneously with gross mineralization as decomposer microbes use available N to build cellular components needed for growth and reproduction. Gross immobilization therefore occurs as a function of the C used to build these new tissues, $C_t \epsilon \delta t$, and the C:N ratio of the new cell materials, Z_f .

$$N_{t+\delta t} = N_t - N_t k_D \delta t + C_t k_D \frac{\varepsilon}{Z_f} \delta t \quad (7)$$

The apparent C decomposition rate, k_C , is directly observable, while k_D values must be inferred. If organic C decomposes at rate k_D , CO₂-C will be evolved at a corresponding rate of $k_C = k_D(1-\varepsilon)$ (days⁻¹). Substituting k_C into Eqs. (6) and (7), reformulating them as differential equations, and solving results in a conventional decay function for C, yields,

$$C = C_o e^{-k_C t} \quad (8)$$

This first-order relationship can then be substituted into Eq. (7), which represents N. The result is then solved by variation of parameters.

$$N = N_o \left[\frac{Z_o}{Z_f} e^{-k_C t} + \left(1 - \frac{Z_o}{Z_f} \right) e^{-k_C t / (\varepsilon - 1)} \right] \quad (9)$$

Here Z_o is the initial measured ratio of organic C to organic N. Carbon and N can be linked by first parameterizing k_C with Eq. (8) and then incorporating the resulting k_C value into Eq. (9). Note that parameter Z_f is also the ultimate C:N ratio of the material as $t \rightarrow \infty$.

These equations apply if C can be modeled using a single compartment, but both C and N decomposition are also often represented separately using two compartments, one labile, and one recalcitrant (Benbi and Richter, 2002; Paustian *et al.*, 1997; Valenzuela-Solano and Crohn, 2006). Because Eqs. (8) and (9) are linear, they can also be used in this way. With two compartments, if subscripts 1 and 2 refer to the labile and recalcitrant compartments, respectively, Eq. (8) is written as

$$C = A C_o e^{-k_{C1} t} + (1 - A) C_o e^{-k_{C2} t} \quad (10)$$

where A is the labile fraction of the material. To apply Eq. (10), the partition fraction, A , and decay coefficients k_{C1} and k_{C2} are fitted to CO₂-C from laboratory incubation data. Equation (9) can similarly be written as follows where B is the labile N fraction of the material:

$$N = B N_{o1} \left[\frac{A Z_o}{B Z_{f1}} e^{-k_{C1} t} + \left(1 - \frac{A Z_o}{B Z_{f1}} \right) e^{-k_{C1} t / (\varepsilon_1 - 1)} \right] + (1 - B) N_o \left\{ \frac{(1 - A) Z_o}{(1 - B) Z_{f2}} e^{-k_{C2} t} + \left[1 - \frac{(1 - A) Z_o}{(1 - B) Z_{f2}} \right] e^{-k_{C2} t / (\varepsilon_2 - 1)} \right\} \quad (11)$$

This equation is parameterized using A , k_{C1} , and k_{C2} values fitted from C respiration data and Eq. (7). Nitrogen mineralization data from incubation experiments are then used to find values for B , Z_{f1} , Z_{f2} , ε_1 , and ε_2 . To avoid overfitting, parameter values will be lumped between different treatments measured treatments whenever reasonable. In Crohn (2011), it was possible to lump all parameters except A , k_{C1} , k_{C2} , and Z_o . The first three parameters can be estimated by measuring the CO₂-C evolved during laboratory incubations, while the last, the C:N ratio, can be measured directly. This may make parameterization much simpler since it avoids the challenges associated with tracking soil N. Figure 6 illustrates the use of Eq. (11) to describe C and N dynamics for four lawn trimmings samples. Parameters were lumped from eight different incubated lawn trimmings collections (Sullivan *et al.*, 2004).

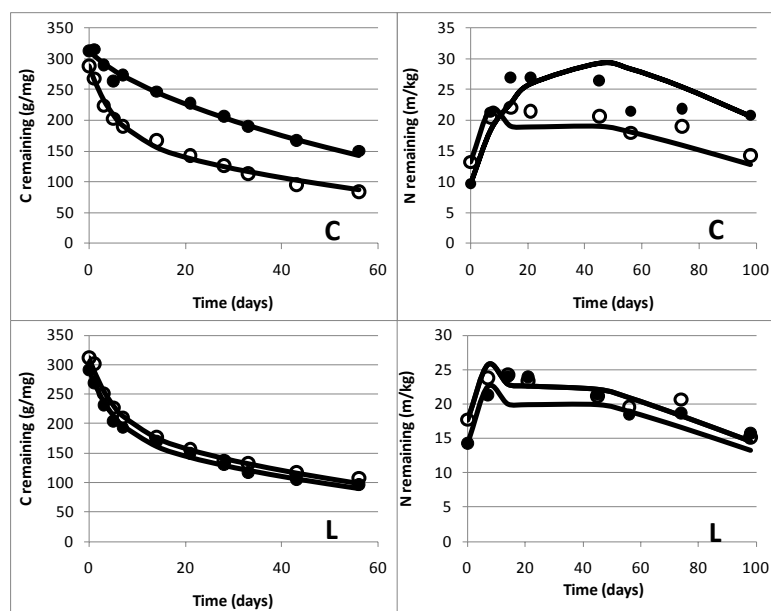


Fig. 6. Organic C and N remaining in incubated yard trimmings collected from two sources collected in April 1999 (observed: ●, modeled: —) and May 1999 (observed: ○, modeled: —) (Crohn 2011).

To parameterize the mineralization relationship for manures and organic fertilizers, incubation experiments will be conducted to determine the C and N mineralization rates of manures and organic fertilizers. We estimate that 8 different materials can be analyzed during each study. C mineralization studies will be conducted in 100 mL serum bottles while parallel N mineralization studies will be determined in 1 quart (946 mL) mason jars. In both the experiments, silt loam soil will be mixed with silica sand in 1:1 ratio to provide good aeration and to minimize denitrification losses. Inorganic N at the rate of 100 mg kg⁻¹ soil will be added to the soil in all treatments in the form of KNO₃ to eliminate the error due to unavailability of inorganic N for decomposition. The mass of each treatment required to provide N at a rate of 400 kg ha⁻¹ will be calculated and mixed thoroughly into the serum bottles and mason jars and packed to represent a field bulk density of 1300 Mg m⁻³. Soil moisture content will be adjusted to 60% of field capacity value by adding distilled de-ionized water and corrected for the moisture content introduced from the treatments. All treatments including control (untreated soil-sand mix) and will be set up in triplicates. Containers will be subjected to aerobic incubations and covered with moist cloth to prevent excessive evaporation. In order to determine the effect of temperature on C and N mineralization rates, three separate experiments will be conducted and maintained at constant temperatures of 12.5, 22.5 and 32.5° C.

Serum bottles will be used to measure carbon mineralization. A 40 g soil-sand media will be mixed with each treatment added to provide 400 kg N ha⁻¹ within a 100 mL serum bottle. To measure CO₂, serum bottles will be crimp-sealed with rubber septa 4 hrs before gas sampling. Gas samples will be obtained from all treatments including control at 24 hr intervals for the first 7 days, then every 72 hrs up to 30 days of incubation, thereafter at weekly intervals up to 60 days from the start of the experiment. A 10 mL gas sample will be collected from the headspace of the serum bottle and analyzed for CO₂ at each sampling event using an EGM-4 infrared gas analyzer from PP systems. After each sampling, the bottles will be opened and purged with fresh air for 2 minutes at 80 psi and covered with moist cloth.

For measuring nitrogen mineralization, 200g by dry weight of the soil-sand mixture will be placed into 1 quart size mason jars along with the treatment applied at the rate of 400 kg ha⁻¹ by dry weight. Two grams of soil will be removed at each sampling event from the jars. Sampling for inorganic N will be conducted at intervals of 0, 2, 5, 8, 12, 16, 21, 26, 32, 38, 45, 52, and 60 days. Potassium chloride will be used to extract the nitrogen from the soil. 10 ml of 2M KCl will be added to the two grams of the soil sample. The samples will be shaken for one hour, centrifuged for 10min, filtered and analyzed for nitrate and ammonium N using colorimetry.

PROCESSING OF ENVIRONMENTAL DATA (YEAR 3)

The CIMIS system contains soil and air temperature data from throughout California. In NBOT soil temperatures strongly affect mineralization and denitrification rates, while air temperatures affect plant development. CIMIS data contain errors that must be cleaned before use. We will code an Excel program for rapidly processing CIMIS data from any desired location station and use that data to calculate mean daily growing-degree days and tempera-

ture-adjusted time values for that location. Outliers will be identified and either removed or replaced with average values determined from running averages. A file will be prepared of data representative of the state's agricultural areas. The processed data will be placed in a file assessable to NBOT.

Experimental Site

Laboratory incubations will be performed at the University of California, Riverside (UCR) in the Department of Environmental Sciences. The department has historically emphasized soil science and is well-equipped for the proposed research. The University of California, Riverside is a Land Grant institution with fully functioning experimental fields and greenhouses. Programming will take place at UCR as well as in Cooperative Extension facilities in Stanislaus County.

Project Management, Evaluation, and Outreach

Management

This project will be managed primarily by David Crohn at the University of California, Riverside. Crohn is experienced in programming and optimization. He has an active laboratory and is equipped for incubation and greenhouse studies. Campbell-Mathews will assist in developing user-friendly data entry interfaces and will supervise Cooperative Extension activities in the Central Valley. Crohn will coordinate the project through site visits, telephone conversations, and email. Crohn and Campbell-Mathews have had a long working relationship. Crohn will be responsible for coordinating with FREP personnel.

Evaluation

The evaluation of our project will be a fundamental part of our project. Results will be used to improve the model, identify new opportunities for its use, as well as to document its impact. As NBOT remains in its late development stage, it is early to measure the economic benefits associated with the program, so cost/benefit data can only be preliminary. We will work with a professional program evaluator, Dr. Kara Crohn, to prepare suitable on-line surveys, using SurveyMonkey.com. A group of approximately six Central Valley users will be monitored closely, along with attendees at related Extension events and those who choose to download the software. Evaluations will characterize performance issues such as ease of use, barriers to use, and user expectations. They will also capture how users expect to or are applying NBOT to make decisions as well as their confidence in the program and their overall satisfaction levels.

Participants will be asked to fill out surveys describing their reaction to NBOT. We will administer follow-up surveys and interviews, as appropriate, to assess how the program is used by the dairy industry and others. We will also consult with area Cooperative Extension farm advisors on their opinion of NBOT and its usefulness. For non-dairy users, we will construct a version that minimizes fertilizer costs to determine the difference between initial fertilizer plans and optimal N schedules.

Outreach

Securing adoption of this tool and the information derived by this tool by growers and consultants is not only an essential component of the project, ultimately this is the whole point of this effort. Outreach efforts will include workshops for both growers and crop consultants in each year of the project, in addition to multiple newsletter and popular press articles. Initially, we will focus on small groups of interested crop advisors and farmers. This outreach will be conducted with the participation of University of California Farm Advisors. Dairy forage outreach will include Marsha Campbell-Mathews (Stanislaus County) and Carol Frate (Tulare County). Vegetable crops outreach will include Aziz Baameur (Santa Clara, Santa Cruz and San Benito Counties) and Richard Smith (Monterey, Santa Cruz and San Benito Counties). Note that year 1 activity will focus on Dairy Forages, while year 2 activity will include Central Coast vegetable crops. Graduates students located at UC Riverside will provide call-in technical support for NBOT, under the supervision of Dr. Crohn.

Presentations at major meetings such as the Plant and Soil Conference and the California Alfalfa and Forage Symposium are also anticipated. Regional meetings, such as Monterey County Irrigation and Nutrient Management Meeting and Cover Crop and Water Quality Field Day, will also be pursued. The program and associated tools and tutorials and documentation will be made available on the manure.ucdavis.edu website and possibly other venues as well. Specific details can be supplied prior to the signing of the final grant, but participants are experienced Cooperative Extension professionals with active outreach programs. This project will also result in peer-reviewed journal publications.

Deliverables

Deliverables	Due Date
Interim Report w/Invoice For services 1/1/12--6/30/12	7/31/2012
Final Report w/Invoice For services 7/1/12--3/31/13	4/30/2013

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