**FINAL REPORT:** January 2013 - January 2016

## A. PROJECT INFORMATION

**Project Title: Evaluation of a 24-Hour Soil $CO_2$ Test for Estimating Potential N Mineralization to Reassess Fertilizer N Recommendations**

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## B. PROJECT OBJECTIVES

1. Evaluate whether the flush of $CO_2$ from soils can predict growing season soil N mineralization across a range of soils that vary in fertilizer N requirements, soil amendments (crop residues and manures and composts), organic matter contents and other agronomic practices.
2. Develop correlations to other tests such as total soil N, total soil organic matter, crop N uptake and pre-crop nitrate levels to predict soil N mineralization potential with the main goal of reassessing fertilizer N applications for important California crops.
3. Evaluate the cost-effectiveness of implementing biologically based soil assays and procedures in commercial soil test labs.

## C. ABSTRACT

A fast, accurate, and easily standardized soil test to account for the inherent ability of a soil to supply plant-available N throughout a growing season, known as nitrogen (N) mineralization has a strong potential to increase the accuracy of N fertilizer recommendations. This supply of N from soil comes from the decomposition of soil organic matter and recent inputs such as composts and plant litter, which is controlled by soil biology and mineralogy, although it is commonly believed that soil biology is a

stronger factor. A suite of soil biological and chemical tests were investigated to develop a robust, scalable soil test to predict soil N supply throughout a season. Biological tests, such as soil respiration, proved most effective in predicting N mineralization in fields that received a winter cover crop, but chemical predictors were more effective in non-cover cropped fields. For both chemical and biological tests, trends existed across growing regions, but were not consistent within a region. This suggests that there is a general relationship between these tests and soil N supplying capacity, but that it lacks substantial general predictive abilities to allow extrapolation to an individual field, particularly across regions. Promising results were found in specific managements in some growing regions, but additional study would be needed to provide a recommendation with acceptable certainty for predicting soil N mineralization. Economic analyses show that adjustment of fertilization could be financially viable for certain crops. However, there are substantial hurdles to adoption by soil test labs, both in terms of economics and consistency of analysis between labs.

## D. INTRODUCTION

Soils have an innate capacity to supply plants with N through decomposition activities, producing available inorganic forms of ammonium ($NH_4^+$) by ammonification and nitrate ($NO_3^-$) by nitrification. Field trials have shown that California agricultural soils can supply 40-280 lbs N/ac (Geisseler, unpublished thesis) and up to 50% of the N that a crop requires during growing season comes directly from the decomposition of organic N into inorganic forms (Kramer et al., 2002; Doane et al., 2009). This decomposition process, referred to as mineralization, is known to be a primarily biological process. The biological process is strongly influenced by soil properties such as texture, mineralogy, and climate (moisture and temperature). The physiochemical soil factors are responsible for the high variability in biological processes making the prediction of N mineralization difficult and highly uncertain. Due to this high uncertainty, fertilizer N recommendations often disregard this process and make recommendations based purely on inorganic N content prior to planting (Magdoff et al., 1990), resulting in some cases in over fertilization of N. This over fertilization can lead to adverse environmental effects, such as increasing greenhouse gas emissions (Stehfest & Bouwman, 2006) or contamination of surface- and ground-water with nitrate (Harter et al., 2012).

A variety of laboratory-based tests to predict soil N mineralization have been proposed, which can broadly be categorized as either chemically or biologically based. Chemical tests are based on the extraction of a portion of the total soil N pool that is susceptible to N mineralization, which is then used to predict how much N will be mineralized into plant-available forms (Gianello & Bremner, 1986; Gianello & Bremner, 1988; Sharifi et al., 2007). Biological tests for a soil N mineralization potential are often based on the assumption that microbial activity, typically measured by soil respiration, is affected by carbon (C) availability and can be correlated to N mineralization (Franzluebbers et al., 2000; Haney et al., 2001; Haney et al., 2008). Some of these respiration-based tests have shown promise at estimating soil N supply at 28 days after sampling using cumulative respiration at 24 or 72 hours after rewetting. Additionally, these procedures have been studied for use in a soil test lab (Haney & Haney, 2010) to allow for comparisons between labs and a higher throughput. However, many of these chemical and biological soil tests have either fallen short in their predictive ability or not been thoroughly tested for extrapolating laboratory results to field outcomes.

Although these lab tests have shown promise in various regions around the United States, they have not been tested in California's unique agricultural context of intensification through inputs and irrigation. California's low-carbon, intensively managed soils present unique challenges for determining the efficacy biological soil tests before they can be utilized in fertilizer N recommendations. This study seeks to address several of the shortcomings for biological soil tests outlined here by examining these relationships across California's diverse growing regions and management strategies. The growing regions surveyed were: Yolo County, San Joaquin County, Fresno/Kern County, and Salinas County. Within the three growing regions, management strategies were subdivided into fields receiving a winter cover crop or fields that were winter fallowed (typical management). Soil was sampled prior to planting, air-dried, and assessed for nutrient status using several chemical indices, with 3-4 samples being taken from each field. Several biological tests were also conducted, including the cumulative flush of $CO_2$ upon the rewetting of the air-dried soil (the main objective of this project). These assays were then utilized to construct guidelines and recommendations for grower use. These guidelines take into account the economic risks and rewards associated with adoption.

## E. WORK DESCRIPTION

**Task 1: Conduct a literature review**- Literature on biological soil N mineralization tests has been reviewed in order to provide a relevant knowledge base for incubations and analyses.

Status: Completed July 2013

**Task 2: Develop sampling protocols and analyze a wide range of target soils**

*Task 2a: Survey soils from major cropping systems in California*- Soil samples from three of California's major cropping systems, corn, tomato, and cotton, have been gathered. These soils have been gathered from approximately 50 fields across California, giving a diversity of textures, parent materials, and climatic regimes.

Status: Completed May 2013

*Task 2b: Analyze soil samples for various soil properties*- In each field, approximately 15 cores were gathered to a depth of 10 inches using a 1.5cm diameter soil core and composited. Within each field, 3-4 subsamples were taken to capture within-field variability. The soils were then air-dried (22°C) and then sieved to pass a 4-mm screen. All soils were then cooled to 4°C for storage prior to analysis. All concentrations are reported using soil air-dried (AD) weight unless otherwise stated.

Soil samples were crushed using mortar and pestle and analyzed for soil organic C and total soil N via dry combustion using a Costech ECS 4010 CHNSO elemental analyzer. All soils were checked for carbonates prior to combustion.

Water holding capacity (WHC) was determined using the funnel method. Whatman filter paper containing approximately 20g of soil was placed into a beaker full of DI water. The water was allowed to imbibe into the soil until the surface of the soil glistened, at which time the funnel was removed and the funnel allowed to drain for 30-45 minutes. A subsample of this soil was then weighed and dried for 24 hours at 105°C.

Water holding capacity was calculated as the difference between the saturated and oven-dried subsample.

Soil pH was determined using a 1:1 soil:water solution (Thomas, 1996). The solution was shaken for 15 minutes on a reciprocal shaker, allowed to settle for 30 minutes and the resulting supernatant was measured for pH.

Parallel soil extractions were performed with 0.5M $K_2SO_4$ and DI water, using 10.0g and 5.0g of air-dry soil, respectively. The soil was mixed with 40mL of extractant and shaken for 45-60 minutes on a reciprocal shaker. They were then centrifuged for 10 minutes at 3500rpm and filtered. The water-extracted soils were additionally centrifuged at 10,000rpm for 10 minutes before filtration due to high residue content in extract. These extractions were then used to determine organic carbon content, using a UV-Persulfate Total Organic Carbon Analyzer (model Phoenix 8000, Tekmar Dohrmann™, Cincinnati, OH). Organic carbon (C) will be referred to as dissolved organic carbon (DOC) when extracted with 0.5M $K_2SO_4$ and water-extractable organic carbon (WEOC), when extracted with DI water.

Inorganic nitrogen ($NO_3^-$ + $NH_4^+$) was determined colorimetrically on a spectrophotometer (model UV mini 1240, Shimadzu) using methods described by Doane and Horwath (2003) for nitrate and Verdouw et al. (1978) for ammonium. Water-extractable organic nitrogen (WEON) was calculated by subtracting water-extractable inorganic N from water-extractable total dissolved nitrogen (TDN). TDN was measured using alkaline persulfate digestion (Valderrama, 1981; Cabrera & Beare, 1993) and then measured colorimetrically for nitrate (Doane & Horwath, 2003). All inorganic N measurements refer to 0.5M $K_2SO_4$ extracted samples, unless otherwise noted.

Cumulative $CO_2$ was measured from approximately 40g air-dried and sieved soil subsamples. The soil was rewetted via capillary action according to the

methods outlined in Haney and Haney (2010). In brief, 50mL polypropylene beakers with 4-5 holes drilled in the bottom and glass microfiber filter were filled with soil and placed in a glass pint-sized Mason jar which had been filled with 20mL DI water. The jars were then capped with a metal lid with a rubber septum at the top of the headspace. The soil was then rewetted to its gravimetric water content via capillary action and any excess water was allowed to drain due to the convex bottom of the jar. For respiration measured at 50% WHC, the procedure was repeated, but samples were rewetted from above using our calculated WHC. Cumulative $CO_2$ measurements were then taken 6, 24, and 72 hours and measured on a Qubit $CO_2$ analyzer (model S-151, Qubit Systems Inc., Kingston, Canada). Calculations of respired C per unit of air-dry soil were calculated using measured headspace and the ideal gas law (Zibilske, 1994).

Glucose-induced respiration was measured similarly to the 50% WHC respiration, but with additions similar to the one used by Anderson and Domsch (1978). Glucose solution was added incrementally to soils at 55% WHC until a plateau was reached in cumulative 6-hour respiration, indicating that the C was no longer metabolic C, but rather being used for microbial growth. This respiration value was then correlated with net N mineralization values. The difference between the glucose-induced respiration and 6-hour respiration using the capillary method ($CMIN_{0-6}$), was also related to N mineralization values.

Permanagate oxidizeable C (POXC) was analyzed using the method described by Weil et al. (2003), but with modifications as described by Culman et al. (2012). In brief, 2.5 g of air-dried soil was placed in a 50mL centrifuge tube with 20mL of 0.02 M $KMnO_4$ solution and shaken on a reciprocal shaker for exactly 2 minutes. This solution was then allowed to settle for 10 minutes, when 0.5 mL of supernatant was added to a second centrifuge tube containing 49.5mL of water for a 1:100 dilution. This diluted

sample was then analyzed using spectrophotometry at 550nm. POXC was determined by loss of permanganate due to C oxidation.

Soils were wetted to 55% WHC to maximize mineralization and incubated at 22°C in 1-quart mason jars with holes drilled in the lid top allow air exchange. A vial of DI water was placed in each jar to maintain constant moisture content. Soils were extracted using 0.5M $K_2SO_4$ by destructive sampling of 10.0g subsamples and analyzed using methods described above for inorganic N determination. Net N mineralization ($NMIN_t$) was calculated as the change in inorganic N ($NO_3^-$ + $NH_4^+$) between a given sampling date (*t*) and the initial inorganic N levels ($N_0$). Extractions were performed at *t*=28, 56, and 105 days after rewetting (*t*=0). Soil texture and taxonomy were retrieved using SoilWeb (http://casoilresource.lawr.ucdavis.edu/soilweb/).

Status: Completed October 2014

**Task 3: Validate the "24-Hour $CO_2$ Evolution Test"**- Soils were aerobically incubated in microcosms at 55% WHC with soil samples taken at days 0, 7, 14, 28, 56, and 105. In a parallel, short-term incubation, cumulative CO2 evolution was read from soils at 6, 24, and 72-hour intervals using several methods: rewetting via capillary action and rewetted to a water content of 50% WHC. Respiration was also measured at 6 hours after soil was rewetted to 55% WHC with a dilute glucose solution, referred to as "glucose-induced respiration". Statistical analyses have been performed on the acquired data to investigate the relationship between C and N mineralization.

Status: Completed August 2015

**Task 4: Field validate "24-Hour $CO_2$ Evolution Test"**- Several target fields were planted with a "full N" and zero N treatments across a broad range of crops. Soil and plant samples were gathered prior to planting and immediately after harvest and measured for inorganic N levels. These results were coupled with plant N uptake to measure apparent in-field N mineralization.

Status: Completed September 2015

**Task 5: Construct guidelines for soil test labs performing the "24-Hour $CO_2$ Evolution Test"**- Protocols for the utilization of this suite of soil tests have been put together for use by growers.

Status: Completed December 2015

**Task 6: Set up an outreach program**- Results have been showcased at several outreach events and have been published in print publications to growers, researchers, industry representatives, and governmental officials. The specifics are discussed in *Section H. Outreach Activities Summary*.

Status: Completed December 2015

## F. DATA/RESULTS

### Soil Characterization

**Table 1. A list of abbreviations used for this study and their associated units.**

| Description | Abbreviation | Units |
|---|---|---|
| Water-extractable organic carbon/nitrogen | WEOC/WEON | mg/kg of air-dried soil |
| Dissolved organic carbon/nitrogen- extracted using 0.5M $K_2SO_4$ | DOC/DON | mg/kg of air-dried soil |
| Total carbon/nitrogen on combustion | Total C/N | g/kg of air-dried soil |
| Cumulative respiration to time *t* (hours)- measured at 100% WHC | $CMIN_{0\text{-}t}$ | mg $CO_2$-C/kg of air-dried soil |
| Cumulative respiration to time *t* (hours)- measured at 50% water-holding capacity | $CMIN.50_{0\text{-}t}$ | mg $CO_2$-C/kg of air-dried soil |
| Cumulative respiration form glucose-induced respiration up to 6 hours | $CMIN_{gl}$ | mg $CO_2$-C/kg of air-dried soil |
| Permanganate oxidizable carbon | POXC | mg/kg of air-dried soil |
| Net N mineralization to time *t* (days) | $NMIN_t$ | mg inorganic N/kg of air-dried soil |

The soils analyzed exhibited a wide range of clay contents (14-50% by weight), with low total C contents (3.7-19.6 g C/kg air-dried (AD) soil) typical of California agricultural soils. Soil N levels varied from 0.4-2.0 g N/kg AD soil of total soil N and 5.57-112.47 mg kg-1 AD soil of inorganic N. Soil organic C and soil N were highly related ($r=0.851$, $p<0.001$) and generally exhibited C:N ratios of 8-12, with a mean of 9.18. Additional soil physical and chemical properties are listed in Supplementary Table 1. A list of abbreviations used in this report, as well as the units associated with them is available in Table 1.

### Respiration Data

For respiration using both the 50% WHC and the capillary method, respiration was greater and had lower variability in fields utilizing cover crops than non-cover cropped fields. In the glucose-induced respiration method, there was no significant difference in respiration between managements, although cover cropped fields had lower variability (Table 2).

Table 2. Mean cumulative respiration by management and time interval, using the capillary method of rewetting, 50% water-holding capacity (WHC), and glucose-induced respiration. Standard errors are in parenthesis.

| Method | Management | Cumulative Respiration (mg $CO_2$-C/kg AD soil) | | | Coefficient of Variation (%) | | |
|---|---|---|---|---|---|---|---|
| | | 6 Hour | 24 Hour | 72 Hour | 6 Hour | 24 Hour | 72 Hour |
| **Capillary** | **All fields** (*n*=157) | 19.48 (0.87) | 61.61 (2.75) | 162.68 (7.60) | 55.74 | 55.76 | 58.32 |
| | **Cover crops** (*n*=76) | 23.08 (1.20) | 77.03 (3.52) | 195.73 (9.43) | 45.30 | 39.79 | 41.71 |
| | **No cover crops** (*n*=81) | 16.06 (1.14) | 47.15 (3.48) | 132.07 (10.71) | 63.26 | 66.49 | 73.02 |
| **50% WHC** | **All fields** (*n*=157) | 69.17 (2.38) | 176.97 (7.10) | 485.61 (30.07) | 42.69 | 49.46 | 76.34 |
| | **Cover crops** (*n*=76) | 84.06 (2.91) | 212.16 (9.07) | 657.29 (51.64) | 29.76 | 36.78 | 67.59 |
| | **No cover crops** (*n*=81) | 55.40 (2.98) | 143.58 (9.43) | 322.73 (18.68) | 48.12 | 57.99 | 51.12 |
| **Glucose-Induced** | **All fields** (*n*=26) | 141.00 (9.93) | -- | -- | 35.90 | -- | -- |
| | **Cover crops** (*n*=12) | 145.30 (4.58) | -- | -- | 10.92 | -- | -- |
| | **No cover crops** (*n*=14) | 138.32 (18.29) | -- | -- | 49.83 | -- | -- |

**Net N Mineralization Data**

After rewetting, the overall rate of N mineralization decreased throughout the incubation periods for all test durations. There were significant effects of management at each date ($p<0.01$), with cover cropped fields having higher rates of mineralization than non-cover cropped fields. There were also significant differences between successive dates within each management ($p<0.001$). Net N mineralization (NMIN) significantly increased to day 28, then plateaued between days 28 and 56, then increased again between day 56 and 105 ($p<0.0001$). This trend was also shown across management strategies (Table 3).

**Table 3. Net N mineralization values (mg N/ kg air dried soil) across all fields and separated by management. Standard errors are in parenthesis.**

| | Incubation Date | | | |
|---|---|---|---|---|
| | 14 | 28 | 56 | 105 |
| **All Fields** (*n*=157) | 11.25 (0.62) | 18.33 (0.63) | 18.22 (0.63) | 21.66 (0.70) |
| **Cover crops** (*n*=76) | 12.56 (0.76) | 21.99 (0.92) | 21.48 (0.93) | 25.53 (0.99) |
| **No cover crops** (*n*=76) | 10.07 (0.94) | 14.91 (0.66) | 15.16 (0.70) | 18.02 (0.80) |

**Chemical Indicators to Estimate Net N Mineralization**

Across all fields, there were positive, significant relationships between all C and N fractions and net N mineralization, but not in their respective C:N ratios. Total N showed the greatest predictive ability, accounting for 18.7% and 31.9% of the variation in 28-day ($NMIN_{28}$) and 56-day net N mineralization ($NMIN_{56}$), respectively. However, correlations between chemical predictors and net N mineralization values showed strong effects of management, with cover cropped fields having generally stronger and more significant relationships (Table 4) than the non-cover cropped fields.

Table 4. Pearson correlation coefficients (r) representing relationships between net N mineralization (NMIN) and predictor variables water-extractable organic C and N (WEOC/N), dissolved organic C and N (DOC/N) and total C and N across all fields and also separated by management.

| | All Fields | | | Cover Crops | | | No Cover Crops | | |
|---|---|---|---|---|---|---|---|---|---|
| | NMIN 28 | NMIN 56 | $NMIN_1$ 05 | NMIN 28 | NMIN 56 | $NMIN_1$ 05 | NMIN 28 | NMIN 56 | $NMIN_1$ 05 |
| Initial N | 0.080 NS | 0.151 NS | 0.217$^{N}$ S | 0.021 NS | 0.171 NS | 0.027$^{N}$ S | 0.136 NS | 0.106 NS | 0.434$^{*}$ |
| WEOC | 0.269$^{*}$ | 0.286$^{*}$ | 0.344$^{**}$ | 0.339$^{*}$ | 0.356$^{*}$ | 0.395$^{*}$ | 0.208 NS | 0.229 NS | 0.321$^{N}$ S |
| WEON | 0.389$^{*}$ | 0.332$^{*}$ | 0.369$^{**}$ | 0.490$^{*}$ | 0.406$^{*}$ | 0.500$^{**}$ | 0.153 NS | 0.140 NS | 0.119$^{N}$ S |
| WEOC:N | -0.140 NS | -0.130 NS | -0.160$^{N}$ S | -0.190 NS | -0.110 NS | -0.126$^{N}$ S | -0.053 NS | -0.134 NS | -0.193$^{N}$ S |
| DOC | 0.191 NS | 0.234 NS | 0.291$^{*}$ | 0.333$^{*}$ | 0.375$^{*}$ | 0.360$^{*}$ | 0.131 NS | 0.164 NS | 0.323$^{N}$ S |
| DON | 0.322$^{*}$ | 0.343$^{*}$ | 0.308$^{*}$ | 0.470$^{*}$ | 0.385$^{*}$ | 0.322$^{N}$ S | -0.022 NS | 0.122 NS | 0.154$^{N}$ S |
| DOC:N | -0.131 NS | -0.049 NS | 0.000$^{N}$ S | 0.028 NS | 0.169 NS | 0.123$^{N}$ S | 0.129 NS | 0.183 NS | 0.236$^{N}$ S |
| Total C | 0.351$^{*}$ | 0.433$^{*}$ | 0.280$^{*}$ | 0.467$^{*}$ | 0.385$^{*}$ | 0.387$^{*}$ | 0.192 NS | 0.455$^{*}$ | 0.122$^{N}$ S |
| Total N | 0.432$^{*}$ | 0.565$^{**}$ | 0.349$^{**}$ | 0.419$^{*}$ | 0.486$^{*}$ | 0.368$^{*}$ | 0.216 NS | 0.516$^{*}$ | 0.088$^{N}$ S |
| Total C:N | -0.059 NS | -0.152 NS | -0.049$^{N}$ S | 0.167 NS | -0.126 NS | 0.104$^{N}$ S | 0.017 NS | 0.015 NS | 0.078$^{N}$ S |

*, **, *** refers to significance at $p<0.05$, $p<0.01$, and $p<0.001$, respectively. NS = not significant.

Table 5. Pearson correlation coefficients (r) representing relationships between net N mineralization (NMIN) and biologically-based predictors—respiration using capillary method (CMIN), respiration at 50% water holding capacity (CMIN.50), glucose-induced respiration (CMINgl), and permanganate-oxidizable carbon (POXC)—across all fields and separated by management.

| | All Fields | | | Cover Crops | | | No Cover Crops | | |
|---|---|---|---|---|---|---|---|---|---|
| | $NMIN_{28}$ | $NMIN_{56}$ | $NMIN_{105}$ | NMIN 28 | NMIN 56 | $NMIN_{105}$ | NMIN 28 | NMIN 56 | $NMIN_{105}$ |
| $CMIN_{0-6}$ | 0.292* * | 0.263* * | 0.210** | 0.273* | 0.295* * | 0.185$^{N}$ S | -0.034 NS | -0.025 NS | -0.041$^{N}$ S |
| $CMIN_{0-24}$ | 0.362* ** | 0.211* * | 0.324** * | 0.393* * | 0.202 NS | 0.355* * | -0.031 NS | -0.141 NS | -0.037$^{N}$ S |
| $CMIN_{0-72}$ | 0.311* ** | 0.294* * | 0.297** | 0.311* * | 0.302* * | 0.288* | 0.045 NS | 0.066 NS | 0.076$^{N}$ S |
| CMIN.50 0-6 | 0.510* ** | 0.544* ** | 0.475** * | 0.547* ** | 0.518* ** | 0.449* ** | 0.183 NS | 0.344* * | 0.214$^{N}$ S |
| CMIN.50 0-24 | 0.371* ** | 0.367* ** | 0.441** * | 0.364* * | 0.277* | 0.354* * | 0.071 NS | 0.191 NS | 0.281$^{N}$ S |
| CMIN.50 0-72 | 0.340* ** | 0.147 NS | 0.306** * | 0.175 NS | -0.138 NS | 0.101$^{N}$ S | 0.065 NS | 0.104 NS | 0.179* |
| $CMIN_{gl}$ | 0.294 NS | 0.308 NS | 0.155$^{N}$ S | 0.232 NS | 0.288 NS | 0.226$^{N}$ S | 0.409 NS | 0.401 NS | 0.205$^{N}$ S |
| POXC | 0.193* | 0.036 NS | 0.134$^{N}$ S | 0.447* ** | 0.192* * | 0.415* * | -0.013 NS | -0.104 NS | -0.088$^{N}$ S |

*, **, *** refers to significance at $p<0.05$, $p<0.01$, and $p<0.001$, respectively. NS = not significant.

There were stark differences in chemical test prediction of N mineralization between managements. Non-cover cropped fields generally had weak and/or non-significant relationships, with the notable exception being total C and N with 56-day N mineralization. In cover cropped fields, the best predictors were measures of labile N, such as WEON and DON. In cover cropped fields, for $NMIN_{28}$ and $NMIN_{105}$, the best

chemical predictor was WEON (**r**=0.490 and **r**=0.500, respectively), whereas for $NMIN_{56}$, the best predictor was total N (**r**=0.486).

**Biological Indicators to Estimate Net N Mineralization**

In general, there were distinct differences between management strategies that influenced the ability of biological indicators to predict N mineralization. Non-cover cropped fields had almost no significant relationships between biological test indicators and N mineralization. In cover cropped fields, most relationships were significant, although there were differences between test indicators.

Within cover cropped fields, the strongest biological test indicator was respiration at 50% WHC, followed by POXC, and respiration when using the capillary method. Glucose-induced respiration had insignificant relationships at all N mineralization time points. Respiration at 50% WHC (CMIN.50) showed the strongest relationships at shorter respiration intervals (6 and 24 hours), whereas respiration at 100% WHC (CMIN) showed them at 24 and 72 hours. POXC showed strongest relationships with N mineralization at 28 and 105 days.

**Multiple Parameters to Estimate Net N Mineralization**

A partial least squares (PLS) regression was run to distinguish differences in variable importance by management and which specific variables are important at which N mineralization time point. Agreement between all N mineralization time points was necessary for a given variable to be included in the “best fit” linear model. These shared parameters were then used to construct a suite of tests to predict N mineralization (Table 6). In general, biological indicators were much more important than chemical indicators in cover cropped fields, but in non-cover cropped fields, chemical indicators were much more important than biological indicators.

Table 6. Linear models constructed using “best fit” variables from partial least squares regression, separated by management.

| | Equation |
|---|---|
| **Cover crops:** | $4.712 + 0.144*(CMIN.50_{0\text{-}6}) - 0.030*(CMIN.50_{0\text{-}24}) + 0.113*(DOC) + 0.097*(WEOC) + 0.010*(POXC)$ |
| **No cover crops:** | $9.873 + 0.008*(\text{Initial N}) + 0.157*(DOC) + 0.742*(\text{Total C:N})$ |

Within fields that did not receive cover crops, there was agreement across N mineralization time points on three of the most important variables in prediction of N mineralization: initial inorganic N content, dissolved organic carbon (DOC) content, and total C:N (Table 6). When these three variables were used together to predict N mineralization, they accounted for 2.5%, 2.8%, and 20.7% of the variability in N mineralization at days 28, 56, and 105, respectively (Table 7). The variation explained by these variables was inconsistent between growing regions, with greater variability being accounted for in the Fresno/Kern County fields.

Within the cover cropped fields, there was agreement on the five most important predictors of N mineralization: WEOC, DOC, POXC, and respiration at 50% WHC measured at both 6 and 24 hours ($CMIN.50_{0\text{-}6}$ and $CMIN.50_{0\text{-}24}$, respectively) (Table 6). When utilized together in a linear model, these variables accounted for 46.1%, 41.0% and 37.7% of the variability in N mineralization at days 28, 56, and 105, respectively (Table 7). When these relationships were examined by growing region, there was much greater variability accounted for in the Fresno/Kern County region, with up to 89% of the variation accounted for at days 28 and 105. Overall, cover cropped fields had a much greater proportion of variability explained by the selected parameters than non-cover cropped fields.

Table 7. Variance in N mineralization (NMIN) at each date explained by the best fit linear model, separated by region and management strategy.

| | Cover Crops | | | No Cover Crops | | |
|---|---|---|---|---|---|---|
| | $NMIN_{28}$ | $NMIN_{56}$ | $NMIN_{105}$ | $NMIN_{28}$ | $NMIN_{56}$ | $NMIN_{105}$ |
| **All** | 46.1% | 41.0% | 37.7% | 2.5% | 2.8% | 20.7% |
| **Yolo County** | 49.9% | 48.5% | 39.9% | 6.2% | 11.3% | 12.5% |
| **San Joaquin County** | -- | -- | -- | 4.0% | 12.5% | 27.6% |
| **Fresno/Kern Counties** | 89.3% | 79.3% | 88.8% | 24.0% | 42.8% | 26.7% |

**External Lab Verification**

A selection of seven (7) soil samples was sent to external commercial soil test labs for verification of results. These samples were chosen to reflect the broad range of soil

total C contents and respiration rates, as well as reflecting diversity of management and growing region. The commercial soil test labs for verification were chosen from the list of Solvita® Certified or Solvita® Certified PLUS labs (https://solvita.com/soil/map) and analyzed for the following indices: total C, total N, water extractable organic C and N (WEOC/N), 24-hour respiration upon rewetting, and the Solvita® soil health score. Data was blocked according to sample to observe the differences in analysis between labs. The block-centered mean of each variable was then compared between labs using a Wilcoxon test for each pair. These results can be seen in Supplementary Table 2.

Table 8. Canonical loadings for discriminant analysis of samples for external lab data. Higher absolute values of loading indicate a stronger correlation on that canonical variable.

| | Total C | Total N | Total C:N | WEOC | WEON | WEOC:N | 24-Hr $CO_2$ | Soil Health |
|---|---|---|---|---|---|---|---|---|
| **Canon1** | 0.097 | 0.202 | -0.188 | 0.968 | 0.797 | -0.252 | -0.090 | -0.014 |
| **Canon2** | -0.153 | -0.270 | 0.177 | 0.230 | -0.181 | 0.619 | 0.695 | 0.007 |

Discriminant analysis was used to present a more concise summation of data. This analysis uses linear combinations of multiple variables—in this case our parameters of interest, total C, total N, etc.—in order to predict membership in a given group (which lab performed the analysis). These predictions are then given a level of confidence, which is aggregated over the entire dataset. In Table 8, we see that the most strongly differentiating combination of variables (Canonical Variable 1) was primarily comprised of water-extractable organic C and N and the ratio between these two. The second strongest differentiating variable (Canonical Variable 2), was evenly distributed between most of the variables, but 24-Hour $CO_2$ and WEOC:N were the strongest differentiators. These two differentiating variables are then used to construct a visual representation of the differences between labs (Figure 1). We can see that Canonical Variable 1 is able to

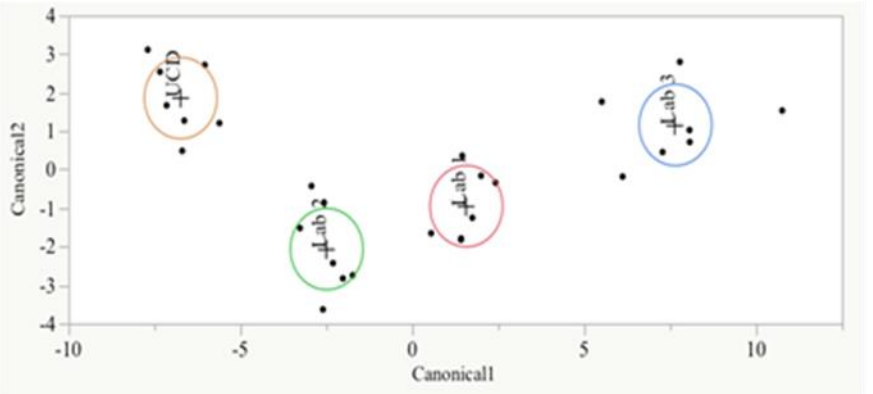


**Figure 1. Discriminant analysis of indices validated by external labs, with 95% confidence ellipses shown.**

easily differentiate between labs, since no 95% confidence ellipses are overlapping, with each lab being distinctly different from one another. Canonical Variable 2 is less able to differentiate between labs, with the UC Davis results being distinctly different from Labs 1 and 2, but no different from Lab 3. The $R^2$ of the overall classification is 0.99993, indicating an extremely high degree of confidence in the differentiation between lab results indicating reproducibility among test results preformed across labs is not reliable.

## Economic Analysis

An economic analysis was conducted to assess the risk vs. reward of utilizing a predictive test of soil N mineralization to adjust fertilizer N recommendations. The ideal suite of tests varies by region and management strategy, so in lieu of incorporating a fixed cost representing this cost, a different approach was utilized. The proposed tests would allow for a prediction of N mineralized within a growing season, which would then be utilized to reduce fertilizer N recommendations. Fertilizer savings equivalents were calculated according to fertilizer source, so several common N-based fertilizers were evaluated: ammonium sulfate, calcium-ammonium-nitrate in a 17% formulation (CAN17), anhydrous ammonia, aqua ammonia, urea, and urea-ammonium-nitrate in a 32% formulation (UAN32). Fertilizer equivalents for each fertilizer were calculated on a per acre basis using the median amount of N mineralized (72.73 lbs N/ac) converted into 2015 dollars per pound of N, averaged over 4 years from 2012-2015 according to data from the UC Davis Cost Studies (http://coststudies.ucdavis.edu/). These potential fertilizer savings were then compared to the equivalent price of a maximum allowable yield loss. In order to exhibit a range of values per ton of yield, three common California row crops were studied: corn (grown for both grain and silage) and processing tomatoes. Prices for these crops were calculated in 2015 dollars using USDA data for California, averaged for the years 2004-2013 (USDA, 2014), which was used to establish the maximum allowable yield loss that could be sustained for each crop*fertilizer combination. However, yields per acre vary for these crops, so a percentage yield loss with average yields for each crop in California (USDA, 2014) was used to normalize across crops.

The more expensive fertilizers, such as aqua ammonia and UAN32, resulted in great potential savings from successful N mineralization predictions (Table 9), which allowed for greater allowable yield losses. Conversely, cheaper fertilizers, such as anhydrous ammonia, resulted in lower potential savings and lower allowable percentage yield losses. Tomatoes had lower allowable yield losses across fertilizers, due to their high yield per acre (46.55 tons/ac) and moderate cost per ton of yield. Corn grown for grain has a high cost per ton, but low yields per acre (5.32 tons/ac), which gives a considerable margin of error in terms of allowable percentage yield loss (Table 9). Corn grown for silage had higher yields per acre (26.33 tons/ac) than corn grown for grain,

but lower price per ton of yield, so there was a comparable level of economically sustainable yield loss between the two types of corn being grown.

Table 9. An economic analysis of fertilizer savings using three common field crops in California, organized by fertilizer. Yield losses are the break-even point of each crop, normalized by average yield for the state to give a percentage allowable yield loss.

| | Fertilizer | | Processing Tomatoes | | Corn (silage) | | Corn (grain) | |
|---|---|---|---|---|---|---|---|---|
| | Price ($/lb N) | Savings ($/ac) | Maximum Yield Loss (tons/ac) | % Yield Loss | Maximum Yield Loss (tons/ac) | % Yield Loss | Maximum Yield Loss (tons/ac) | % Yield Loss |
| **Ammonium sulfate** | 1.27 | 92.4 | 1.27 | 2.73 | 2.58 | 9.81 | 0.57 | 10.68 |
| **CAN17** | 1.41 | 102.7 | 1.41 | 3.03 | 2.87 | 10.91 | 0.63 | 11.87 |
| **Anhydrous ammonia** | 0.90 | 65.6 | 0.90 | 1.94 | 1.84 | 6.97 | 0.40 | 7.59 |
| **Aqua ammonia** | 2.68 | 195.2 | 2.68 | 5.77 | 5.46 | 20.74 | 1.20 | 22.56 |
| **Urea** | 1.36 | 99.2 | 1.36 | 2.93 | 2.78 | 10.54 | 0.61 | 11.47 |
| **UAN32** | 2.10 | 152.9 | 2.10 | 4.52 | 4.28 | 16.24 | 0.94 | 17.67 |

Table 10. Cost of soil analyses for three commercial soil labs used for external validation, separated by management. Numbers in parentheses denote number of recommended assays not offered at specific lab.

| | With Cover Crops | Without Cover Crops |
|---|---|---|
| **Lab 1** | $30.50 (2) | $30 (1) |
| **Lab 2** | $25 (3) | $20.25 (1) |
| **Lab 3** | $49.50 (2) | $21 (1) |

A separate economic evaluation was conducted to assess the cost for soil analysis in our three surveyed soil labs. None of the surveyed labs offered to test dissolved organic carbon (DOC), which was a suggested assay for both cover cropped and non-cover cropped fields. None of the labs offered POXC, which was one of the variables suggested for predicting N mineralization in cover cropped fields. In terms of cost for analysis, the increased number of assays suggested in cover cropped fields led to

generally higher costs of analysis than in non-cover cropped fields (Table 10). The exception to this trend is Lab 1, which showed comparable prices for both.

## G. DISCUSSION/CONCLUSION

Overall, there are no singular predictors of N mineralization that are consistently accurate across managements and growing regions. Chemical indicators are generally performed better over biological indicators in fields that did not receive cover crops, but biological indicators are more effective at predicting N mineralization in cover cropped fields.

**Objective 1:** The flush of $CO_2$ upon rewetting has a low degree of accuracy for a majority of fields surveyed. In non-cover cropped fields, respiration had little to no relationship with N mineralization potential. Within cover cropped fields, the all methodologies were variable in their accuracy to predict N mineralization. At 24 hours, the relationship with N mineralization was comparable between 50% WHC and 100% WHC. At this respiration interval, 7.7-15.4% of variation in N mineralization was explained. However, unlike the 100% WHC method, respiration measured using 50% WHC had an increased accuracy at the shorter, 6-hour interval of $CO_2$ respiration. At this interval, respiration explained a minimum of 20.2% of the variation in N mineralization at 105 days and a maximum of 29.9% of the variation in N mineralization at 28 days, with a clear trend of decreasing accuracy of prediction as the N mineralization interval increased. This low level of certainty illustrates that using soil respiration is not a reliable or accurate standalone predictor of N mineralization. In addition, the high variability of soil respiration (Table 2) and significant differences between soil test labs (Figure 1 and Supplementary Table 2) bring in to question the accuracy of any individual measurement of respiration that would be used to estimate N mineralization. The 6-hour soil respiration at 50% WHC ($CMIN.50_{0\text{-}6}$) in cover cropped fields showed the lowest coefficient of variability of all soil respiration measurements (Table 2: 29.8%), which suggests that this method*management combination may be the most viable in the context of a soil test lab. However, the method for measuring water content would need to be standardized across commercial soil test labs in order to minimize the inter-lab variability. This is likely to burdensome task for soil test labs to have to determine 50% WHC for each soil sample.

**Objective 2:** The use of many traditional, largely chemically-based assays in alone did not prove anymore useful in predicting N mineralization. While traditional measures, such as total N or measures of labile N, explained the most variation in both non-cover cropped and cover cropped fields, respectively. Previous studies using labile organic N have shown that much of the DON pool is utilized within hours (Jones et al., 2005) or days (Geisseler & Horwath, 2014), which suggests that these strong relationships between labile N pools and net N mineralization are purely correlative and therefore subject to variation and uncertainty in prediction.

Combining several of these more traditional, chemically-based indices of soil fertility with biologically-based assays resulted in an increased ability to predict N mineralization. However, there were differences in best-fit parameters by management. In non-cover cropped fields, the suggested assays were all chemically-based and had generally low $R^2$ values, with a mean of 18.6% variation explained within any growing region. Although the trend was for increased accuracy in more arid regions, the level of certainty was still low, with a max of 42.8% of N mineralization explained at 56 days in Fresno/Kern Counties. Cover cropped fields integrated several respiration measures ($CMIN.50_{0\text{-}6}$ and $CMIN.50_{0\text{-}24}$) into the suggested suite of tests, but their ability to predict N mineralization varied highly by region. In Yolo County, the best fit linear model accounted for 40-50% of the variability in N mineralization, but in Fresno/Kern Counties, the model accounted for 80-90% of the variation. This shows that there is potential for field- or region-specific calibrations to accurately predict N mineralization.

**Objective 3:** The cost effectiveness of implementing respiration-based tests in a commercial lab are mixed. The potential savings from reduced fertilizer costs associated with these tests are greater than the cost of sample analysis in soil test labs (Tables 9 and 10) for both management strategies. However, there is an unacceptable amount of uncertainty (>50%) associated with only utilizing a single test, respiration- or chemically-based assay (Tables 4 and 5). Some of this uncertainty arises from the inherent complexity of the relationship between N mineralization and its predictors, but some uncertainty likely lies in analytical or procedural error or collectively “quality control”.

In order to assess the cost-effectiveness of implementation of the 24-hour test or the suggested suite of tests in a soil test lab, the analytical error inherent in lab procedures must be weighed against the cost of analysis, which includes: labor, materials, and the cost for any additional equipment needed to perform the necessary analyses. The use of paddles to standardize the measurement of respiration across soil test labs eliminates the labor-intensive use of titrations for measuring soil respiration using sodium hydroxide (NaOH) (Anderson, 1982) or an infrared gas analyzer, potentially reducing cost of analysis. However, the single-use nature of these paddles causes the cost per sample to increase considerably. Our current results show that, where soil respiration is a helpful predictor of N mineralization (in cover cropped fields), both the 6- and the 24-hour measurements are needed, potentially doubling the cost for paddles. Additionally, we have shown that there is low agreement on respiration values determined among Solvita® certified test labs, which utilize Solvita® paddles, as well as low agreement between these test labs and other, more conventional methods, such as those used in the UC Davis lab (Figure 1; Supplementary Table 2). Special attention must also be given to the differences in water content used for respiration: the 50% WHC offers increased accuracy over the 100% WHC method of rewetting, but requires additional drying oven space and a considerable increase in labor to calculate the value of 50% WHC for each soil sample. There was also low agreement between labs on the values for WEOC and total C:N (Supplementary Table 2), which were suggested tests for cover cropped and non-cover cropped fields, respectively (Table 6). In addition to the lack of inter-lab agreement on vital test parameters across management types, none of our surveyed labs offered a DOC analysis, which was a suggested parameter for both management strategies. To include this analysis would incur additional costs to commercial test labs for purchasing necessary equipment.

**Viability of Implementation by Growers:** While there is only a moderate level of certainty associated with the adoption of these tests to predict N mineralization, there are some instances where there is a great potential for adoption and subsequent adjustment of N fertilization (Table 7). However, even with a high level of accuracy in prediction of N mineralization, there are additional considerations for adoption (Table 9). The limited set of crops and fertilizers analyzed here begin to explore the contexts in which growers can adopt the proposed fertilization adjustments and the levels of risk

associated with each permutation. In this way, the current study addresses the first two "R's" of fertilizer application—right source and right rate—but still leaves the final two to be integrated into future studies.

## H. PROJECT IMPACTS

This project was successful at increasing the understanding of the myriad of intertwined factors that surround the prediction of N mineralization within a growing season in California. The use of soil respiration to predict N mineralization has recently gained traction in both public and private sector and the current study examines its applicability here in California. Throughout presentations and interactions with industry and research, many have expressed gratitude that the claims are being rigorously tested within the state. One of the main takeaways for many growers that have been at outreach events is that their soil has an innate ability to supply a considerable amount of N to their crops that they are likely not accounting for it. Additionally, this study provides information about the range of expected values for N mineralization in California, which can provide rough estimates to be integrated into current Nutrient Management Budgets.

The current study did not examine interactions that can occur between N mineralization and fertilizer application rates, but future studies can build on our current findings to integrate this vital missing information. With the integration of this final piece, growers can begin to confidently reduce their N fertilization rates to account for in season soil N mineralization, which can lead to potential increases in profitability as well as mitigating any adverse environmental effects of reactive N loss to the environment. Although the current study only begins to explore the economic viability of supplying soil tests to growers to assess in season soil N mineralization (Table 9), our hope is to provide a basis for future studies to develop more rigorous tests and economics to examine profitability in a way that is easily translatable to growers' needs.

## I. OUTREACH ACTIVITIES SUMMARY

**Event 1:** 43rd Annual Plant & Soil Conference

**Date/Location:** February 4-5, 2014; Fresno, CA

**Participants/audience:** 100+ growers, Certified Crop Advisors, consultants, and governmental employees.

**Effectiveness:** Overall, the presentation was effective at highlighting the unknowns in predicting N mineralization. The lack of a viable method to estimate N mineralization did not offer a solution, although it did update interested parties on the current state of knowledge.

**Event 2:** Russell Ranch Field Day

**Date/Location:** May 28, 2014; Davis, CA

**Participants/audience:** ~150 growers, extension specialists and researchers

**Effectiveness:** The poster presentation was effective in facilitating dialogue with growers about existing respiration tests. The preliminary nature of the dataset made it difficult to make specific statements.

**Event 3:** ASA, CSSA, SSSA International Annual Meeting

**Date/Location:** November 2-5, 2014; Long Beach, CA

**Participants/audience:** ~300 researchers, consultants, advisors and extension specialists

**Effectiveness:** Although this event offered a very large overall audience (500+ overall participants), the poster session offered limited opportunity to reach a large audience simultaneously. It did, however, allow for interested parties to be engaged and dialogued with.

**Event 4: Western Plant Health Association Professional Development Seminar**

**Date/Location:** November 18, 2014, Sacramento, CA

**Participants/Audience:** ~45 crop consultants, crop advisors, and growers

**Effectiveness:** Data was presented on soil testing value to predict soil N availability and was well-received with interest expressed in future findings.

**Event 5: Western Plant Health Association Professional Development Seminar**

**Date/Location:** December 3, 2014, Paso Robles, CA

**Participants/Audience:** ~80 crop consultants, crop advisors, and growers

**Effectiveness:** Data was presented on soil testing value to predict soil N availability and was well-received with interest expressed in future findings.

**Event 6:** Northern CA Tomato Growers Conference

**Date/Location:** January 10, 2015; Woodland, CA

**Participants/Audience:** ~80 crop consultants, crop advisors, and tomato growers

**Effectiveness:** Data was included in farm advisor presentation and was well-received with interest expressed in future findings.

**Event 7:** Western Nutrient Management Conference

**Date/Location:** March 5, 2015; Reno, NV

**Participants/Audience:** ~300 crop consultants, crop advisors, industry members, growers, and researchers

**Effectiveness:** The specific session was dedicated to soil health and fertility, which allowed for connections to previous presentations to be made and trends to be brought out. Overall, feedback was positive.

**Event 8:** Nickels Orchard Field Day

**Date/Location:** May 6, 2015; Arbuckle, CA

**Participants/Audience:** ~100 crop consultants, crop advisors, and growers

**Effectiveness:** The inclusion of the data in the program of research at Nickels was effective at educating about the availability of these methods. The inclusion of only one almond orchard in the dataset made drawing concrete, almond-specific conclusions difficult.

**Event 9:** Russell Ranch Field Day

**Date/Location:** May 21, 2015; Davis, CA

**Participants/Audience:** ~200 crop consultants, crop advisors, government officials and extensions specialists

**Effectiveness:** The oral presentation went well and the questions showed that the audience was somewhat aware of this current testing protocol. Handouts were effective at emphasizing the main points.

**Event 10:** Northern CA Corn Grower Meeting

**Date/Location:** August 28, 2015

**Participants/Audience:** <20 corn growers

**Effectiveness:** Presentation effectiveness was limited by growers being unsure of

what the term “mineralization” means and how they can utilize this new information. Much discussion was had about the implications of this process.

**Event 11:** FREP Western Plant Health Association Conference

**Date/Location:** November 5, 2015; Seaside, CA

**Participants/Audience:** >100

**Effectiveness:** Questions regarding the effectiveness of the test were asked. The conclusion was the test is by itself not useful but maybe useful when combined with other tests such as total soil N.

**Event 12:** US:NZ Science Workshop – Water Utilization and Nutrient Management in Perennial Horticulture

**Date/Location:** October 20 to October 22, 2015

**Participants/Audience:** 38

**Effectiveness:** Shared experiences with New Zealand Scientists and local UC Cooperative Extension on soil testing and management to increase nutrient and irrigation use efficiency. Effectiveness was gauged from the perspective that nutrient use and irrigation management cannot be separated.

## J. FACTSHEET

**Project Title:**
Evaluation of a 24-Hour Soil $CO_2$ Test for Estimating Potential N Mineralization to Reassess Fertilizer N Recommendations

**Grant Agreement Number:**
12-0384-SA

**Project Leaders:**
Professor William R. Horwath, Professor Soil & Biogeochemistry, Department of Land, Air, & Water Resources, University of California, Davis.
Dr. Martin Burger, Project Scientist, Department of Land, Air, & Water Resources, University of California, Davis.
Dr. Jeffrey Mitchell, Cooperative Extension Specialist, University of California.
Jordon Wade, Graduate Student Researcher, Department of Land, Air, & Water Resources, University of California, Davis.

**2013-2016**

**Location:**
UC Davis, three commercial soil test labs across the United States

**Counties:**
Yolo, San Joaquin, Salinas, Fresno, Kings, and Kern Counties

**Highlights:**

1) In fields that have received cover crops, biological tests are more effective standalone predictors of N mineralization than chemical tests, but in non-cover cropped fields, chemical tests are more effective than biological tests.
2) Combining biological and chemical tests results in greater accuracy of prediction of N mineralization, but their accuracy is dependent on agricultural region.
3) Adoption of these tests can potentially be economically viable, but high uncertainty about consistency and accuracy of measurements causes it to be high risk.

**Introduction:**
Soils vary in their inherent ability to supply plant-available N. This supply of N comes from the breakdown of soil organic matter from complex forms into available inorganic forms. Mineralization of N has been shown to provide upwards of 50% of crop N uptake in a given season, yet is mostly not taken into account when making fertilizer recommendations. This results in excess N fertilization that can lead to adverse economic and environmental outcomes. It is commonly accepted that this uncertainty comes from the differences in soil biology and soil physical properties with their interaction causing substantial variability. In order to account for this uncertainty and predict the N supplying capacity of a soil, one test that has recently been employed across the United States involves the approximation of microbial metabolism by measuring soil respiration, or $CO_2$ production in 24-72 hours. However, this test has not been studied in California's unique, highly intensively managed and productive agricultural context.

**Methods/Management:**

Soils were sampled across four of California's prime growing regions prior to planting in the spring: Salinas County, Yolo County, San Joaquin County, and the Fresno/Kern Counties. In the latter of these three regions, two management strategies were compared: fields that had received cover crops in the preceding winter and those that had not. These soils were then incubated in the lab to estimate each soil's N supplying capacity throughout a growing season. These values were then compared with a variety of biologically- and chemically-based tests commonly found in literature and in commercial soil test labs. These tests were then combined to create a suggested set of predictive tests. These tests were then compared across commercial labs for both economic and analytical viability to predict soil N mineralization.

**Findings:**

There are distinct differences in effectiveness between biologically- and chemically-based tests, with the former being more effective in cover cropped fields and the latter being more effective in non-cover cropped fields. These predictions became more accurate when incorporating multiple tests in predictive models, although the increases in accuracy were inconsistent across growing regions. A subset of samples was sent to commercial soil test labs for analysis and several key measures were found to be inconsistent between labs, which is cause for concern when looking to make recommendations for growers. Although there is a strong potential for substantial savings from reduced fertilizer costs, the inconsistency of lab results presents a high level of risk for the adoption of this technology. Further study may allow for regional recommendations and calibrations to predict N mineralization potential, but this technology is currently not robust enough for adoption across the state as a standardized soil test to predict in season soil N mineralization.

## K. PRODUCTS

Results are being developed into one or more peer-reviewed journal articles which will be sent to CDFA-FREP upon publication.

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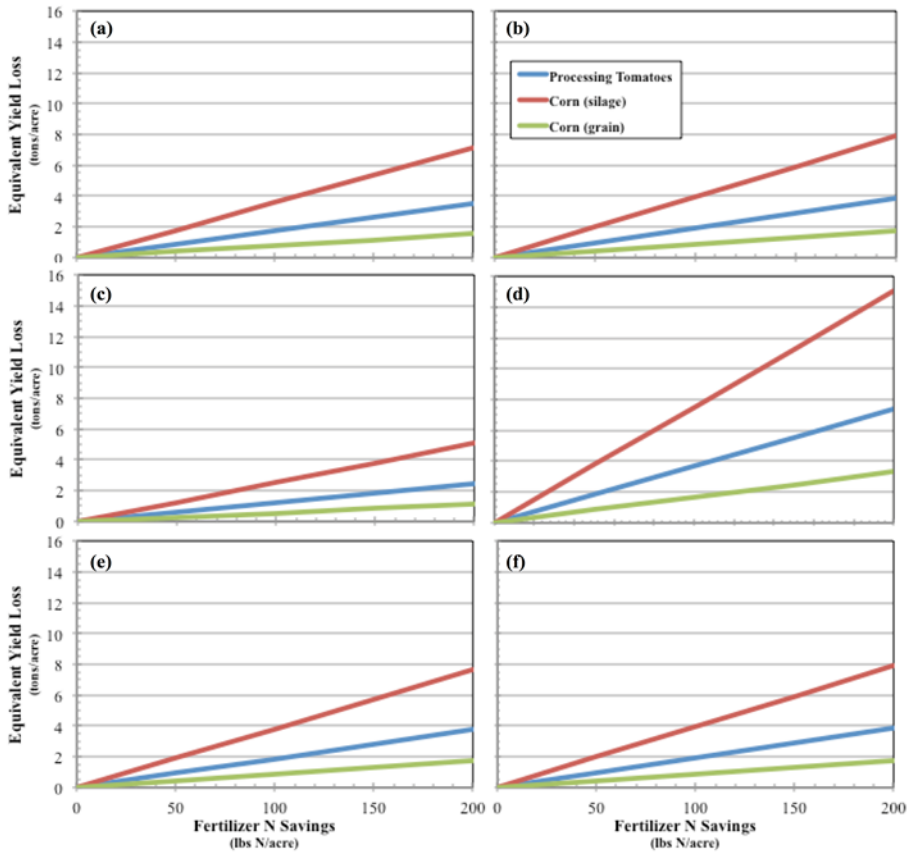
Supplementary Table 1. Site characteristics for fields studied, including management, crops, total organic carbon content (g C/kg air-dried soil), and pH (1:1 water).

Supplementary Tables and Figures

| Location | Soil Series | Classification | Textural Class | Management | Crops | Total C | pH |
|---|---|---|---|---|---|---|---|
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | no cover crops | processing tomatoes | 8.90 | 6.68 |
| Yolo | Sycamore | Fine-silty, mixed, nonacid, thermic Aeric Haplaquept | silt loam | no cover crops | processing tomatoes | 15.79 | 7.10 |
| Yolo | Marvin | Fine, smectitic, thermic Aquic Haploxeralfs | silty clay loam | cover crops | processing tomatoes | 10.29 | 7.03 |
| Yolo | Tehama | Fine-silty, mixed, thermic Typic Haploxeralf | loam | cover crops | processing tomatoes | 7.18 | 6.74 |
| Yolo | Capay | Fine, montmorillonitic, thermic Typic Chromoxerert | silty clay | no cover crops | processing tomatoes | 12.86 | 7.06 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | no cover crops | corn (grain) | 10.45 | 8.16 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | no cover crops | corn (grain) | 8.54 | 7.63 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | no cover crops | corn (grain) | 8.01 | 7.31 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | corn (grain) | 10.98 | 7.19 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | corn (grain) | 11.22 | 7.40 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | cover crops | corn (grain) | 11.31 | 6.98 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | corn (grain) | 12.24 | 7.25 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | corn (grain) | 14.57 | 6.80 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | cover crops | corn (grain) | 13.45 | 7.12 |

| Location | Soil Series | Classification | Textural Class | Management | Crops | Total C | pH |
|---|---|---|---|---|---|---|---|
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | corn (grain) | 11.49 | 7.01 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | no cover crops | corn (grain) | 8.65 | 7.13 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | corn (grain) | 8.90 | 6.71 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | cover crops | corn (grain) | 10.35 | 7.37 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | no cover crops | corn (grain) | 9.30 | 7.13 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | cover crops | corn (grain) | 13.10 | 6.97 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | no cover crops | processing tomatoes | 9.66 | 7.52 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | processing tomatoes | 11.13 | 7.24 |
| Yolo | Yolo | Fine-silty, mixed, nonacid, thermic Typic Xerorthent | silt loam | cover crops | processing tomatoes | 10.94 | 7.03 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | cover crops | processing tomatoes | 10.47 | 7.19 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | cover crops | processing tomatoes | 12.54 | 7.27 |
| Yolo | Rincon | Fine, montmorillonitic, thermic Mollic Haploxeralf | silty clay loam | no cover crops | processing tomatoes | 8.62 | 7.20 |
| Yolo | Arbuckle | Fine-loamy, mixed, superactive, thermic Typic Haploxeralf | sandy loam | no cover crops | almonds | 4.37 | 5.41 |
| San Joaquin | Jacktone | Fine, montmorillonitic, thermic Typic Pelloxerert | clay | no cover crops | processing tomatoes | 14.35 | 6.97 |
| San Joaquin | Stockton | Fine, montmorillonitic, thermic Typic Pelloxerert | clay | no cover crops | processing tomatoes | 16.68 | 7.55 |
| San Joaquin | Capay | Fine, montmorillonitic, thermic Typic Chromoxerert | clay | cover crops | processing tomatoes | 10.19 | 7.42 |
| San Joaquin | Stomar | Fine, montmorillonitic, thermic Mollic Haploxeralf | clay loam | cover crops | processing tomatoes | 6.82 | 7.47 |

| Location | Soil Series | Classification | Textural Class | Management | Crops | Total C | pH |
|---|---|---|---|---|---|---|---|
| San Joaquin | Stockton | Fine, montmorillonitic, thermic Typic Pelloxerert | clay | no cover crops | corn (grain) | 10.37 | 7.02 |
| San Joaquin | Stockton | Fine, montmorillonitic, thermic Typic Pelloxerert | clay | no cover crops | corn (silage) | 11.15 | 6.82 |
| Salinas | Stockton | Fine, montmorillonitic, thermic Typic Pelloxerert | clay | no cover crops | lettuce | 10.56 | 7.10 |
| Salinas | Chualar | Fine-loamy, mixed, superactive, thermic Typic Argixerolls | sandy loam | no cover crops | lettuce | 10.48 | 7.08 |
| Fresno/Kern | Westhaven | Fine-silty, mixed, superactive, thermic Fluventic Haplocambid | loam | cover crops | processing tomatoes | 6.69 | 7.45 |
| Fresno/Kern | Calflax | Fine-loamy, mixed, superactive, thermic Sodic Haplocambid | clay loam | cover crops | processing tomatoes | 6.90 | 6.47 |
| Fresno/Kern | Fresno | Fine-loamy, mixed, thermic Natric Durixeralf | fine sandy loam | no cover crops | processing tomatoes | 10.11 | 7.34 |
| Fresno/Kern | Fresno | Fine-loamy, mixed, thermic Natric Durixeralf | fine sandy loam | no cover crops | processing tomatoes | 7.21 | 7.32 |
| Fresno/Kern | Westhaven | Fine-silty, mixed, superactive, thermic Fluventic Haplocambid | loam | no cover crops | processing tomatoes | 5.37 | 7.41 |
| Fresno/Kern | Westhaven | Fine-silty, mixed, superactive, thermic Fluventic Haplocambid | loam | no cover crops | processing tomatoes | 7.21 | 7.43 |
| Fresno/Kern | Westhaven | Fine-silty, mixed, superactive, thermic Fluventic Haplocambid | loam | no cover crops | cotton | 6.47 | 8.41 |
| Fresno/Kern | Calflax | Fine-loamy, mixed, superactive, thermic Sodic Haplocambid | clay loam | no cover crops | cotton | 8.34 | 7.86 |
| Fresno/Kern | Panoche | Fine-loamy, mixed, superactive, thermic Typic Haplocambid | clay loam | cover crops | sorghum | 6.68 | 7.34 |
| Fresno/Kern | Panoche | Fine-loamy, mixed, superactive, thermic Typic Haplocambid | clay loam | cover crops | sorghum | 6.99 | 7.64 |
| Fresno/Kern | Panoche | Fine-loamy, mixed, superactive, thermic Typic Haplocambid | clay loam | no cover crops | sorghum | 5.72 | 6.98 |
| Fresno/Kern | Panoche | Fine-loamy, mixed, superactive, thermic Typic Haplocambid | clay loam | no cover crops | sorghum | 5.53 | 7.56 |




**Supplementary Figure 1. Fertilizer N savings and the equivalent yield loss for processing tomatoes and corn grown for both grain and silage, separated by fertilizer: (a) ammonium sulfate, (b) calcium ammonium nitrate (17-0-0) (c) anhydrous ammonia (d) aqueous ammonia, (e) urea, and (f) urea-ammonium-nitrate (32-0-0).**

Supplementary Table 2. Differences in sample results between external labs and UC Davis analysis. Blocking effects were analyzed by sample and are excluded from these results in order to isolate effects of individual lab analysis.

| Total C | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | NS | * | NS |
| Lab 1 | NS | -- | NS | NS |
| Lab 2 | * | NS | -- | NS |
| Lab 3 | NS | NS | NS | -- |

| Total N | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | NS | ** | ** |
| Lab 1 | NS | -- | ** | ** |
| Lab 2 | ** | ** | -- | NS |
| Lab 3 | ** | ** | NS | -- |

| Total C:N | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | NS | NS | * |
| Lab 1 | NS | -- | * | * |
| Lab 2 | NS | * | -- | NS |
| Lab 3 | * | * | NS | -- |

| WEOC | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | ** | * | ** |
| Lab 1 | ** | -- | ** | ** |
| Lab 2 | * | ** | -- | ** |
| Lab 3 | ** | ** | ** | -- |

| WEON | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | ** | ** | ** |
| Lab 1 | ** | -- | * | ** |
| Lab 2 | ** | * | -- | ** |
| Lab 3 | ** | ** | ** | -- |

| WEOC:N | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | NS | ** | NS |
| Lab 1 | NS | -- | * | NS |
| Lab 2 | ** | * | -- | * |
| Lab 3 | NS | NS | * | -- |

| Solvita 24-Hour Respiration | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | ** | ** | NS |
| Lab 1 | ** | -- | NS | ** |
| Lab 2 | ** | NS | -- | ** |
| Lab 3 | NS | ** | ** | -- |

| Soil Health Score | | | | |
|---|---|---|---|---|
| | UC Davis | Lab 1 | Lab 2 | Lab 3 |
| UC Davis | -- | NS | NS | NS |
| Lab 1 | NS | -- | ** | ** |
| Lab 2 | NS | ** | -- | NS |
| Lab 3 | NS | ** | NS | -- |

*, **, *** refers to significance at $p<0.05$, $p<0.01$, and $p<0.001$, respectively. NS = not significant.