## A. Project Information

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## B. Abstract:

The Central Valley Regional Water Quality Control Board implemented Nitrogen Management Plans (NMP) in 2014 to estimate potentially leachable nitrogen and reduce nitrate contamination of groundwater. However, container-plant nursery production does not fit well in the NMP worksheet since crops consist of the entire plant, along with the growing substrate, and are harvested year-round. We conducted an experiment to determine the fate of applied nitrogen in woody ornamental plant production. The system nitrogen balance indicated that NMP calculations overestimate the amount of potentially leachable nitrogen from container-plant production. Environmentally-harmful discharges were identified as aqueous nitrogen leached and nitrous oxide ($N_2O$) emitted from the soilless substrate and experiments were conducted to mitigate these losses. Mechanically incorporating polymeric resin-coated controlled-release fertilizer resulted in damage to prills and over two times more inorganic nitrogen leaching losses than gentler incorporation methods. However, controlled-release fertilizer coated in polyurethane or thermoplastic resin resisted mechanical damage and resulted in much lower leaching losses of mineral fertilizer. Reducing concentrations of nitrogen applied to soilless substrates did not reduce $N_2O$ emissions from the tested soilless substrate. In the same

substrate, reducing water content below 30% volumetric water content ceased $N_2O$ emissions but this may not be feasible in production because 30% volumetric water content leaves very little moisture for plant growth. Almost all $N_2O$ emissions from soilless substrates were derived from denitrification and the magnitude varies with type of organic amendments. As the NMP calculations overestimate potentially leachable nitrogen from nursery production, implementation and reporting of irrigation and nitrogen best management practices should be used in place of the NMP for reducing nitrate leaching to groundwater. Future work should develop best management practices to mitigate $N_2O$ from soilless substrates and help California meet climate neutrality goals.

## C: Introduction:

A report by Harter and Lund (2012) determined that a large proportion of groundwater in the Central Valley is either contaminated with nitrate or at risk of contamination. This report identified that cropland contributed 97% of the nitrate contamination to groundwater and 54% was directly from synthetic fertilizers (Harter and Lund, 2012). Additionally, Harter and Lund (2012) indicated that nitrate contamination will continue for decades as large quantities are already in the soil and will continue to leach as groundwater aquifers are recharged.

To reduce the risk of future nitrate contamination to groundwater, the Central Valley Regional Water Quality Control Board (CVRWQCB) required the implementation of Nitrogen Management Plans (NMP) by growers within the Central Valley Basin. The NMP consisted of documenting yearly nitrogen inputs and outputs to develop an N balance sheet. Potential N available for leaching into groundwater was calculated by subtraction of N outputs from inputs. Inputs consisted of total N in soil and in the fertilizer, organic amendments, and irrigation water applied. Output was based on harvested yield and the N content of that material. Amount of N in harvested parts of major crops, like almonds or table grapes, were readily available (Geisseler, 2016). However, some agricultural commodities, like container-grown nursery crops, did not fit neatly into the NMP worksheet.

Container plant production is very different and much more complex than the in-ground production of annually harvested nut, fruit, vegetable, or cereal crops. In nurseries, thousands of different plant taxa may be grown in specially formulated growing substrates in a range of sizes from small propagation stock to large trees. The whole product, including the roots and substrate, is harvested continuously and shipped off of the nursery grounds to retail and other customers. The portion of N remaining in the container substrate at the time of shipment is dependent on the fertilizer application rate but can range from 0-41% of applied N (Cabrera, 2003; Narvaez *et al.*, 2012, 2013). Container nursery production is prone to high losses of aqueous N from growing areas as irrigation with nutrient solution is common and water application efficiency is poor due to the prevalence of overhead irrigation and wide plant spacing (Fulcher *et al.*, 2016). Both Cabrera (2003) and Narvaez et al. (2013) could not account for a significant proportion of applied N and attributed it to denitrification. However, N gas flux was not measured and confirmation of denitrification in container plant production was necessary. There are nursery specific practices that may encourage denitrification processes and reduce N leaching into groundwater, including: frequent irrigation to maintain container substrate moisture content and saturated conditions in the soil below growing beds.

As nursery production uses large amounts of synthetic fertilizers including N, it was necessary to: 1) identify what happens to the N applied in production and 2) mitigate environmentally harmful discharges of N. We proposed developing a whole system N balance for container plant production focused on the growing bed and the plants produced thereon. After the N balance was developed, mitigation strategies for environmentally harmful N discharges were evaluated.

## D. Objectives:

1. Develop system N balance for container plant production.
2. Test strategies to mitigate environmentally harmful N losses from growing system.
3. Economic analysis for BMPs and mitigation strategies.
4. Extend nitrogen balance results to the industry, regulators, and scientific community.

## E. Methods:

### Objective 1: Develop system nitrogen balance for container plant production.

### System nitrogen balance for container plant production

Eight experimental beds, four lined with impervious material and four unlined, were installed at a nursery. *Lagerstroemia indica* ‘Whitt II’ plants were transplanted from a #1 container into a #3 container with fir bark substrate incorporated with 3.47 kg Apex 9-2-0 sulfur-coated urea and 6.16 kg Osmocote Plus 15-9-12 controlled release fertilizer (CRF) $m^{-3}$ substrate. On day three after planting, 35 g of 20-9-9 fertilizer was applied to the substrate surface of each container. Runoff volume and N concentration was monitored from each bed. Nitrous oxide ($N_2O$) flux samples were collected from #3 containers and from growing bed soil. Twelve plants were randomly selected from each of the experimental beds at both the beginning and end of the experiment. Plant shoots were cut at the crown, dried, and measured for N concentration.

### Statistics

To improve normality of the residual errors and homoscedasticity, the number of plants and the amounts of N input, utilized by plant shoots, and remaining in the substrate was Box-Cox transformed. Optimal lambda ($\lambda$) was 39.0 for the plants per bed data and 36.7 for the other transformed data. A Student’s t-test was performed to determine significant differences ($\alpha = 0.05$) between different N variables measured for the lined and unlined beds. All statistical analyses were conducted in R statistical software.

## Objective 2: Test strategies to mitigate environmentally harmful N losses from growing system.

### Effect of rate of 20-9-9 surface-applied fertilizer on nitrous oxide emissions from soilless substrate

Twenty-four *Lagerstroemia indica* ‘Whitt II’ plants were transplanted from a #1 container into a #3 container with fir bark substrate incorporated with 3.47 kg Apex 9-2-0 sulfur-coated urea and 6.16 kg Osmocote Plus 15-9-12 controlled release fertilizer (CRF) $m^{-3}$ substrate. The plants were placed on 61-cm centers in a greenhouse and randomly separated into three treatments, with eight plants per treatment. All treatments had the same amount of CRF incorporated into the substrate, but varied in the amount of surface-applied fertilizer. Treatments included 0 (0 g), 5 (5 g), or 35 g (35 g) of surface-applied 20-9-9 fertilizer resulting in total of 13.7, 14.7, and 20.7 g nitrogen fertilizer per plant for the 0 g, 5 g, and 35 g treatments, respectively. Nitrous oxide flux was measured on days 1, 4, 7, 10, 14, 21, 28, 35, 42, 49, 56, 63, 70, 78, and 84. Cumulative $N_2O$ emission and global warming potential was calculated (GWP). Substrate temperature and volumetric moisture content were measured on sampling days. Pour-through extracts (Wright, 1986) were collected after sampling and analyzed for electrical conductivity, pH, ammonium ($NH_4$-N), and nitrate ($NO_3$-N) concentration. At 84 days after planting, plant height and width in both directions was measured and a plant growth index was calculated. Plant material was harvested and dried before weighing to determine total biomass.

### Statistics

To improve the normality of the residual errors and homoscedasticity, the $N_2O$-N flux, substrate temperature, and volumetric water content (VWC) data from the greenhouse experiment were transformed using a Box-Cox transformation. Optimal lambda ($\lambda$) were 0.30, -3.12, and 3.21 for the $N_2O$-N flux, substrate temperature, and VWC data, respectively. Before Box-Cox transformation, the $N_2O$-N data was translated by adding 0.01 mg $N_2O$-N $m^{-2}$ $hr^{-1}$ per value to remove negative values. No transformation was performed on the pH data. Treatment means were determined and Tukey’s test was used for means separation ($\alpha = 0.05$) of transformed $N_2O$-N flux, substrate temperature, VWC, and non-transformed pH data between treatments within the greenhouse experiment on each day. All statistics were performed in R statistical software. A regression model was developed to estimate the predictors ($p < 0.05$) of the common logarithm ($\log_{10}(x)$) of $N_2O$-N flux from bark substrate using the common logarithm of variables (substrate temperature and VWC, pour-through $NH_4$-N concentration, $NO_3$-N concentration, pH, and container number) measured at gas flux sampling time.

### Volumetric water content effect on nitrous oxide response from uc mix soilless substrate

Composted redwood 1:1:1 sawdust:peat:sand (v:v) substrate (UC Mix) was wetted to 0, 10%, 20%, 30%, 40%, 50% and 60% VWC. Substrate at experiment VWC was packed to bulk density of 0.62 g $cm^{-3}$ into 28-cm tall, 10-cm diameter polyvinyl chloride gas cylinders that were closed at the bottom. Substrate column height was approximately

25-cm, which is similar to substrate height in a #3 (14-L) container. There were three replicates of each VWC treatment in the gas cylinders. The experimental design was a completely randomized design with gas cylinders placed on a lab bench and sampled in a randomly selected order each sampling day. Substrate was incubated at room temperature for 48 hours before $N_2O$ gas flux samples were collected from individual columns. The substrate columns were sealed at the bottom, forcing all gases to escape from the top. To mimic the effect of concentrating nutrients as substrate VWC decreases, the same mass of nitrate ($NO_3^-$) was applied to each treatment, resulting in more concentrated solution for the 10% treatment than the 60%. Dry granular potassium nitrate was added to the 0% VWC treatment. Gas flux samples were collected and calculated as previously described. A follow-up experiment was conducted to test the minimum VWC threshold for $N_2O$ flux in UC Mix. Substrate was wetted to 27%, 30%, 33%, 36%, 39%, and 42% and all other methods were similar to those above.

### Statistics

To improve the normality of the residual errors and homoscedasticity, the $N_2O$-N flux, data from the 0 - 60% VWC experiment was transformed using a Box-Cox transformation. Optimal lambda (λ) was 0.0169 for the $N_2O$-N flux data. Prior to Box-Cox transformation, the $N_2O$-N data was translated by adding 0.01 mg $N_2O$-N $m^{-2}$ $hr^{-1}$ per value to remove negative flux values. Treatment means were determined and Tukey's test was used for means separation ($\alpha = 0.05$) of transformed $N_2O$-N flux. No data transformation was performed for the $N_2O$-N flux data from the 27 – 42% VWC experiment. Tukey's Honest Significant Difference Test was used for determining means separation.

### Nitrate concentration effect on nitrous oxide response from uc mix soilless substrate

A soilless substrate composed of 1:1:1 (V:V:V) peat:composted redwood sawdust:sand (UC Mix) was treated with different rates of $KNO_3$ solution and incubated at the same VWC (40%) for 48 hours at room temperature. The different $NO_3^-$ treatments were 0, 25, 50, 75, 100, 200, and 300 mg $NO_3$-N $L^{-1}$. There were three replicates of each treatment in the gas cylinders and gas flux samples were collected after the 48-hour incubation period. Gas flux samples were collected and calculated as previously described.

### Statistics

Model assumptions of homoscedasticity and Gaussian distribution of residual errors for $N_2O$-N flux were met and it was determined that no transformations were necessary. Tukey's Honest Significant Difference Test was used to determine differences between multiple treatments.

### Comparing inorganic nitrogen leaching from mechanically- or manually incorporated controlled release fertilizer

Osmocote Plus (15-9-12) was incorporated either mechanically or manually at 5.083 kg $m^{-3}$ into fir bark substrate. On day zero, *Lavandula angustifolia* 'Provence' plants were individually transplanted from #1 containers into #3 containers of fir bark substrate with either mechanically- or manually-incorporated CRF. There were 10 replicate containers of substrate with each incorporation method. Ten containers of each substrate were left unplanted. Containers were placed on 61-cm centers in the greenhouse. Containers were leached weekly with enough deionized water to provide a leaching fraction of 20%. Leachate volume was measured and a sample was analyzed for electrical conductivity, pH, and concentration of $NH_4$-N and $NO_3$-N. The plants were harvested on day 76. The shoots of the lavender plants were cut at the crown and weighed. The shoots were then dried at 60°C for 48 hours, and weighed again.

### Statistics

Tukey's Honest Significant Difference test was used to determine differences between mean total cumulative inorganic N leached from each of the treatments. Compared to the other plants, one from each CRF-incorporation treatment had very little shoot biomass growth during the experiment. The total shoot dry biomass for these two plants was removed to improve normality of residual errors before Student's t-test was used to determine means separation.

### Contribution of denitrification and nitrification to nitrous oxide emissions from three organic soilless substrates

Three substrates were prepared with fir bark, peat moss, and sand. Individually, peat moss or fir bark was mixed with sand at 7:1 (v:v) and a combination of peat moss and fir bark were mixed with sand at 3.5:3.5:1 (v:v:v). To standardize relative gas diffusion rate, the three substrates were maintained at similar air-filled porosity throughout the experiment. Three ammonium nitrate fertilizer treatments and one treatment without nitrogen fertilizer (Unfertilized) were applied to each substrate. The treatments were $NH_4NO_3$ at natural abundance, $^{15}N$-enriched $^{15}NH_4NO_3$ or $NH_4{}^{15}NO_3$ (at 10 atom%), and background treatment which had no added $NH_4NO_3$. Substrates were packed to a column height of 25-cm in polyvinyl chloride cylinders for gas and extract sampling. Nitrous oxide flux samples were collected every other day for 21 days and a single gas sample for flux sample was analyzed for $N_2O$ with $^{15}N$. Saturated media extract samples were collected on days 1, 5, 11, 16, and 21 and were analyzed for $NH_4$-N and $NO_3$-N. Isotope analysis of inorganic N was performed on aliquots of the extract using a sequential diffusion method (Sørensen and Jensen, 1991). The isotope analysis of $NH_4$-N, $NO_3$-N, and $N_2O$ were used to calculate relative contribution of ammonia oxidation or denitrification to $N_2O$ production.

### Statistics

The common logarithm [$\log_{10}(x)$] of $N_2O$ gas flux samples was utilized to improve normality of residual errors of $N_2O$ flux. A constant (1.54) was added to the product of the common logarithm transformation before $N_2O$ flux was calculated to accommodate the inability of ‘gasfluxes’ (Fuss, 2019) to use negative gas concentration values. A weighted model was fitted to account for heteroscedasticity in $N_2O$ response from the different substrates on different days. Kenward-Roger method was used for approximating degrees of freedom for weighted models of log-transformed $N_2O$ flux. Model assumptions were confirmed by Levine’s and Shapiro-Wilks tests. Tukey’s test was used for separation of means ($\alpha = 0.05$) for $N_2O$ flux on each sampling day between the $NH_4NO_3$ and unfertilized treatments within each substrate, and total $N_2O$ emitted from $NH_4NO_3$ treatments per substrate.

### Robustness of controlled release fertilizer coating

Two different release longevities of three polymer-coated CRF were evaluated for their robustness to mechanical incorporation equipment. The three different polymer coatings were polyurethane (Apex NPK), thermoplastic resin (Nutricote), and polymeric resin (Osmocote) which represent three of the major types of polymers used for coating CRF prills. Longevities tested were 8-10 month and 3-5 month at 70°F. All fertilizers were incorporated in a 4.5:4.5:1 peat:fir bark:sand (v:v:v) substrate at 0.741 g N $L^{-1}$ substrate. To represent mechanical mixing, CRF prills were placed into a 2-gal bucket and stirred for 1-min with a paint stirrer on a cordless drill. Another set of prills was not exposed to simulated mechanical-incorporation. The substrate with CRF was put into 1-gal containers and randomly placed on benches. No plants were planted into the substrates. All pots were watered with DI water and leachate was collected on day 0, 1, 2, and 3. Total leachate volume was measured and analyzed for electrical conductivity. Electrical conductivity was multiplied by 10 to calculate salt concentration in meq $L^{-1}$ (Richards, 1954). Salt concentration was multiplied by leachate volume from each day and these values were summed to determine the total amount of salts leached.

The total amount of applied fertilizer salt was measured by crushing and dissolving a weighed sample of fertilizer in DI water and measuring EC. Water volume and EC were used to calculate the total salt as described above.

### Statistics

The common logarithm [$\log_{10}(x)$] of total salts leached was calculated to improve normality of residual errors and homoscedasticity. Shapiro-Wilks and Levene’s tests were used to test assumption of normality of residual errors and homoscedasticity, respectively. Student’s t-test was used to determine if there was a significant difference in log-transformed values of total salts leached between simulated mechanical-incorporation for each combination of CRF and longevity.

### Objective 3: Economic analysis for BMPs and mitigation strategies.

Cost of mitigating additional $N_2O$ emissions from reduced application of surface-applied fertilizer included the cost of purchasing the fertilizer and the cost of applying 35 g of fertilizer by nursery staff.

The cost of mechanically-incorporating Osmocote Plus 15-9-12 fertilizer was estimated by calculating the total fertilizer N saved by manual incorporation and multiplying by the price per bag.

The costs of utilizing peat moss instead of Douglas fir bark to reduce $N_2O$ emissions was based on the per volume cost of each substrate and the volume used per hectare.

The financial savings associated with using CRF with more resistant coatings is based on applying 28% less total nitrogen for resistant CRF. The total bags of fertilizer per ha was calculated as 72% of total N applied and multiplied by N per bag. The total cost of CRF was calculated as total bags multiplied by price per bag.

### Objective 4: Extend nitrogen balance results to the industry, regulators, and scientific community.

Please refer to outreach activities summary for information on this objective.

## F. Results:

### Objective 1: System nitrogen balance for container plant production.

Mean plant number, total applied N, total N in sold crop, emitted $N_2O$-N, and unaccounted N were not significantly different ($p > 0.05$) between lined and unlined experimental beds (Table 1). Lined beds had significantly greater runoff N ($p = 0.016$) than unlined beds (Table 1).

### Objective 2: Test strategies to mitigate environmentally harmful N losses from growing system.

### Effect of rate of 20-9-9 surface-applied fertilizer on nitrous oxide emissions from soilless substrate

The treatment with 35 g of 20-9-9 surface-applied fertilizer had significantly greater cumulative $N_2O$ emissions over the course of the experiment than the 5 g treatment (Tables 2 and 3). Interestingly, there was no difference in cumulative $N_2O$ emissions seen between the 0 g treatment and the 5 g or 35 g treatments (Tables 2 and 3). There was no significant difference in mean plant dry weight (Tables 4 and 5) or plant growth index (Tables 4 and 6) between the treatments.

The pour-through extract $NH_4$-N and $NO_3$-N concentrations, substrate temperature, and VWC were predictors of $N_2O$ flux response in that order of significance. The predictors showed a strong positive correlation with $N_2O$-N flux ($R^2 = 0.76$).

### Volumetric water content effect on nitrous oxide response from uc mix soilless substrate

The first VWC experiment tested the effect of 0-60% VWC, in 10% increments, on $N_2O$ flux. The drier treatments (0-30%) had significantly lower $N_2O$ flux compared to the wetter treatments (40-60%) (Figure 1, Table 7 and 8). These results prompted a more focused VWC experiment to determine the VWC at which $N_2O$ flux is activated in UC Mix. It appears there is a threshold VWC between 30-33% when $N_2O$ emissions are initiated as there were no significant differences for the treatments from 30-42% VWC (Figure 2, Table 9 and 10).

### Nitrate concentration effect on nitrous oxide response from uc mix soilless substrate

The treatment with zero mg $NO_3$-N $L^{-1}$ had the lowest $N_2O$ flux of all the treatments (Figure 3). However, there were no significant differences in $N_2O$ flux from UC Mix with different concentrations of $NO_3$-N in media solution. (Figure 3, Table 11 and 12).

### Comparing inorganic nitrogen leaching from mechanically- or manually incorporated controlled release fertilizer

The leaching losses were similar among the soilless substrates with same method of CRF incorporation, with or without a plant, until about day 40 (Figure 4). After day 40, the rate of inorganic N leaching loss for the substrate without plants continued to increase, while leaching loss rate from the substrate with plants decreased (Figure 4). Tukey's Honest Significant Difference Test indicated that there was significant difference ($p < 0.0001$) in total cumulative inorganic N leached between some treatments (Figure 4, Table 13 and 14). The substrate with mechanically-incorporated CRF without a plant had the greatest total cumulative inorganic N leached and the substrate with manually-incorporated CRF with plants was lowest (Figure 4, Tables 13 and 14). For the substrate with plants, mechanically-incorporated CRF leached over twice as much inorganic N as the manually-incorporated treatment (Tables 13 and 14). It is no surprise that the substrate without plants leached more total inorganic N than their counterpart treatment with plants (Figure 4 and Table 13). Increased N leaching after weeks five and six from the substrate without plants indicate that plant roots take up the majority of released N after this period (Figure 4). Plant shoot dry biomass was not significantly different ($p = 0.31$) between the two CRF-incorporation methods.

### Contribution of denitrification and nitrification to nitrous oxide emissions from three organic soilless substrates.

Nitrous oxide-N flux was low among the three different substrates fertilized with $NH_4NO_3$ at experiment initiation, and began to increase on day three (Figure 5). The fir bark substrate had a rapid increase in $N_2O$ flux, with large emissions observed from day five until almost the end of the experiment (Figure 5). Nitrous oxide-N flux from peat:fir bark substrate increased until day 13, after which it fluctuated until the end of the experiment (Figure 5). Nitrous oxide-N flux from peat substrate increased slightly until day seven, then decreased until day 17 before increasing again on the last days of the experiment (Figure 5). Total $N_2O$-N emitted was greatest from the fir bark substrate and lowest from the peat substrate (Tables 15 and 16). The peat:fir bark substrate had a mean total $N_2O$-N emitted that was close to the value observed from the fir bark substrate (Table 15). The majority of $N_2O$-N emitted from each substrate was from denitrification, with peat substrate emitting the most $N_2O$-N from nitrification (Table 15, Figure 5).

### Testing robustness of controlled release fertilizer coatings

The treatments with CRF prills coated in polymeric resin had significantly greater salt leaching losses when the prills were exposed to simulated mechanical-incorporation (p

$< 0.0001$) (Figure 6 and Table 17). There was no significant increase when the polyurethane-coated or thermoplastic resin-coated CRF prills were exposed to simulated mechanical incorporation (Figure 6 and Table 17). For those prills not exposed to simulated mechanical-incorporation, the 8-9 and 3-4 month products leached 1.5 - 2.9% and 1.8 - 6.3% of total applied salts, respectively (Table 17). For the polymeric resin-coated prills exposed to simulated mechanical-incorporation, the 8-9 and 3-4 month products leached 10.7% and 8.6% of total applied salts, respectively (Table 17).

### Objective 3: Economic analysis for BMPs and mitigation strategies.

Please refer to the discussion for economic results.

### Objective 4: Extend nitrogen balance results to the industry, regulators, and scientific community.

We presented results from this research to 577 individuals from industry, regulatory agencies, and academic institutions at 11 different virtual and in-person venues during the grant agreement. Additionally, we presented results to UC Davis students enrolled in ENH120 “Management of Container Media” during the 2019-20, 2020-21, and 2021-22 academic years. Dr. Pitton’s Horticulture and Agronomy graduate seminar was presented to a total audience of 32, including eight Nursery Specialists from leading U.S. land-grant universities. We published two peer-reviewed papers and plan to publish three more describing the results of this work.

We will continue to share the results of this research with industry, regulators, and students taking the “Management of Container Media” class. This research information will be shared in future workshops presented by the UC Nursery and Floriculture Alliance (UCNFA) on Fertilizers and Nutrition Management and other programs that focus on plant nutrition, nitrogen management, and water quality.

## G. Discussion

### Objective 1: Develop system nitrogen balance for container plant production.

A large percentage (62%) of applied N was either taken up by the plant or remained in the substrate when the plant was shipped from the nursery (Table 18). At the retail location, the plant may sit for over a year before being purchased and/or planted in the ground by the end consumer and a fertilizer reserve in the growing substrate ensures the plant will maintain a healthy and aesthetic appeal until retail sale. During the 81-day production cycle, 1.5% of applied N was emitted as nitrous oxide from the substrate, 6.5% was runoff N from the growing area, 2.4% of N infiltrated into the growing bed soil, and 27.7% of N was unaccounted for (Table 18). The difference in runoff N between the lined and unlined beds was the amount of N that infiltrated into the soil (Table 18). It is unclear how N mass infiltration into growing bed soil compares to other crops, but it is a small percentage of applied N (Table 18). The majority of unaccounted for N was likely lost as dinitrogen gas from denitrification, with a smaller part attributed to ammonia volatilization and $NO_x$. Regrettably, quantification of dinitrogen gas was not possible because methods developed for mineral soils did not work in the high-porosity growing substrate. A very small fraction, only 0.1%, of applied N was emitted as gas from the saturated bed soil surface. This indicates that there is little denitrification occurring in the saturated growing bed soil and the N that infiltrates soil is not remediated here.

## Objective 2: Test strategies to mitigate environmentally harmful N losses from growing system.

### Rate of 20-9-9 surface-applied fertilizer on nitrous oxide emissions from soilless substrate

Reducing the amount of 20-9-9 surface-applied fertilizer did not significantly affect plant growth but did result in a decrease in total cumulative $N_2O$ emissions (Table 2 and 3). The combination of immediately available N and mineralized urea-formaldehyde are likely responsible for the increase in total $N_2O$ emissions from the 35 g treatment as this increased total fertilizer N by 63% over the 0 g treatment. The lack of a detectable difference in total cumulative $N_2O$ emissions between the 0 g and 5 g treatments (Table 2 and 3) may indicate that abundant N was available from controlled release fertilizer N for denitrification. This seems reasonable as the 5 g treatment only increased total fertilizer N by less than one percent. As surface-applied fertilizer did not affect plant growth (Table 5 and 6), eliminating this will provide financial benefits for the nursery because it is applied by hand which is very labor intensive.

### Volumetric water content effect on nitrous oxide response from uc mix soilless substrate

It appears that there is a minimum VWC for denitrification to occur in soilless substrates. For UC Mix this threshold is between 30% and 33% VWC (Figure 2 and Table 10) but may be different for other substrates. Although, growing plants below 30% VWC in UC Mix may decrease $N_2O$ emissions, this is not likely to occur because at 30% VWC, plants would begin to experience water stress and there would not be enough water available in the substrate to support plant growth between irrigation events. The greater than one magnitude difference seen between the 0-60% and the 27-42% VWC experiments (Figure 2 and 3) could be due to substrate preparation or incubation condition differences.

### Nitrate concentration effect on nitrous oxide response from uc mix soilless substrate

No significant differences were detected among different nitrate concentrations in the substrate solution (Figure 3). However, the 0 and the 300 mg $NO_3$-N $L^{-1}$ treatments had the smallest and greatest $N_2O$ flux response (Figure 3), respectively. Detectable differences in $N_2O$ flux may have been observed if the magnitude of flux was greater for all treatments. All treatments were incubated at 40% VWC, which was above the threshold for initiating denitrification in UC Mix as determined by the VWC experiments. The increase in $N_2O$ flux from 0 to 25 mg $NO_3$-N $L^{-1}$ observed in this study agrees with previous research from horticultural peats where an increase in total denitrification was observed at similar concentrations (Amha and Bohne, 2011). The lack of significant difference in $N_2O$ flux for UC Mix (Table 12) with different nitrate concentrations in substrate solution indicates that growers are not likely to significantly decrease $N_2O$ emissions by reducing $NO_3$-N concentrations because 50 mg N $L^{-1}$ is the recommended rate for growing woody ornamentals (Evans, 2014).

### Comparing inorganic nitrogen leaching from mechanically- or manually incorporated controlled release fertilizer

The fir bark:sand substrate with mechanically-incorporated CRF had significantly more total cumulative inorganic N leached compared to manually-incorporated CRF, whether plants were present or not (Figure 4, Tables 13 and 14). This indicates that CRF prills are damaged by the mechanical substrate mixing equipment during the substrate preparation process. Huett and Morris (1999) determined that damaged prills leached more inorganic N than new prills, especially in the first week of their experiment.

The product should last for 8-9 months at an average substrate temperature of 21°C and with a consistent release pattern (Cabrera, 1997; Merhaut *et al.*, 2006). Therefore, 30% of applied nitrogen would be released during the experiment which was similar to the amount of inorganic N leached from the manually-incorporated CRF without plants (Table 13). The large amount of N leached means that plants grown in substrate with mechanically incorporated CRF may not provide sufficient N through the duration of the production cycle.

### Contribution of denitrification and nitrification to nitrous oxide emissions from three organic soilless substrates

Heterotrophic denitrification was the major pathway of $N_2O$-N emissions from all three substrates but played a larger role in the fir bark and peat:fir bark substrates (Figure 5, Tables 15 and 16). Consistent with results from Agner and Schenk, (2006a) saturated substrate in the bottom of the gas cylinders resulted in an anaerobic zone where conditions were prime for denitrification to occur. Six-percent of total $N_2O$-N emissions from peat substrate were from nitrification-derived $N_2O$-N and this contribution could increase if the experiment continued because contribution from nitrification started on day 11 and increased until day 21.

As nitrification-derived $N_2O$-N emissions from all substrates was a small proportion of total emissions, a greater proportion of $NH_4$-N fertilizer, possibly with nitrification inhibitors, could be provided for plant growth. Plants significantly decrease substrate volumetric water content through transpiration which has the potential to decrease $N_2O$-N emitted as substrate water content decreases (Agner and Schenk, 2006b).

### Robustness of controlled release fertilizer coating

The polyurethane- and thermoplastic resin-coated CRF prills were resistant to damage from simulated mechanical incorporation while the polymeric resin-coated CRF was not (Figure 6 and Table 17). The difference in salt leaching between the polymeric resin-coated CRF exposed to simulated mechanical incorporation or not was much greater for the 8-9 month product than the 3-4 month product (Figure 6 and Table 17). The difference between CRF longevity in polymeric resin-coated CRF is the amount of coating applied (Goertz, 1993) with the 3-4 month having a thinner coating which may have been damaged from incorporating CRF into the substrate by gloved hands. For those growers utilizing mechanical substrate preparation equipment, it would be wise to use a polyurethane- or thermoplastic resin-coated CRF.

**Objective 3: Economic analysis for BMPs and mitigation strategies.**

Eliminating surface-applied fertilizer could save $1,445 per hectare through direct reductions in fertilizer and labor costs of $1,195 and $250 per hectare, respectively.

A grower incorporating Osmocote Plus 15-9-12 fertilizer into #3 containers could save over $900 per hectare if they switched to a gentler incorporation method. This is a 28% savings in fertilizer nitrogen applied per hectare which, for a $500,000 fertilizer budget results in a savings of $142,000. There is no financial benefit to using peat moss as a growing substrate to reduce $N_2O$ emissions because the high cost of transporting peat moss to California. Peat moss, harvested in north eastern Canada, costs about seven times as much as California-harvested fir bark. It would cost a California grower over $22,000 per hectare to switch to using peat moss instead of fir bark. However, in locations closer to peat moss production, a grower could reduce this cost because a significant amount of the price is connected to transportation. A grower utilizing a CRF product resistant to mechanical incorporation could reduce their CRF costs by $561 – 693 per hectare or a 28 – 37% savings compared to using a product that would be easily damaged.

## Conclusions

The results of the system nitrogen balance show that the original NMP and the newer Irrigation and Nitrogen Management Plan (INMP) do not work well for crops grown in containers using soilless substrate production systems. The system nitrogen balance calculated from this research shows that using the NMP will result in gross overestimation of potentially leachable nitrogen. The NMP and INMP will estimate that 39% of applied nitrogen is potentially leachable but our research indicates that less than 3% of applied nitrogen leached into the soil below the growing bed. Therefore, implementation of nutrient and water best management practices should be utilized for soilless substrate production systems instead of the NMP and INMP worksheets. Best management practices to mitigate $N_2O$ emissions from soilless substrate production systems needs to be completed to help California meet carbon neutrality goals. Further research into organic substrate properties effect on heterotrophic denitrification-derived $N_2O$ emissions could potentially identify additional opportunities to mitigate global warming potential from soilless substrates.

## H. Challenges

We were hindered in providing additional Nursery Nitrogen Management Workshops in 2020 because of restrictions due to the novel coronavirus. However, we will continue to share the results through oral and written media with as many audiences as possible.

There was a delay in research because non-essential research activities at UC Davis were halted for a period during the Spring 2020. However, FREP granted a no-cost extension that allowed us to complete the project and meet objectives.

## I. Project impacts

We developed a system nitrogen balance that shows the NMP calculations grossly overestimate the amount of potentially leachable nitrogen from container-plant production. We have shared these results with the Central Valley Regional Water Quality Control Board to influence an alternative reporting option for container-plant nurseries. This is becoming more impactful as additional Regional Water Quality Control Boards adopt INMP requirements. Our recommendation is for container-plant nurseries to document irrigation and nitrogen best management practices to reduce nitrate leaching into groundwater and meet reporting requirements.

We identified that California nursery production results in very large $N_2O$ emissions and there is a need for mitigation. We identified that denitrification contributed the majority of $N_2O$ emitted from soilless substrates and variability in the magnitude of $N_2O$ emissions exists among different soilless substrate organic constituents. These results provide a foundation for developing best management practices to reduce $N_2O$ emissions from soilless substrates and will help California meet carbon neutrality goals.

We determined that some controlled-release fertilizer coatings are less resistant to mechanical damage and should not be used with mechanical-incorporation equipment. By identifying controlled-release fertilizer coatings that are more resistant to mechanical damage, we have provided the nursery industry with alternatives that will reduce nitrogen leaching and save money. We are assisting a Central Valley nursery in using a controlled-release fertilizer that will withstand their mechanical-incorporation equipment, thereby reducing nitrogen loss and improving economic sustainability.

## J. Outreach activities summary

*Substrate, water, and nutrient relationship.* Everde Growers Plant Health Meeting. December 1, 2021. Virtual. Audience 27. Industry audience. This was an effective presentation and explained the value of keeping fertilizers in soilless substrates for maintaining plant health. However, the audience education level may have been below the level of the material presented.

*Management of gaseous and soluble nitrogen loss in soilless container plant nursery systems.* Bruno J.L. Pitton PhD graduate seminar. November 16, 2021. Davis, CA and virtual. Audience 32. Industry and academic audience. This was a very effective presentation and we had a thoughtful discussion about nitrogen in nursery production.

*Controlled release fertilizers.* ENH 120 Management of Container Media. October 28, 2021. Davis, CA. Audience 16. Academic audience. This was a very effective presentation, we received a lot of excellent questions and had a thoughtful discussion about controlled-release fertilizers.

*Nitrogen fate in nursery production.* Fertilizer Research and Education Program and Western Plant Health Association Annual Conference. October 27, 2021. San Luis

Obispo, CA. Audience 120. Industry, regulatory, and academic audience. This was a very effective presentation and there were many thoughtful questions and a discussion about controlled release fertilizer afterwards

*Nitrogen fate in nursery production.* Virtual Climate Action and Agriculture Symposium. May 26, 2021. Virtual. Audience 41. Industry, regulatory, and academic audience. This was a very effective presentation and there were many thoughtful questions about how the research affects nitrogen management plans in nursery production.

*Controlled release fertilizers.* ENH 120 Management of Container Media. November 5, 2020. Davis, CA. Audience 15. Academic audience. This was a very effective presentation, we received a lot of excellent questions and had a thoughtful discussion about controlled-release fertilizers.

*Nitrogen leaching from controlled-release fertilizer*. Plant California Alliance Research Meeting. September 16, 2020. Virtual. Audience 18. Academic and industry audience. This was a very effective presentation and we had many good questions afterwards.

*Nitrogen fate in nursery production.* Nitrogen Management Plan Workshop. March 11, 2020. Winters, CA. Audience 20. Industry, regulatory, and academic audience. This was a very effective presentation and we had a thoughtful discussion about NMPs and how they apply to the nursery industry.

*Nitrogen nutrition in containerized nursery crops.* Nitrogen Management Plan Workshop. March 11, 2020. Winters, CA. Audience 20. Industry, regulatory, and academic audience. This was a very effective presentation.

*Managing irrigation to reduce runoff.* Nitrogen Management Plan Workshop. March 11, 2020. Winters, CA. Audience 20. Industry, regulatory, and academic audience. This was a very effective presentation.

*Controlled release fertilizers.* ENH120 Management of Container Media. October 31, 2019. Davis, CA. Audience 15. Academic audience. This was a very effective presentation, we received a lot of excellent questions and had a thoughtful discussion about controlled-release fertilizers.

*Nitrogen management plans in nursery production.* Cultivate. July 14, 2019. Columbus, Ohio. Audience 25. Industry audience. This was a very effective presentation and we received a lot of excellent questions afterwards.

*Gas flux from a fir-bark substrate at an ornamental nursery*. International Symposium on Growing Media, Composting, and Substrate Analysis. June 24-28, 2019. Milan, Italy. Audience 100. Academic audience. This was a very effective presentation and we received a lot of excellent comments and questions afterwards.

*A system nitrogen balance for container plant production: Filling knowledge gaps for nitrogen management plans.* California Association of Nurseries and Garden Centers Research Advisory Committee. February 13, 2019. Davis, California. Audience 40. Academic and industry audience. This was a very effective presentation and we received a lot of excellent questions afterwards from industry attendees.

*Fertilization practices and Nitrogen Management Plans in nursery production.* California Department of Food and Agriculture – Fertilizer Research and Education Program and Western Region Certified Crop Advisor Nitrogen Management Update, Anaheim, CA. October 13, 2018. Audience 150+. This was a very effective presentation to a large industry audience.

*Nitrogen Management Plans: Filling in the knowledge gaps for container nursery grower compliance*. AmericanHort Webinar. September 6, 2018. 29 Audience 9. This was an effective webinar to inform growers about the research being undertaken.

## K. Literature Cited

Agner, H., Schenk, M.K., 2006a. Nitrogen emissions ($N_2O$+$N_2$)and redox potential of a peat medium during pot plant cultivation. European Journal of Horticultural Science 71, 237-239.

Agner, H., Schenk, M.K., 2006b. Plant effects on variability of denitrification N emissions in cultures of potted ornamental plants. European Journal of Horticultural Science 71, 15-20.

Amha, Y., Bohne, H., 2011. Denitrification from the horticultural peats: effects of pH, nitrogen, carbon, and moisture contents. Biology and Fertility of Soils 47, 293-302.

Cabrera, R.I., 1997. Comparative evaluation of nitrogen release patterns from controlled-release fertilizers by nitrogen leaching analysis. Hortscience 32, 669-673.

Cabrera, R.I., 2003. Nitrogen balance for two container-grown woody ornamental plants. Scientia Horticulturae 97, 297-308.

Evans, R.Y., 2014. Nutrition and fertilization, In: Newman, J.P. (Ed.), Container Nursery Production and Business Management Manual. University of California, Agriculture and Natural Resources Communication Services, Richmond, CA, pp. 69-80.

Fulcher, A., LeBude, A.V., Owen, J.S., White, S.A., Beeson, R.C., 2016. The Next ten years: Strategic vision of water resources for nursery producers. Horttechnology 26, 121-132.

Fuss, R., 2019. gasfluxes: Greenhouse gas flux calculation from chamber measurements., R package version 0.4-3 ed.

Geisseler, D., 2016. Nitrogen concentrations in harvested plant parts - A literature overview. University of California, Davis.

Goertz, H.M., 1993. Controlled release technology, Agricultural. Kirk-Othmer Encyclopedia of Chemical Technology.

Harter, T., Lund, J., 2012. Addressing nitrate in California’s drinking water: Executive summary.

Huett, D.O., Morris, S.C., 1999. Fertiliser use efficiency by containerised nursery plants - 3. Effect of heavy leaching and damaged fertiliser prills on plant growth, nutrient uptake, and nutrient loss. Australian Journal of Agricultural Research 50, 217-222.

Merhaut, D.J., Blythe, E.K., Newman, J.P., Albano, J.P., 2006. Nutrient release from controlled-release fertilizers in acid substrate in a greenhouse environment: I. Leachate electrical conductivity, pH, and nitrogen, phosphorus, and potassium concentrations. Hortscience 41, 780-787.

Narvaez, L., Caceres, R., Marfa, O., 2012. Effects of climate and fertilization strategy on nitrogen balance in an outdoor potted crop of *Viburnum tinus* L. Spanish Journal of Agricultural Research 10, 471-481.

Narvaez, L., Caceres, R., Marfa, O., 2013. Effect of different fertilization strategies on nitrogen balance in an outdoor potted crop of *Osteospermum ecklonis* (DC.) Norl. 'Purple Red' under Mediterranean climate conditions. Spanish Journal of Agricultural Research 11, 833-841.

Richards, L.A., 1954. Diagnosis and improvement of saline and alkali soils. LWW.

Sørensen, P., Jensen, E.S., 1991. Sequential diffusion of ammonium and nitrate from soil extracts to a polytetrafluoroethylene trap for $^{15}$N determination. Analytica chimica acta 252, 201-203.

Wright, R.D., 1986. The pour-through nutrient extraction procedure. Hortscience 21, 227-229.

## L. Appendix

Table 1. Mean nitrogen mass applied as fertilizer, sold in plant/substrate, emitted as $N_2O$-N gas from substrate, in runoff, and unaccounted for in two experimental bed systems at a Central Valley nursery. All means comparisons and p-values were determined using Student's t-test.

| | | | Nitrogen (kg N bed$^{-1}$) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Inputs | | | | | | Outputs | | | | | | | | | |
| | Plants bed$^{-}$ | | Substrate | | Irrigation | | fertilizer | | Shoot uptake | | Substrate | | $N_2O$-N | | Runoff | | Unaccountable | |
| **Bed type** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** |
| Lined | 153 | 0.82 | 4.680 | 0.026 | 0.007 | 0.923 | 1.071 | 0.006 | 0.296 | 0.016 | 3.317 | 0.018 | 0.089 | 0.000 | 0.521 | 0.058 | 1.683 | 0.064 |
| Unlined | 151 | 5.44 | 4.773 | 0.179 | 0.007 | 0.565 | 1.057 | 0.040 | 0.292 | 0.110 | 3.274 | 0.123 | 0.087 | 0.003 | 0.377 | 0.063 | 1.797 | 0.071 |
| P-value | 0.77 | | 0.94 | | 0.87 | | 0.94 | | 0.94 | | 0.94 | | 0.77 | | 0.016 | | 0.054 | |
| Replicate | 4 | | 4 | | 4 | | 4 | | 4 | | 4 | | 4 | | 4 | | 4 | |

Table 2. Mean and standard deviation of total cumulative $N_2O$ emissions, total mean cumulative global warming potential, and number of replicates from three treatments with different amounts (0, 5, or 35 g) of surface-applied 20-9-9 fertilizer.

| 20-9-9 surface applied (g) | Mean Cumulative $N_2O$ (mg pot$^{-1}$) | SD Cumulative $N_2O$ (mg pot$^{-1}$) | Mean Cumulative GWP (g $CO_2$e pot$^{-1}$) | SD Cumulative GWP (g $CO_2$e pot$^{-}$ | # replicates |
|---|---|---|---|---|---|
| 0 | 801 | 115 | 239 | 34.3 | 8 |
| 5 | 704 | 159 | 210 | 38.9 | 8 |
| 35 | 933 | 131 | 278 | 47.4 | 8 |

Table 3. Results of Tukey test for mean cumulative nitrous oxide ($N_2O$) emissions for three levels of 20-9-9 surface-applied fertilizer.

| 20-9-9 surface applied (g) | 0 | 5 | 35 |
|---|---|---|---|
| 0 | *** | 0.348 | 0.154 |
| 5 | 0.348 | *** | 0.008 |
| 35 | 0.154 | 0.008 | *** |

Table 4. Mean and standard deviation of plant growth parameters for three levels of 20-9-9 surface-applied fertilizer.

| 20-9-9 surface applied (g) | Mean Dry Wt. (g) | SD Dry Wt. (g) | Mean RPGI (cm$^3$) | SD RPGI (cm$^3$) | # replicate |
|---|---|---|---|---|---|
| 0 | 124 | 55.9 | 0.4 | 0.007 | 8 |
| 5 | 91 | 41.6 | 0.038 | 0.005 | 8 |
| 35 | 109 | 63.7 | 0.035 | 0.006 | 8 |

Table 5. Results of Tukey test (p-values) for mean harvested dry biomass for three levels of 20-9-9 surface-applied fertilizer.

| 20-9-9 surface applied (g) | 0 | 5 | 35 |
|---|---|---|---|
| 0 | *** | 0.455 | 0.849 |
| 5 | 0.455 | *** | 0.781 |
| 35 | 0.849 | 0.781 | *** |

Table 6. Results of Tukey test (p-values) for mean plant growth index for three levels of 20-9-9 surface-applied fertilizer.

| 20-9-9 surface applied (g) | 0 | 5 | 35 |
|---|---|---|---|
| 0 | *** | 0.819 | 0.245 |
| 5 | 0.819 | *** | 0.554 |
| 35 | 0.245 | 0.554 | *** |

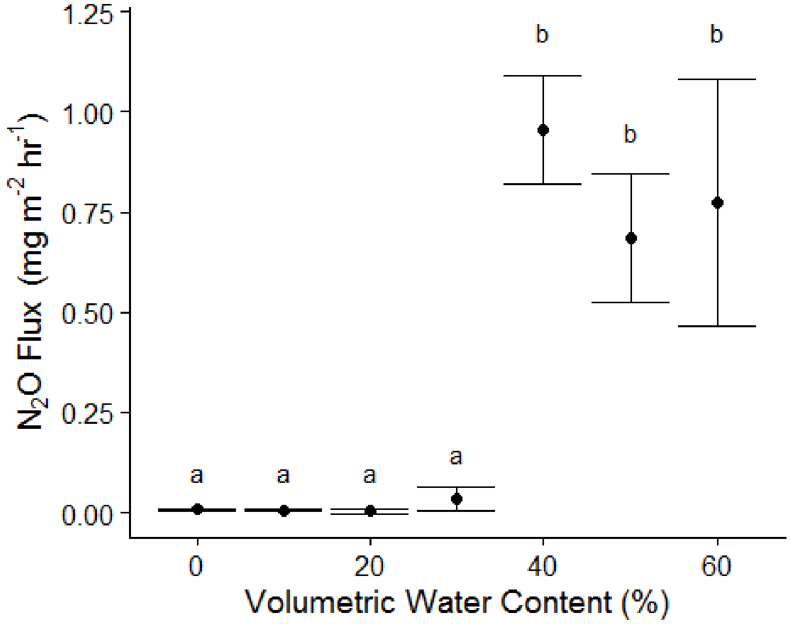

Figure 1. Nitrous oxide ($N_2O$) flux from 25-cm deep media in columns at seven volumetric water contents. Different letters above each treatment indicate significant differences ($p < 0.05$) in mean $N_2O$ flux between different treatments. Error bars represent one standard error of the mean.

Table 7. Mean and standard deviation of nitrous oxide ($N_2O$) flux from 25-cm deep media in columns at seven volumetric water contents (VWC).

| VWC (%) | Mean $N_2O$ Flux (mg $m^{-2}$ $hr^{-1}$) | SD $N_2O$ Flux (mg $m^{-2}$ $hr^{-1}$) | # replicate |
|---|---|---|---|
| 0 | 0.005 | 0.007 | 3 |
| 10 | 0.004 | 0.004 | 3 |
| 20 | 0.002 | 0.01 | 3 |
| 30 | 0.023 | 0.052 | 3 |
| 40 | 0.636 | 0.243 | 3 |
| 50 | 0.455 | 0.288 | 3 |
| 60 | 0.514 | 0.561 | 3 |

Table 8. Results of Tukey test (p-values) for different volumetric water content (VWC) effect on $N_2O$ flux.

| VWC (%) | 0 | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|---|
| 0 | *** | 1.000 | 0.996 | 0.865 | 0.0001 | 0.0001 | 0.0001 |
| 10 | 1.000 | *** | 0.996 | 0.870 | 0.0001 | 0.0001 | 0.0001 |
| 20 | 0.996 | 0.996 | *** | 0.551 | 0.0001 | 0.0001 | 0.0001 |
| 30 | 0.865 | 0.870 | 0.551 | *** | 0.0001 | 0.0001 | 0.0001 |
| 40 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | *** | 0.973 | 0.979 |
| 50 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.973 | *** | 1.000 |
| 60 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.979 | 1.000 | *** |

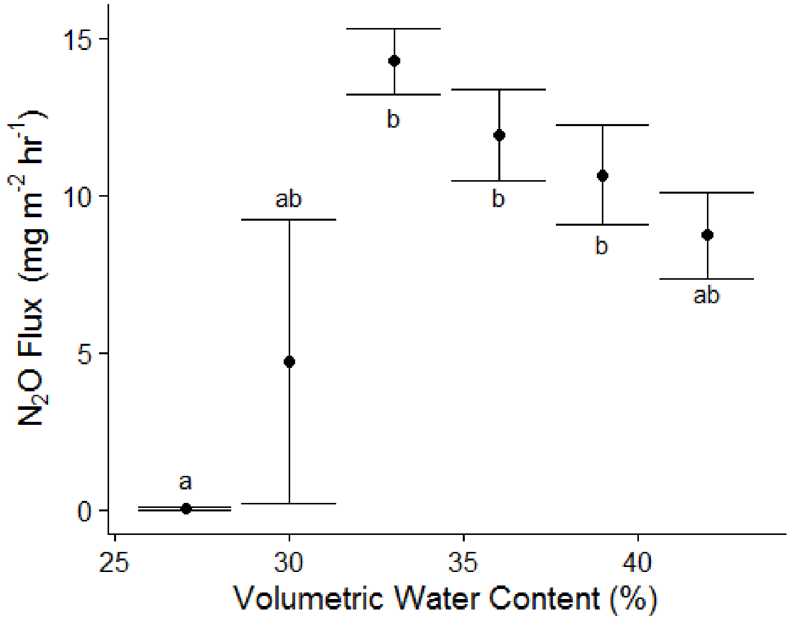

Figure 2. Mean nitrous oxide ($N_2O$) flux from 25-cm deep media in columns at six volumetric water contents (VWC). Different letters above each treatment indicate significant differences ($p < 0.05$) in mean $N_2O$ flux between different treatments. Error bars represent one standard error of the mean.

Table 9. Mean and standard deviation of nitrous oxide ($N_2O$) flux from 25-cm deep media in columns at seven volumetric water contents (VWC).

| VWC (%) | Mean $N_2O$ Flux ($mg\ m^{-2}\ hr^{-1}$) | SD $N_2O$ Flux ($mg\ m^{-2}\ hr^{-1}$) | # replicate |
|---|---|---|---|
| 27 | 0.022 | 0.058 | 3 |
| 30 | 3.137 | 7.785 | 3 |
| 33 | 9.493 | 1.811 | 3 |
| 36 | 7.936 | 2.488 | 3 |
| 39 | 7.086 | 2.765 | 3 |
| 42 | 5.812 | 2.367 | 3 |

Table 10. Results of Tukey test (p-values) for different volumetric water content (VWC) effect on $N_2O$ flux.

| VWC (%) | 27 | 30 | 33 | 36 | 39 | 42 |
|---|---|---|---|---|---|---|
| 27 | *** | 0.649 | 0.0055 | 0.0198 | 0.0401 | 0.113 |
| 30 | 0.649 | *** | 0.072 | 0.240 | 0.42 | 0.769 |
| 33 | 0.0055 | 0.072 | *** | 0.968 | 0.834 | 0.490 |
| 36 | 0.0198 | 0.240 | 0.968 | *** | 0.998 | 0.892 |
| 39 | 0.0401 | 0.42 | 0.834 | 0.998 | *** | 0.986 |
| 42 | 0.113 | 0.769 | 0.490 | 0.892 | 0.986 | *** |

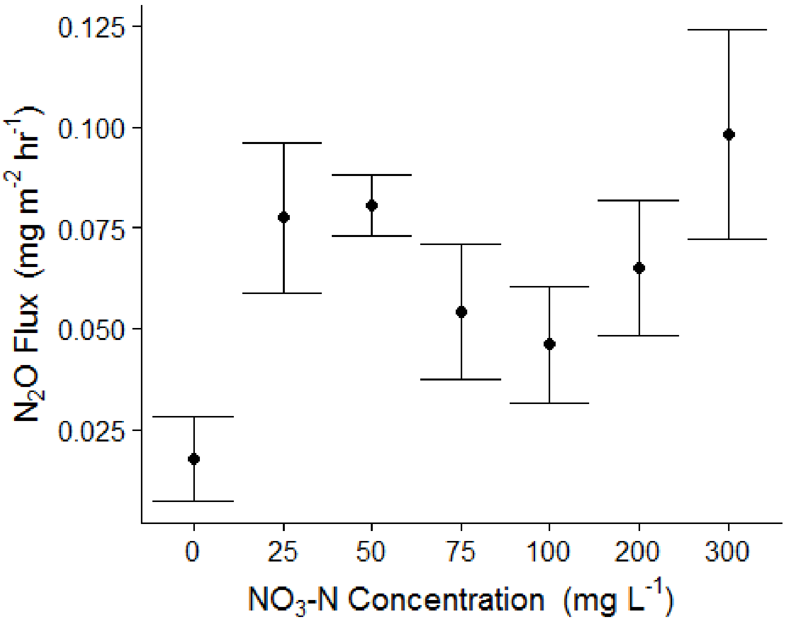

Figure 3. Mean nitrous oxide ($N_2O$) flux from 25-cm deep media in columns at six nitrate-nitrogen ($NO_3$-N) concentrations. Different letters above each treatment indicate significant differences ($p < 0.05$) in mean $N_2O$ flux between different treatments. Error bars represent one standard error of the mean.

Table 11. Mean and standard deviation of nitrous oxide ($N_2O$) flux from 25-cm deep media in columns at seven nitrate concentrations in substrate solution.

| Nitrate Conc. (mg L$^-$ | Mean $N_2O$ Flux (mg m$^{-2}$ hr$^{-1}$) | SD $N_2O$ Flux (mg m$^{-2}$ hr$^{-1}$) | # replicates |
|---|---|---|---|
| 0 | 0.018 | 0.018 | 3 |
| 25 | 0.077 | 0.032 | 3 |
| 50 | 0.081 | 0.013 | 3 |
| 75 | 0.054 | 0.029 | 3 |
| 100 | 0.046 | 0.025 | 3 |
| 200 | 0.065 | 0.029 | 3 |
| 300 | 0.098 | 0.045 | 3 |

Table 12. Results of Tukey test (p-values) for different nitrate concentrations effect on $N_2O$ flux.

| Nitrate Conc. (mg L$^-$ | 0 | 25 | 50 | 75 | 100 | 200 | 300 |
|---|---|---|---|---|---|---|---|
| 0 | *** | 0.2228 | 0.1814 | 0.7216 | 0.8843 | 0.4532 | 0.0518 |
| 25 | 0.2228 | *** | 1 | 0.9487 | 0.8293 | 0.9981 | 0.9712 |
| 50 | 0.1814 | 1 | *** | 0.9115 | 0.7632 | 0.9934 | 0.9872 |
| 75 | 0.7216 | 0.9487 | 0.9115 | *** | 0.9998 | 0.9989 | 0.5336 |
| 100 | 0.8843 | 0.8293 | 0.7632 | 0.9998 | *** | 0.9803 | 0.3543 |
| 200 | 0.4532 | 0.9981 | 0.9934 | 0.9989 | 0.9803 | *** | 0.7978 |
| 300 | 0.0518 | 0.9712 | 0.9872 | 0.5336 | 0.3543 | 0.7978 | *** |

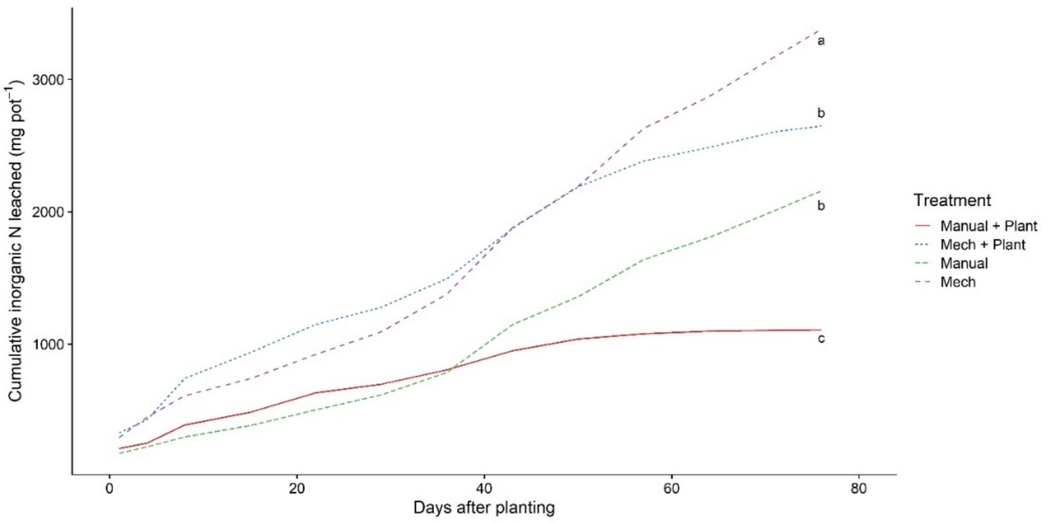

Figure 4. Mean cumulative inorganic N leached from the substrate with controlled-release fertilizer mechanically- or manually-incorporated and with or without a plant.

Table 13. Total mean inorganic nitrogen (ammonium and nitrate) leached from fir bark: sand substrate with controlled release fertilizer incorporated mechanically or manually and with or without plants.

| Treatment | Mean Total Inorganic N leached (mg) | SD Total Inorganic N leached (mg) | # replicates | Total Applied N Leached[a] |
|---|---|---|---|---|
| Manual + Plant | 1,106 | 350 | 10 | 20.4% |
| Mech + Plant | 2,647 | 422 | 10 | 48.9% |
| Manual | 2,157 | 249 | 10 | 28.9% |
| Mech | 3,379 | 664 | 10 | 45.2% |

Table 14. Results of Tukey test for mean total inorganic nitrogen leached from fir bark: sand substrate with controlled release fertilizer incorporated mechanically or manually and with or without plants.

| **Treatment** | Hand + Plant | Mech + Plant | Hand | Mech |
|---|---|---|---|---|
| Manual + Plant | *** | < 0.0001 | < 0.0001 | < 0.0001 |
| Mech + Plant | < 0.0001 | *** | 0.0875 | 0.0044 |
| Manual | < 0.0001 | 0.0875 | *** | < 0.0001 |
| Mech | < 0.0001 | 0.0044 | < 0.0001 | *** |

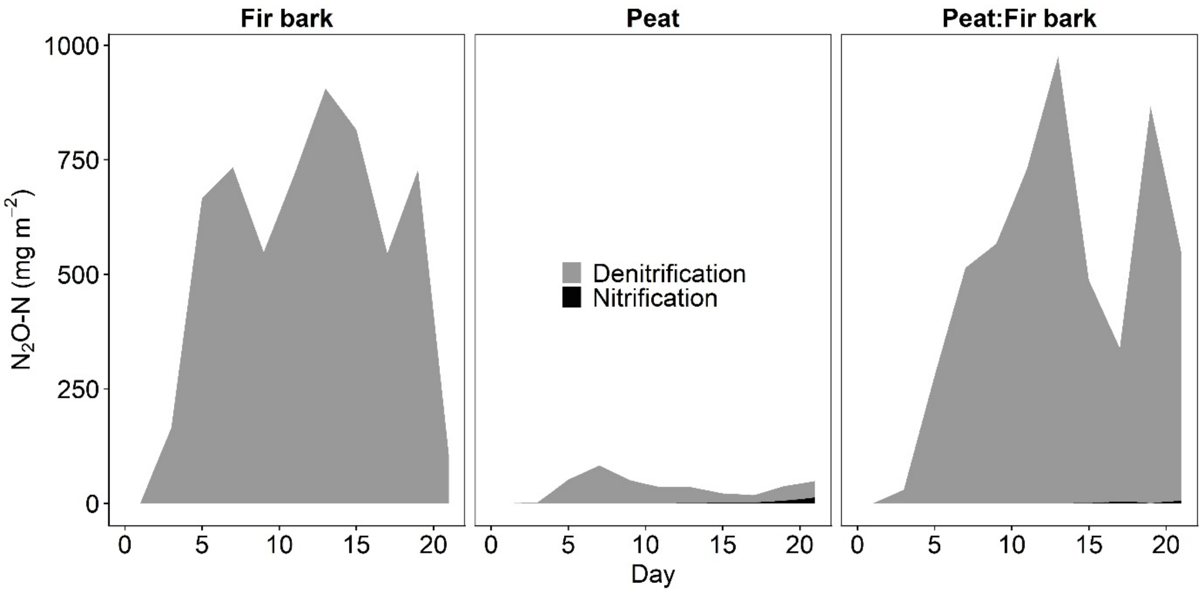

Figure 5. Contribution of heterotrophic denitrification or nitrification to nitrous oxide-nitrogen emitted from three substrates with $NH_4NO_3$ applied.

Table 15. Mean total $N_2O$-N emitted over 21 days from three substrates with $NH_4NO_3$ applied.

| Media | Total $N_2O$-N emitted (g $m^{-2}$) | Nitrification-derived emissions | # replicates |
|---|---|---|---|
| Fir bark | 11.81 | 0.009% | 12 |
| Peat | 0.70 | 5.898% | 12 |
| Peat:Fir bark | 10.37 | 0.207% | 12 |

Table 16. Results of Tukey test for mean total $N_2O$-N emitted over 21 days from three substrates with $NH_4NO_3$ applied.

| **Media** | Fir bark | Peat | Peat:Fir bark |
|---|---|---|---|
| Fir bark | *** | 0.0001 | 0.0407 |
| Peat | 0.0001 | *** | 0.0001 |
| Peat:Fir bark | 0.0407 | 0.0001 | *** |

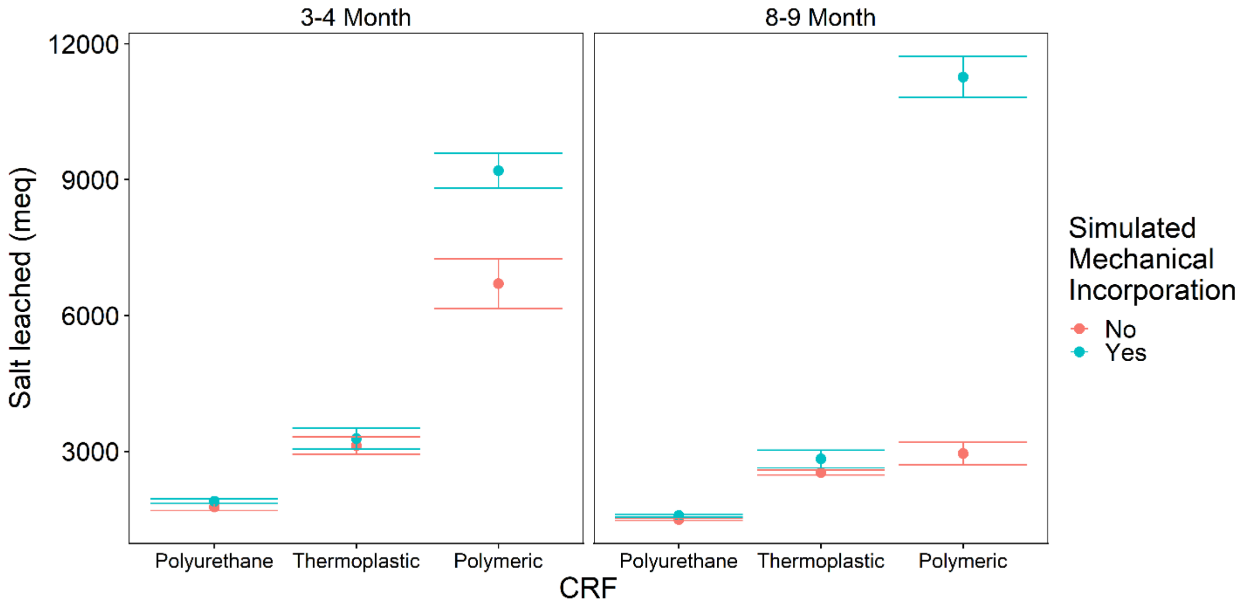

Figure 6. Mean total salts leached from two different longevities of controlled-release fertilizer prills coated with different materials and with or without exposure to simulated mechanical incorporation. Error bars represent one standard error of the mean.

Table 17. Mean total salts leached from two different longevities of controlled-release fertilizer prills coated with different materials. P-value indicates significant differences observed between CRF prills that were and were not exposed to simulated mechanical incorporation.

| CRF coating | Longevity (mos) | Simulated Mech Incorp | Mean salts leached (meq) | SD salts leached (meq) | # Replicates | % Leached of Total Applied | p-value |
|---|---|---|---|---|---|---|---|
| Polyurethane | 3-4 | No | 1770 | 172.8 | 5 | 1.7% | 0.348 |
| | | Yes | 1902 | 119.5 | 5 | 1.8% | |
| | 8-9 | No | 1498 | 48.1 | 5 | 1.5% | 0.4859 |
| | | Yes | 1583 | 66.6 | 5 | 1.5% | |
| Thermoplastic Resin | 3-4 | No | 3127 | 443.7 | 5 | 3.1% | 0.5487 |
| | | Yes | 3284 | 513.9 | 5 | 3.3% | |
| | 8-9 | No | 2536 | 121.2 | 5 | 2.6% | 0.2 |
| | | Yes | 2833 | 436.1 | 5 | 2.9% | |
| Polymeric Resin | 3-4 | No | 6705 | 1224.9 | 5 | 6.3% | 0.0001 |
| | | Yes | 9199 | 855.9 | 5 | 8.6% | |
| | 8-9 | No | 2951 | 557.3 | 5 | 2.7% | 0.0001 |
| | | Yes | 11267 | 1014.1 | 5 | 10.2% | |

Table 18. Nitrogen mass balance for a typical container production system. Nitrogen mass of applied fertilizer, sold with plant/substrate, emitted as nitrous oxide gas, in runoff, infiltrated into soil, unaccounted for, and denitrified from soil bed.

| | **Input[a]** | **Sold[b]** | **Substrate $N_2O$-N** | **Bed runoff[c]** | **Bed infiltration[d]** | **Bed ($N_2$ + $N_2O$)-N** | **Unaccounted[e]** |
|---|---|---|---|---|---|---|---|
| Nitrogen (kg ha$^{-1}$) | 917.83 | 568.23 | 13.93 | 59.70 | 22.47 | 0.33 | 253.18 |
| Percent of Input N | 100.0% | 61.9% | 1.5% | 6.5% | 2.4% | <0.01% | 27.7% |

a. Input N is the sum of N from incorporated CRF, fir bark, and plant roots at transplanting, fertilizer surface-applied on day 3, and irrigation water throughout the experiment.
b. The amount of N sold is the sum of total N in plant product at time plants are ready for sale and includes N remaining in the CRF, fir bark substrate, and plant shoots and roots.
c. Calculated as the total mass of N in the runoff from the unlined beds.
d. The mass of N infiltrating the soil below the growing bed was calculated as the difference of runoff N from the lined and unlined beds.
e. Unaccounted N is the sum of Sold, Substrate $N_2O$-N, Bed runoff, Bed infiltration, and Bed ($N_2$ + $N_2O$)-N subtracted from the total Input N.

## M. Factsheet

**Project title: A system nitrogen balance for container plant production.**
**FREP grant number: 17-0516-000-SA**

**Project leaders:**

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**Counties:** Sacramento and Yolo

**Highlights:**

- The system nitrogen balance shows that Nitrogen Management Plan calculations overestimate potentially leachable nitrogen.
- Nitrous oxide emissions from soilless substrate production systems are significant and best management practices should be developed.
- Nitrous oxide from soilless substrates are predominantly from denitrification.
- Mechanical-incorporation of polymeric resin-coated controlled-release fertilizer into soilless substrate can increase nitrogen leaching.

## INTRODUCTION:

A large proportion of groundwater in the Central Valley is either contaminated with nitrate or at risk of contamination due to fertilizer and manure use on cropland. To reduce the risk of future nitrate contamination to groundwater, the Central Valley Regional Water Quality Control Board (CVRWQCB) required the implementation of Nitrogen Management Plans (NMP) by growers within the Central Valley Basin. The NMP consisted of documenting yearly nitrogen (N) inputs and output. Output N was based on harvested yield and the N content of that material with the mount of N in harvested parts of major crops, like almonds or table grapes, were readily available. Potential leachable N was calculated by subtraction of N outputs from inputs. However, some agricultural commodities, like container-grown nursery crops, did not fit neatly into the NMP worksheet.

Container plant production is very different and much more complex than the in-ground production of annually harvested nut, fruit, vegetable, or cereal crops. In nurseries, thousands of different plant taxa may be grown in specially formulated growing substrates in a range of sizes from small propagation stock to large trees. The whole product, including the roots and substrate, is harvested continuously and shipped off of the nursery grounds to retail and other customers. A large portion of applied N can remain in the container substrate at the time of shipment. Container nursery production is prone to high losses of aqueous N from growing areas as irrigation with nutrient solution is common and water application efficiency is poor due to the prevalence of overhead irrigation and wide plant spacing. There are nursery specific practices that may encourage denitrification and reduce N leaching into groundwater, including: frequent irrigation to maintain container substrate moisture content and saturated conditions in the soil below growing beds.

As nursery production uses large amounts of synthetic fertilizers including N, it was necessary to: 1) identify what happens to the N applied in production and 2) mitigate environmentally harmful discharges of N. We proposed developing a whole system N balance for container plant production focused on the growing bed and the plants produced thereon. After the N balance was developed, mitigation strategies for environmentally harmful N discharges were evaluated.

## METHODS:

We conducted an experiment to determine the fate of applied nitrogen in woody ornamental container-plant production. Environmentally-harmful discharges were identified as aqueous nitrogen leached and nitrous oxide ($N_2O$) emitted from the soilless substrate and experiments were conducted to mitigate these losses.

## FINDINGS:

The system N balance indicated that NMP calculations overestimated the amount of potentially leachable nitrogen from container-plant production. Mechanically incorporating polymeric resin-coated controlled-release fertilizer resulted in damage to prills and over two times more inorganic N leaching losses than gentler incorporation methods. However, controlled-release fertilizer coated in polyurethane or thermoplastic resin resisted mechanical damage and resulted in much lower leaching losses of mineral fertilizer. Reducing concentrations of N applied to soilless substrates did not reduce $N_2O$ emissions from the tested soilless substrate. In the same substrate, reducing water content below 30% volumetric water content ceased $N_2O$ emissions, but this may not be feasible in production because 30% volumetric water content leaves very little moisture for plant growth. Almost all $N_2O$ emissions from soilless substrates were derived from denitrification and the magnitude varies with type of organic amendment. As the NMP calculations overestimated potentially leachable N from nursery production, implementation and reporting of irrigation and N best management practices should be used in place of the NMP for reducing nitrate leaching to groundwater from soilless substrate production systems. Future work should develop best management practices to mitigate $N_2O$ from soilless substrates and help California meet climate neutrality goals.