**ANNUAL REPORT**
**COMPREHENSIVE RESEARCH ON RICE**
**January 1, 2010-December 31, 2010**

PROJECT TITLE: Improving fertilizer guidelines for California's changing rice climate.

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## OBJECTIVES OF THE PROPOSED RESEARCH

Our overall objective of this project is to develop fertilizer guidelines for California rice growers which are economic viable and environmentally sound. Toward this objective, we proposed the following specific objectives for 2010:

1. To improve N fertilizer guidelines for stale seedbed systems.
2. Quantify $N_2O$ and $CH_4$ emissions in California rice systems
3. Quantify N losses due to $NO_3$ leaching in California rice systems
4. Evaluate the effectiveness of early (fall or early spring) applied P and P applied up to 30 DAS in relation to P availability and rice growth. This work will be carried out in conjunction with David Spencer.
5. Development of a web based decision tool to help growers determine how long they will need to keep their fields flooded for different weeds-based on P applications and temperature and weeds. Done in conjunction with Albert Fisher

## CONCISE GENERAL SUMMARY OF CURRENT YEAR'S RESULTS:

1. We were not able to conduct research on stale seedbeds due to unusual climate conditions.
2. Research on GHG emissions highlight the importance between agronomic management and environmental quality in rice systems, where management practices appear to regulate GHG emissions more than N fertilizer rate. Nitrification appears to be the major process involved in $N_2O$ emissions in flooded rice systems, although denitrification during the dry down periods may also contribute to overall emissions. Methane emissions were not directly affected by addition of fertilizer N but high fertilizer N application may lead to high crop residue inputs which eventually increase $CH_4$ emissions. Frequent flood-drain cycles resulted to high $N_2O$ emission events. To mitigate emissions, continuous flooding practices and avoid flood-drain cycles during the growing season may reduce nitrogen losses from rice fields and consequently lower global warming potentials. Also, applying N deep into the soil as aqua ammonia may reduce $N_2O$ losses compared to surface N applications. Application of high N fertilizer does not necessarily increase GWP values provided that rice is grown with best management practice resulting in high resource use efficiency.
3. Soil $NO_3$ beneath rice fields were low. The reasons that $NO_3$ levels are low may be due to one or more of the following factors:
    a. Soil nitrate levels are low in the surface soil to begin with (0.4 to 4.2 ppm)
        i. Winter weeds take up
        ii. Straw immobilizes
    b. Growers do not (should not) apply $NO_3$ fertilizer
    c. Soils remain flooded for much of the season preventing nitrification ($NH_4$ to $NO_3$)
    d. Denitrification rates are very high ($NO_3$ to N gas)
    e. Hydraulic conductivity is very low preventing downward movement of $NO_{3.}$
4. In summary we can make the following recommendations for growers wishing to reduce algal growth by applying P at a different time.
    a. If the field is not P deficient then P fertilizer can be applied at anytime, including the Fall. Most fields in the Sacramento Valley are not deficient in P.

b. If the field is deficient and the grower wishes to apply in the Fall, then a higher P rate should be used initially.
c. If the field is P deficient and the grower wishes to apply at planting then the P fertilizer should be incorporated as much as possible.
d. If the field is P deficient, P can be applied as late as 35 DAS (this is conservative). We recommend applying the P when the rice is above the water surface (3-4 weeks). If applying after planting then the water should be held for a 2 wk period.

5. In summary, we hypothesized that early season physiological temperatures in the Sacramento Valley are heterogeneous and spatially dependent and that they can be used in concert with lab derived parameters to predict weed emergence at the field scale. We confirmed the spatial and temporal heterogeneity of watergrass-specific thermal units and found that watergrass emergence can be predicted using lab-derived parameters. Nonetheless, these parameters can be refined based on our 2010 field observations and such refinements should further improve the accuracy of the emergence model. Finally, we observed that air temperature is a better predictor of watergrass emergence than temperatures recorded at the soil surface. Therefore, a decision support tool that uses spatially explicit air temperatures to predict watergrass emergence has the potential to provide useful information to growers managing weeds with alternative stand establishment methods.

## EXPERIMENTAL PROCEDURE TO ACCOMPLISH OBJECTIVES:

### OBJECTIVE 1: TO IMPROVE N FERTILIZER GUIDELINES FOR STALE-SEEDBED SYSTEMS.

2010 was an unusually year in terms of climate. The spring (particularly April and May) were cool and wet. These conditions made it unattractive for growers to collaborate with us on stale-seedbed systems and to experiment with anything out of the ordinary. Given this situation we were unable to conduct any research in this area.

Also, in a meeting with various rice stake holders following the Rice Field Day, it was voiced that at the moment there is relatively little adoption or interest in stale seedbed systems. Given this sentiment, we will no longer continue in this line of research but instead focus on synthesizing past research efforts. At the moment there are good recommendations for the use of stale seedbeds if growers would like to pursue this option. Fertility guidelines are good and can be adjusted for field conditions. If interest in this area increases in the future, we can consider further research at that time.

### OBJECTIVE 2: QUANTIFY $N_2O$ AND $CH_4$ EMISSIONS IN CALIFORNIA RICE SYSTEMS

California rice is produced by direct seeding into standing water with permanent flood for most of the season. Limited acreage is drill seeded and also uses permanent flood after crop establishment. Flooding the rice fields lead to conditions favorable for production of greenhouse gases (GHG) such as methane and nitrous oxide. Methane ($CH_4$) a greenhouse gas is about 20 times more potent than carbon dioxide, and accounts for a fifth of the global atmosphere’s warming potential. Methane emission from rice fields is the net effect of $CH_4$ production (methanogenesis) and $CH_4$ oxidation (methanotrophy). Incorporation of organic matter in flooded fields stimulates $CH_4$ emissions. Nitrous oxide ($N_2O$) is about 296 times warming potential than $CO_2$ with atmospheric lifetime of 114 years. Main source of $N_2O$ in rice systems is application of synthetic N fertilizers. In response to growing demand for rice in the US, the use of synthetic fertilizers is projected to increase, which in turn may accelerate the rate of increase of atmospheric $N_2O$ content. Improved quantitative estimates of the amounts of $CH_4$ and $N_2O$ coming from the rice fields are needed to prioritize effective mitigation rice practices.

## Objectives

- Quantify GHG emissions for conventional and drill seeded rice production systems in the Sacramento Valley as affected by nitrogen (N) fertilizer rates, flooding, and rice seeding practices
- Determine environmental variables and management practices affecting GHG emissions
- Identify mitigation strategies for N fertilizer (e.g. rate, timing, source, placement) and crop management to reduce GHG emissions
- Link annual GHG emissions with grain yields and develop a new metric for assessing mitigation practices in rice cropping systems in California

## Materials and Methods

Two on-farm experiments were implemented in 2010 at sites with contrasting rice establishment practices. The conventional field was aerially seeded at 200 lbs $ac^{-1}$ (M-206) (224 kg seed $ha^{-1}$), and a permanent flood was maintained for the duration of the growing season. In the drill seeded site rice seed (Koshihikari) was drilled into the soil at 75 lbs $ac^{-1}$ (84 kg seed $ha^{-1}$). The field was flooded for several days and then drained to provide an aerobic environment for seedling emergence. Water management during crop establishment differed greatly compared to the conventional system, as the field was flushed three times before the permanent flood was applied approximately one month after seeding. At both sites the field was drained approximately one month prior to harvest.

*Table 1. Fertilizer rates*

*Conventional seeded system.*

| Treatment | Fertilizer N rate, kg N $ha^{-1}$ |
|---|---|
| N0 | 0 |
| N80 | 80 |
| N140 | 140 |
| N140s | 80/60 |
| N200 | 200 |
| N260 | 260 |

*Drill seeded system.*

| Treatment | Fertilizer N rate, kg N $ha^{-1}$ |
|---|---|
| N0 | 0 |
| N50 | 50 |
| N100 | 100 |
| N100s | 25/75 |
| N150 | 150 |
| N200 | 200 |

N rates ranging from 0 to 260 kg N $ha^{-1}$ were applied at the conventional site in the form of aqua ammonia injected three to four inches below the soil surface (Table 1). As growers often apply the majority of their N as aqua ammonia and a smaller portion of their N to the soil surface, we included an additional split N treatment of 80 + 60 kg N $ha^{-1}$ (subsurface aqua ammonia plus surface applied urea, respectively) to assess the effects of N placement on emissions. At the drill seeded site, N rates ranging from 0 to 200 kg N $ha^{-1}$ were applied as urea to the soil surface immediately prior to the permanently flood, which occurred approximately thirty days after seeding. As growers often apply a small amount of N at planting in drill seeded systems and the majority before the permanent flood, we included an additional split N treatment (25 kg N $ha^{-1}$ preplant + 75 kg N $ha^{-1}$ preflood) to assess the effects of N application timing on emissions.

GHG emissions for each N rate were quantified using a vented cylindrical surface chamber, with 14.7 cm diameter and varying chamber height (15.2- 30.5 cm) as rice growth progressed was placed within each N treatment plot. Fluxes were calculated according to the change in gas concentration inside the chamber over a one hour sampling period. To determine peak gas fluxes, daily gas sampling occurred at each site for seven to ten days following any flooding, N application, or field drainage events, after which samples were obtained every four to seven days throughout the growing season.

Other ancillary soil and plant variables related to GHG emissions were measured such as soil and air temperatures, flood water depth, soil exchangeable $NH_4$-N and $NO_3$-N at 15 cm soil depth, plant N uptake, crop biomass after harvest and rice grain yields at 14% moisture content.

## Results

*Grain Yields*

N fertilizer addition significantly increased grain yields at both sites (Table 2). At the conventional site, yields reached maximum levels at 140 kg N $ha^{-1}$ and above, with no further increases observed at 200 or 260 kg N $ha^{-1}$. These results are similar to what has been observed in previous studies and are consistent with current N recommendations that suggest growers apply around 150 kg N $ha^{-1}$ to meet crop N demands. Interestingly, the 140s treatment (which represented the typical grower practice of splitting their N application between subsurface aqua ammonia and surface applied starter N) did not significantly increase grain yields compared to the subsurface 140 kg N $ha^{-1}$. This suggests growers can skip the extra step of applying starter N and more efficiently apply their entire N rate as aqua ammonia.

*Table 2. Grain yields for both GHG study sites (reported in Mg $ha^{-1}$ at 14% moisture). N rate refers to kg N $ha^{-1}$.*

| Conventional | | Drill Seeded | |
|---|---|---|---|
| N rate | Yield | N rate | Yield |
| 0 | 4.3 c | 0 | 4.4 b |
| 80 | 8.5 b | 50 | 7.0 a |
| 140 | 12.0 a | 100 | 8.0 a |
| 140s | 12.2 a | 100s | 7.8 a |
| 200 | 13.1 a | 150 | 8.0 a |
| 260 | 13.1 a | 200 | 8.4 a |

At the drill seeded site, yields were maximized with only 50 kg N $ha^{-1}$. Treatments of 100 kg N $ha^{-1}$ and above resulted in only modest yield gains that were not significantly greater than the 50 kg N $ha^{-1}$ rate. Due to flood-drain cycles during stand establishment, it is difficult to match N supply with N demand in drill seeded rice and N losses may have occurred at higher N rates via ammonia volatilization. In addition, this particular rice variety (Koshihikari) accumulates N more slowly than medium grain Calrose varieties, thus it has lower N fertility requirements of around 50-100 kg N $ha^{-1}$. Regarding the timing of N application, the N100s treatment (split between preplant and preflood) did not result in higher grain yields than the N100 preflood treatment. This suggests although growers typically apply some N at planting, this practice may not translate into yield benefits and a single N application prior to the permanent flood is sufficient.

*Climate*

Temperature differences occurred during the main growing season (May 7 to October 18), with air temperature, ranging from 10.3 to 28.7°C and soil temperature ranging from 15.7 to 27.6°C for both rice seeding systems (Fig. 1). Total rainfall was about 338 mm for the months of January to October and only 20 mm during the growing season. A total of 99 rainfall events occurred between Jan to Oct 2010, with only about 15% of those during the growing season. Solar radiation ranged from 24 to 8611 W $m^{-2}$ with high values measured during the growing season. High rates of evapotranspiration (5 to 10 mm) were measured during months of June to August.

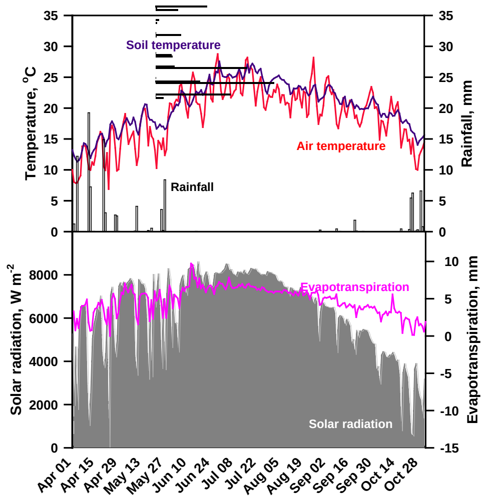


*Figure 1. Seasonal weather conditions in the study sites.*

*Soil Nitrogen Dynamics*

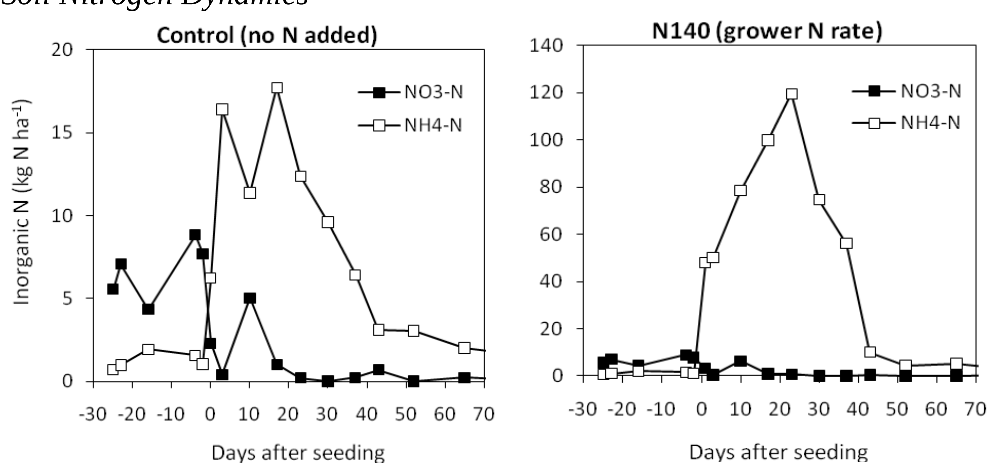


*Figure 2. Soil nitrogen dynamics (0-15 cm) in the control and N140 treatments at the conventional site.*

Soil N dynamics in the control plot at the conventional site show that preseason soil nitrate was lost upon flooding the field for seeding, presumably through denitrification processes (Fig. 2). As such, we expected $N_2O$ emissions to increase during this period, yet this was not observed during our daily gas sampling. Nitrate accumulated again ten days later when the field was drained for the Leather's method, but upon reflooding no significant $N_2O$ emissions occurred, suggesting nitrate is typically reduced completely to $N_2$ under flooded conditions in California rice fields. Soil N dynamics for N140 show that despite much higher soil ammonium concentrations after aqua N application, little N fertilizer underwent nitrification during the Leather's method drain. It appears the majority of N remained as ammonium in the reduced soil layers and was thereby protected from losses. Ammonium values remained high in both control and fertilized plots until mid-tillering, at which point N fertilizer was rapidly consumed by the crop. Soil nitrate values remained low for the duration of the season (data not shown), even after the field was drained prior to harvest.

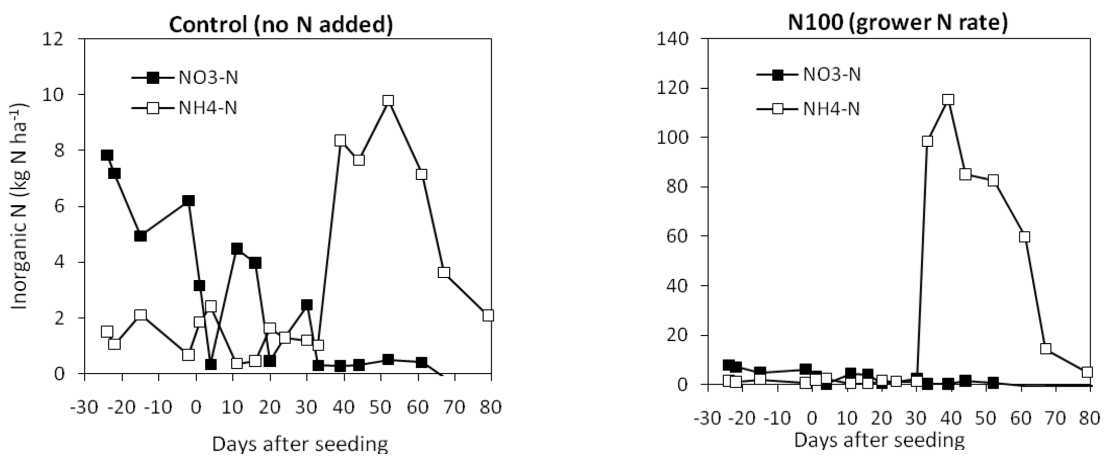


*Figure 3. Soil nitrogen dynamics (0-15 cm) in the control and N100 treatments at the drill seeded site.*

Soil N dynamics at the drill seeded site differed substantially as there were two flushes for crop establishment. Nitrate in the control plots accumulated during each dry down period (Fig. 3). These nitrification processes were related to significant $N_2O$ fluxes that occurred after the first two field flood-drain events. As we observed at the conventional site, little to no $N_2O$ emissions occurred when soil conditions favored denitrification over nitrification (i.e. the field was flooded). Although N fertilizer was applied directly to the soil surface in this system, soil N dynamics in N100 show that very little N fertilizer was converted to nitrate (Fig. 3). These findings are important as N is most susceptible to gaseous losses early in the season when plants are small and there is little N uptake occurring. Furthermore, despite delayed ammonium uptake by the rice crop (most likely due to delayed crop growth) and high soil ammonium concentrations until mid-tillering, $N_2O$ fluxes continued to be negligible during midseason flooded periods which suggests nitrification-denitrification processes were not occurring under these reduced conditions. Interestingly, significant $N_2O$ flux occurred when the field was drained for harvest, but soil nitrate did not increase during this period (as it did at the beginning of the season) despite soil conditions that appeared to be favoring nitrification.

*Greenhouse gas emissions*

*$CH_4$ efflux*

Methane emissions were low (<15 g $CH_4$-C $ha^{-1}$ $d^{-1}$) during early flooding period (Fig. 4). As the soil started to warm in May, methane emissions still remained low with concentrations closed to ambient level (1.8 ppm) for both sites. Emissions increased after about 30 d of flooding and when rice plant reached tillering stage. The presence of rice plants with size/age that can dominate gas transport along with the highly reduced soil condition led to high $CH_4$ emissions.

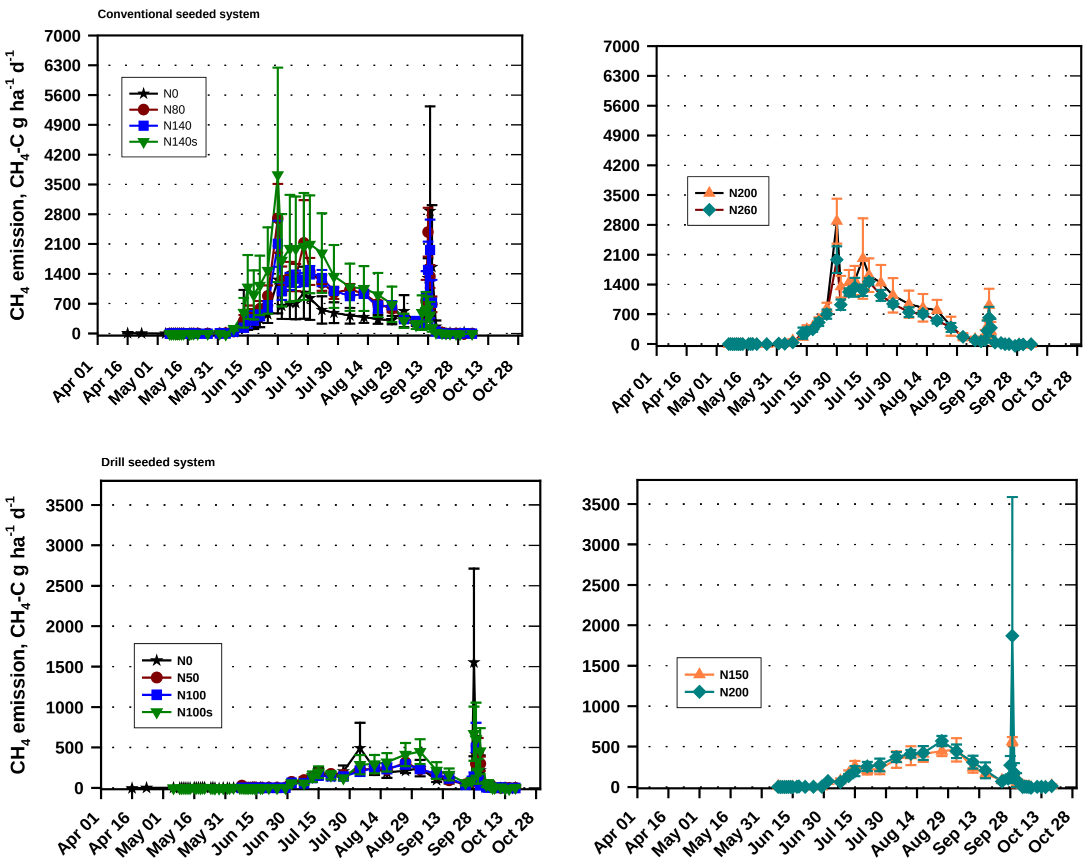


*Figure 4. Growing season methane emissions in conventional and drill seeded systems.*

For both sites, large methane flux increases (56 to 3730 g $CH_4$-C $ha^{-1}$ $d^{-1}$) occurred in June to July and declined after 100% of rice plants reached heading stage. Methane emissions in conventional seeded site were >5 times larger than emissions in drill seeded site (p=0.010). Better crop stand, cultivar type, and high plant density in the conventional seeded may have caused significant differences in $CH_4$ emissions in the two sites.

For conventional and drill seeded sites, $CH_4$ emissions were not significantly different among fertilizer N treatments ($P$ = 0.978). Early drained condition did not produce significant $CH_4$ peaks in all N treatments due to absence of anoxic condition during this period. However, large pulses of $CH_4$ were measured 2 to 3 d after the absence of floodwater in soil surface during the post drain period prior to harvest for both sites. These post drain peaks were about 2 to 13% of the total growing emissions with the highest percentage observed in control treatment (N0) for both sites. Emissions from grower's N rate treatments for both sites (N100 and N140) were roughly 5% of the total growing season emissions. The increase in $CH_4$ emission is likely due to rapid release of entrapped $CH_4$ gas from soil pore spaces as the soil started to dry.

*$N_2O$ efflux*

Seasonal differences in $N_2O$ emissions were observed in both sites (Fig. 5). In conventional seeded system, $N_2O$ emissions were low during early spring and remained low (<5 g $N_2O$-N ha$^{-1}$ d$^{-1}$) close to ambient concentration (0.318 ppm) as rice plant reached anthesis. The low emissions during this period suggest that any $N_2O$ gas produced in the soil was completely reduced to $N_2$ in this system where floodwater was permanently maintained up to crop maturity.

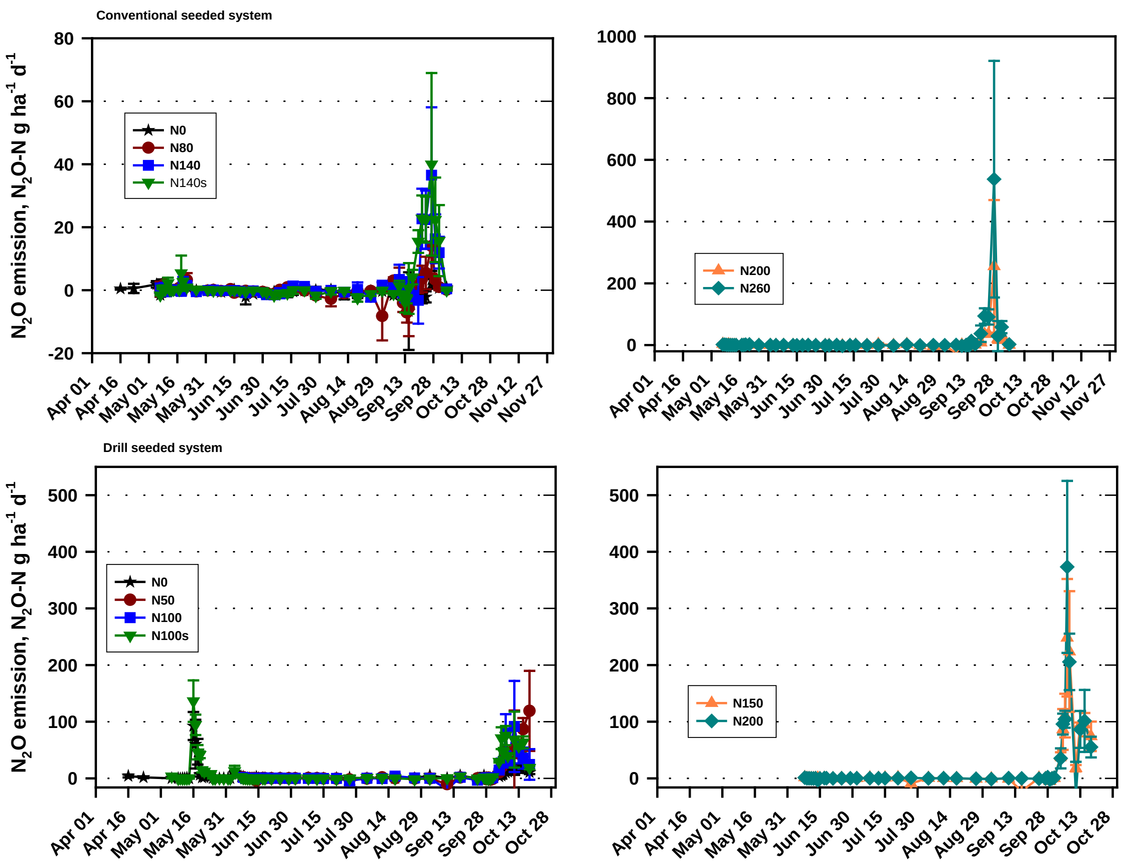


*Figure 5. Growing season nitrous oxide emissions in conventional and drill seeded systems.*

In contrast, large $N_2O$ emissions were measured in drill seeded system after the first dry down period with the highest emission measured in the N100s treatment (136 g $N_2O$-N ha$^{-1}$ d$^{-1}$). These $N_2O$ peaks were about 36% of the total growing season emissions. Immediately after flooding, $N_2O$ emissions went back to pre-drained emissions. Two to 3 d after drying the field prior to harvest, significant high $N_2O$ emissions (p=<0.0001) were measured in both systems. In high N treatments, $N_2O$ emission rates during this period were 2 times larger than the emissions measured during the first drain. And the magnitude of $N_2O$ emitted during post drain period was highly related to the amount of N applied. These high-emission events during post drain period accounted for about 6 to 91% of the total growing season emissions. The large $N_2O$ peaks observed during the last dry down period could be due to strong release of entrapped $N_2O$ gas upon soil drying. Another possible reason is that soil microbial activity is strongly influenced by

soil water content. $N_2O$ emissions increased after the last drain period because water content reached maximum thresholds (60-90% water-filled pore space) where the limiting effects of substrate and oxygen diffusions are equal. Following this condition, an increase in substrate supply through N mineralization of microbial biomass and root decomposition may fuel microbial nitrification and denitrification despite soil nitrate concentrations measured were consistently low (Linn and Doran, 1984, Adviento-Borbe et al, 2006).
$N_2O$ emissions were significantly different among fertilizer N rates (p=0.009). High $N_2O$ emissions were measured in plots with high N rates (>100 kg N $ha^{-1}$).
Between sites, drill seeded system had significantly high $N_2O$ emissions than conventional seeded system (p=0.005). The large $N_2O$ peaks measured during the two periods of draining contributed to the high $N_2O$ emissions in drill seeded field.
Small negative $N_2O$ fluxes (-6 to -0.01 g $N_2O$-N $ha^{-1}d^{-1}$) were observed in all treatments during the measurement periods. These negative fluxes occurred under conditions that have been proposed to favor the use of atmospheric $N_2O$ as the only electron acceptor left for denitrification, (i.e. wet soil, very low soil $NO_3$-N concentration and moderate temperatures (Ryden, 1981). It is also possible that concentrations of $N_2O$ in the gas samples were very low such that the 30-min measurement interval was insufficient to detect an increase in the efflux rates.

*Growing season GHG emissions and global warming potential*

Since GHG flux rate measurements were performed frequently, cumulative $CH_4$ and $N_2O$ emissions were calculated for each individual soil chamber area using linear interpolation of daily emission rates. The interpolations covered the measurement period of first flooding to harvest, and we refer to this period as the growing season emissions.

*Table 3. Cumulative GHG emissions and global warming potentials in conventional seeded system.*

| Fertilizer N applied | Growing season emissions $CH_4$-C | $N_2O$-N | | Global warming potential | |
|---|---|---|---|---|---|
| | *kg ha$^{-1}$* | *kg ha$^{-1}$* | % of Fertilizer N | *Mg $CO_2$-$C_e$ ha$^{-1}$* | *Mg $CO_2$-$C_e$ ton$^{-1}$ grain* |
| 0 | 55± 29*a* | -0.07 ± 0.0*b* | | 1.24 ± 0.67*a* | 0.28 ± 0.14*a* |
| 80 | 93 ± 19*a* | -0.02 ± 0.1b | | 2.14 ± 0.46*a* | 0.26 ± 0.07*a* |
| 140 | 81 ± 12*a* | 0.25 ± 0.2*b* | 0.23 | 1.95 ± 0.31*a* | 0.16 ± 0.02*a* |
| 140s | 120 ± 69*a* | 0.28 ± 0.1*b* | 0.25 | 2.84 ± 1.56*a* | 0.24 ± 0.09*a* |
| 200 | 89 ± 25*a* | 0.75 ± 0.4*ab* | 0.41 | 2.27 ± 0.72*a* | 0.17 ± 0.05*a* |
| 260 | 71 ± 7*a* | 2.1 ± 0.9*a* | 0.83 | 2.25 ± 0.16*a* | 0.17 ± 0.02*a* |

Cumulative fluxes of $CH_4$ over the growing season were greater in conventional seeded than in drill seeded system mainly because flooded condition was maintained in the field which resulted to more production of methane (Table 4 and 5). Draining the field several times during the growing season exposes the field to oxygen which delays the development of highly reduced condition for methanogenesis to occur. Frequent draining such as the case of drill seeded system led to less methane emissions.Total growing season $CH_4$ emissions were similar in all fertility N treatments for both sites (p=0.737). The lack of fertilizer effect on $CH_4$ emissions for the two sites strongly suggests that fertilizer N may not be the main driving factor for $CH_4$ emission. Although the addition of fertilizer N may increase crop residues in the field, the effect of fertilizer N is through increase in soil C pool leading to more substrate C that may increase methane production relative to fertility N treatments.

For both sites, total growing season $N_2O$ emissions were significantly higher in high N treatments (Table 4 and 5). The grower's N rate (N100 and N140) had low total growing $N_2O$ emissions suggesting that CA rice growers managed fertilizer N efficiently. As expected application of fertilizer N in excess of rice crop uptake led to strong release of $N_2O$ from the field. Generally, percent fertilizer N that was lost as $N_2O$ was larger at higher N rates. The increase in $N_2O$ emissions following the addition of high N rates was not necessarily surprising because synthetic $NH_4$ substantially increase substrate $NO_3^-$ and $NH_4^+$ availability for microbial nitrification and denitirification. Cumulative $N_2O$ emissions were significantly lower ($p=0.005$) in conventional seeded system than in drill seeded system, which is due mainly to low emissions during flooded period. Although rates of fertilizer N applied were much higher in this site, deep placement of aqua N avoids large $N_2O$ losses from the field.

*Table 4. Cumulative GHG emissions and global warming potentials in drill seeded system.*

| Fertilizer N applied | Growing season emissions CH4-C | N2O-N | | Global warming potential | |
|---|---|---|---|---|---|
| | *kg ha$^{-1}$* | *kg ha$^{-1}$* | % of Fertilizer N | *Mg $CO_2$-$C_e$ ha$^{-1}$* | *Mg $CO_2$-$C_e$ ton$^{-1}$ grain* |
| 0 | 21 ± 10*a* | 0.6 ± 0.1*c* | | 0.66 ± 0.2*b* | 0.16 ± 0.06*a* |
| 50 | 17 ± 2*a* | 1.1 ± 0.2*abc* | 1.00 | 0.74 ± 0.1*b* | 0.10 ± 0.01*a* |
| 100 | 16 ± 3*a* | 0.9 ± 0.4*bc* | 0.30 | 0.60 ± 0.2*b* | 0.10 ± 0.02*b* |
| 100s | 23 ± 9*a* | 1.3 ± 0.2*ab* | 0.70 | 0.94 ± 0.2*ab* | 0.12 ± 0.01*b* |
| 150 | 25 ± 6*a* | 1.9 ± 0.1*a* | 0.87 | 1.13 ± 0.2*a* | 0.14 ± 0.02*a* |
| 200 | 28 ± 5*a* | 1.8 ± 0.4*a* | 0.60 | 1.17 ± 0.0*a* | 0.15 ± 0.03*a* |

In order to evaluate the effects of management practices and N fertility treatments to GHG emissions, cumulative $CH_4$ and $N_2O$ emissions were expressed in terms of global warming potentials (GWP). The GWP of $N_2O$ and $CH_4$ emissions was calculated in units of $CO_2$ equivalents ($CO_2$e-C) over a 100-yr time horizon (i.e., radiative forcing potential relative to $CO_2$ was 296 for $N_2O$ and 23 for $CH_4$)(Houghton et al.,2001). Expressing the GWP in terms of unit of area, GWP ranged from 0.66 to 2.84 *Mg $CO_2$-$C_e$ ha$^{-1}$* in all sites. GWP was higher in conventional seeded system than drill seeded system mainly due to large methane emitted from conventional seeded site. GWPs were not significantly different in all N treatments in conventional seeded system while significantly higher in high N treatments in drill seeded system. This pattern of GWP was not observed when GWP values were expressed in terms of grain yield (Fig. 6). Results of GWP per ton of yield were different in the two sites. Although not significantly different, GWP per ton of yield tended to be low in high N application rates while small application of fertilizer N or no application of N at all resulted to high GWP per yield in conventional seeded system (Fig. 6). In contrast, GWP does not necessary low at high N treatments because yield was low for drill seeded system. In this site, the grower's N rate had the lowest GWP values in all N rates. This is due to combine effect of high yield and low GHG emissions. Because of high $N_2O$ emission events during the last dry down period in drill seeded system, GWP values of high N rate treatments were identical to GWP values of control (no N addition) (Fig.6). The strong correspondence between yield and fertility N rate and greenhouse gas emissions expressed in global warming potential suggests while aiming at high rice yield through high fertilizer N input the magnitude of GHG emissions can be maintained at lower levels as long as agronomic efficiency is at optimum.

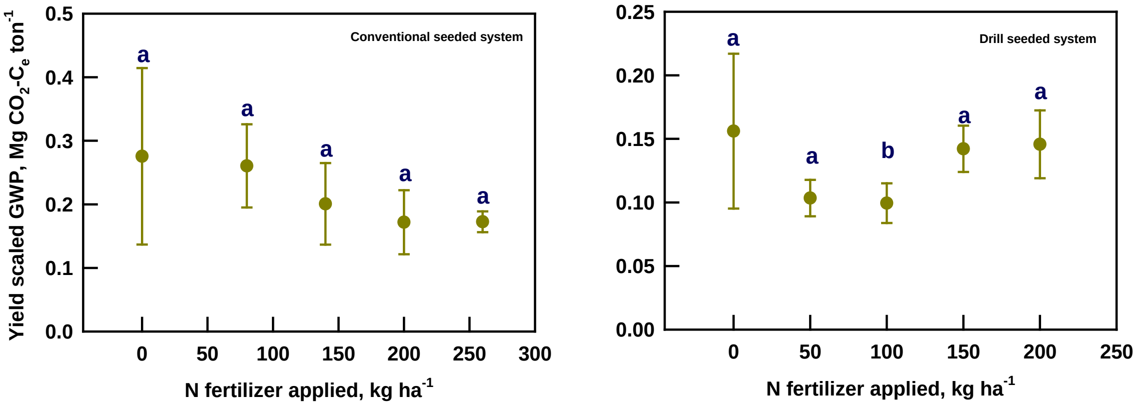


*Figure 6. Global warming potentials of conventional and drill seeded systems at various fertility N rates.*

*Mitigation Options*

While addition of fertilizer N and flooding the rice field resulted to emissions of $N_2O$ and $CH_4$, the best possible strategy to reduce emissions is to manage the magnitude of $CH_4$ and $N_2O$ losses from flooded rice fields. Based on our results, one possible strategy to keep GHG emissions at low levels is deep placement of fertilizer N and avoids surface oxidation of applied $NH_4^+$ to $N_2O$ gas. The amount of fertilizer N applied should also be in accordance to crop N uptake. Continuous flooding of rice field suggests lesser $N_2O$ emissions because high $N_2O$ emission events are prevented during flood-drain cycles.

*Summary*

These results highlight the importance between agronomic management and environmental quality in rice systems, where management practices appear to regulate GHG emissions more than N fertilizer rate. Nitrification appears to be the major process involved in $N_2O$ emissions in flooded rice systems, although denitrification during the dry down periods may also contribute to overall emissions.

Methane emissions were not directly affected by addition of fertilizer N but high fertilizer N application may lead to high crop residue inputs which eventually increase $CH_4$ emissions. Frequent flood-drain cycles resulted to high $N_2O$ emission events. To mitigate emissions, continuous flooding practices and avoid flood-drain cycles during the growing season may reduce nitrogen losses from rice fields and consequently lower global warming potentials. Also, applying N deep into the soil as aqua ammonia may reduce $N_2O$ losses compared to surface N applications. Application of high N fertilizer does not necessarily increase GWP values provided that rice is grown with best management practice resulting in high resource use efficiency.

*References*

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## OBJECTIVE 3: QUANTIFY N LOSSES DUE TO $NO_3$ LEACHING IN CALIFORNIA RICE SYSTEMS

The irrigated lands program may begin putting water quality restrictions on agricultural management practices that allow $NO_3$ to enter surface and ground waters. In a previous CALFED funded project we have addressed $NO_3$ in surface waters. This project will now focus on ground water and $NO_3$ leaching. There is very little data available that quantifies $NO_3$ leaching is flooded rice systems. Some studies from Asia have reported $NO_3$ leaching below the root zone in rice systems (Yoon et al., 2006 and Zhu et al., 2000); however the methodology employed in these studies may have caused this leaching. In another study, Bouman et al. (2002) reported potential leaching beneath rice fields but that it was minimal compared to other systems. In California, rice soil are relatively impermeable and it is thought that the potential for $NO_3$ leaching is minimal due to the slow percolation of water downward and the fact that the anaerobic conditions in flooded soils would cause the $NO_3$ to denitrify (lost to the atmosphere as gas) before it had a chance to leach beyond the rice rooting zone. While this is a good theory it has not been proven in the field. The objective of our study is to quantify $NO_3$ leaching losses in rice fields.

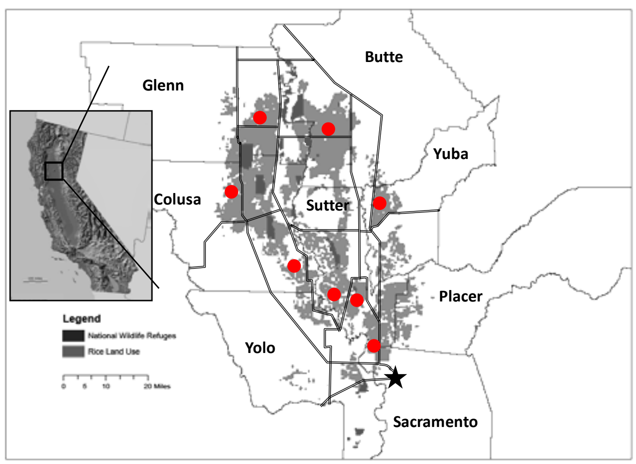


*Figure 1. Location of field sites where soils samples were collected for $NO_3$ analysis.*

In 2010, we collected soil samples to a depth of 2 m (7 ft) from 7 fields that represented typical rice fields and one field that was very sandy (unrepresentative) (Fig. 1). Soil samples were collected in April of 2010. The soil samples were divided into the following sections: 0-15 cm, 15-33 cm, 33-66 cm, 66-100 cm, 100-133 cm, 133-166 cm and 166-200 cm. Soil samples were extracted and analyzed for $NO_3$. If leaching is a potential problem in these fields we would expect to see higher $NO_3$ concentrations below the rooting zone. Additionally we determined the denitirifcation potential of the surface soils. We hypothesized that when soils are flooded any $NO_3$ will be rapidly denitrified and thus will not be available for leaching.

Nitrate concentrations in excess of 10 ppm $NO_3$-N is considered a health hazard by the EPA. In our study the highest $NO_3$ levels we found were 4.2 ppm and this was in the surface soil (Fig 2). In general, surface soils had more NO3 than subsurface soils ranging from about 0.4 to 4.2 ppm. These levels are relatively low most likely due to immobilization of N by rice straw and uptake of N by winter weeds. Below the rooting zone nitrate levels were all 3 ppm or less. In most cases nitrate levels were less than 0.5 ppm. This suggests that $NO_3$-N in subsurface ground waters is not a big concern in CA rice systems. At two sites $NO_3$ levels were above 2 ppm below the rooting zone. These locations are near Robbins, CA where rice is rotated with other crops. $NO_3$ is likely a bigger problem for other crops as there is usually a lot more $NO_3$ in the soil and N fertilizers are applied as $NO_3$ or rapidly convert to $NO_3$.

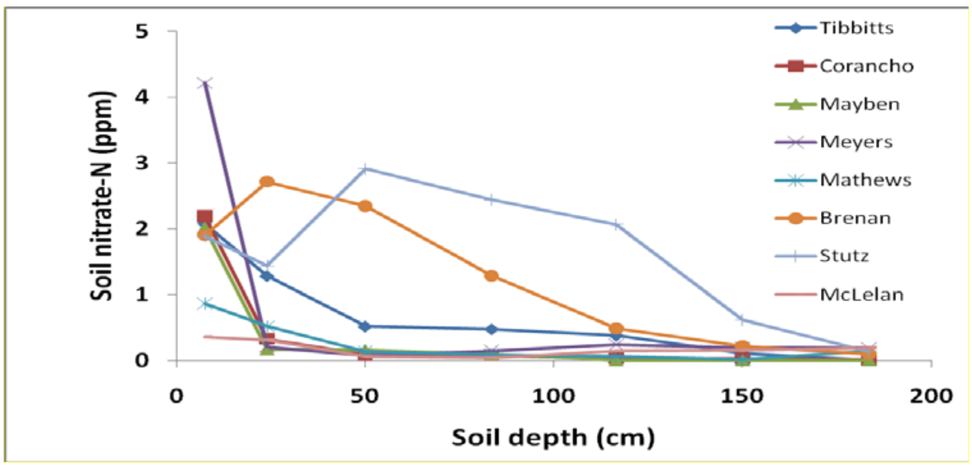


*Figure 2. Soil $NO_3$ across soil depths in 8 California rice soils.*

In a laboratory study, the top soil from each of these sites was used to determine the rate at which $NO_3$ denitrifies. When $NO_3$ denitrifies it is lost to the atmosphere as N gas. Our results show that by 1.5 days over 98% of the $NO_3$ that was in the soil was lost as gas (Fig 3). This shows that upon flooding a rice field most of the $NO_3$ that is present in the soil does not have time to leach as it is lost to the atmosphere via denitrification.

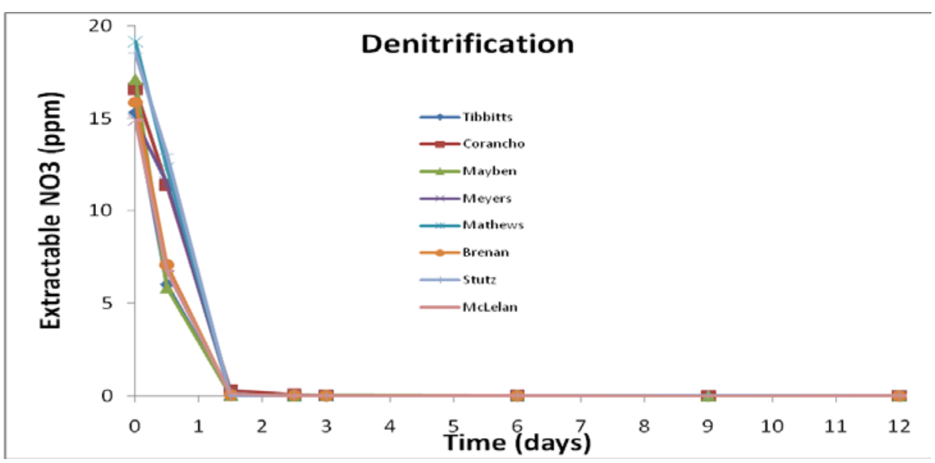


*Figure 3. Soil NO3 during a 12 day anaerobic laboratory incubation.*

*Research summary*

In summary, we found that soil $NO_3$ beneath rice fields were low. The reasons that $NO_3$ levels are low may be due to one or more of the following factors:

- Soil nitrate levels are low in the surface soil to begin with (0.4 to 4.2 ppm)
  - Winter weeds take up
  - Straw immobilizes
- Growers do not (should not) apply $NO_3$ fertilizer
- Soils remain flooded for much of the season preventing nitrification ($NH_4$ to $NO_3$)
- Denitrification rates are very high ($NO_3$ to N gas)
- Hydraulic conductivity is very low preventing downward movement of $NO_3$ .
  - We need to quantify this better though.

### OBJECTIVE 4: EVALUATE THE EFFECTIVENESS OF LATE P APPLICATIONS IN RELATION TO P AVAILABILITY, RICE PRODUCTIVITY AND ALGAE GROWTH.

In 2009, two P studies in fields that were deficient in P showed that delaying the application of P fertilizer until 35 days after planting gave the same yields as when P was applied just before planting (conventional practice). In five other field scale studies conducted in cooperation with Dr. Spencer, UC Davis (USDA ARS Exotic & Invasive Weeds Research Unit) we found that delaying the P application by between 16 and 32 days algae growth was reduced and yields maintained. In 2010, in cooperation with Dr. Spencer, we followed up on these studies. Experiments were conducted in two P deficient fields. Microcosms (metal rings inserted into the soil) were installed. Four microcosms were assigned to each of the following treatments: no added P fertilizer, P fertilizer at at planting, P fertilizer added 14 days after flooding, P fertilizer added 28 days after flooding, and P fertilizer added 42 days after flooding. Each day the surface of each microcosm was photographed using a time lapse camera to determine the abundance of floating algae and cyanobacteria. One week after each P fertilizer addition, the biomass of all of the algae/cyanobacteria in each microcosm were harvested and dried at 80 C for 48 hours. Twice a week, water samples will be collected for phosphate-P analysis and rice leaf samples analyzed for tissue P content at 35 DAS. At the end of the growing season rice yield was determined in each microcosm.

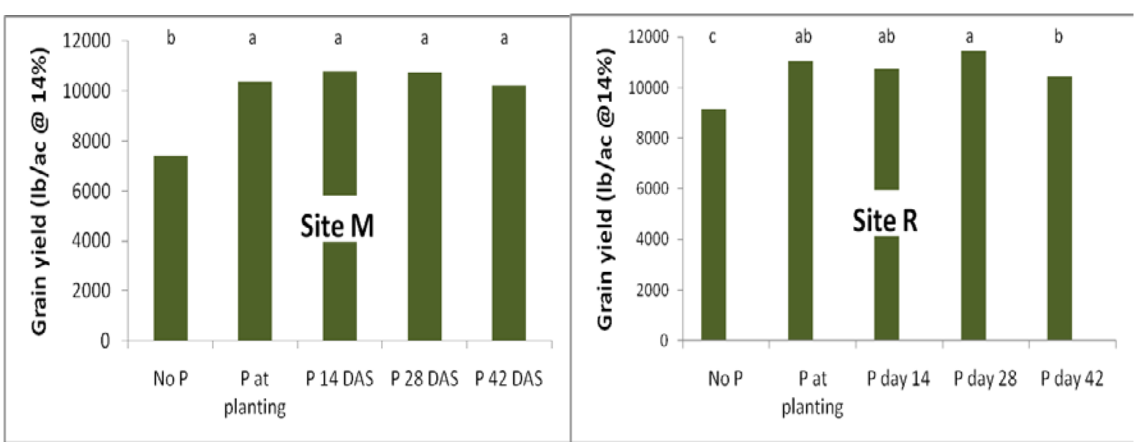


*Figure 1. Grain yields at the Meyers site in response to varied times of P application.*

Results on the effects of these treatments on algae will be reported on by Dr. David Spencer. Here we report on the effect on yields and water P concentrations. At the Meyers (Site M) site yields where 7400 lb/ac when no P was applied. Soils were deficient in P as applying P fertilizer at planting increased yields to 10,400 lb/ac – an increase of 3000 lb/ac (Fig. 1). Delayed applications of P by 14, 28 and 42 days resulted in similar yields as to when it was applied at planting. These results are similar to those we reported on in 2009. At the Rystrom site (Site R) the soil was also deficient in P. Yields in the absence of P were 9,200 lb/ac. Applying P from planting to 28 days after planting increased yields to 11,100 – an increase of 1900 lb/ac. While delaying the P application until 42 days after planting still increased yields, the increase in yields was only 1300 lb/ac – not as effective as applying P earlier. These results are consistent with similar studies in 2009 where P applications up to 35 days after planting were equally effective to applying P at planting but not after that.

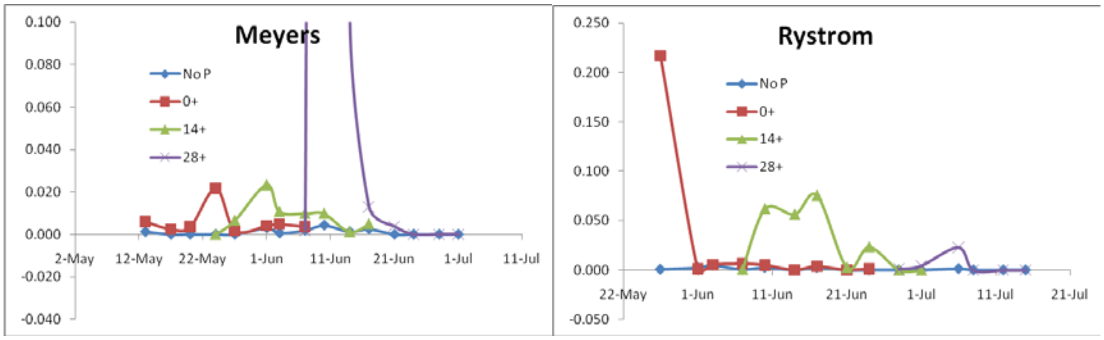

*Figure 2. Water P concentrations following the application of P fertilizer at two locations.*

One issue in applying P later in the season is that P is being broadcast into the water, resulting in high water P concentrations and the increased possibility of offsite contamination. In each of the treatments (except 42 d) we monitored the water P concentration for 3 weeks following application. We saw water P concentration increase (sometimes dramatically) following P applications (Fig. 2). In general, water P concentrations reduced to normal levels within 2 weeks. We therefore recommend holding water for a two week period following P applications.

*Research summary*

In summary we can make the following recommendations for growers wishing to reduce algal growth by applying P at a different time.

1. If the field is not P deficient then P fertilizer can be applied at anytime, including the Fall. Most fields in the Sacramento Valley are not deficient in P.
2. If the field is deficient and the grower wishes to apply in the Fall, then a higher P rate should be used initially.
3. If the field is P deficient and the grower wishes to apply at planting then th P fertilizer should be incorporated as much as possible.
4. If the field is P deficient, P can be applied as late as 35 DAS (this is conservative). We recommend applying the P when the rice is above the water surface (3-4 weeks). If applying after planting then the water should be held for a 2 wk period.

**OBJECTIVE 5: DEVELOPMENT OF A WEB BASED DECISION TOOL TO HELP GROWERS DETERMINE HOW LONG THEY WILL NEED TO KEEP THEIR FIELDS FLOODED FOR DIFFERENT WEEDS-BASED ON P APPLICATIONS AND TEMPERATURE AND WEEDS.**

The overarching goal of this research is to develop a decision support tool useful for managing rice weeds via alternative stand establishment systems in the Sacramento Valley. Central to such a tool is the ability to predict weed emergence across a spatially and temporally heterogeneous landscape. Our objectives were to 1) characterize the spatial distribution of physiological temperatures (thermal units) in the Sacramento Valley during the early season using historical temperatures, 2) test whether thermal units vary between locations as predicted by historical temperatures, 3) test whether emergence models with lab derived parameters can adequately predict weed emergence using location-specific temperatures, and 4) determine whether location-specific air temperatures predict weed emergence as effectively as block-specific temperatures recorded at the soil surface.

To accomplish the first objective, from the CIMIS (http://wwwcimis.water.ca.gov) and UC Davis IPM (www.ipm.ucdavis.edu) websites, we collected historical daily hi/low air temperatures between April 15$^{th}$ and May 15$^{th}$ for the years 2000-2009 from a total of 13 weather stations in the rice growing region. We used the triangle method and a base temperature of 8.85 C, a lab-derived physiological threshold specific to early watergrass (Boddy, L. and Fischer, A., personal communication), to calculate the cumulative thermal units during the time period. We then interpolated the thermal units between these locations using the inverse distance weighted method with 1 SD tolerance and projected the result using ARCMap software (Fig. 1).

As depicted in Figure 1, the cumulative thermal units at 8.85 C base temperature are spatially correlated during the early part of the growing season between 2000 and 2009, with the region south and east of Sutter Buttes generally accumulating less thermal units than the region north and west of Sutter Buttes. The average daily accumulation of thermal units in this dataset is 14 TU d$^{-1}$, and the difference between the maximum and minimum cumulative thermal units is 43 TU. This indicates that, within the 30-day period represented, the development of early watergrass would be predicted to be approximately three days further along in the hottest part of the region compared to the coolest part of the region.

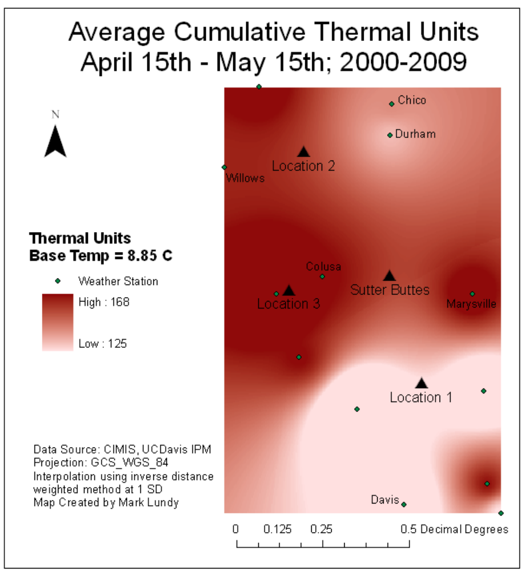


*Figure 1. Graphical depiction of the results of inverse distance weighted interpolations of average cumulative thermal units between 4/15 and 5/15 from 2000-2009 in 13 locations in the California rice growing region.*

Our second objective was to validate these historical differences within a single season. We did so by comparing air temperatures from three locations within a timeframe that would represent the predicted emergence period for early watergrass. We placed air temperature sensors in 3 locations within the region and compared thermal unit accumulation between sites from May 8$^{th}$ to May 26$^{th}$. One of the sensors (Location 1; Figure 1) was located in the coolest part of the region, while the other two sensors (Locations 2, 3; Fig. 1) were located in the warmest part of the region.

There was a significant difference in daily thermal units between Location 1 and Locations 2 and 3 ($p<0.005$; Figure 2). Eighty percent emergence for early watergrass would be achieved at 13.8 days after the onset of water in Location 1 and 12.9 days after the onset of water in Locations 2 and 3. Additionally, these differences are heterogeneous across time ($P=0.03$), meaning that comparisons beginning on different dates might result in more or less of a difference in predicted emergence times between sites. Therefore, from both the interpolation of historical air temperatures and the between site comparisons of air temperature during the 2010 growing season, we can conclude that early season physiological temperature is heterogeneous in the Sacramento Valley and that the heterogeneity is both spatially and temporally dependent. Further, relative to other warm season weeds in the Sacramento Valley, early watergrass has a low base temperature, and the base temperature used to calculate the thermal units will influence the magnitude of heterogeneity. We will be conducting a similar analysis for smallflower, which has a base temperature estimated to be as high as 13 C, and we expect that the predicted differences between locations will be greater in magnitude.

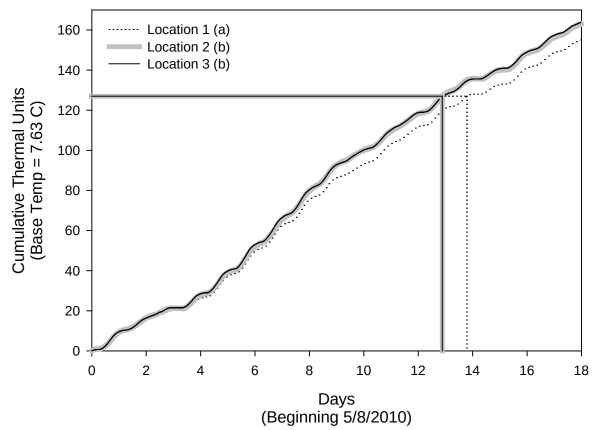


*Figure 2. Comparison of thermal unit accumulation between 5/8/2010 and 5/26/2010 in three locations in the Sacramento Valley using a base temperature of 7.63 C and with reference lines drawn to indicate the predicted time to 80% emergence for early watergrass in each location (127 TU); different letters (a,b) indicate significant difference in daily thermal units.*

Our third and fourth objectives were to determine whether lab-derived parameters can accurately predict weed emergence at the field scale and whether air temperatures can do so as effectively as temperatures taken at the soil surface. Although we collected data for both watergrass and smallflower, up until now, we have completed the data analysis for watergrass only. Therefore, our results apply to watergrass alone.

In the same 3 locations where we recorded air temperature, following the onset of flooding, we recorded weed emergence every 2-4 days as well as the temperature at the soil surface in 4 (Location 3), 5 (Location 1), and 6 (Location 2) blocks. Location 1 was tilled, drill-seeded and intermittently flooded; Location 2 had both spring-till and no-till sections that were managed as stale seedbeds, with intermittent flooding before water seeding; and Location 3 was managed as a no-till, stale seedbed. No weed emergence was observed at Location 3; therefore it is not included in the weed emergence analysis. Within locations, blocks were situated in high and low spots in the checks in order to maximize the variability in water depth and soil moisture between blocks. Since surface applications of calcium phosphate have been shown to stimulate emergence of smallflower and other rice weeds, each block included a treatment with 125 kg $ha^{-1}$ TSP surface applied and another treatment without. Within each treatment 2 subplots locations were established where weeds were consistently counted during each field visit. Daily emergence is expressed as the percentage of the total weeds emerged per subplot averaged across subplots for each block-treatment combination.

To develop the predictive curve for watergrass, we fit a non-linear, log-logistic sigmoid function to a hydrothermal response curve developed by Louis Boddy and Albert Fischer at UC Davis in a laboratory setting. Using these data, a base temperature (7.63 C), thermal time to 50% emergence (90 TU), slope (12.1 TU $d^{-1}$) and upper and lower bounds for emergence (0.93 and 0, respectively) were estimated for watergrass. We used these lab-derived parameters and the log-logistic function to predict weed emergence with both location-specific air temperatures and block-specific soil surface temperatures. We then compared the predicted and observed emergence and assessed the accuracy of the model using RMSE and Pearson's R (Table 1) and by plotting predicted and observed values (Figure 3) and their squared differences as a function of total emergence (Figure 4).

| Prediction Source | | RMSE | Pearson's R | n |
|---|---|---|---|---|
| Air temperature (location specific) | Location 1 | 0.20 | 0.87 | 5 |
| | Location 2 | 0.20 | 0.90 | 4 |
| | Location 2 (no-till) | 0.28 | 0.85 | 2 |
| Soil temperature (block specific) | Location 1 | 0.39 | 0.81 | 5 |
| | Location 2 | 0.24 | 0.86 | 4 |
| | Location 2 (no-till) | 0.28 | 0.84 | 2 |

*Table 1. RMSE and correlation coefficients for predicted and observed watergrass emergence in two locations as a function of thermal time derived from either location-specific air temperatures or block-specific soil temperatures.*

Watergrass emergence was most accurately predicted in tilled areas and using location-specific air temperature, which resulted in RMSE and Pearson's R values of (respectively) 0.20 and 0.87 in Location 1 and 0.20 and 0.90 in Location 2 (Table 1). The model tended to under-predict days to full emergence in the tilled areas (Figure 3) and over-predict days to full emergence in the no-till areas (not shown). The under-prediction for emergence in the tilled areas is likely due to the fact that emergence can be observed both more frequently and at earlier stages of growth in the laboratory setting compared to the field setting. When the predicted time to 50% emergence was iteratively increased from 90 to 106 TU, Pearson's R increased from 0.89 to 0.92 and the RMSE was reduced to 0.17 from 0.20, which supports the idea that observable emergence is later in the field than in the laboratory setting. The squared difference between predicted and observed values in the tilled context decreased with increasing emergence and was below 0.1 from 50% emergence onward (Fig. 4). This indicates that, as the population reached full emergence, the model increased in accuracy. The over-prediction for emergence in the no-till areas might be explained by the fact that seeds in an undisturbed seedbed have been accumulating thermal units throughout the spring and are therefore closer to the emergence threshold than seeds that have been brought to the surface via tillage. However, iterative adjustment to the predicted time to 50% emergence did not improve model accuracy for the no-till predictions. Although emergence was significantly different between blocks (P=0.001), the block-specific temperatures recorded at the soil surface predicted emergence less accurately than the location-specific air temperatures (Table 1). Finally, surface application of the TSP had no effect on watergrass emergence.

In summary, we hypothesized that early season physiological temperatures in the Sacramento Valley are heterogeneous and spatially dependent and that they can be used in concert with lab derived parameters to predict weed emergence at the field scale. We confirmed the spatial and temporal heterogeneity of watergrass-specific thermal units and found that watergrass emergence can be predicted using lab-derived parameters. Nonetheless, these parameters can be refined based on our 2010 field observations and such refinements should further improve the accuracy of the emergence model. Finally, we observed that air temperature is a better predictor of watergrass emergence than temperatures recorded at the soil surface. Therefore, a decision support tool that uses spatially explicit air temperatures to predict watergrass emergence has the potential to provide useful information to growers managing weeds with alternative stand establishment methods. We intend to apply the same analyses presented in this report to the data we recorded for smallflower emergence. During the 2011 field season we plan to validate the adjusted watergrass and smallflower emergence models and assess their utility for decision support.

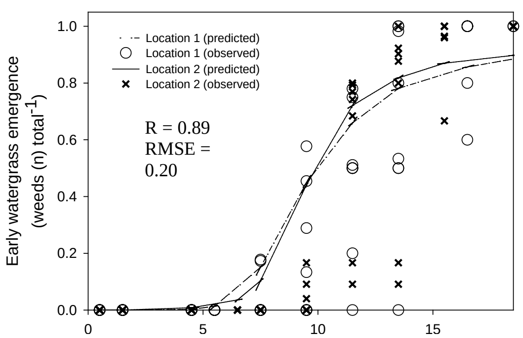


*Figure 3. Predicted and observed emergence as a function of time; tilled seedbeds with intermittent early season flooding.*

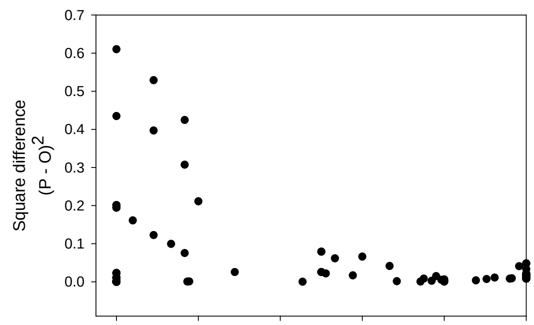


*Figure 4. Squared difference in predicted and observed values as a function of the proportion of total emergence; tilled seedbeds with intermittent flooding.*

PUBLICATIONS OR REPORTS:

**Publications (2009, 2010):**

1. Linquist, B.A., J.E. Hill, R.G. Mutters, C.A. Greer, C. Hartley, M.D. Ruark and C. van Kessel. (2009). Assessing the necessity of surface applied pre-plant nitrogen fertilizer in rice systems. Agronomy Journal 101:906-915.
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3. Lundy, M, A. Fisher, C. van Kessel, J.E. Hill, M. Ruark, and B.A. Linquist. 2010. Surface-applied calcium phosphate stimulates weed emergence in flooded rice. Weed Technology 24:295-302.
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5. Linquist, B.A., M.D. Ruark, and J.E. Hill. (In Press). Soil order and management practices control soil phosphorus fractions in managed wetland ecosystems. Nutrient Cycling in Agroecosystems.
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1 **Linquist, B.A.**, M.D. Ruark, C. van Kessel, J.E. Hill and J. Six. 2009. Carbon and Nutrient Losses in Rice Field Drainage Water. Meeting of the Soil Science Society of America, American Society of Agronomy, and Crop Science Society of America. Houston, TX. November, 2010 (Oral Presentation).

2 **Linquist**, B.A., J. Hill, M. Lundy, K. Koffler, C. van Kessel. 2009. Surface applied starter fertilizers in California rice systems: When do you need it and how do you manage it? Poster presentation and published abstract. Annual Rice Field Day, Aug 26, 2009. Rice Experiment Station, Biggs, California.

3 Pittelkow, C.M., **Linquist, B.A.**, van Kessel, C., Hill, J.E., Espino, L., Greer, C.A., and Mutters, R.G. 2009. Nitrogen fertility management in alternative rice establishment systems. Poster presentation and published abstract. Annual Rice Field Day, Aug 26, 2009. Rice Experiment Station, Biggs, California.

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5 Pittelkow, C.M., **Linquist, B.A.**, van Kessel, C., Hill, J.E., Espino, L., Greer, C.A., and Mutters, R.G. 2010. Nitrogen fertility management in alternative rice establishment systems of California. Oral presentation and published abstract. Rice Technical Working Group, Feb 22-25, 2010. Biloxi, Mississippi.

6 Wild, P.L., van Kessel, C., Lundberg, J. and **Linquist, B.A.** 2010. Evaluation of nitrogen sources for organic rice production. Rice Technical Working Group, Feb 22-25, 2010. Biloxi, Mississippi.

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8 Krupa, M., C. van Kessel, **B.A. Linquist**, K.W. Tate, J. Six and R.G.M. Spencer. 2010. Influence of land use, water management, and soil properties on DOC fluxes and trihalomethane formation potential from rice-dominated watersheds. Presentation at 95th Ecological Society of America Annual Meeting. August 2, 2010. Pittsburgh, PA.

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15 Lundy, M. E., D. F. Spencer, C. van Kessel, **B. A. Linquist**. 2010. Managing phosphorus fertilizer to reduce algae, maintain water quality and sustain yields in direct-seeded, flooded rice. Annual Meeting of the Soil Science Society of America, American Society of Agronomy, Crop Science Society of America. Long Beach, CA, 1 November, 2010 (Oral presentation and published abstract).

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19 **Linquist, B.A.** 2010. Maintaining water quality while ensuring sustainable yields and other environmental services from rice systems in California. Presentation at the International Rice Congress, Hanoi, Vietnam. Nov 8-12.

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