FERTILITY & CROP NUTRITION

Introduction

When considering profitable agriculture from a practical perspective, the factors affecting plant growth and harvestable productivity are of the utmost importance. A myriad of factors, such as genetics, environment, and irrigation management, impact yields independently and through interactions. Knowledge of these factors, the interactions, and how to manipulate them make it possible for the farm operation to maximize the return. Of course, all are not under the control of the grower. However, crop nutrition and soil fertility can be managed for good yields and production efficiency.

There are 17 elements that are essential to the growth of plants in general. Not all are required for all plants. Carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur are the elements required for proteins and cell walls. The other thirteen elements include calcium, magnesium, potassium, iron, manganese, molybdenum, copper, boron, zinc, chlorine, and silicon. A few plants require sodium, cobalt, and vanadium. Among the essential nutrients, nitrogen, phosphorus, potassium, zinc, and to a lesser extent sulfur and iron are the nutrients of concern in the California rice cropping system. The behavior of these elements and their management is somewhat unique in rice as compared to other cropping systems because of the anaerobic soil due to flooding.

Soil under rice cultivation

The major characteristic of a submerged soil is the depletion of oxygen (O^2). Microorganisms deplete the free O^2 throughout most of the plow-layer within a few days of flooding. The water contains dissolved O^2, which can diffuse a short distance into the soil. The deeper the water, the less O^2 can move from the air to the soil. The thickness of the oxidized layer at the soil/water interface ranges up to about 1 inch thick depending on the microbial activity. For example, in a soil with a large supply of decomposable organic matter (i.e. incorporated straw) the oxidized layer is very thin. Once the soil O^2 supply becomes depleted, the soil bacteria are forced to extract O^2 from other compounds. These compounds in the order of utilization are nitrate, manganese oxide, iron hydroxide, and sulfate-sulfur. Once this pool of compounds is exhausted, the soil bacteria will use the energy stored in organic compounds by fermenting organic matter to carbon dioxide and methane. Another unique property of flooded soil is that upon flooding the soil, regardless of the starting pH, the pH approaches neutrality (pH 6.5 to 7.5). This occurs in about two weeks. As a result, the chemistry of an anaerobic soil alters the level and forms of some plant nutrients and results in the production of compounds which are sometimes toxic to rice.

Approaches to nutrient management

The goal in nutrient management is to match nutrient supply with crop requirements and to minimize nutrient losses from fields. Properly managed fertilizers support cropping systems that provide economic, social and environmental benefits. On the other hand, poorly managed nutrient applications can decrease profitability and increase nutrient losses, potentially degrading water and air quality.

The 4R approach is one that offers enhanced environmental protection, increased production, increased farmer profitability, and improved sustainability. The concept is to use the **right fertilizer source**, at the **right rate**, at the **right time**, with the **right placement**.

In order to implement the 4R approach it is necessary to understand some fundamentals about when the crop needs nutrients and how much it needs. In general, maximum nutrient uptake occurs from tillering and goes through to the onset of the reproductive stage (Fig. 1). The peak nutrient uptake rate coincides with the maximum root biomass accumulation. As the grain ripens

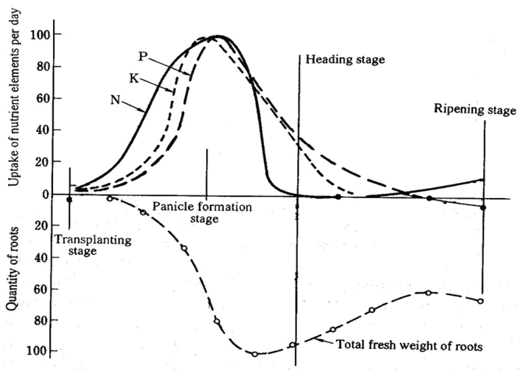

Figure 1. Seasonal uptake rate of selected nutrients and root growth by a rice plant

nutrients and carbohydrates are transported from the vegetative parts of the plant into the panicle. Therefore, the critical time frame for nutrient management is between planting and panicle initiation. In the case of some specialty varieties, there may some fertility management decisions based on grain quality that would justify later applications of nitrogen.

The plant gets nutrients from the soil, irrigation water and atmospheric deposition. What is not provided from these sources needs to be made up from other nutrient inputs (fertilizer, manure, cover crops, etc). Nutrients have different roles within the plant and thus are needed in different quantities by the plant. Of the three main nutrients that are typically applied the rice plant demands similar amounts of N and K (33-34 lb N or K /ton) and less of P (6 lb P/ton grain yield) (Table 1). To put this in fertilizer equivalents where P is expressed as P_2O_5 and K as K_2O the crop takes up 14 lb P_2O_5/ton and 40 lb K_2O/ton grain yield (Table 1).

Soil and tissue sampling

Nutrient deficiencies can be determined from both soil and tissue tests. Soil samples are usually taken before planting and before any fertilizers have been applied. Soil samples are useful in that you may be able to determine deficiencies before the season and take corrective measures.

Table 1. Concentration and uptake of N, P and K in rice at time of harvest. (Data com- piled from Dobermann and Fairhurst, 2000)

Plant part	Nitrogen	Phosphorus	Potassium
	lb nutrient/ton grain yield		
	N	P	K
Grain	21.2	4.2	5.4
Straw	12.6	2.0	27.8
Grain+Straw	33.8	6.2	33.2
	lb nutrient/ton grain yield (in fertilizer equivalents)1		
		P_2O_5	K_2O
Grain		9.6	6.5
Straw		4.6	33.4
Grain+Straw		14.2	39.8
	Concentration of nutrients		
	%N	%P	%K
Grain	1.06	0.21	0.27
Straw	0.63	0.10	1.39
1 - %P_2O_5 = %P x 2.29; %K_2O = %K x 1.2			

Tissue samples are taken during the season. The exact tissue (usually leaf or whole plant) and time of sampling will vary depending on nutrient of interest. While such tests can be helpful, lab results will often come back too late to be able to correct the deficiency in the current season. However, they do provide valuable information for the following season. Leaf color charts of chlorophyll meters are able to provide instant readings of leaf "greenness" and are a good indicator of N deficiencies (discussed in Nitrogen section).

For soil samples using a soil, auger or shovel (shovel is best in tilled field) to a depth of 6 inches (roughly the plow layer). Take about 20 samples in a 20 to 40 acre field by walking randomly through the field (Fig. 2). Be sure to collect samples from all quadrants of the field to achieve a representative sample. Mix the soil sample in a non-metallic container and let the soil air dry. Transfer the mixed sample into a labeled paper or plastic bag, and send to a qualified laboratory for analysis. Sample problem areas separately every year and non-problem areas every two to three years.

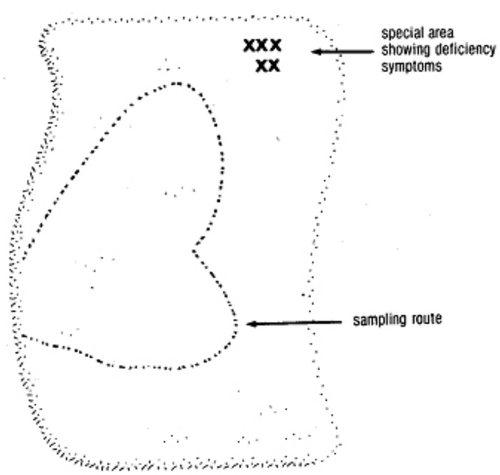

Figure 2. Sampling pattern for taking soil or leaf samples to test for nutrient deficiencies.

Nitrogen

Plant function

Nitrogen is an essential part of all amino acids, proteins, enzymes, chlorophyll molecules, and nucleotides (e.g. DNA). Because nitrogen is present in so many essential compounds even slight deficiencies can result in reduced growth and productivity.

Deficiency symptoms

Nitrogen deficiency is the most common nutrient deficiency in rice. Older leaves (and sometime all leaves) are light green (or even yellow) and may be chlorotic at the tip. Under severe N stress older leaves will die and young leaves will be narrow, short and yellowish green. Visually, N deficiencies can look like S deficiencies (which are not very common); however, in an S deficiency all leaves turn light green/yellow.

Nitrogen cycle/soil nitrogen

Figure 3 depicts the major pathways, transformations, and chemical species in nitrogen cycling. Nitrogen can be lost from the soil, thereby reducing the efficiency of fertilizer applications because of these conversions. Nitrogen losses in the soil occur mainly from denitrification, ammonia volatilization, leaching, and surface runoff. Of these, ammonia volatilization and denitrification are the main N loss pathways. Additionally, immobilization and ammonium fixation make nitrogen temporarily unavailable to the rice crop. Nitrogen conversion processes are defined in Table 2.

Denitrification of nitrogen fertilizer and subsequent loss as nitrogen gas, can result in high losses of the applied nitrogen, particularly when applied in a nitrate form (nitrate fertilizers should not be applied to rice systems) or when

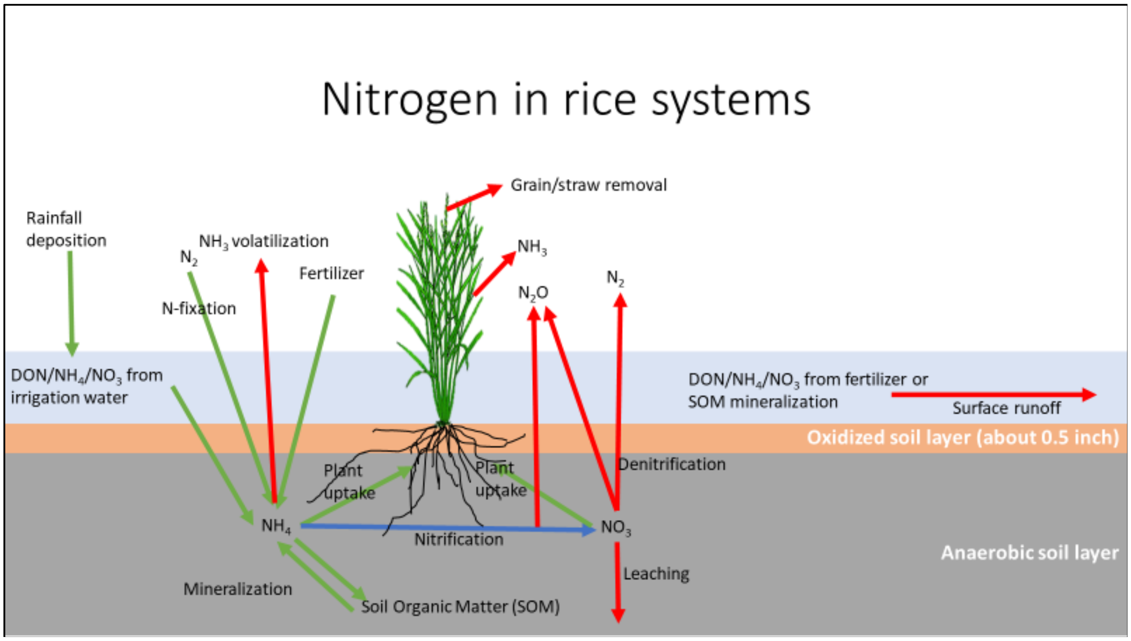

Figure 3. Nitrogen inputs, losses and transformations in rice systems

there has been significant nitrification of N fertilizers (aqua ammonia, urea or ammonium sulfate). The conversion occurs in the anaerobic zone of the soil. Manageable factors contributing to denitrification include wet/dry cycles and fertilizer management. Severe nitrogen losses occur in soils subjected to alternate draining (aerobic) and flooding (anaerobic) which occur after N fertilizer has been applied. Lowering water following planting for a short time period to ensure good crop establishment (Leather's Method) does not lead to significant denitrification losses provided the soils a reflooded relatively quickly.

Another important mechanism of nitrogen loss is the volatilization of ammonium formed as a result of mineralization. Among the factors affecting the process are moisture content, pH, cation exchange capacity, lime content, temperature, flood depth, and the type of fertilizer. Again, maintaining a constant flood is one method by which growers can minimize the loss. Surface applied urea volatilizes more readily than incorporated aqua-ammonia. Regardless of the form, however, the longer the time between application and the establishment of the permanent flood the greater the loss.

Another critical process of particular relevance to California is immobilization. The incorporation of straw (carbon) stimulates microbial activity. Consequently, nitrogen becomes unavailable for plant uptake because the nitrogen is incorporated into the microbial biomass.

Determining a deficiency

Standard soil tests are not reliable for determining the amount of nitrogen available for a rice crop. The dynamic nature of the various forms of nitrogen in a flooded soil makes it difficult to sample and analyze the soil in a condition that is representative of actual growing conditions. For example, if sampled in a dry aerobic state, nitrate-nitrogen may be the dominant form available to the plant, but once flooded the soil becomes anaerobic, nitrate-nitrogen is lost via denitrification.

Later in the season leaf tissue tests, leaf col-

Table 2. Definition of terms describing major processes in the nitrogen cycle

Nitrogen fixation	The process by which atmospheric nitrogen is converted to biologically usable forms of nitrogen by microorganisms.
Mineralization	The breakdown of organic matter resulting in the release of ammonium (NH_4) and other nutrients which can be used by plants.
Nitrification	The conversion of ammonium (NH_4) to nitrate (NO_3).
Denitrification	The conversion of nitrate (NO_3) to nitrogen gas (N_2), resulting in a loss of plant available N.
Immobilization	The assimilation (tying up) of inorganic N (NH_4 and NO_3) by microorganisms resulting in the nitrogen being unavailable for plant uptake.
Ammonia volatilization	The loss of ammonia gas to the atmosphere, following the conversion of ammonium (NH_4) to ammonia (NH_3).

or charts, chlorophyll meters or remote sensing tools may be used to identify deficiencies. These will be discussed later.

4R management

—Right rate—

Despite the fact that N is required in greater quantities than any other nutrient and is usually the most expensive nutrient input, there are no good soil tests to determine the correct nutrient rate to use in rice systems. Therefore, many growers use historical experience to decide on their N rate. However, with changing practices over time (i.e. straw management, fertilizer N management, water management, and varieties) the optimal N rate can change. With the increased use of yield monitors, an effective way to identify the correct N rate for a particular field is to do test strips using different N rates. To do this we recommend

1. Identifying a representative field and check.
2. Within a check apply a test strip (full length of field) at an N rate of 25 lb N/ac above and below the N rate being applied to the rest of the field using aqua rig (Fig. 4).
3. the aqua rig used to apply the N strips needs to be at least as wide as the combine header. If not, apply two strips of each N rate. After applying N to test strips flag each strip.
4. test strips should not be directly adjacent to the levee.
5. Monitor strips throughout the season.
6. At harvest, using a yield monitor, determine the yield from each test strip. Make sure to adjust for moisture since higher N rates are likely to be slightly delayed in maturity.
7. Comparing yields from test strips will let you know if you under or over applied
8. By doing this over different fields and years (along with keeping good records), growers can confidently adjust their N rate.

—Right source—

There are a number of N-fertilizer choices available for rice growers. However, N sources containing nitrate-N should not be used due

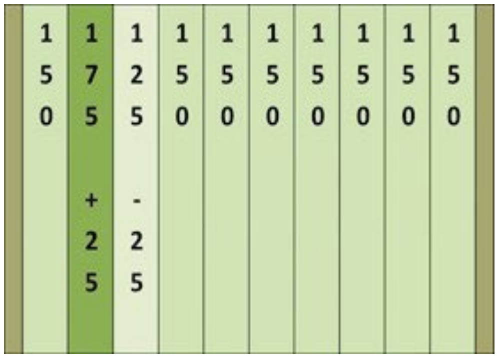

Figure 4. Example of a field with test strips of different N rates

to potential for high N loss (via denitrification). The N source applied in largest quantities to water-seeded rice systems is aqua-ammonia or “aqua”. Aqua contains 20% N. Other common N sources used in California rice systems are urea (45-46% N), ammonium sulfate (21% N) and various starter blends which are usually blended from ammonium phosphates and ammonium sulfate.

Growers typically apply the majority of their N rate as aqua (60-75%) and apply the rest of the N rate in the starter blend and sometimes as a top-dress later in the season. The rational for applying starter N is to provide young emerging seedlings with readily available N until the rice roots grow into the aqua that is injected 3-4” below the soil surface. On-farm research addressing the need for starter N shows that starter N is not necessary. In fact, at equivalent N rates higher yields and N uptake were achieved when all of the N was applied as aqua (Fig. 5). The reason for this is that the N injected below the soil surface is better protected from both ammonia volatilization and denitrification losses. While applying starter did increase plant size early in the season in some of the trials, this never translated into increased yields at the end of the season. Results of this research suggest that overall N rates to achieve optimal yields could be reduced by 10 lb/ac if all the N was applied as aqua.

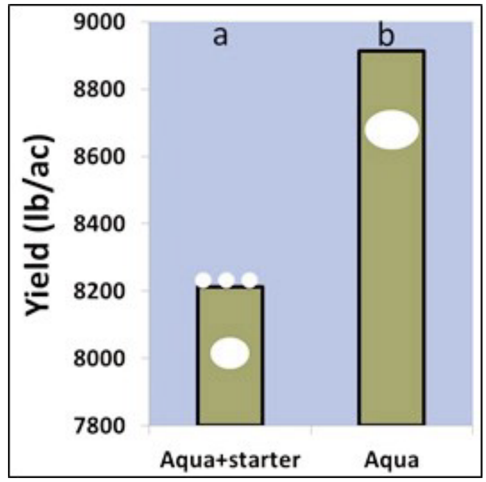

Figure 5. Effect of N source and placement on yields. The N shown here is 100 lb N/ac and the data represent the average response across different fields.

While starter N may not be necessary, P fertilizer is often required and P is usually only available as ammonium phosphates (i.e. a fertilizer that contains N). Thus, applying P fertilizer usually requires that some N fertilizer is also applied. Applying P is usually applied as a starter fertilizer before planting. Therefore, if a starter fertilizer is necessary (due to need for P), we recommend using a starter blend with the lowest amount of N possible. The N in the starter should be considered as part of the total N rate.

If a top dress is necessary, ammonium sulfate is often used as it has a lower N content and is easier to apply uniformly by air. However, urea could also be used and is generally a cheaper source of N.

—Right time—

Numerous research trials have shown that the most efficient time to apply N to water seeded rice systems is to apply it all before planting. These trials have shown no benefit to splitting the N rate between planting and a top-dress application. Therefore, there is no benefit to planning a top-dress application of N. In drill seeded systems or when water is drained from the field for an extended period of time it may be neces-

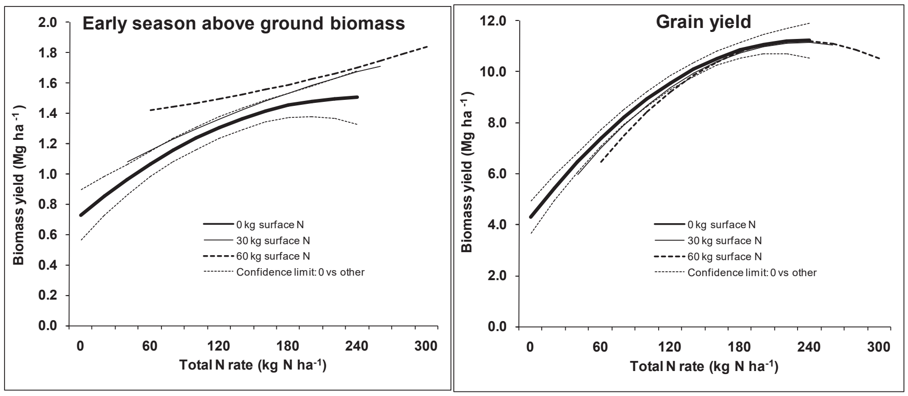

Table 3. Interpretive guide for leaf nitrogen percentage. Total leaf N concentrations are for California medium grain varieties.

sary to apply fertilizer at different times.

All the nitrogen should be applied before planting. However, there may be cases where a top-dress is necessary. For example, if the growing season is particularly favorable resulting in greater growth and yield potential. Or, an unplanned water drainage event may necessitate a top-dress due to N losses associated with draining the field. Top-dress N fertilizer should be applied at or before PI.

In these cases, a decision on whether or not to top-dress can be made with a leaf color chart, chlorophyll meter or Green Seeker.

Leaf color chart: The UC leaf color chart is a series of eight color panels against which leaves are compared (Fig. 6). With some practice, leaf nitrogen can be predicted with a high degree of accuracy using the LCC. Furthermore, it does not take a lot of practice to get good results. On the back of the chart there is table relating panel color to leaf nitrogen. Refer to Table 3 to determine if the leaf N concentration is adequate. The LCC has been calibrated for medium grain varieties which have similar leaf color. Some specialty varieties have a more yellow leaf color and the LCC would need to be calibrated separately for them.

Chlorophyll Meter (SPAD meter). The meter is a hand-held device that estimates leaf nitrogen based on leaf color and transmitted light. The meter is quick. However, the meter displays numbers which are not directly related to leaf nitrogen. Consequently, considerable effort is required to establish a calibration curve. Moreover, leaf thickness can influence the readings because the chlorophyll meter relies on transmitted light. Thus, a single curve may not accurately describe leaf nitrogen for all varieties. Table 4 presents the relationship between the SPAD meter reading and leaf N (%) at panicle initiation for ten rice varieties. It is relative-

Figure 6. The effect of early season N placement on early season biomass (about 35 days after sowing) and yield. Shows that at same total N rates, applying the effect of applying 30 or 60 kg N/ha (34 and 78 lb N/ac) as a surface applied starter increases early season biomass but has no effect on yield potential; while at the lower N rates, yields are reduced. Note: lb/ac = Mg/ha * 890 .

% Nitrogen at Panicle Initiation									
SPAD	S-102	Calhikari	M-202	M-204	M-205	L-204	L-205	Calmati	Akita	Koshi
25	2.3	2.6	2.4	2.4	2.5	2.4	2.2	2.2	1.8	1.8
26	2.4	2.7	2.5	2.5	2.7	2.5	2.4	2.4	1.9	1.9
27	2.5	2.8	2.6	2.7	2.8	2.6	2.5	2.5	2.0	2.0
28	2.6	2.9	2.8	2.8	2.9	2.8	2.6	2.7	2.1	2.1
29	2.7	3.0	2.9	2.9	3.1	2.9	2.8	2.8	2.2	2.2
30	2.8	3.1	3.0	3.0	3.2	3.0	2.9	3.0	2.3	2.3
31	2.9	3.3	3.2	3.1	3.3	3.2	3.0	3.1	2.4	2.4
32	3.0	3.4	3.3	3.2	3.5	3.3	3.2	3.3	2.5	2.5
33	3.1	3.5	3.4	3.4	3.6	3.4	3.3	3.5	2.6	2.6
34	3.2	3.6	3.5	3.5	3.7	3.5	3.4	3.6	2.7	2.7
35	3.3	3.7	3.7	3.6	3.8	3.7	3.6	3.8	2.8	2.8
36	3.4	3.8	3.8	3.7	4.0	3.8	3.7	3.9	2.9	2.9
37	3.5	4.0	3.9	3.8	4.1	3.9	3.9	4.1	3.0	3.0
38	3.6	4.1	4.1	3.9	4.2	4.1	4.0	4.2	3.1	3.1
39	3.7	4.2	4.2	4.1	4.4	4.2	4.1	4.4	3.2	3.2
40	3.8	4.3	4.3	4.2	4.5	4.3	4.3	4.6	3.3	3.3
41	3.9	4.4	4.5	4.3	4.6	4.5	4.4	4.7	3.3	3.4
42	4.0	4.5	4.6	4.4	4.8	4.6	4.5	4.9	3.4	3.5
43	4.1	4.6	4.7	4.5	4.9	4.7	4.7	5.0	3.5	3.6
44	4.2	4.8	4.9	4.6	5.0	4.8	4.8	5.2	3.6	3.7
45	4.3	4.9	5.0	4.8	5.1	5.0	4.9	5.3	3.7	3.7

Table 4. Leaf N content (%) at panicle initiation of select rice varieties and the corresponding chlorophyll meter (SPAD, Minolta) readings

ly old data which does not include newer varieties. However, M-202 or M-205 calibration would provide a reasonable estimation of leaf N for the newer medium grain varieties. For medium grains, using the %N value from Table 4, one can determine if crop N is sufficient using Table 3.

Remote Sensing. Remotely sensed data of the crop canopy can be obtained from proximal sensors, drones, airplanes or even satellite data. We have looked at the GreenSeeker which is a proximal sensor with an active light source as well as imagery from a drone which uses passive light (sun light). The Green Seeker measures the NDVI (Normalized Difference Vegetation Index) of the canopy. The camera on the drone measured NDVI as well as Normalized difference Red edge (NDRE). We have developed a sufficiency index (SI) to help growers decide when a top-dress N application is necessary (Fig. 7). The SI value will vary depending on cost of fertilizer and rice prices. The SI is the NDVI reading of the field test area divided by the NDVI of an enriched N strip (representing a crop with unlimited N). The N enriched strip is an area where extra N was added to the field (could be done by overlapping an area with an aqua rig). For example, if the N enriched strip gave an NDVI value of 78 and the field test area gave an NDVI value of 70, the SI would be 0.90 (70/78) and this would indicate the need for a top-dress N application with an average yield increase from the top dress of more than 400 lb/ac (Fig. 7). Note, some researchers calculate a response index (RI). The RI is the inverse of the SI; so using the above example, the RI would be 1.11 (78/70).

Some limitations to the Green Seeker are that it is still relatively limited in area that can be tested; although it is much faster to take readings and therefore get a quicker assessment of the field. You can also not use the Green Seeker

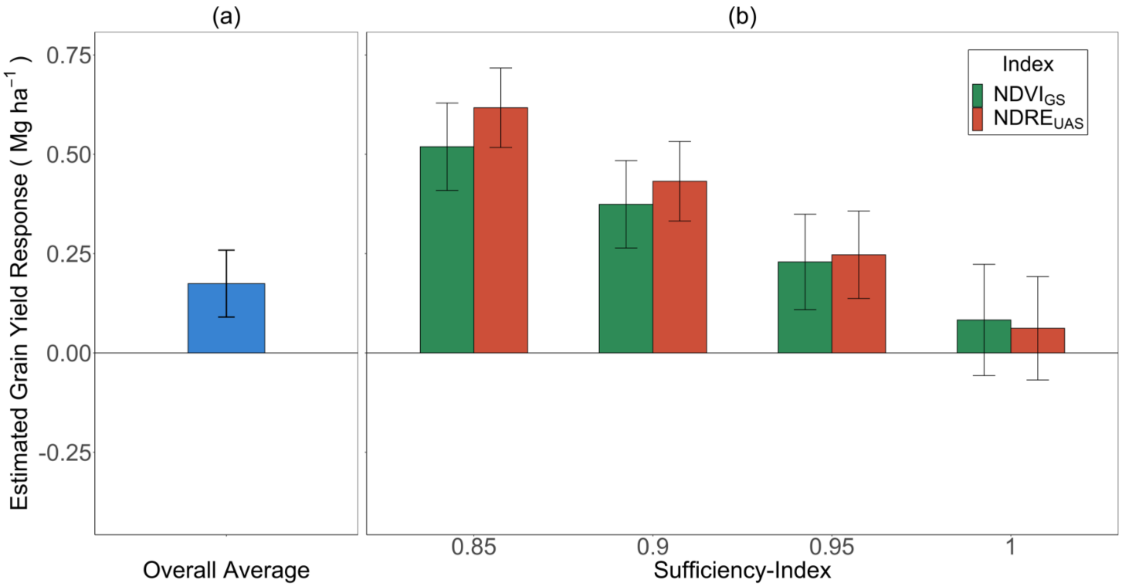

Figure 7. The estimated rice grain yield response (lb/ac=kg/ac X 0.89) to top-dress N applied at the panicle initiation (PI) growth stage at 30 lb N/ac. (a) overall average (averaged across SI 0.85 to 1.00), and (b) for GreenSeeker (GS) Normalized Difference Vegetation Index (NDVIGS) and unmanned aircraft system (UAS) Normalized Difference Red-Edge Index (NDREUAS) at specific SI values corresponding to the typical management range (i.e., pre-plant N rates 150 to 200 lb N/ac) as estimated by linear mixed-effects models. The error bars represent the standard error around the estimated grain yield response.

when leaves have dew or rainfall on them. The Green Seeker also does not work well where there is poor stand establishment or a high amount of weeds.

Drones allow growers to access a larger portion of the field more rapidly. Our research indicated that the NDVI captured from a drone is not very useful in quantifying N status. However, NDRE provided similar RI results to the Green Seeker (Fig. 7).

—Right place—

In water-seeded rice systems, the objective needs to be to get as much of the fertilizer N as possible below the soil surface. In a flooded system the top 0.5” of soil is oxidized and fertilizer N in this area can be nitrified which can then lead to N losses via denitrification. Many studies both in California and in other parts of the world have shown that N placed deep into the soil results in greater N use efficiency.

Given that the majority of N applied to water-seeded rice systems is aqua-ammonia the issue of fertilizer placement is not so relevant as aqua is always injected into the soil. The main issue then becomes how deep should aqua be injected. This has not been a topic of research; however, most growers apply aqua at 3-4 inches deed which is adequate to get good soil coverage following application. N applied at this depth will ensure that the fertilizer is in the zone of soil that is reduced following flooding which will help minimize N losses. At this time there does not seem to be a good rational for placing the aqua any deeper than the 3-4 inches currently being practiced.

Starter and top-dress fertilizers are usually applied to the surface. To reduce N losses from N in the starter fertilizer, growers should seek to limit the amount of N in the starter blend by using a blend containing the lowest amount of N possible. Also, lightly harrowing fertilizer into the soil can help prevent N losses. For the top-dress N, this N is usually applied later in the season (i.e. between maximum tillering and panicle initiation) when the crop is growing rapidly and the demand for N is high. Therefore, much of the N is taken up by the crop rapidly after application which helps to minimize losses.

When you can not apply aqua-NH_3 as a primary N source

Most rice in California receives the majority of N fertilizer in the form of preplant aqua-ammonia (Aqua). Some starter N is applied before planting or delayed by a few weeks as mentioned above. This strategy is efficient and effective. However, it is not uncommon for rains to force growers to plant their rice before fertilizer application. Similarly, there have been times when aqua is not available. So, when aqua cannot be applied, what are the options?

In 2020 and 2021, research was conducted both on-farm and at the RES to look at different options. This research evaluated different N sources (enhanced efficiency fertilizers, urea, ammonium sulfate), different timing of applications, and split urea applications. In brief our findings were:

1. Aqua or urea applied to a dry soil before flooding, resulted in the best yields. So, this remains the best option.
2. None of the enhanced efficiency fertilizers tested (Agrotain, SuperU or Agrocote) did better than urea applied alone at the same time.
3. Urea was similar to ammonium sulfate in all cases
4. Split applications did the best of all of the alternatives. Based on the results, splitting the N application 4 times at 3, 4, 5 and 6 after planting at a ratio of 20%:30%:30%:20% will give good results. In a split application, the first application should be the starter which contains N, P, K and any other nutrient being applied. The other applications

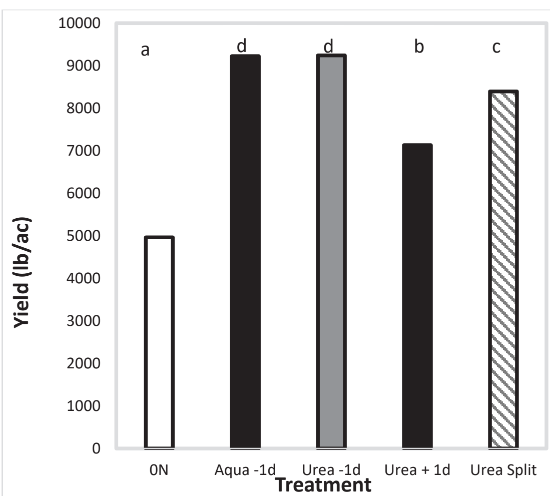

Figure 8. Yield response to aqua and urea applied 1 day before flooding (-1d), urea 1 day after flooding (+1d) and a split application of urea compared to a treatment that received no nitrogen (0N). All treatments received 135 lb N/ac. The split urea was applied at a ratio of 20:30:30:20% at 2, 4, 6 and 8 weeks after flooding.

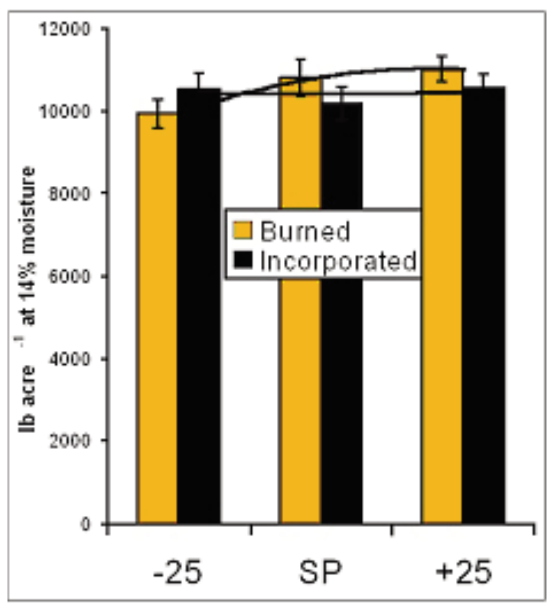

Figure 9. Yield of burned and straw incorporated/flooded fields when fertilized at the standard grower practice (SP) and plus of minus 25 lb.

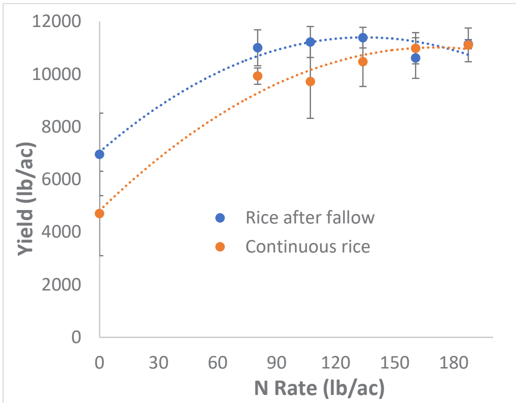

Figure 10. Rice grain yield when the rice crop followed a fallow year versus following a previous rice crop. Data are from 2022 at the Rice Experiment Station.

should be urea. Our research suggests that the overall N rate in a split application may need to be higher than what would normally be applied as aqua (Fig. 8).

Effect of straw management on N management

California rice growers annually incorporate about 9000 lb/ac of straw across most of the Sacramento Valley. This straw contains approximately 57 lb of N (Table 1). This large introduction of organic matter influences the immobilization-mineralization dynamics and consequently nitrogen fertility management. Straw incorporation results in more nitrogen in the soil microbial biomass. Since microbial biomass is a prime source of available nitrogen for the crop, straw incorporation can lead to an increase in crop available soil nitrogen. Depending on how straw is managed it can lead to either an increase or decrease in the amount of N applied.

A number of studies have shown that the overall N rate applied to rice can be reduced by about 25 lb N/ac when rice straw is incorporated in the fall and the field is winter flooded. An example of this is shown in Figure 9 where burned and incorporated fields were compared. In fields where the straw was burned the standard grower N rate provided optimal yields and lower yields when the N rate was reduced by 25 lb N/ac. In contrast, where the rice straw was incorporated, the N rate could be reduced by 25 lb N/ac without a yield reduction.

Importantly, this N benefit from straw incorporation is

1. Typically observed only after about three years of incorporation.
2. Is only observed when the straw is incorporated and flooded (or the soil remains moist) during the winter. If the straw is left standing or on the soil surface during the winter and only incorporated during the spring land preparation the rice straw can lead to N immobilization (Table 2) at the start of the season resulting in reduced growth, yellow plants and reduced yields. If straw is managed in this fashion, it will most likely be necessary to apply additional N fertilizer to overcome early season N immobilization.

Nitrogen management following a fallow year

It is not uncommon, especially in drought years, for fields to be fallowed during the growing season. Growers often report that rice yields in fields which were fallowed in the previous year are higher than when rice is grown following a previous rice crop. A couple years of research at the Rice Experiment Station (RES) has indicated that yields are generally higher following a fallow year (Fig. 10). One of the reasons for higher yields is that the incidence of stem rot was lower. We also saw in one year that similar yields could be achieved but the continuous rice system required more N fertilizer to achieve the same yields as the fallow rice system. Research at the RES and elsewhere has shown that phenols build up in soils where rice is grown

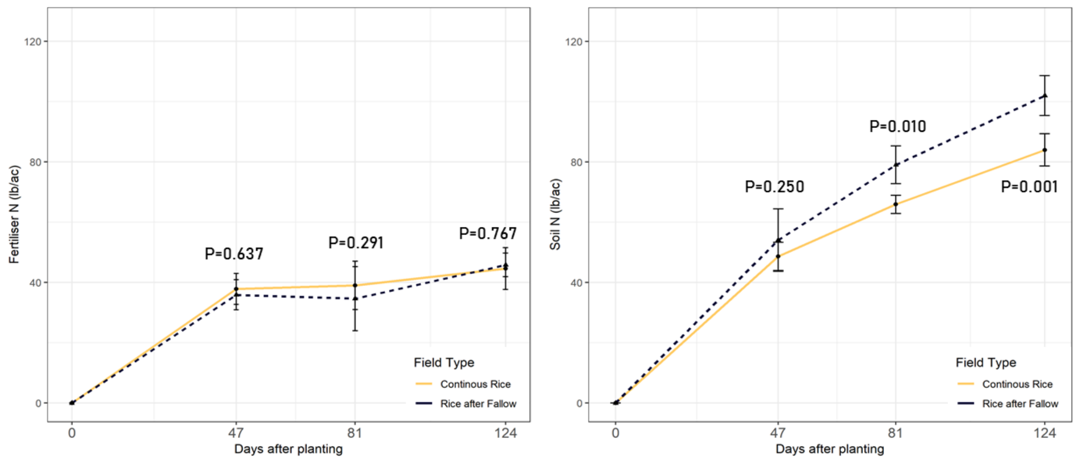

Figure 11. Source of N taken up by the crop in continuous rice systems versus rice following a fallow year determined from 15N labeled N fertilizer applied at a rate of 135 lb Na/ac. The left graph shows the amount of N in the plant that came from fertilizer and the right graph shows the amount coming from the soil.

continuously and fields remain flooded for large parts of the year. Phenols can bind nitrogen. At the RES, we did see greater amounts of phenols in fields which were continuous rice. Supporting this, we found that in continuous rice fields, the N availability from the soil was reduced later in the season (after PI) (Fig. 11). What this suggests is that continuous rice fields are likely to require more fertilizer N – especially later in the season.

Effect of variety

There is very little difference in the overall N fertilization requirement and strategy for California's major short and medium grain conventional varieties. While the data is old and some of the varieties are no longer available, Table 5 clearly shows that the N rate required for maximum yields was the same (in this case 150 lb N/ac) for all varieties over the two sites.

Nitrogen management practices do vary significantly for specialty rice varieties. Many of these specialty rice varieties are lower yielding and highly susceptible to lodging and thus require lower N rates. Furthermore, grain quality characteristics can be affected by N management. Research and grower experience demonstrated that yield and grain quality characteristics in specialty varieties benefit from split applications of nitrogen. For example, the yields of Akitakomachi responded favorably to split applications of nitrogen. A preplant/panicle initiation (PI) split of 40-40 lb/a nitrogen produced the highest yields across all locations (Table 6). Furthermore, gains in grain quality were associated with desirable changes in physicochemical properties and improved agronomics, such as reduced lodging. Lodging causes uneven ripening which results in a greater spread in individual kernel moisture contents. In a sample of rice with an average moisture content of 23%, it is possible for individual kernel moisture to range from 16 to 34%. Reduced lodging does not guarantee complete uniformity of ripening because plant genetics are a factor. However, good nitrogen management minimizes the moisture content range. Lodging also contributes to the development of off-odors which degrades quality, particularly for the north-eastern Asia market.

Table 5. Yield response (@ 14% MC) of selected varieties variable rates of pre- plant nitrogen in Sutter County (top) and Butte County (bottom).

N Rate	S-102	M-104	M-202	M-205	M-206	M-402	Mean
0	3723	3878	3745	4350	3789	4074	3927
50	5902	5707	5932	5886	6182	6775	6064
100	7306	6978	6794	8181	7755	7690	7451
150	8527	7972	7791	8743	8528	8523	8347
200	7317	7709	7114	8613	8175	7820	7791
Mean	6555	6449	6275	7155	6886	6977	6716
N Rate	S-102	M-104	M-202	M-205	M-206	M-402	Mean
0	4137	3880	4479	4254	4754	4241	4291
50	6776	6428	7358	6993	7461	6863	6980
100	9568	9269	9770	9641	9936	9190	9562
150	9766	9753	10644	10181	10788	10292	10238
200	8515	8175	8538	8748	8894	8552	8570
Mean	7752	7501	8158	7963	8367	7828	7928

Table 6. Yield response of Akitakomachi to different preplant and topdressing rates of nitrogen at three locations in the Sacramento Valley.

Treatment	Pleasant Grove lb/a	Colusa lb/a	Richvale lb/a	Average lb/a
0	4916	4270	4892	4693
60 - 0 - 0	5511	6045	5623	5727
80 - 0 - 0	5307	5442	5358	5369
40 - 40 - 0	5806	6268	5943	6006
100 - 0 - 0	4901	4956	4742	4860
50 - 50 - 0	5941	5890	5297	5709

Cover Crops

Diversifying a continuous rice system by adding a winter cover crop has a number of benefits including: improving soil health and soil structure, providing nitrogen for the following rice crop, and providing wildlife habitat. In California, cover crops are not commonly used in conventional systems but they are in organic systems. Generally, they are planted after rice harvest in the fall and terminated before land preparation in the spring.

When considering the use of cover crops in rice systems it is important to think about the timing and compatibility of cover crops with the rice growing season; the compatibility of cover crops with rice soils (often poorly drained); equipment and labor requirements; and desired benefits.

-Cover crop species-

Potential cover crop species can be broadly divided in leguminous and non-leguminous. Legumes fix atmospheric N, thus adding nitrogen to the system which may be able to replace fertilizer N. Common legumes used as cover crops in CA rice systems include various vetch species, winter peas, and bell beans. Non-legumes, do not fix nitrogen. Non-legumes include grasses such as oats, wheat and rye, or broad leaves such as radish.

Cover crops should be chosen carefully since some varieties do not grow well in particular soils or climates. In CA, cover crops should be adapted to a cool season as these crops will be growing during the winter and early spring. Also, legumes generally do not do well in water-logged soils. Some species will do better than others, depending on the effort a farmer wants to invest.

Often farmers plant a blend of various cover crop species. This has a number of advantages. First, depending on rainfall, temperature, soil conditions, and land preparation some species will do better than others, thus planting a blend helps insures that at least some of the species establish. Secondly, legumes tend to have a low carbon to nitrogen (C:N) ratio. This results in rapid decomposition after the crop is terminated and incorporated into the soil. Decomposition releases the nitrogen into the soil and if it is released before a plant can take it up, it could be lost. Adding non-legumes (higher C:N ratio) to the mix will slow decomposition and the release of N so plants can take it up more efficiently.

-Planting and Termination-

The majority of cover crops in California rice systems are planted in the fall/winter, following rice harvest. Planting should be timed so that little to no irrigation is needed. In many cases, farmers will incorporate the rice straw into the field and then aerial seed the cover crop seed onto the field, then wait for rain. To improved establishment and success, a light harrow or roller could be passed over the field after aerial seeding to improve seed soil contact. This is especially important for larger seeded cover crops. Ditches should also be put throughout the field and run toward the outlet boxes to aid in runoff in the case of heavy winter rains.

Generally, farmers will not apply fertilizer when establishing the cover crop. However, as with any crop, if the soil is deficient in nutrients, the crop will not reach its potential. Importantly for legume cover crops, soil phosphorus is important as it is closely linked with N-fixation.

Termination depends on the cover crop variety, available equipment, precipitation, and desired objectives. Some considerations:

- Ideally, the cover crop should not be going to seed when crop is terminated. During grain development, N from the plant tissues will be translocated to the seed, leaving less N in the biomass.
- Termination can be accomplished with the

use of herbicides or mechanically.

- Termination should occur at least a month before planting.
- When there is a lot of biomass it may be better to mow/chop it before incorporation into soil (Fig. 12).

Figure 12. A cover crop being terminated by mowing and then being disked into the soil.

-Nutrient Management

Cover crops are often grown to provide a readily available source of nutrients to the following crop. These nutrients become available to the crop as the cover crop decomposes in the soil and releases nutrients. A leguminous cover crop can provide up to 100 lb N ac to the following crop but this will depend on how well it grew during the winter and when it was terminated. Since the amount is variable, it will be important to monitor the rice crop during the season for N status. As mentioned earlier, by mixing legumes with non-legumes the cover crop N will be released slower making it available when the crop needs it the most.

-Drawbacks-

While there are benefits to cover crops as mentioned earlier, there are also drawbacks, some of which have already been alluded to above. These include:

- A large cover crop requires extra work after termination to break down the residues and allow for optimal seedbed preparation
- Cover crop establishment and growth in a field can be highly variable. Thus, N availability increases across a field, leading to challenges in efficiently managing fertilizer N across the field.
- Early season decomposition of large amounts of readily decomposable biomass can lead to sulfide and iron toxicity early in the season.
- Cover crops will lead to an increase in greenhouse gas emissions – particularly methane.

Phosphorus

Plant function

The major roles of phosphorus in plants are energy storage, transport of metabolites, and cell membrane integrity. Adequate levels in the plant promote tillering, root development, flowering, and ripening. It is particularly important during the early stages of growth. Similar to potassium, the uptake rate of phosphorus peaks at the early reproductive stage (Fig. 1). If an adequate soil supply was available during vegetative growth, enough will have been taken up to supply the plant requirements for grain production.

Deficiency symptoms

Phosphorus deficient plants are stunted with reduced tillering. Leaves are narrow, dark green, short, and erect. Overall plant height is compromised. Red or purple colors may develop on the older leaves, which eventually turn brown. Phosphorus deficiency also contributes to delayed maturity, unfilled grains, and reduced response to nitrogen application.

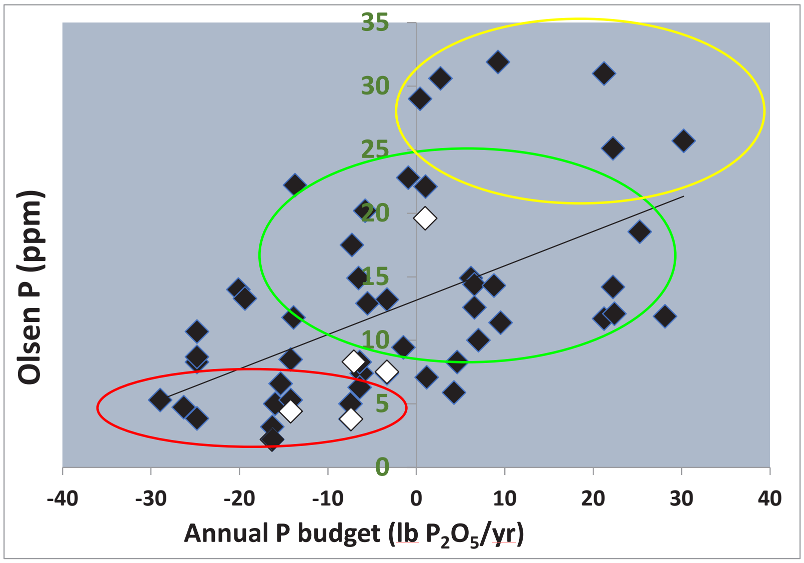

Figure 13. The relationship between soil Olsen-P values, P balance and yield response to P fertilizer (left). Data are from on-farm studies and the P balance reflects the 5 yr average of inputs and outputs. . Circles indicate fields in which different P management strategies need to be used. The open diamonds indicate a study in which there was a significant yield response to added P fertilizer.

Soil phosphorus

Most soils have very high amounts of total phosphorus; however only a small portion of this is available for plant uptake during the growing season. The transformation processes of phosphorus in flooded soils are different from those in non-flooded soils. Flooded soils exhibit a greater capacity to supply plant available phosphorus than non-flooded soils. Crops grown on flooded soils may not show a response to phosphorus applications, while crops grown on the same soil under aerobic conditions may exhibit deficiencies.

Determining a deficiency

In a study evaluating rice yield response to P fertilizer in roughly 60 California rice fields, less than 10% of the soils were deficient based on whether or not grain yields responded significantly to added fertilizer P. There are a number of ways to identify P deficiencies, each with its own benefits and setbacks as discussed at the start of this section. These tests provide a general indication of a deficiency. Using more than one provides a better indication.

-Soil test-

A number of soil tests are available; however, for rice soils the Olsen-P test (also called the sodium bicarbonate test) has been shown to be best at identifying a deficiency. The Bray test has also been evaluated and is a poor indicator of P deficiency on rice soils. The Olsen-P test is also the most widely used soil test for rice soils around the world. The critical Olsen-P value is 6 ppm and this has been confirmed in California rice fields.

Leaf tissue tests-

Leaf tissue tests taken at 35 days after planting (around maximum tillering) can also be useful in predicting a P deficiency. Y-leaf tissue concentrations of less than 0.2% suggests a deficiency.

-Input-output budgets-

A good idea of whether a soil is P deficient can be achieved by developing a P input-output budget. In terms of inputs, almost all P that enters a rice field is from fertilizer (very little in irrigation water, rainfall, etc). Also, almost all outputs are the P that is removed in grain (yield) and straw (if it is removed from the field). Burning does not result in a significant loss of P. Also, very little to no P is lost via leaching or run-off. Therefore, a simple budget can be developed using the following equation:

P balance = Inputs (lb/ac of P2O5 as fertilizer) – Outputs (lb/ac removed in grain and straw).

For best results determine the P balance using a 5-yr average of inputs and outputs over the previous 5 years. A negative balance indicates that more P is being removed from the soil than is being added and thus it could be deficient. This will be discussed later when we discuss the correct rate.

As shown in Figure 13, the P budget reflects soil P (Olsen-P) status. As the P budget becomes more negative, the soil becomes increasingly P deficient. It is also apparent that where there were significant yield responses to P fertilizer were usually were P balance was negative and Olsen-P values were low.

4R Management

—Right rate—

Before determining the appropriate P rate, it is first necessary to determine if it is even necessary to apply P fertilizer. This can be best determined using the Olsen-P value and the soil P balance.

Apply no P when there is both high soil P and a positive P balance (yellow circle in Fig. 13).

Apply maintenance P rates when soil P values are between 6 and 20 ppm (green circle in Fig. 13). Maintenance rates can be determined from depending on whether or not rice straw is being removed.

Build-up soil P when soil P is less than 6 and there is a negative P balance (red circle in Fig. 13). P build-up rates can be determined from Table 7 depending on whether or not rice straw is being removed. To build up P one would need to add more than the maintenance rate.

—Right source—

While there are many different P fertilizers, most P fertilizers using in CA rice systems are some form of ammonium phosphate (contains both N and P). In order to meet our N management objectives of applying as much N as possible in aqua form, the P fertilizer with the lowest N content should be used (often 11-52-0).

—Right time—

Generally speaking, we recommend most of the P being applied during tillage and seedbed preparation. Most growers will apply a starter blend containing P just before flooding the field. To avoid potential algae (scum) problems we recommend this fertilizer be lightly harrowed into the soil rather than sitting on top of the soil.

If algae is a severe problem, one can manage P fertilizer in a way so as to reduce the algae build-up early in the season. Many studies have shown that algae increases with increasing P concentration in water. Fertilizer P applications increase water P concentrations and can lead to increased algae build-up in rice fields.

Research has shown that incorporating P into the soil or delaying the P application by 30 days (or until the rice leaves have emerged above the soil surface) can reduce algae problems (or delay algae growth until it is not a problem for rice). An example is shown in Figure 14 which shows that overall, algae varied between the different growers. However, in both cases, algae was highest when it was applied on the soil surface. Incorporating the P into the soil

Table 7. Charts relating rice yield with how much P (expressed in fertilizer equivalents-P2O5) is removed from the soil. The chart on the left assumes only grain is removed while the chart on the right is for when grain is removed and half of the rice straw. Alternatively, an on-line P budget tool has been developed based on the values in the table and is available at http://rice.ucanr.edu/P_Budget_calculator/.
To determine P balance first determine P outputs. To do this determine average yields from field over past 5 years. Based on if straw was removed or not choose appropriate chart. The amount of P removed based on average yields will be the value under the "0" P fertilizer added or removed column. For example if average yields were 85 cwt and only grain was removed then the amount of P removed was 44 lb/ac.

Grain yield (cwt@14%)	P fertilizer added (pounds P_2O_5/ac)														
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
	P balance (pounds P_2O_5/ac)														
50	-26	-21	-16	-11	-6	-1	4	9	14	19	24	29	34	39	44
55	-29	-24	-19	-14	-9	-4	1	6	11	16	21	26	31	36	41
60	-30	-26	-21	-16	-11	-6	-1	4	9	14	19	24	29	34	39
65	-34	-29	-24	-19	-14	-9	-4	1	6	11	16	21	26	31	36
70	-37	-32	-27	-22	-17	-12	-7	-2	3	8	13	18	23	28	33
75	-39	-34	-29	-24	-19	-14	-9	-4	1	6	11	16	21	26	31
80	-42	-37	-32	-27	-22	-17	-12	-7	-2	3	8	13	18	23	28
85	-44	-39	-34	-29	-24	-19	-14	-9	-4	1	6	11	16	21	26
90	-47	-42	-37	-32	-27	-22	-17	-12	-7	-2	3	8	13	18	23
95	-50	-45	-40	-35	-30	-24	-20	-15	-10	-5	0	5	10	15	20
100	-52	-47	-42	-37	-32	-27	-22	-17	-12	-7	-2	3	8	13	18
105	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15
110	-57	-52	-47	-42	-37	-32	-27	-22	-17	-12	-7	-2	3	8	13

Grain yield (cwt@14%)	P fertilizer added (pounds P_2O_5/ac)														
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
	P balance (pounds P_2O_5/ac)														
50	-31	-26	-21	-16	-11	-6	-1	4	9	14	19	24	29	34	39
55	-34	-29	-24	-19	-14	-9	-4	1	6	11	16	21	26	31	36
60	-37	-32	-27	-22	-17	-12	-7	-2	3	8	13	18	23	28	33
65	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30
70	-43	-38	-33	-28	-23	-18	-13	-8	-3	2	7	12	17	22	27
75	-46	-41	-36	-31	-26	-21	-16	-11	-6	-1	4	9	14	19	24
80	-49	-44	-39	-34	-29	-24	-19	-14	-9	-4	1	6	11	16	21
85	-52	-47	-42	-37	-32	-27	-22	-17	-12	-7	-2	3	8	13	18
90	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15
95	-58	-53	-48	-43	-38	-33	-28	-23	-18	-13	-8	-3	2	7	12
100	-61	-56	-51	-46	-41	-36	-31	-26	-21	-16	-11	-6	-1	4	9
105	-64	-59	-54	-49	-44	-39	-34	-29	-24	-19	-14	-3	-4	1	6
110	-67	-62	-57	-52	-47	-42	-37	-32	-27	-22	-17	-12	-7	-2	3

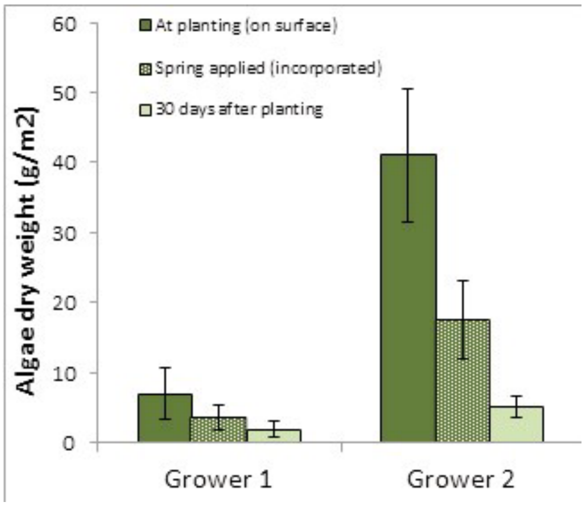

Figure 14. Effect of P fertilizer management (timing and placement) on algal growth in two rice fields

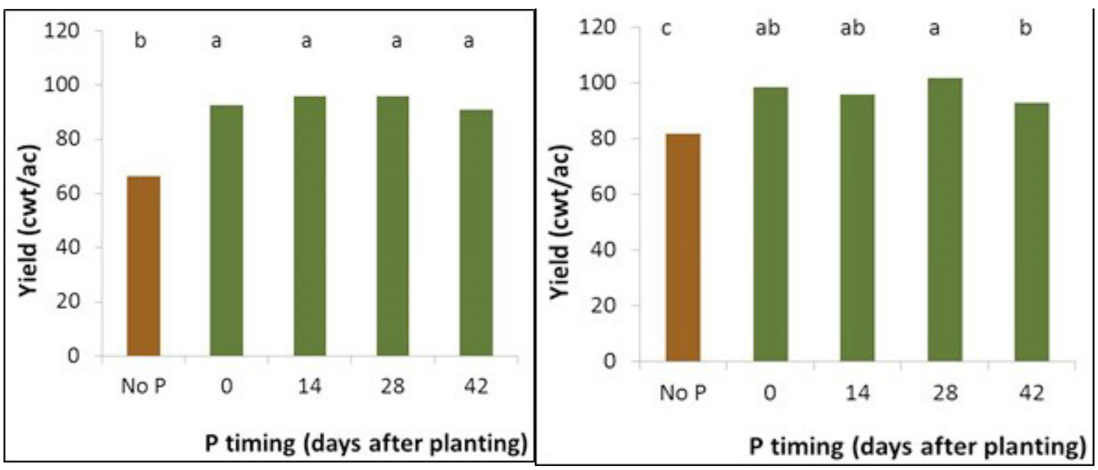

Figure 15. Effect of P fertilizer timing on rice yields in two rice fields

reduced algae levels by over 50%; however, delaying the P application (applying 30 days after planting) reduced algae levels by almost 90% on average.

It is important that delaying P fertilizer applications does not reduce yields. A number of studies have examined this and results show that in fields where P is deficient that delaying P application by up to 28 days has no negative effect on yield. However, applications later than this can result in lower yields (Fig. 15).

One issue related to late P applications is that P can leave the field in the run-off water – a potential off-site pollution concern. Therefore, for late P applications, the water should be held for about 2 weeks after P application.

-Right place—

As mentioned above, if P is applied before flooding and planting it should be lightly incorporated to help reduce algae problems.

Effect of straw management on P management

The main effect of straw management is whether or not it is removed from the field or not. There is approximately 5 to 6 lb P2O5 in every ton of rice straw. Removing straw from the field will affect the soil P budget and require that more fertilizer P be added to maintain existing P balances.

Potassium

Plant function

Potassium (K) functions in osmoregulation, enzyme activation, regulation of stomatal function, transport of assimilates, cell wall synthesis, and cellular pH. Adequate potassium nutrient increases leaf chlorophyll contents, delays leaf senescence, and therefore contributes greater photosynthesis. It improves the plants tolerance to adverse environmental conditions and improves tolerance to disease. It remains in ionic form and is very mobile within the plant. Potassium is readily transported from old senescing to young developing leaves. Yield response to potassium requires sufficient supplies of other nutrients, especially nitrogen. Similar to nitrogen, potassium uptake rate peaks at the onset of the reproductive phase (Figure 1).

Deficiency symptoms

Potassium deficiency show up as dark green plants with yellow/brown leaf margins starting at tip of leaf or dark brown or rusty brown necrotic spots on leaf-also starting on leaf tips and margins. These symptoms first appear on older leaves, then along leaf edge and finally at leaf base. Yellow stripes may appear in the interveinal portions of the leaf and lower leaves become droopy. K deficiencies can also lead to increased diseases in rice. This is because K deficiency results in an accumulation of sugars and amino acids that are good food sources for pathogens. An example of this is show in Figure 16 where aggregate sheath spot severity increases when K concentrations are low in the leaf.

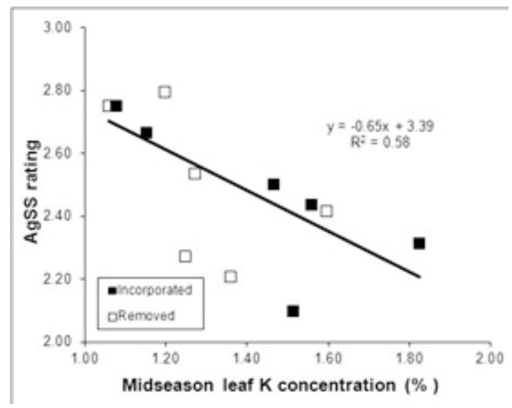

Figure 16. Aggregate sheath spot (AgSS) rating as affected by Y-leaf (at panicle initiation) K concentration in fields where straw was either incorporated or removed.

Soil potassium

Potassium (K) is present in soils in four forms, which are in dynamic equilibrium. The forms are soluble K (readily available); exchangeable K (easily mobilized reserve); non-exchangeable K (slowly mobilized); and mineral K (semi-permanent reserve). Only about 1 2 % of the total potassium in a mineral soil is readily available for plant uptake. Under certain conditions, fertilizer potassium is fixed by the soil colloids and therefore not readily available to the plant. Clays of 2:1 type, such as montmorillinite, commonly found in the Sacramento Valley can readily fix large amounts of potassium. Wet-dry cycles and presence of lime influences the magnitude of the fixation. Under continuous flooding, plant uptake favors the release of fixed potassium.

Determining a deficiency

A number of factors can lead to a soil being deficient in K and, apart from visual plant symptoms or soil/tissue tests, these can be used as a guide in determining if K deficiencies are likely. In California, in a study of over 30 fields the only fields having soil K values below 100 ppm were located east of the Sacramento River. Lower soil K values were observed as one moved further east to the red soils nearer the foothills. While differences in soil K is due in part to differences in soil type, the irrigation water supplied to rice soils in these regions also varies. Irrigation water from the Sacramento River which supplies much of the irrigation on the west side of the valley is higher in K than in the Feather River or other Sierra rivers which supply water on the east side (Fig. 17). K concentrations in well water were the highest but also most variable. Over time, these differences in K concentration could affect soil K values; however, these differences also affect how much K fertilizer may need to be recommended.

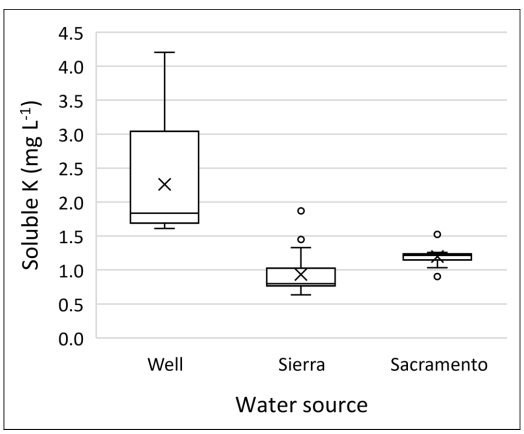

Figure 17. Irrigation water potassium concentrations. Sierra rivers include the Feather, Yuba and Bear rivers.

—Soil—

A soil test is a good way to determine if a soil is deficient in K fertilizer. Critical levels at which a soil is considered deficient using the common 1N NH4OAc-extractable soil K test varies with figures ranging from 60 to 85 ppm. However, in recent research where soil K values were compared to flag leaf K concentrations, it appeared that where soil K values were above 100 ppm that flag leaf K values were high (above 1.2%) and unaffected by soil K (Fig. 18). However, when soil K was below 120 ppm, flag leaf K concentrations were lower and many below the level considered to be deficient (1.2%). Therefore, taking a conservative approach, when soil K values are 100 ppm or below the soil may be deficient in K.

—Plant leaf tissue—

To determine a K deficiency using plant tissue, Y-leaf samples can be taken between tillering and panicle initiation or a flag leaf sample can be taken at heading or flowering. Critical values for tissue samples taken during this time are 1.5% for Y-leaf samples or 1.2% for flag leaf samples. Data from Figure 18 also confirm that flag leaf samples of about 1.2% are deficient in K.

—Location in Valley—

Due to differences in soil types around the Sacramento Valley, certain regions are more likely to experience soil K deficiencies (Fig 19). Soil low in extractable K are much more common on the east and north side of the valley than along the west side. Soils which fix potassium and have a low k saturation are also more common in the same area.

4R Management

—Right rate—

Average K fertilizer rates used in California are about 30 lb K2O/ac. Potassium fertilizer rates will depend on a number of factors including soil test value, straw management, and irrigation water source. Given that relatively few

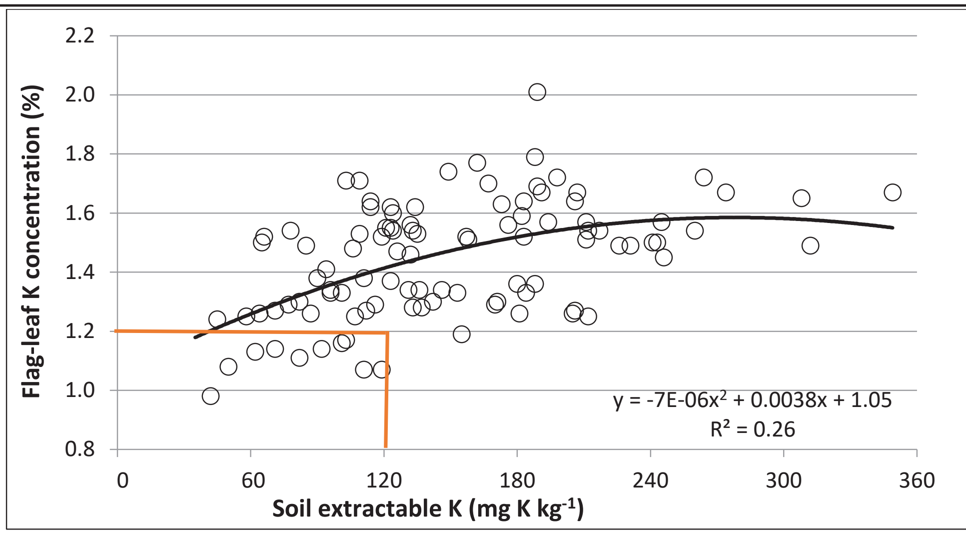

Figure 18. The relationship between soil K and flag leaf K values (taken at flowering) in fields where K fertilizer was not applied.

fields in California are deficient in K, there has not been a focused effort at calibrating soil test values to K application rates. Here we provide a few guidelines.

To maintain soil K based on nutrient removal in harvest consider that about 5 to 6 lb K2O/ton is removed in grain and 33 lb K2O/ton in straw. Therefore, with a grain yield of 85 cwt, if only grain is harvested and the straw stays in the field, 24 lb K2O is removed. However, if 2 ton/ac of straw is also removed then an additional 66 lb K2O/ac is removed. To simply maintain soil K levels then is very different depending on how straw is managed.

1. If irrigation water is from the Sacramento River, then K rates can be reduced by about 5 lb/ac.
2. High water flow rates during the winter flood can lead to high K losses from field during the winter.

—Right source—

The main source used in California is muriate of potash (or KCl) which contains 60 to 62% K2O. Sulfate of potash (potassium sulfate – K2SO4) is another option and this contains 50 to 53% K2O. Sulfate of potash is usually more expensive but could be considered if the high chloride content of KCL is a concern or if sulfur deficiencies are of concern. Various fertilizer blends used in rice (i.e. 15-15-15) are usually made from one of the K sources blended with other N and P sources.

—Right time—

Usually K fertilizer is applied at planting or early in the season (in starter blends) where it is most beneficial and effective. If K deficiency symptoms appear early in the season it may be possible to correct deficiency with an application of K fertilizer. Research from Asia has shown responses to K fertilization as late as flowering. However, in most of the rice soils in CA which require relatively low rates and soils are heavy clays a single application at the start of the season is adequate.

—Right place—

If K is applied before flooding it should be lightly incorporated into the soil. This is of benefit to ensuring maximum use of the K fertilizer and also the P and N fertilizer in the starter blend.

7.6 Effect of straw management on K fertility

Incorporation of rice straw adds significant potassium to the soil. The average concentration of potassium in the straw is around 1.4% with a range of 0.6 to 1.8%. The amount of potassium removed when straw is baled can be as much as 90 lb/a. The continual removal of straw can have a profound effect on available soil potassium levels. Results from the Rice Experiment Station showed that the extractable potassium in the top inches declined to less than 60 ppm after 3 years of baling. Field studies in District 10 demonstrated that straw removal reduced soil potassium 30 ppm after one year.

Other nutrients

Nutrient Deficiency Survey

Rice farmers in California routinely apply N, P and K fertilizers and these have been well studied. However, almost no research has been conducted on other nutrients: both macro(Ca, Mg, and S) and micro(Mn, Zn, B, and others). That said, growers commonly apply these nutrients, not sure if they are necessary or not. Sometimes this is adding S or Zn (or other micronutrient) in the started blend, or using ammonium sulfate instead of urea. Furthermore, farming practices are changing across the valley. One of the bigger changes is the removal of rice straw following harvest. At harvest, S, Ca, Mg, Zn, Fe and Mn concentrations in rice straw are all similar to or present in higher quantities than in rice grain. Thus, removal of straw, could potentially alter soil nutrient balances and require a different approach to nutrient management.

In 2021 we took a broad survey of rice fields by sampling soil and plant samples from 28 rice fields from around the Sacramento Valley, representing different farming practices and soils. Soil samples were taken from three locations in the field. Soil samples (0-6 inches) were taken in the spring before any fertilizers were applied. During the season, took a Y-leaf sample from the same three locations in each field. Soil and plant samples were analyzed for of all the nutrients of concern. Additionally, we gathered nutrient input and straw management data over the past five years from each field sampled. In addition to these 2021 soil samples, a set of soil samples taken in 2012 and 2013 representing an additional 55 rice fields we also analyzed.

While there is a lot that could be discussed about this data, the following general statements can be made.

Nutrient deficiencies

- Nutrients where we found no soil or Y-leaf deficiencies: Mg, S, Zn, Mn, Fe, Cu
- Nutrients where the soil test showed deficiency but not the Y-leaf: B
- Nutrients were we saw Y-leaf deficiency but not soil: Ca
- **Excessive nutrient concentrations that may lead to toxicity**
- B observed excessive levels in soils but not Y-leaf
- Mn, Fe observed excessive levels in the Y-leaf but not the soil,
- Cu observed excessive levels in soils but not sure of critical Y-leaf concentration
- **Regionality of results**
- The southern part of valley tended to have lower soil S and Zn values than the northern half of the valley.
- Higher organic matter soils tended to have more S.
- Low B levels (<0.3) were most common in the NE part of valley

Relationship between soil and plant nutrient concentration

Only soil Mg and B were correlated with leaf tissue Mg and B. That is to say that lower soil

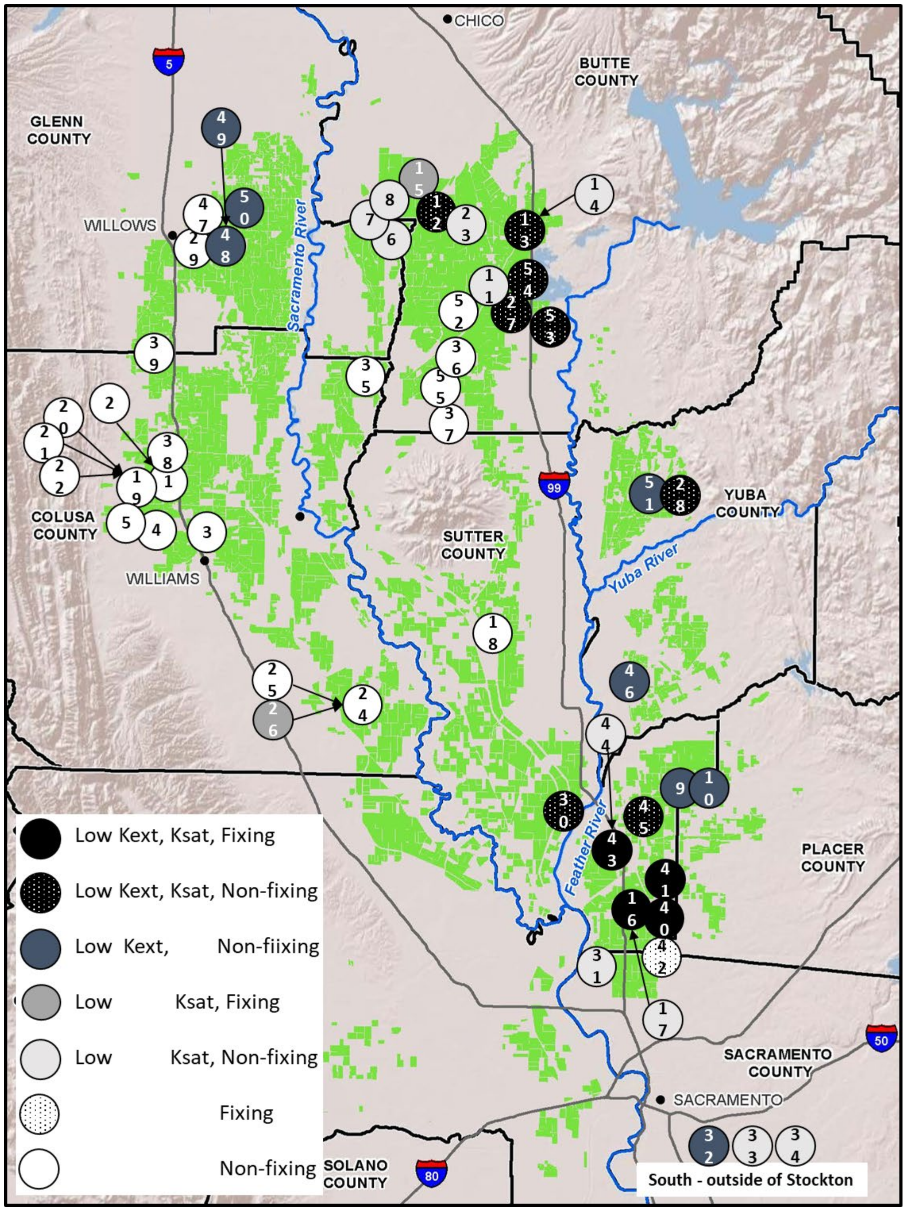

Figure 19. Map showing locations of fields in the Sacramento Valley. The different shade of circles indicate if fields (mean of all samples from the field) have low soil extractable K (Kext<120 mg kg-1) or low K saturation (Ksat<1.6%) and if the soil is a fixing or non-K fixing soil. In all cases where fertilizer K was applied, flag-leaf K values were > 1.2%. At sites that did not receive fertilizer K, at the following sites flag-leaf K values were <1.2% in at least one of the field checks tested:16, 41, 43, 49, 52 and 53.(Source: Linquist et al., 2022).

levels were seen with lower Y-leaf levels of these nutrients.

History of S or Zn application

While S and Zn were not limiting in any of the soil or plant samples, fields that had a history of S or Zn application also had higher soil test values for those nutrients.

In summary, apart from N, P and K, there were few other nutrient deficiencies that were common. However, while these results represent over 80 fields from around the valley, any given field could have unique nutritional problems. Boron (B) was perhaps the micro-nutrient that could present the most problems. We saw indications of both B deficiencies and toxicity.

While we did not find S or Zn deficiencies, below we discuss this briefly because growers tend to apply these nutrients.

Zinc

Plant Function. Zinc (Zn) is essential for numerous biochemical processes, such as chlorophyll production, enzyme activation, and nucleotide synthesis.

Soil Zinc. Zinc deficiency, originally called "alkali disease," is common in high pH, sodic soils, and in areas where the topsoil has been removed by land leveling or where irrigation water is high in bicarbonate (>4 milli-equivalents [meq]). In zinc-deficient soils (< 0.5 ppm), rice seedling growth may be reduced and, in severe cases, stand loss may occur. Preflood surface applications of 2 to 16 pounds per acre of actual Zn, depending on the source, have effectively corrected this deficiency. Zinc deficiency occurs more frequently in cool weather during stand establishment. Zinc fertilizer in the form of zinc sulfate, zinc oxide, or zinc chelate is broadcast or sprayed on the soil surface after the last seedbed tillage for maximum effectiveness.

Zinc deficiencies: There is very little translocation from old to new leaves. Consequently, deficiency symptoms are more pronounced on the young leaves. Plants may grow out of Zn deficiencies early in the season. Severe Zn deficiencies reduce tillering, delays crop maturity and can increase spikelet sterility. Midribs near the base of young leaves become chlorotic and older leaves become droopy and turn brown. Overall plant growth is stunted and leaf blade size is reduced.

The Y-leaf at tillering should have a zinc concentration of 25-50 ppm. If it is below 20 ppm it is considered deficient.

Sulfur

Plant Function. Sulfur is a component of proteins and amino acids. Most sulfur in the plant is the organic form, as opposed to inorganic forms. Sulfur concentration in the plant decrease with time.

Soil Sulfur. Rice plants absorb sulfur as sulfate, which has similar dynamics in the soil as nitrate. Thus, analysis for soil sulfur is unreliable and of little value for predicting deficiencies in rice soils. Under flooded conditions, sulfate can change to sulfide and combine with zinc and iron to form unavailable compounds. Large amounts of decaying organic matter may intensify the immobilization of sulfur.

Sulfur deficiencies. Sulfur is not as readily translocated; thus, deficiency symptoms are more pronounced on the younger leaves. Overall light yellowing of the whole plant with the worst of such symptoms in the younger leaves are signs of low sulfur. Field symptoms are generally less uniform than nitrogen deficiencies. While it may be confused with nitrogen deficiency, nitrogen deficiency symptoms occur first on the older leaves. However, at the early stages of growth, the two are sometimes difficult to distinguish. Healthy rice shoots at tillering should have between 0.15 and 0.30% sulfur. At maturity, if the straw contains less than 0.06% sulfur it is considered deficient.

Sulfur Fertilizers. Any sulfate containing fertilizer, such as ammonium sulfate and 16-20-0, will suffice. If either nitrogen or phosphorus are not needed, gypsum (calcium sulfate) or magnesium sulfate work well. Mixed with aqua, ammonium thiosulfate solution is effective.

Elemental sulfur can be used, but plant response will be slower. Application rates of 25 to 50 lb/a sulfur are suggested. Extreme cases may require more. Preplant applications are best, but topdressing to correct a mid-season plant deficiency is also effective. Unlike nitrogen, sulfur deficiencies may be treated late in the season. However, such late applications are unlikely to restore the full yield potential.

Adjustments for other establishment systems

Drill seeding

In drill (or dry) seeded systems in California, rice is planted and then the field is flushed one to three times to establish the crop. At about the 3to 4-leaf stage a permanent flood is bought on the field. The best time to apply all fertilizers is just before permanent flood. There have been some that have recommended a small portion of the N rate (i.e. 25 lb N/ac) being applied at planting. However, research addressing the need for this preplant N indicates there is no benefit to applying N at that time. Since N is applied when the crop is already established, aqua is not an option. Usually urea is used as the primary N source. Research evaluating urea versus ammonium sulfate shows no difference between these N sources. Therefore, unless the soil is deficient is sulfur, there is no benefit to ammonium sulfate.

For P and K applications can also be made at permanent flood – at the same time as the N application. There is no harm in applying these nutrients earlier, however if P is being applied, some N is also likely being applied and this needs to be accounted for in the overall N rate.

Stale seedbed

From a nutrient management standpoint, the stale seed bed presents some challenges – especially for nitrogen management. Management is

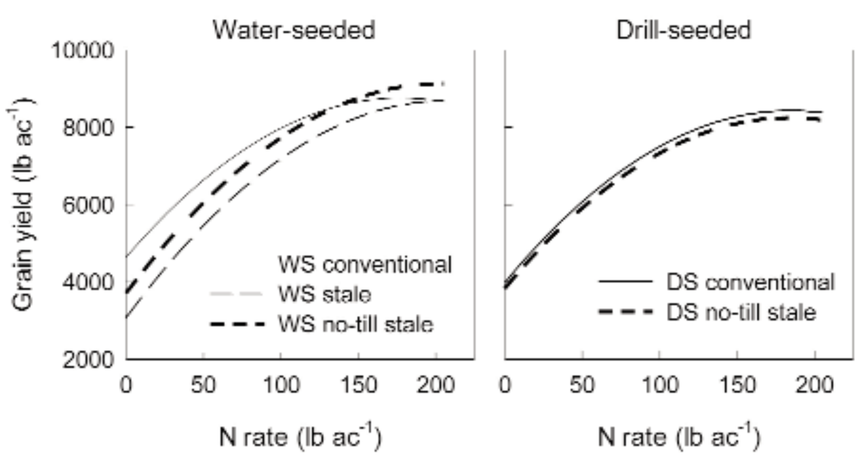

Figure 20. Grain yield response to N fertilizer in water and drill seeded rice when managed conventionally or with a stale seedbed. In the water seeded system both a tilled and no-till stale seedbed system was evaluated.

a different depending of if rice is established by drill or water seeding.

In water-seeded systems, flushing the soil with water prior to planting to induce weed germination can stimulate N mineralization but it can also promote N losses through denitrification. Prior to planting especially, it may be likely that there is a large supply of nitrate in the soil that is lost to denitrification when the field is flooded for planting. Furthermore, the N fertilizer needs to be applied to the soil surface because in stale seedbeds one does not want to disturb the soil after the stale seedbed treatment. Urea is typically applied, but as discussed above, surface applications of N fertilizer can lead to increased N losses. These increased losses result in the need to apply a higher rate of N fertilizer to achieve desired yields than for conventionally managed water seeded systems (Fig. 20). Research conducted at the Rice Experiment Station has shown that water seeded stale seedbed systems require about 30 lb N/ac more. Other research has shown that this fertilizer is best applied as urea just before flooding the field for planting.

In drill-seeded systems there was no difference in N requirement between conventional and water seeded systems (Fig. 20). Therefore, it is recommended to apply the same N rate, using urea and at the same time as one would (just before to permanent flood) in conventionally managed drill seeded systems.

Since fertilizer N needs to be surface applied in stale seedbed systems the main fertilizer choices are urea and ammonium sulfate. Research comparing these two N sources in both water and drill seeded stale seedbed systems shows no difference. Unless sulfur is deficient in the soil or the soil is alkaline, urea would be the best choice of fertilizer given its high N content (45-46%) and generally more favorable cost.

Phosphorus and potassium fertilizer rates remain the same when using stale seedbed systems. These nutrients can be applied at the same time as the N fertilizer.

Nutrient deficiency symptoms in rice are mainly expressed in the color and size of the leaves, stems, and roots, plant height and tillering habit, the development of the root system, and the effect of nutrient deficiency on crop phenology, particularly in terms of advanced or delayed maturity. Most deficiencies are best detected during early stages of rice growth.

Localized on older leaves first				Localized on younger leaves first							Not localized symptoms
Light green, narrow, short leaves	Dark green, narrow, erect leaves	Green to dark green leaves Chlorotic necrotic leaf margins Rusty brown necrotic spots Green & yellow stripes running parallel Leaf rolling	Orange-yellow interveinal chlorosis, patchy Pale overall color Green coloring remains patchy (no stripes)	Soft, droopy leaves and culms	Light green, pale leaves Chlorotic upper leaves Whole plant affected, but upper leaves affected first	Chlorotic-necrotic split or rolled leaf tips Symptoms only visible under severe deficiency	Interveinal yellowing and chlorosis of emerging leaves Reduced chlorophyll content in leaves Later, entire leaves chlorotic or whitish	Pale grayish green interveinal chlorosis at the tip of young leaves Necrotic spotting	Chlorotic streaks Blusih green leaves Wilting young leaves	White, rolled leaf tips of young leaves Death of growth point if severe	Soft, droopy leaves
Stunted plants Poor tillering	Stunted plants Poor tillering	Shorter plants		Stunted plants Poor tillering	Stunted plants Reduced tillering			Shorter plants	Reduced tillering	Reduced plant height	
Whole field appears yellowish Early maturity	Delayed maturity	Early wilting and maturity Unhealthy root system Increased incidence of diseases	Unhealty root systems	Uneven, patchy field growth	Delayed maturity	Unhealthy root system Very rare in irrigated rice	Only on dry soil Very rare in irrigated rice	Only on dry soil Very rare in irrigated rice	Increased spikelet sterility	Panicle emergence fails Very rare in irrigated rice	Lodging Increased incidence of disease
N	**P**	**K**	**Mg**	**Zn**	**S**	**Ca**	**Fe**	Mn	**Cu**	**B**	**Si**

DISEASES

Microorganisms such as fungi, bacteria and viruses are known to cause plant diseases and limit the health, quality and production potential of crop plants. There are many factors that determine the incidence and severity of a specific disease in the field, but there are three principal elements that must be present for the occurrence of a plant disease: a susceptible host, a pathogen, and favorable environmental conditions for disease development. Disease pressure in California is relatively low when compared to tropical and subtropical production areas. The lack of precipitation and low humidity during the growing season limit the development of severe epidemics; however, diseases can become a limiting production factor when the three elements are present.

All of the diseases affecting rice in California are fungal diseases; no bacteria or viruses are known to cause diseases in California. The following discussion is meant to provide you with the tools needed to identify rice diseases and understand the interaction among the rice plant, pathogen and environment. With this information, you will be able to make informed disease management decisions based on biology. Remember that the best tools you have are your eyes so be sure to scout your fields regularly so you may make the most educated decision.

Seed Rot and Seedling Disease

Seed rot and rice seedling diseases may be-caused by *Achlya klebsiana* and *Pythium* species. These diseases are widespread throughout the rice growing areas of California and may occur wherever rice is water seeded. Seed rot and seedling disease often result in poor stand establishment.

Symptoms of seed rot and seedling disease appear shortly after seeding. The most common sign of the pathogen is whitish fungal hyphae growing over the surface of the seed and young seedling (fig. 1). Algae often colonize the mycelium, turning it green. A dark circular spot may also occur on the soil surface around infected seed due to the growth of algae and bacteria on the fungal hyphae and infected seed. Seeds that are infected shortly after seeding often don’t germinate because the endosperm or embryo is rapidly destroyed. Growth of seedlings may be greatly impeded when seeds are infected following germination. Symptoms of seedling disease may include stunting, yellowing or rotting of the seedlings.

Unfavorable conditions for seed germination and seedling growth favor the development of these diseases. Cool weather at planting is the most common factor that predisposes seed and seedlings to these diseases because of decreased germination and seedling development rates. Once seedlings are established, they will often outgrow the disease under environmental conditions favorable for seedling growth with little effect on plant growth and survival.

The seed rot and seedling disease fungi survive in the soil and produce zoospores (swimming spores) in response to flooding of the soil. Zoospores are attracted to cracks in the seed coat where the endosperm is exposed or to the germinating seedlings. Feeding by rice seed midge or tadpole shrimp may predispose seed or seedlings to seed rot and seedling disease.

Laser leveling and maintaining a flood of 4 inches promotes rapid germination and stand establishment without the loss of weed control often associated with draining for stand establishment. Planting high quality seed with 85% germination or more when water temperatures are favorable for seed germination and growth (> 70°F) is an important cultural management practice for these diseases. Higher seeding rates can compensate for losses due to seed rot and seedling disease.

Bakanae

Bakanae disease of rice is widely distributed in Asia and was first recognized in Japan in 1828. The word bakanae in Japanese means "foolish seedling" and describes the excessive elongation often seen in infected plants. Symptoms of elongated seedlings led to the identification of bakanae in California rice fields in 1999. The disease has now become widespread throughout the rice growing areas of California.

Bakanae is caused by the fungus *Gibberella fujikuroi* (anamorph *Fusarium fujikuroi*). The fungus infects plants through the roots or crowns and grows systemically within the plant where it produces the growth hormones gibberellin, which causes plant elongation, and fusaric acid, which causes stunting. The types of symptoms produced by an infected plant may be dependent upon the strain of the fungus and nutritional conditions. The most visually striking symptoms of the disease are chlorotic, elongated, thin seedlings that are often several inches taller than healthy seedlings (fig. 2 and 3). Infected seedling may also be stunted and chlorotic, exhibiting a rot and crown rot. Infected seedlings usually die. Older plants infected with the fungus may exhibit abnormal elongation, stunting or normal growth, yellowing, crown rot (fig. 4) and if they survive to maturity produce no panicle or empty panicles. As death approaches infected plants, leaf sheaths are usually covered with a mass of white or pinkish growth and sporulation of the fungus near the waterline (fig. 5). Leaves sheaths of infected plants may also turn a blue-black color with the production of sexual reproduction structures called perithecia.

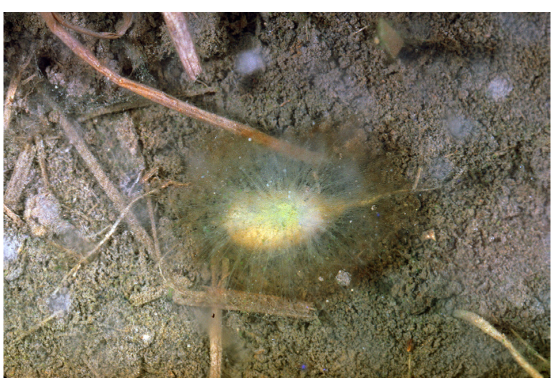

Figure 1. Seeds infected by seed rot show white fungal hyphae growing on the surface of the seed. Photo Credit: UC IPM

Bakanae is primarily a seedborne disease and

Figure 2. Seedlings infected with bakanae are elongated with thin leaf blades.

Figure 3. Healthy (left) and bakanae infected (right).

Figure 4. The crown of bakanae infected plants rots, resulting in premature plant death. Crown of infected plant (left) compared to a healthy crown (right).

Figure 5. Bakane Sporulation in infected mature plants can be white or pink, developing above the water level.

may be moved from one location to another on infested seed. Airborne spores of the fungus may contaminate seed after heading or during harvest. The fungus does not appear to infect the seed internally but rather contaminate the outside of the seed coat. Survival of the fungus in crop residue or the soil is thought to play a minor role in the disease cycle of bakanae.

Planting clean seed is the most effective management method for bakanae. Destruction of crop residue in fields infested with the pathogen may provide some benefits by limiting the amount of inoculum that may carry over to the next crop. Soaking seed in a sodium hypochlorite soak solution is effective in reducing bakanae incidence. Since 2003, Ultra Clorox Germicidal Bleach has been labeled for bakanae control. The product label specifies using a thoroughly premixed solution of five gallons of product to 100 gallons of water, seed is soaked for two hours, then drained and soaked in fresh water for the remaining time. Alternatively, the label specifies using a thoroughly premixed solution of 2.5 gallons of product to 100 gallons of water; seed is soaked for 24 hours, then drained and planted within 12-24 hours. In some cases, bakanae can be observed in fields seeded with treated seed. When seed is held for more than 24 h because seeding is delayed, the temperature increase of the seed due to its physiological activity may result in growth and sporulation of surviving bakane inoculum, resulting in increased incidence of the disease in the field.

Stem Rot

Stem rot disease occurs in most rice growing regions of the world and is caused by the fungus *Magnaporthe salvinii*. The stem rot pathogen is most often found in its sclerotial state, *Sclerotium oryzae*, in the field. The initial symptoms of stem rot appear after mid-tillering as very small irregular black lesions on the outer leaf sheath of the tiller at the waterline (fig. 6). As the season progresses, the lesions enlarge and the fungus moves inward, infecting interior leaf sheaths (fig. 7). Infected leaf sheaths often die and slough off throughout the season. In severe cases, the fungus will penetrate and rot the culm killing the entire tiller (fig. 8). Tiny black sclerotia (hard resting structures) often form within diseased leaf sheaths or culms (fig. 9). Sclerotia and white fungal mycelium may also be found inside the culm of severely infected plants near maturity (fig. 10). Disease incidence and severity is positively correlated with the number of sclerotia present in the upper layer of soil prior to planting (fig 11).

The fungus overwinters mostly as sclerotia associated with diseased crop residue. When the field is flooded for the following season, the sclerotia float to the surface and infect developing seedlings at the waterline. When young plants are infected, tillers are often killed or fail to produce panicles. Moderate infections result in chlorotic leaves. In severe cases where the culm is infected, plants lodge and senesce prematurely (fig. 12), and panicle blanking increases. Yield and quality may be significantly reduced.

Cultural control methods play a key part in the management of stem rot. Since sclerotia overwinter in crop residue, one of the most valuable management tools is limiting the amount of inoculum that carries over from one season to the next. Burning of crop residue in the fall is a very effective method of reducing sclerotial inoculum levels in a field and reducing the amount of crop residue available for sclerotia to form on while overwintering. Swathing at ground level and removing the straw from the field may be nearly as effective as burning. Incorporation of straw and winter flooding has also proven helpful in reducing carry over of sclerotia to the following season (fig. 13).

Although all California rice varieties are susceptible to the stem rot pathogen, slight differences between varieties exist. Varieties with shorter developmental periods tend to have higher stem rot severity when compared to varieties with

Figure 6. Initial symptoms of stem rot appear as small black lesions on the outer leaf sheath of the tiller at the water level. Photo Credit: UC IPM

Figure 7. As stem rot develops, black lesions enlarge, affecting the leaf sheath and affecting leaves. Sometimes while sporulation can be observed at the water level.

Figure 8. In severe cases, stem rot penetrates and rots the culm, killing the tiller.

Figure 9. Stem rot sclerotia can develop on leaf sheaths and culms.

longer developmental periods (fig. 14). Stem rot is more severe in dense stands of rice and with excessive levels of nitrogen fertilization. Low potassium levels in the soil can increase the susceptibility of plants to stem rot. To minimize the severity of stem rot, use seeding rates to establish 20-25 plants per square foot and fertilize fields to maintain soil nutrient levels required for optimum productivity.

The fungicide azoxystrobin (Quadris, QuiltXcel) is registered for stem rot control. Application of azoxystrobin between the late boot stage (when the panicle has not yet emerged) and early heading (when 10 to 20% of panicles have emerged from the boot and can be seen over the canopy) can reduce the severity of stem rot. In trials, treatment with azoxystrobin has resulted in stem rot severity reductions of 20 to 30%.

Figure 10. At maturity, severely infected plants will show large number of sclerotia inside infected culms. These sclerotia survive in the straw residue and become the inoculum for next season.

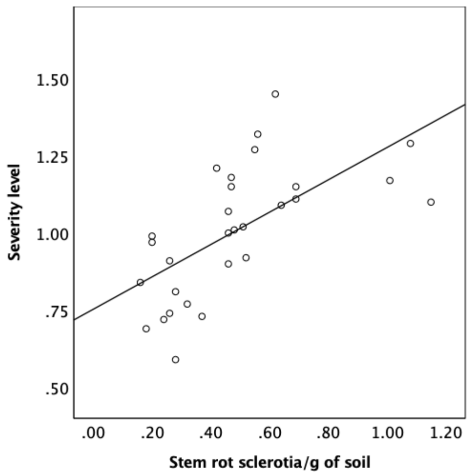

Figure 11. Disease severity (0=healthy, 4=culm rotted through) is positively correlated with the number of sclerotia present in the upper layer of soil prior to planting. From Webster et al., Hilgardia 49 (3), 1981.

Figure 12. Stem rot infection can cause premature plant senescence and lodging.

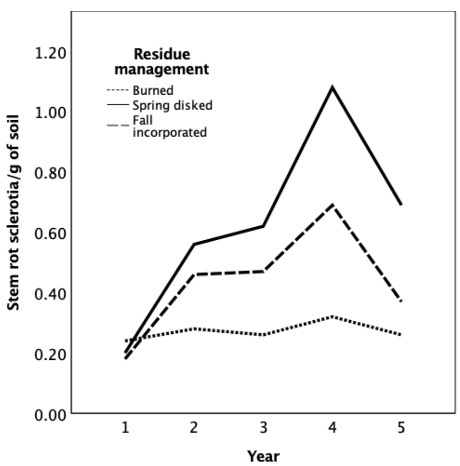

Figure 13. Residue management plays a key role in the management of stem rot. Burning or decomposing straw during wintertime can reduce the number of sclerotia in the soil, resulting in lower disease levels during the season. From Webster et al., Hilgardia 49(3), 1981.

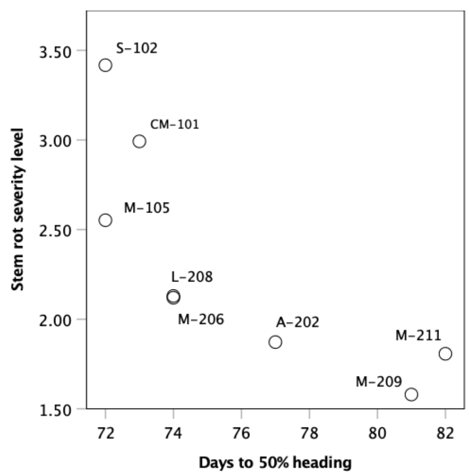

Figure 14. Stem rot severity (0=healthy, 4=culm rotted through) at the end of the season among selected varieties. Varieties with longer periods of development tend to have lower stem rot severity. Richvale, Butte County, 2021.

Aggregate Sheath Spot

The fungus *Rhizoctonia oryzae-sativae* causes aggregate sheath spot disease of rice. Lesions of the disease first appear at the waterline during the tillering stage as oval lesions with gray-green to straw-colored centers surrounded by a brown margin (fig. 15). Additional margins often appear around the initial lesion forming concentric bands. As the season progresses, aggregate sheath spot lesions move upward and form lesions on the upper leaf sheaths (fig. 16). Lesions often coalesce and cover the entire leaf sheath. Leaves of infected leaf sheaths turn bright yellow (fig. 17) and eventually die. Under favorable conditions, the disease may spread to the flag leaf or panicle rachis and result in partially filled panicles (fig. 18).

Rhizoctonia oryzae-sativae produces irregular brown sclerotia that are larger than stem rot sclerotia on the surface of infected leaf sheaths and cylindrical sclerotia inside the cells of infected tissue (fig. 19). Potassium deficiency has been associated with more severe disease symptoms. Excess nitrogen fertilization does not increase the severity of aggregate sheath spot as it does for stem rot. The same cultural management methods used for stem rot may be used for aggregate sheath spot. The disease cycles of the two diseases are very similar so reducing the carry over of sclerotia to the following season is key. Just as with stem rot, the fungicide azoxystrobin (Quadris, QuiltXcel) is effective in reducing the severity of the disease when applied between the late boot and early heading stage. Reductions of up to 80% in disease severity have been observed.

Figure 15. Initial symptoms of aggregate sheath spot develop on leaf sheaths at the water level as oval lesions with gray-green to straw-colored centers surrounded by a brown margin.

Figure 16. As the season progresses, aggregate sheath spot lesions move upward and form lesions on the upper leaf sheaths.

Figure 17. Leaves of leaf sheaths infected with aggregate sheath spot turn bright yellow and eventually die.

Figure 18. Under favorable disease conditions, aggregate sheath spot lesions can infect the flag leaf sheath or panicle rachis, potentially producing panicle blanking.

Figure 19. Aggregate sheath spot sclerotia are cylindrical and develop inside infected tissue

Rice Blast

Rice blast disease is caused by the fungus *Pyricularia grisea* and is widely distributed throughout the rice growing regions of the world but was only identified in California in 1996. The incidence of rice blast is relatively low most years, but severe epidemics have occured. Blast is considered to be the most important disease of rice worldwide and may cause crop losses of up to 50% when conditions are favorable for disease development. *Pyricularia grisea* may infect most aboveground parts of a rice plant including leaves, leaf collars, nodes, panicles and grains. Rice blast disease may be called by different names depending on the part of the plant infected.

Symptoms of leaf blast typically consist of elongated diamond-shaped lesions with gray or whitish centers and brown or reddish brown margins. Lesions can coalesce and result in large, irregular, affected areas on leaves (fig. 20). Leaf collars may also be infected by the fungus and produce a brown or reddish-brown necrotic area at the junction of the leaf blade with the sheath creating a “collar rot” symptom (fig. 21). Collar rot may lead to death of the entire leaf, which may have a significant effect on yield when occurring on the flag leaf. Stem node infections result in a blackened node and may result in complete death of the tiller above the infection point . “Neck blast” is considered to be the most destructive phase of the disease and occurs when the fungus infects the node just below the panicle resulting in a brown or black lesion that encircles the entire node (fig. 22). Depending on the time of infection and progress of the pathogen, neck blast may result in blanking of the panicle or incomplete grain filling. In addition, panicle branches and spiklet pedicles may also be infected resulting in reduced yield and/or milling quality.

Figure 20. Blast lesions on leaves are diamond-shaped, with gray or whitish centers and brown or reddish brown margins. Lesions can coalesce and result in large, irregular, affected areas on leaves.

Infected seed and crop residue are thought to be the most important sources of fungal inoculum in California. Only a small amount of starting inoculum is needed to produce a high incidence of rice blast disease as the pathogen may go through several reproductive cycles per season under favorable conditions. Each cycle consists of a spore of the fungus infecting a plant, producing a new lesion, and resulting in thousands of new spores that may infect other plants within a matter of 7-10 days under favorable conditions. With each spore capable of producing a new lesion, this disease may increase rapidly in a suitable environment. The fungal spores are dispersed by air and may be carried long distances, so it is possible to develop collar and neck rot in a field with no previous signs of leaf blast.

Rice blast development is favored by high nitrogen fertilization, extended periods of leaf wetness, high relative humidity, little or no wind and nighttime temperatures of 63-73°F. Spores are produced and released only under high relative humidity conditions and infection of the plant requires a lengthy period of free moisture on the plant tissue surface before the process is complete. Most years, environmental conditions appear to be permissive but not optimal for rice blast development in California rice fields.

Planting resistant cultivars is one of the primary methods of managing rice blast in many areas of the world. In California, M-210 is currently the only rice cultivar with resistance to rice blast; all other varieties are susceptible, with some differences in their degree of susceptibility. Several cultural practices are helpful in managing rice blast. Destruction of crop residue in infested fields, planting clean seed, water seeding, maintaining a continuous flood, and avoiding excessive nitrogen fertilization are recommended to limit the incidence and severity of rice blast. Azoxystrobin (Quadris, QuiltXcel) and trifloxystrobin (Stratego) fungicides are registered for use on rice in California as protectants against neck blast. Applications should be made at the late boot to early heading stage to protect panicles. During severe epidemics, a second application may be necessary. As panicles mature, they become less susceptible to the pathogen. Applications to control leaf blast are usually not necessary unless large areas of the field are affected.

Figure 21. Blast can produce a collar rot that may lead to leaf death.

Figure 22. "Neck blast" is considered to be the most destructive phase of the disease and occurs when the fungus infects the node just below the panicle resulting in a brown or black lesion that encircles the entire node and a empty or partially filled panicle.

Kernel Smut

Kernel smut, caused by the fungus *Tilletia barclayana*, is generally considered a minor disease of rice in California. Kernel smut is characterized by a black mass of spores (chlamydospores) that replace the endosperm of individual kernels near maturity (fig. 23). Generally, a panicle may only have a few smutted kernels at random locations. Kernel smut is most noticeable early in the morning when dew causes infected kernels to swell and erupt in a black ooze of spores. Severe epidemics have occurred in California, resulting in yield and quality losses. In severe cases, milled grain whiteness can be significantly reduced (fig. 24)

The disease cycle of kernel smut is rather complicated. The fungus may overwinter in or on seed or in the soil as chlamydospores dislodged during the harvest of infected grain. When fields are flooded the following spring, chlamydospores float to the surface and germinate to produce primary sporidia. Large numbers of secondary sporidia are produced from the primary sporidia and are forcibly discharged into the air where they may infect individual florets or kernels.

Figure 23. Kernel smut produces a black mass of spores that replace the endosperm of individual kernels near maturity.

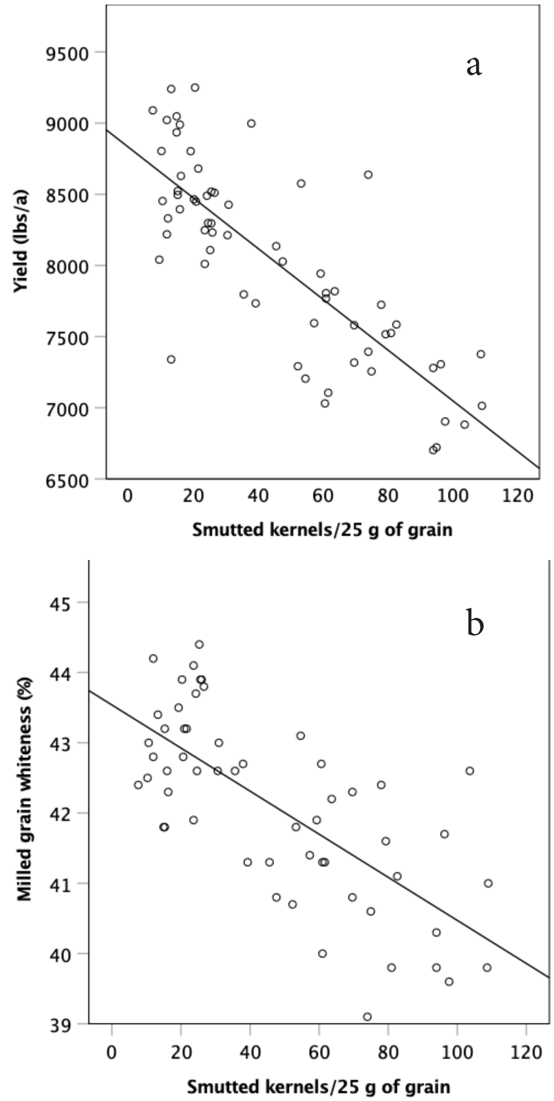

Figure 24. Relationship between kernel smut infection in a long grain variety with yield (a) and milled grain whiteness (b). As the number of smutted kernels increases, both parameters decrease. Richvale, Butte County, 2020.

Short and medium grain rice varieties are less likely to have significant amounts of kernel smut compared to long grain varieties (fig. 25). This resistance is thought to be because long grain varieties have a longer duration of anthesis and a larger floret opening, resulting in a greater chance of spores entering the floret.

Kernel smut is a difficult disease to manage. Plant certified seed and avoid excessive nitrogen fertilization that may favor disease development. If a field has a history of kernel smut, avoid planting the more susceptible long grain varieties. Fungicides containing propiconazole (Tilt, QuiltXcel, Stratego) are registered for use on rice in California and provide protection against kernel smut. Applications should target the mid to late boot stage when panicles have not emerged yet. Applications made after panicle emergence have little effect on the disease.

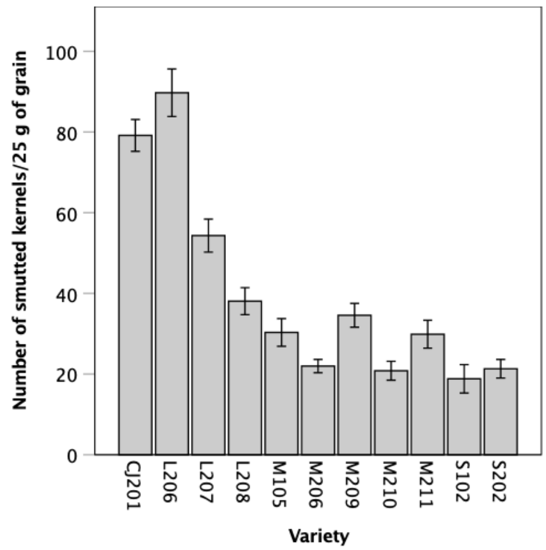

Figure 25. Response of common rice varieties to kernel smut. Short and medium grain varieties are considered less susceptible than long grain varieties. Glenn County, 2018.

False Smut

False smut disease, caused by the fungus *Ustilaginoidea virens*, was identified in a single Glenn County field in the fall of 2006 and subsequently in a couple of other Colusa and Glenn County fields. This pathogen replaces the rice kernels with globose, velvety spore balls up to 1 cm in diameter, which erupt from between the glumes. The spore balls consist of three spore-producing layers surrounding a hard core of fungal mycelium. The inner most and middle layers contain immature spores of yellow to orange coloration (fig. 26). The outermost layer consists of mature spores that are olive to black in color. One or more irregular, hard, black sclerotia are found at the center of the mature spore ball. Generally, only a few grains of a panicle are affected by this disease.

While this disease was reported to have occurred on rice in California many years ago the details of the extent of disease distribution are not well documented. No reports of negative effects on yield or quality exist from California.

Figure 26. False smut has only been identified in a few fields in Glenn and Butte counties. No reports of negative effects of the disease on yield or quality have been documented in California. Photo by Don Groth, LSU Ag Center.