Fertility and 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.

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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 root zone 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.

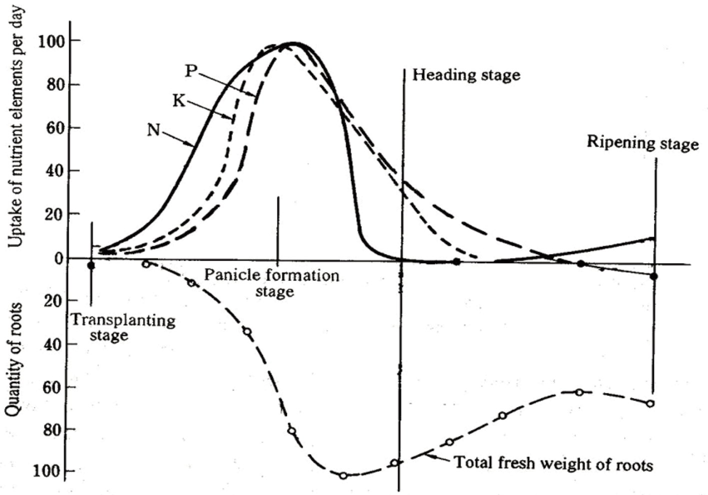

Figure 1. Seasonal uptake rate of selected nutrients and root growth by a rice plant.

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 nutrients and carbohydrates are transported from the vegetative parts of the plant into the panicle. Therefore, the critical time frame for careful 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 compiled 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.

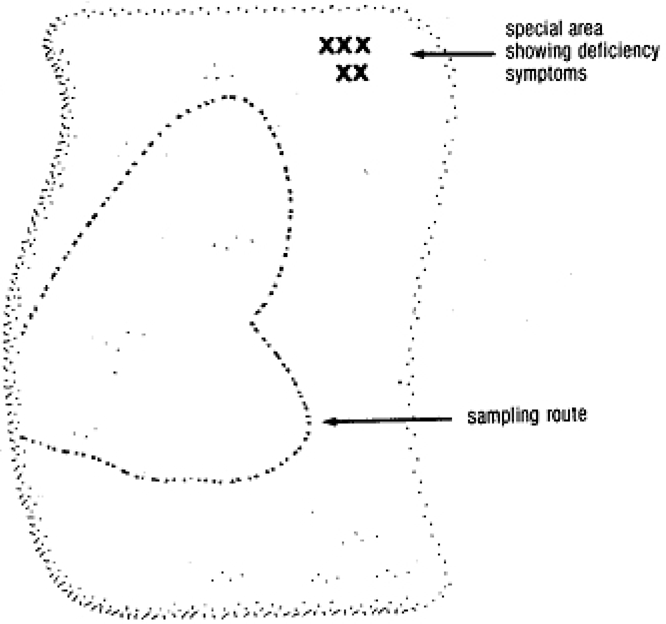

Figure 2. Sampling pattern for taking soil or leaf samples to test for nutrient deficiencies.

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

The diagram (Fig. 3) depicts the major pathways, transformations, and chemical species in nitrogen cycling. Thickness of the arrow depicts relative abundance. 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 dentrification 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.

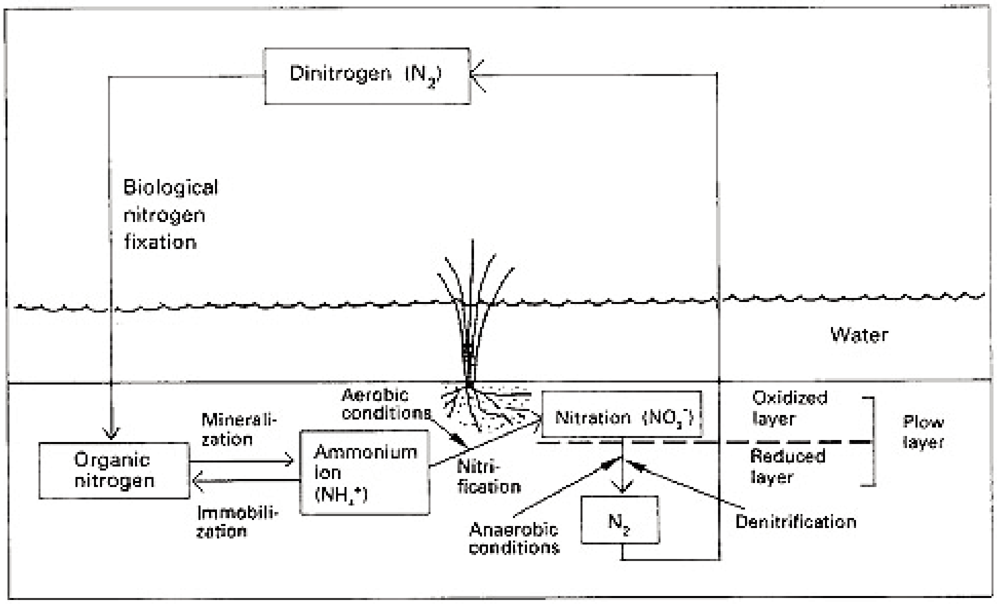

Figure 3. The nitrogen cycle in rice systems (Source: Food & Fertilizer Technology Center)

Denitrification of nitrogen fertilizer and subsequent loss as nitrogen gas, can result in high losses of the applied nitrogen, particularly when

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).

applied in a nitrate form (nitrate fertilizers should not be applied to rice systems) or when 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 and ammonium sulfate volatilize 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.

Latter in the season leaf tissue tests, leaf color charts, or chlorophyll meters 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).
    a. 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.
    b. test strips should not be directly adjacent to the levee.
3. Monitor strips throughout the season.
4. 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.
5. Comparing yields from test strips will let you know if you under or over applied.
6. By doing this over different fields and years (along with keeping good records), growers can confidently make adjustments to their N rate.

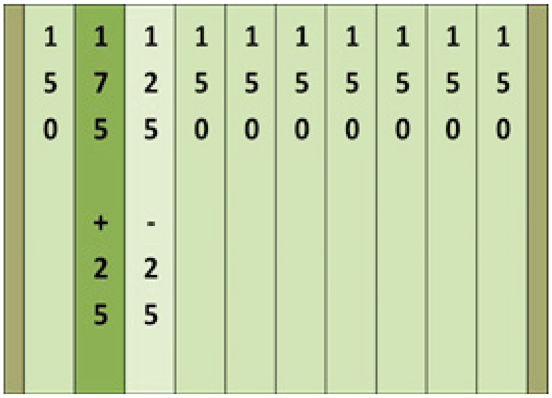

Figure 4. Example of a field with test strips of different N rates

—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 to potential for high N loss. 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 starters 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 topdress later in the season. The rational for applying starter N is to provide young emerging seedlings with a 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.

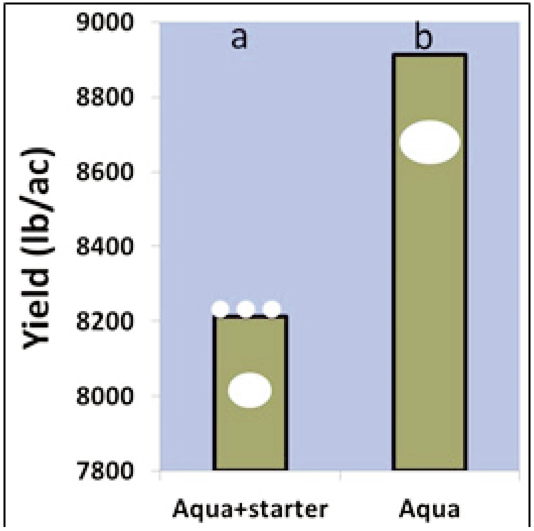

Figure 5. Effect of N source and placement on yields. The N rate shown here is 100 lb N/ac and the date represent the average response across 7 different fields.

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 topdress application. In drill seeded systems or when water is drained from the field for an extended period of time it may be necessary to apply fertilizer at different times.

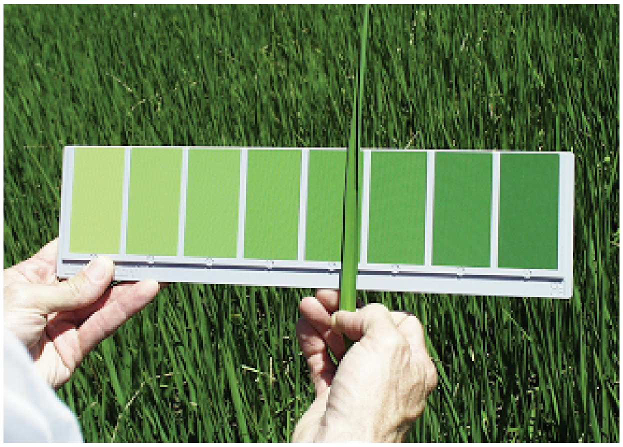

Figure 6. The UC leaf color chart determines leaf nitrogen based on leaf color

Therefore, there is no benefit to planning a topdress application of nitrogen. All the nitrogen should be applied before planting. However, there may be cases where a topdress 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 topdress due to N losses associated with draining the field. Topdress N fertilizer should be applied before PI.

In these cases a decision on whether or not to topdress can be made with a chlorophyll meter or a leaf color chart.

Leaf color chart: The UC leaf color chart is a series of 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 4 to determine if the leaf N concentration is adequate.

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 3 presents the relationship between the SPAD meter reading and leaf N (%) at panicle initiation for ten rice varieties. It is based on currently available information which does not include newer varieties such as M-206. In this case, M-202 calibration would provide a reasonable estimation of leaf N for M-206. Using the %N value from Table 3, one can determine if crop N is sufficient using Table 4.

***Table 3**. Leaf N content (%) at panicle initiation of select rice varieties and the corresponding chlorophyll meter (SPAD, Minolta) readings*

% 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**. Interpretive guide for leaf nitrogen percentage. Total leaf N concentrations are for California short, medium and long grain varieties.*

Plant growth stage	*Critical*	*Adequate*
mid-tillering	4.0	4.0 - 4.6
maximum tillering	3.6	3.6 - 4.2
panicle initiation	3.2	3.2 - 3.6
flag leaf	2.8	2.8 - 3.2

—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 topdress fertilizers are usually applied to the surface. To redcue N losses from N in teh 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 topdress 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.

Effect of straw management on N management

California rice growers annually incorporate about 8000 lb/ac of straw across most of the Sacramento Valley. This straw contains approximately 50 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.

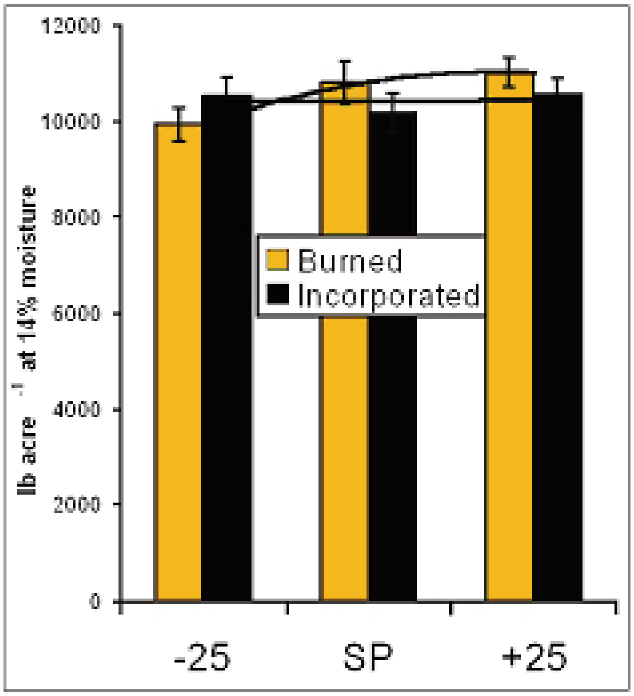

Figure 7. Yield of burned and straw incorporated/flooded fields when fertilized at the standard grower practice (SP) and plus of minus 25 lb N/acre averaged over three years.

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 7 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 implementing this practice.
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.

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. This is shown clearly in Table 5 where the N rate required for maximum yields was the same (in this case 150 lb N/ac) for all varieties over two sites.

Table 5. *Yield response (@ 14% MC) of selected varieties variable rates of preplant 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

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 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

3. 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.

Soil phosphorus

Most soils have very high amounts of total phosphorus; however only a very small portion of this is available for plant uptake during a typical growing season. The transformation processes of phosphorus in flooded soils are quite 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 and the use of more than one can provide 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, just about 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 P_2O_5 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 8, 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.

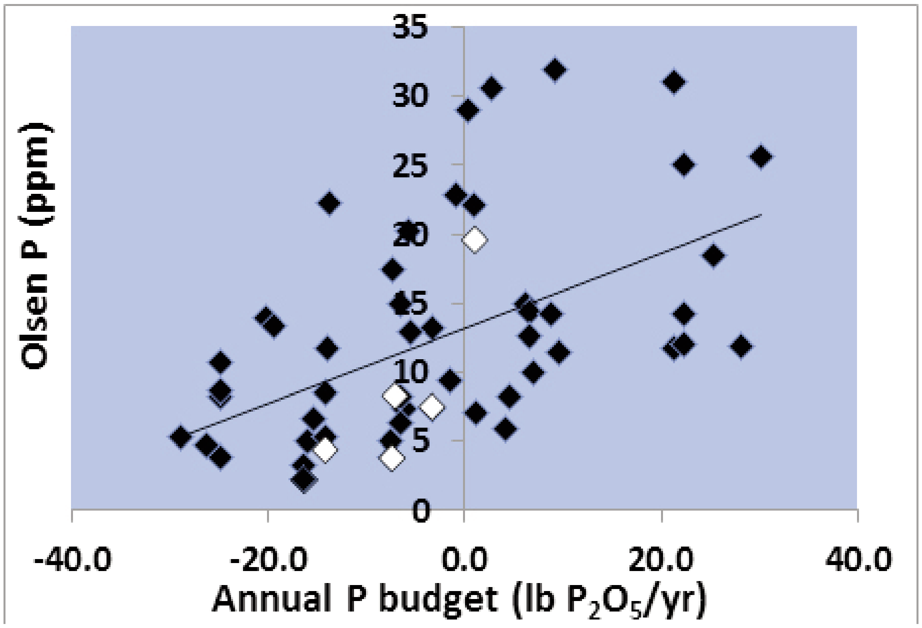

Figure 8. The relationship between soil Olsen-P values, P balance and yield response to P fertilizer. Data are from on-farm studies and the P balance reflects the 5 yr average of inputs and outputs. The open diamonds indicate a study in which there was a significant yield response to add P fertilizer.

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. 9).

Apply maintenance P rates when soil P values are between 6 and 20 ppm (green circle in Fig. 9). Maintenance rates can be determined from Table 7 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. 9). P build-up rates 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.

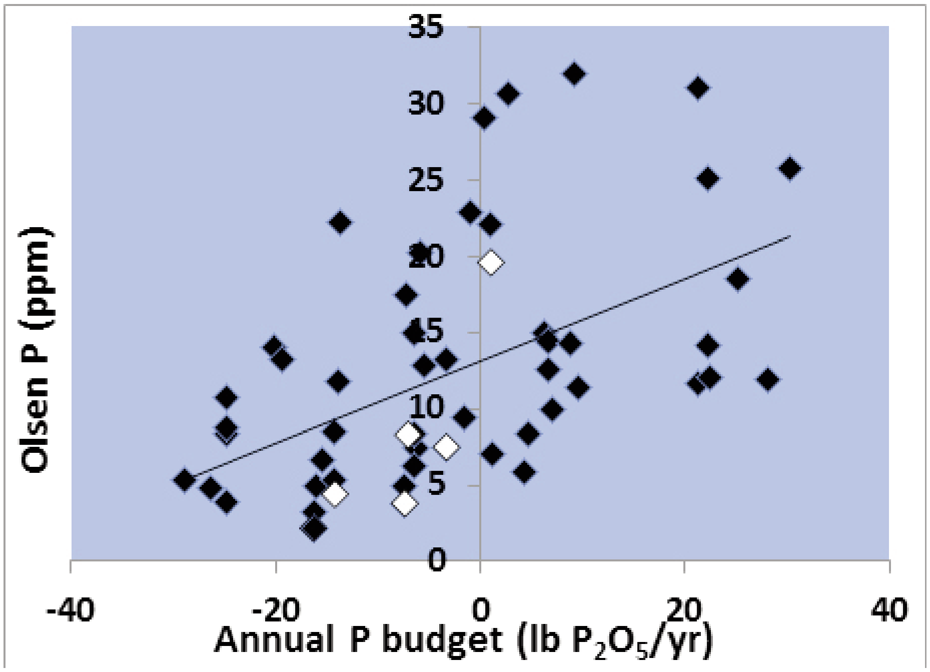

Figure 9. The relationship between soil Olsen-P values, P balance and yield response to P fertilizer. Circles indicate fields in which different P management strategies need to be used.

—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

Table X. Charts relating rice yield with how much P (expressed in fertilizer equivalents-P_2O_5) 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.

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

should be chosen.

—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.

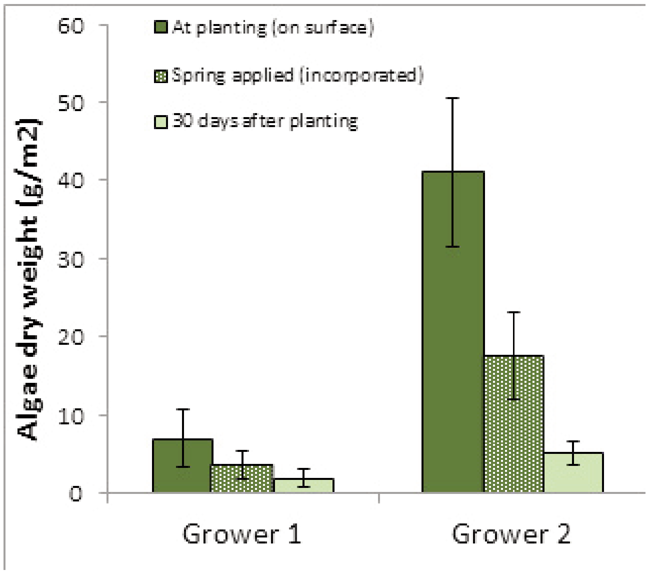

Figure 10. Effect of P fertilizer management (timing and placement) on algal growth in two rice fields

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 si not a problem for rice). An example is shown in Figure 10 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 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. 11).

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

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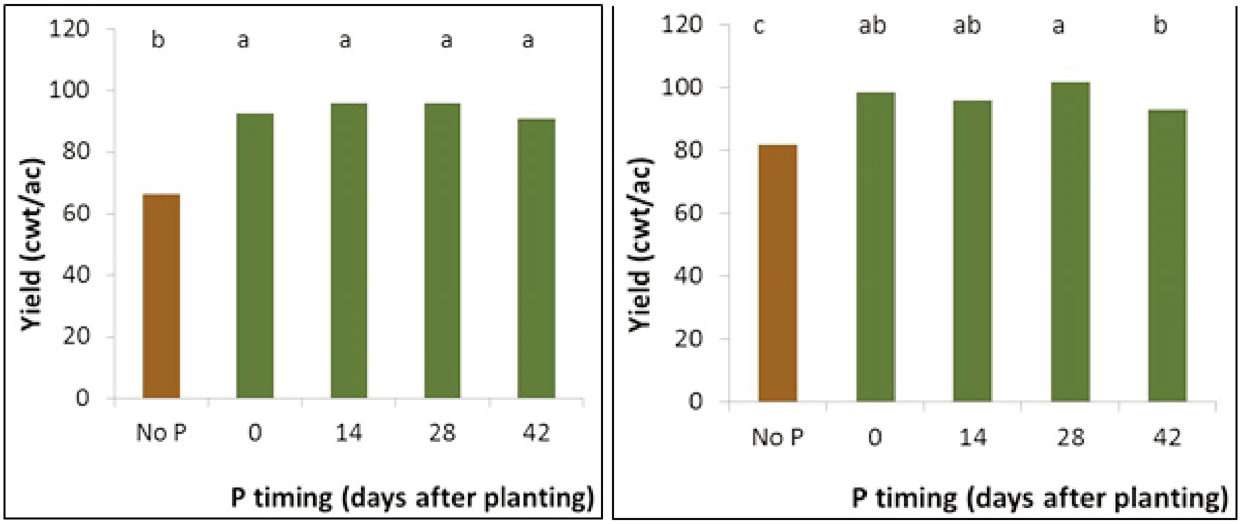

Figure 11. Effect of P fertilizer timing on rice yields in two rice fields

—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.

4. 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 senescencing 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 along leaf interveins 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 12 where aggregate sheath spot severity increases when K concentrations are low in the leaf.

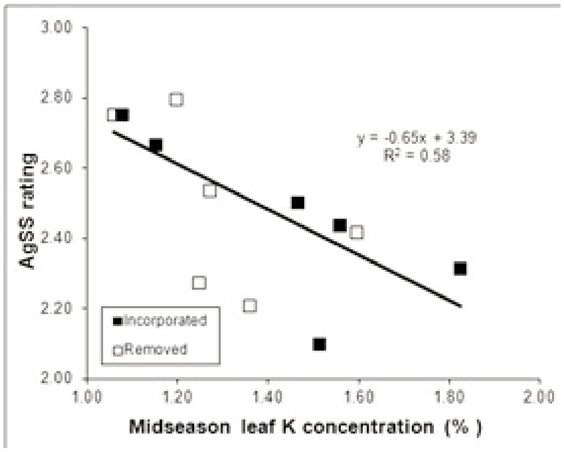

Figure 12. Aggregate sheath spot (AgSS) rating as affected by Y-leaf (at panicle initiation) K concentration.

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 much higher in K than in the Feather River or other Sierra rivers which supply water on the east side (Fig. 13). Over time, these differences

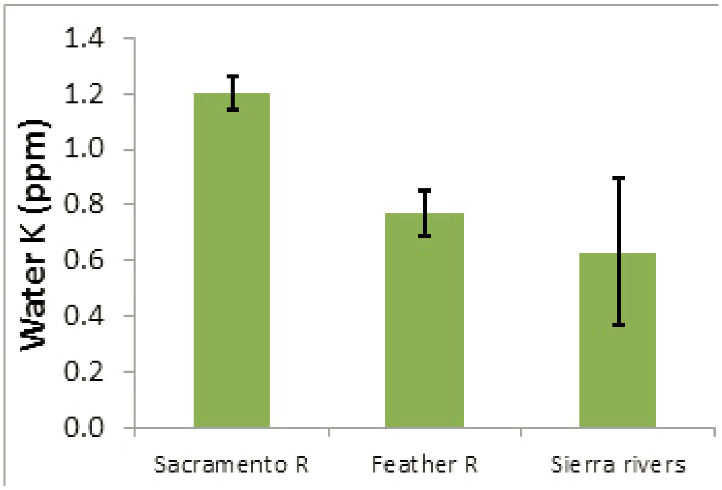

Figure 13. Irrigation water potassium concentrations. Sierra rivers include the Yuba River and Bear River. Irrigation water was sampled from clean (not recycled) irrigation canals during the 2012 growing season.

in K concentration could affect soil K values; however these differences also affect how much K fertilizer may need to be recommended.

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 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 was appeared that where soil K values were above 100 ppm that flag leaf K values were high (between 1.4 and 1.8%) and unaffected by soil K (Fig. 14). However, when soil K was below 100 ppm (only two fields), flag leaf were lower and around the level considered to be deficient (see below). Therefore, taking a conservative approach, when soil K values are 100 ppm or below the soil may be deficient in K.

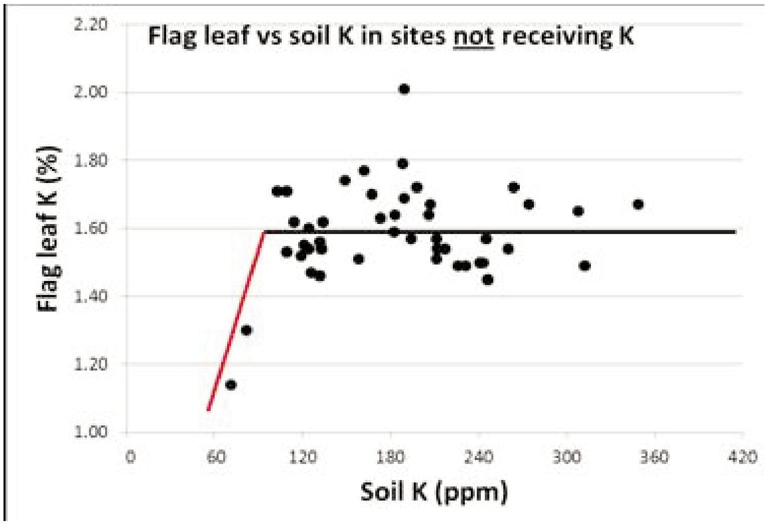

Figure 14. The relationship between soil K and flag leaf K values (taken at flowering) in fields where K fertilizer was not applied.

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 14 also confirm that flag leaf samples of about 1.2% are deficient in K.

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 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.

1. To maintain soil K based on nutrient removal in harvest consider that about 5 to 6 lb K_2O/ton is removed in grain and 33 lb K_2O/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 K_2O is removed. However, if 2 ton/ac of straw is also removed then an additional 66 lb K_2O/ac is removed. To simply maintain soil K levels then is

very different depending on how straw is managed.

2. If irrigation water is from the Sacramento River, then K rates can be reduced by about 5 lb/ac.
3. 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% K_2O. Sulfate of potash (potassium sulfate – K_2SO_4) is another option and this contains 50 to 53% K_2O. 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.

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.

5. Other 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 cholorotic 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.

6. 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 3- to 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 be presents some challenges – especially for nitrogen management. Management is 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. 15). 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. 15). 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.

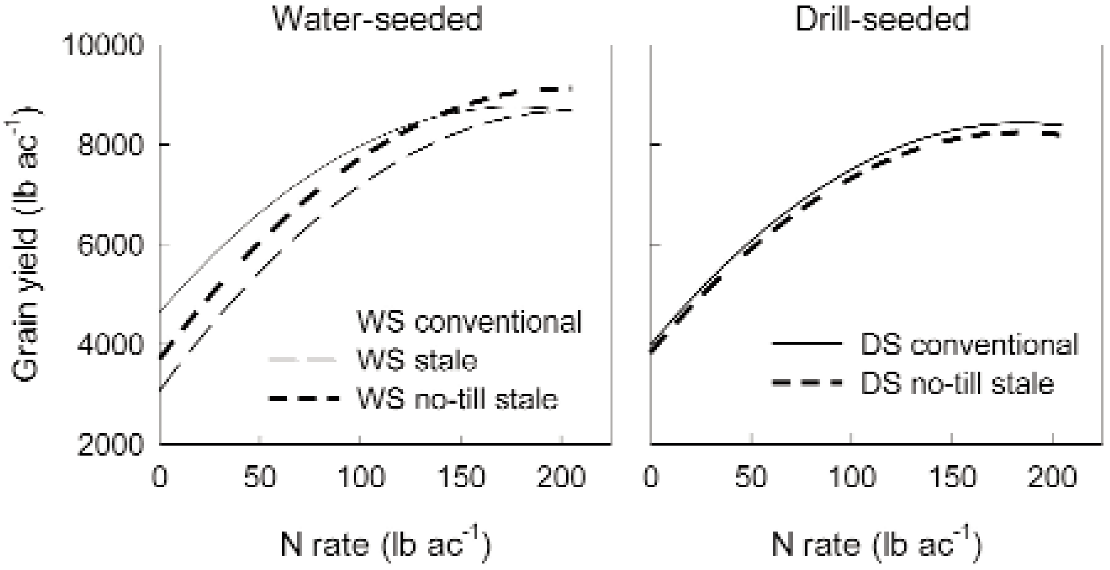

Figure 15. Grain yield response to N fertilizer in water and drill seeded rice when managed conventionally or with a stale seedbed. In the water seeded system both a tilled and no-till stale seedbed system was evaluated.

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 (Fig. 16). 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.

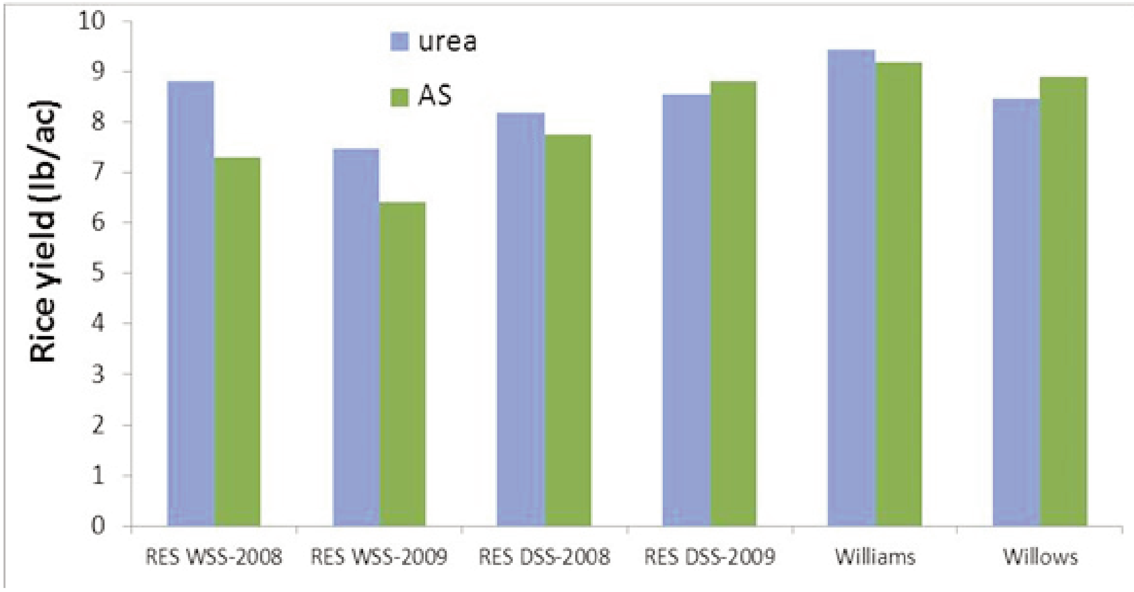

Figure 16. Comparison of urea and ammonium sulfate (AS) as the sole nitrogen fertilizer source. Data are for wet seeded stale seedbed (WSS) and drill seeded stale seedbed (DSS) systems at the Rice Experiment Station (RES) and two growers fields in Maxwell and Willows that used wet seeded stale seedbed systems. The N rate used in this comparison was 100 lb N/ac. In no case was the yield difference between urea and ammonium sulfate significant.

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