Rice

Production Manual

Produced In Collaboration With The California Rice Research Board

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University of California
Agriculture and Natural Resources

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RICE GROWTH & DEVELOPMENT

Introduction

So, you want to grow a 12,000 lb/acre rice crop? The modern short-statured varieties for California certainly are capable of producing yields this high or higher. Of course, not all the conditions to achieve such yields will be under your control. Most notably, untimely rainfall, cold temperatures and many other weather-related events are simply out of your control. But many things are under your control, and most all of them require a good knowledge of how the rice plant grows from seedling to grain filling. This knowledge will help you make informed decisions and better use the many practices and tools that are available. This section will be a lesson in applied rice botany for the primary purpose of understanding what goes into the making of a rice grain crop.

The Yield Components

Generally, one thinks of yield as the total weight of rough rice from a field, usually in "sacks" or cwt per acre. At harvest you may think in terms of trailer loads to compare a field's performance from the previous year as sort of a "back of the envelope" estimate of yield. But just how is all that grain in the trailer made?

Generally, crop health is assessed at the whole field level and not at the details of the plant. However, the clues to what went right or wrong in a season can often be determined from the yield components. Rice grain yields are the product of the plant's yield components. Why is it important to know about yield components? Every management practice affects the yield components—but the question is, which ones and when? So, before trying to understand where yield components fit into the life cycle of the plant and how to maximize them, it's important to know what they are.

Yield components are:

1) the number of panicles per given area (often called fertile panicles)
2) the number of spikelets or grains per panicle
3) the percentage of filled kernels or grains and
4) the weight of the kernel—each grain.

Yield, then, is the product of each of the four components.

YIELD = Panicles/area x spiklets (grains)/panicle x % filled pikelets x kernel wt

Let's use an example of yield components converted to a per acre basis to see how they all add up to yield.

Your crop has 60 panicles per square foot and each has 70 kernels. The kernel weight is 30 grams/1000 grains, there is 10% blanking, what is the yield?

Conversion Factors: 1 lb = 454 grams

1 ac = 43,560 ft2 Abbreviations: grams = g

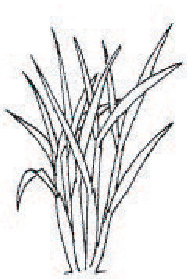
Pound = lb Square foot = ft2

Step 1:
60 panicle/ft2 x 70 kernel/panicle x 90% filled spikelets = 3780 kernels/ft2

Step 2:
30 g/1000 kernels x 3780 kernel/ft2/ 454 g/lb = 0.250 lb/ft2

Step 3:
0.250 lb/ft2 x 43,560 ft2/acre = 10,880 lb/ acre

Panicles per unit area



The total number of panicles in a given area is a product of the number of established seedlings and the number of fertile tillers produced by each seedling. A fertile tiller is one that produces a panicle. In some cases, such as in very dense stands, many of the tillers are shaded out and die shortly after panicle initiation (PI) and therefore do not produce panicles. Of all the yield components, the number of panicles per unit area is the most easily influenced by management practices. The number of seedlings per unit area, we commonly call "stand," is directly related to the seeding rate. Seeding rates of 125 lb/ac to 200 lb/ac typically provide seed densities as shown in Table 1.

These seedling densities based on seeding rates are ballpark estimates. The number of seeds/ft^2 can range widely depending on the seed size of the varieties. Koshihikari is the smallest and S-102 the largest of grown varieties (see Figure 2 later in this chapter). Thus, some adjustment in seeding rate may be necessary to compensate for seed size. One seedling can produce a number of tillers (depends of stand density - see Figure 5 later in chapter) and ultimately panicles; however, 60 to 70 panicles/ft^2 are about optimum for good yields with Calrose type varieties (Table 2).

Importantly, in water seeded rice systems seed density does not translate into plant density as many seeds (up to 50%) fail to produce a viable seedling due to wind, pests and diseases (see Chapter 4 for more information on this). For example, M-206 at a seeding rate of 150 lb/ac, would give 50+ seeds/ft^2 almost enough, if they all survived, to provide an adequate number of panicles without tillering. However, we all are familiar with damage to stands from wind, tadpole shrimp, bakanae and many other things that can cause moderate to heavy stand losses. High seeding rates are a form of insurance against stand losses. As a cautionary note, however, too high seeding rates can result in weak stems and increased incidence of foliar disease. The bottom line is that to achieve panicles densities high enough for good yields, tillers must be produced by each seedling. Varieties vary in their tillering capacity, ranging from high tillering tropical indicas to our relatively lower tillering calrose or japonica types. All of California varieties, however, have more than adequate tillering capacity to produce high yields in direct-seeded culture. If conditions are good during the tillering stage, the plant is capable of producing many more tillers than are needed for

Table 1. Field seed densities from typical seeding rates. The seed densities range due to differences in seed size (Figure 2). Densities for M-206 are shown for comparison.

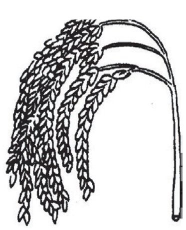
Seeding rate (lb/ac)	Density range (seeds/ft^2)	M206 (seeds/ft^2)
125	40-58	45
150	48-69	54
175	60-81	63
200	65-92	72

Table 2: Rice stand, yield and yield components.

Seeding Rate	Yield Components					
	Established Plant Stand	Panicle Density	Grain Weight	Spikelets/Panicle	Filled Spikelet	Yield
seeds/ft^2	plants/ft^2	ft^2	mg	no.	%	lbs/ac
11	11	53	25.2	90.8	86.6	8692
22	21	65	25.6	74.8	85.8	9267
33	27	61	25.8	71.6	86.2	9438
45	34	66	25.5	64.3	85.6	9393
56	34	68	25.9	63.1	86.2	9423
78	43	75	25.9	58.9	86.8	9456

high yields (see Figure 6 later in chapter). If conditions are not good, then an inadequate number of tillers will be developed and yields will suffer. Fortunately, the rice plant has a remarkable ability to compensate for low stands. As stand density goes down, tillers per plant increase. For example, in a Butte County nitrogen by variety trial in 1984 and 1985, 12 plants/ft^2 produced 4.8 tillers per plant, 21 plants/ft^2 produced 3.1 tillers per plant and 27 up to 34 plants/ft^2 produced about 2 tillers per plant. In a more recent study using M-206 at the RES, similar findings were reported with 16 tillers per plant at the lowest plant density (3 plants/ft^2) and between 2 and 3 tillers per plant at plant densities of 25 to 55 plants/ft^2 (Table 3). At optimal plant densities, tiller density is about 60 tillers/ft^2 or more (Table 3) and will give a panicle density of about 60 panicles/ft^2 or more (Tables 2 and 3).

Spikelets Per Panicle



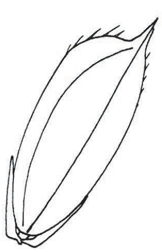
Spikelets are formed when the apical meristem or growing point changes from producing leaves to producing the panicle (reproductive structures). This occurs late in the tillering stage and triggers panicle initiation or reproductive growth. The entire panicle—branches and spikelets are developed at this time. Although they cannot be seen with the naked eye, under a microscope, their surface appears as a series of small nodes, each to become a spikelet or grain. Typically, we identify PI by cutting the stem or culm longitudinally with a pocketknife. At the start of PI, the panicle is not visible but a green band is visible above the top node (thus referred to as "green-ring"). The green band is only visible for a couple of days so it is easy to miss it. Once the panicle is produced, the top node begins to elongate and move up the stem, increasing the space between the nodes (Figure 1). Usually by the time we see the young panicle it is several days after PI.

The maximum panicle size of most California Calrose types is around 100 spikelets per panicle, but is more on the order of 70 spikelets per panicle with typical densities of 60 to 70 panicles/ft^2. The number of spikelets per panicle, however, can vary genetically from varieties with relatively small panicles to varieties with panicles of over 150 spikelets or more. Some of the Chinese hybrids, for example, have very large panicles. Man-

Figure 1. Young panicle

agement practices can influence the number of spikelets per panicle. Most commonly, stand density has the greatest influence on panicle size. Rice plants will compensate for low stand densities by producing more spikelets per panicle (as well as by producing more tillers per plant) as shown in Table 2. Usually, however, panicle size will not increase enough to overcome lower yields from poor stands.

Percentage Filled Grains



The percentage of filled spikelets per panicle can be greatly reduced by cold air temperature. Low water temperature can also reduce the number of filled spikelets. California varieties are among the most cold tolerant in the world, but they can still be damaged during meiosis (occurs during period about 10 days after PI and 10 days before heading) by temperatures below 55º and 60º F (depending on variety). When this occurs, the spikelets become sterile and result in "blanks". Blanking can be as high as 40-50% when low nighttime temperatures continue for four or five consecutive days. Blanking on a "normal" year is around 12%. Increasing water height during the critical meiosis stage can greatly reduce cold damage. Water should be raised to a level above the developing panicle (8-10 inches) to act as a heat sink and thus keep temperatures above the critical level.

Kernel weight

Kernel weight differs among varieties from a 1000 kernel weight for the small-seeded Calhikari and Koshihikari varieties (22.5 to 24.9 g), to S-102 at over 32 g (Figure 2). Common medium grains range between 27 and 30 g/1000 kernels. In the field, kernel weights are the least variable yield component. They generally cannot be increased by good management practices to compensate for poor tillering or smaller panicles. For example, Table 2 shows that across all seeding rates and resulting panicle densities, and even at the lowest seeding rate where panicle size increases, grain weight remains constant at about 25 g per 1000 kernels. Kernel weight, however, can be reduced by bad management or bad luck (such as draining too soon or from drying north winds). Fields that are too dry at the end of the harvest can limit grain filling and reduce kernel weight as well as quality.

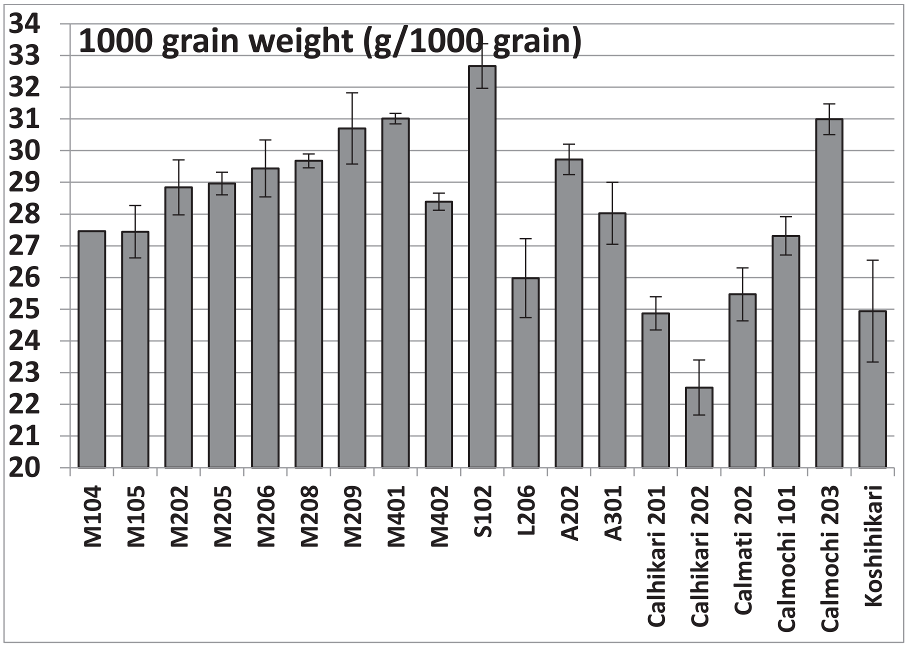


Figure 2. 1000 grain weights for common California rice varieties

Rice Growth and Formation of Yield Components

The yield components described above develop in different stages in the life cycle of the rice plant. Thus, management practices must be timed properly to positively influence the desired yield component. For example, once plant/crop growth is beyond the critical stage of tiller development, management practices, no matter how well intended, cannot increase the number of tillers. The growth of the rice plant can be divided into three stages: vegetative, from seed germination to PI; the reproductive stage from PI to flowering; and the ripening stage from flowering to grain maturity. The time required for each of these stages is dependent largely on the choice of variety, but is also affected by management practices, weather and other environmental conditions.

The Vegetative Stage

Vegetative growth begins with seed germination and lasts through the tillering stage (Figure 3). It can be subdivided into seedling growth and tillering. The best opportunity for management practices to influence yield is in the vegetative stage. In the seedling stage, good seedling emergence, stand establishment and seedling growth can be enhanced by the use of high-quality seed, proper seed soaking, land leveling, seedbed grooving (rolling) and other management practices that are described in detail in other sections of this workbook. Up to about the 2 or 3-leaf stage the seedling (Figure 4) is largely dependent on the stored seed reserves for growth.

At the 3 to 4-leaf stage the young rice plant becomes self-supporting or autotrophic, relying on the sun's energy and nutrients from the soil for growth. Practices to enhance rooting and allow for emergence through the water will enhance rice stands. Generally, plant stands of 20 to 25 seedlings per ft^2 will provide optimum tiller and panicle densities.

The seedling develops into the main stem. At tillering, the second stage of vegetative growth, the primary tillers develop in the axils (base) of each leaf beginning with the second leaf. Tillers typically begin to appear at about the fifth leaf stage.

When the sixth leaf appears, the second tiller

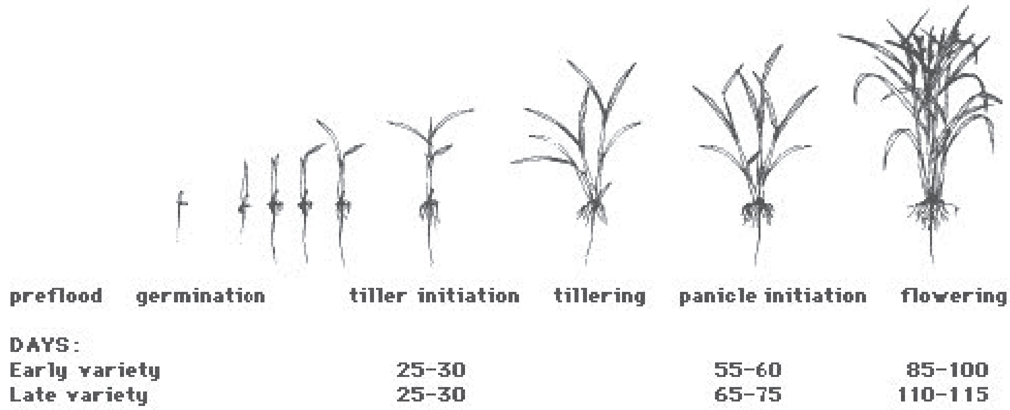


Figure 3. Growth stages of rice through flowering

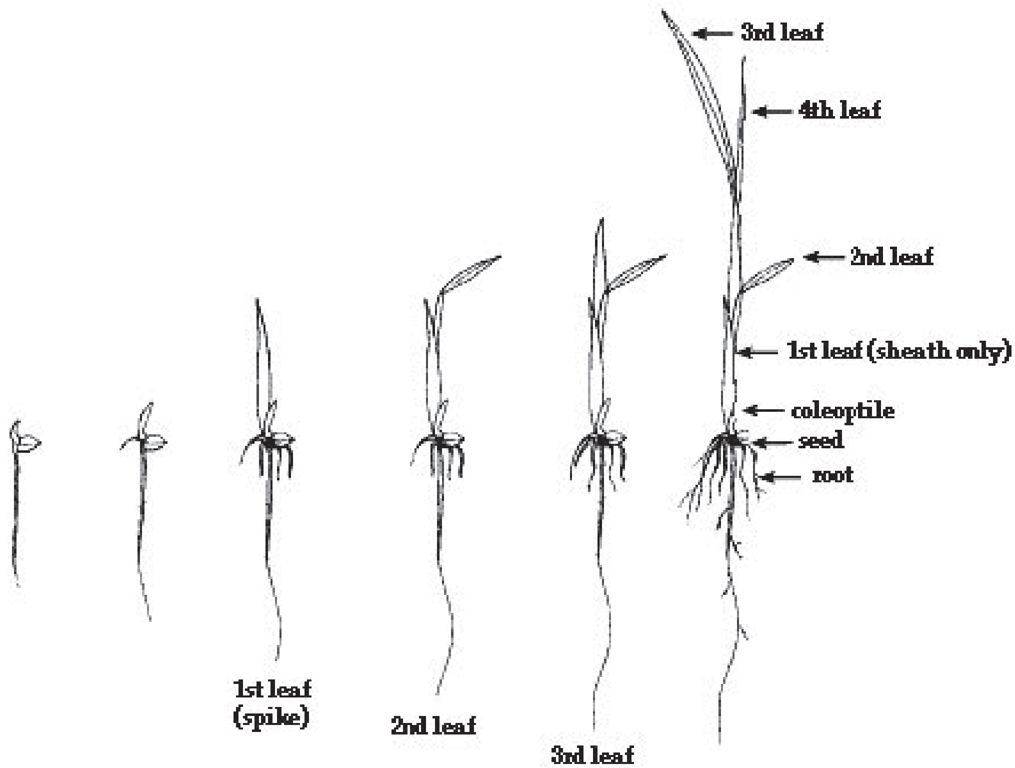


Figure 4. The stages of seedling development

emerges from the third leaf and so on. Each tiller is also capable of developing sub-tillers or secondary tillers. The total number of tillers developed from a single seedling depends on stand density, nitrogen (as well as status of other nutrients), weed competition and damage from pests. The tillering stage is even more important to final panicle density and yield than the number of seedlings established. It is also one of the critical stages that can be most influenced by management practices. The period of tillering does not vary much among varieties, although some of the very late varieties such as M-401, have a slightly longer vegetative stage, meaning that tiller initiation may extend over a longer period (see Table 3 later in chapter). The management factors affecting tiller formation include good nutrition, especially N management, water management (deep water reduces tillering, but usually not below critical levels when other

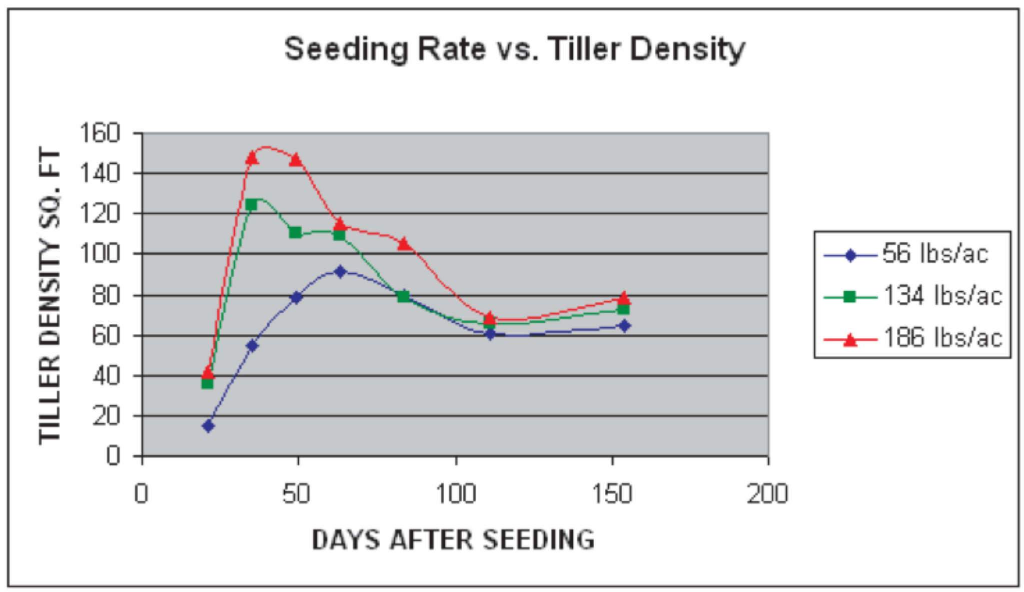


Figure 5. Tiller development over the season as affected by seeding rate

factors are well managed—see Water Management section), weed competition, insects and diseases. The management of these factors is discussed in other sections of this workbook. Generally, panicle densities should be in the range of 60 to 70 panicles (fertile tillers) per ft^2 to maximize yields. Under good conditions, the number of tillers formed on the plant at maximum tillering may be twice what is necessary for high yields. In this case, many of the tillers die before flowering. Figure 5 shows how tillers develop over the season at different seeding rates. Note that at very low seeding rates, all the tillers survive (and are needed for high yield) whereas at high seeding rates the number of tillers is very high at maximum tillering but about half die off from shading. Final tiller number is about constant across these seeding rates.

The Reproductive Stage

The reproductive stage begins at PI (Figure 1) and extends through flowering. The duration of the reproductive stage varies quite a bit among varieties of different duration with longer duration varieties having a longer reproductive period (Table 4) Furthermore, some varieties (e.g. M-401) are sensitive to day length and PI must be induced by shorter days. These varieties tend to be much longer duration than many varieties which are not photo-period sensitive. The panicle develops within each tiller at the base of the plant just above the soil surface. The start of PI can be seen by the formation of a green ring just above the top node when the stem is cut longitudinally (thus referred to as "green-ring"). The green band is only visible for a couple of days so it is easy to miss it. At about one week following PI the young panicle is large enough to see when the stem is sliced longitudinally through the base. At this time jointing or stem elongation of the upper internodes begins. The young panicle is about 1-2 inches above the soil surface and differentiating into spikelets; the number of spikelets per panicle are determined at this time.

In the final stages of differentiation, pollen is formed within each immature spikelet and this is the most sensitive period to cold temperatures. Cold temperatures of 55 to 60°F (depending on variety) or less can cause sterility by inhibiting pollen formation and resulting in excessive blanking. This is referred to as cold-temperature induced blanking. Although field practices cannot increase the number of spikelets formed during PI, raising the water level above the developing panicle at PI to mitigate cold temperature can greatly increase the percentage of spikelets that become filled grains. This is the most important management practice available at PI to maintain good yields. To be safe, keeping water high from about 10 days after PI to 10 days before heading should help reduce cold blanking. Figure 6 shows how to identify the most cold sensitive period before flowering. Of lesser importance is spikelet sterility caused by too much N. Excessive N from over fertilization, particularly in a cool season or from fertilizer overlaps can increase sterility and blanking. This is why it is important to fertilize preplant only for a cool year and top-dress as needed if the season is warm. Other management practices such as herbicide treatments at PI may also have an effect on grainfilling.

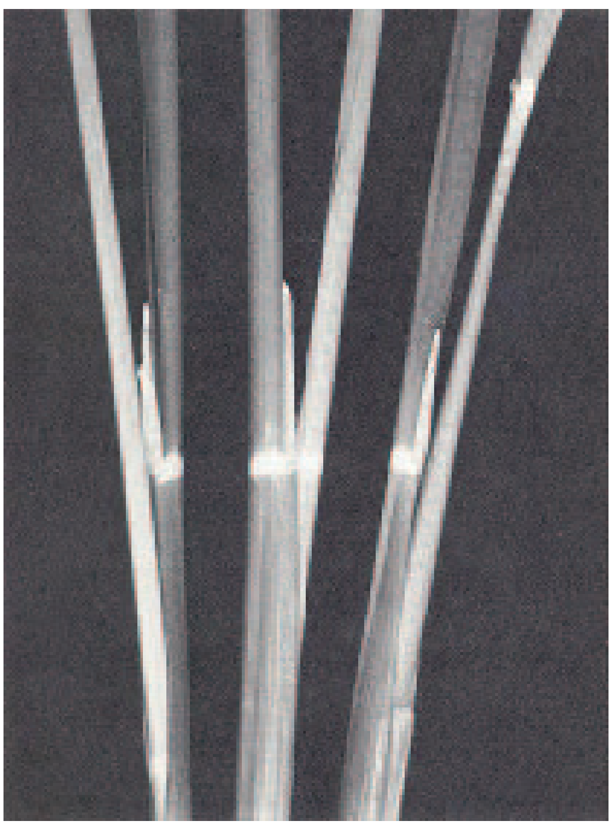


Figure 6. Pollen formation and cold sensitivity occurs when the collar of the flag leaf is aligned with the collar of the previous leaf (center).

Table 4 shows data from a greenhouse study comparing time to critical stages for a number of common CA varieties across a range of planting dates. Greenhouse studies tend to have warmer air temperatures than outdoor so the exact number of days shown in Table 4 is shorter than normal. Importantly though, the data show that across varieties, the time to PI is relatively similar (across varieties the time to PI may vary by about 10%). The big difference between varieties is the time from PI to 50% heading (over 30% variation in time). Finally, the time from 50% heading to R7 (when at least one grain on panicle has yellow hull and is about when growers should consider draining the field in preparation for harvest) also varies by quite a bit between varieties but the time is much shorter.

Flowering, the second part of the reproductive stage, occurs over two to three weeks. The time of flowering varies with the varietal maturity group (Table 5) and location (due to differing temperatures) (Figure 7).

Very high temperatures at flowering can dry the germinating pollen tube before fertilization and cause blanking. Generally, these temperatures must be above 104 °F. Heat induced sterility is of far less consequence to yield than is cold temperature induced floret sterility which occurs between PI and flowering. Nothing can be done to mitigate high temperature damage by management practices.

The Ripening Stage

The fourth and final yield component, kernel weight, is determined at ripening. Ripening begins at the completion of flowering and lasts through physiological maturity. The developing kernel is filled from materials stored in the leaves and stem and from new carbohydrate produced from photosynthesis in the upper-

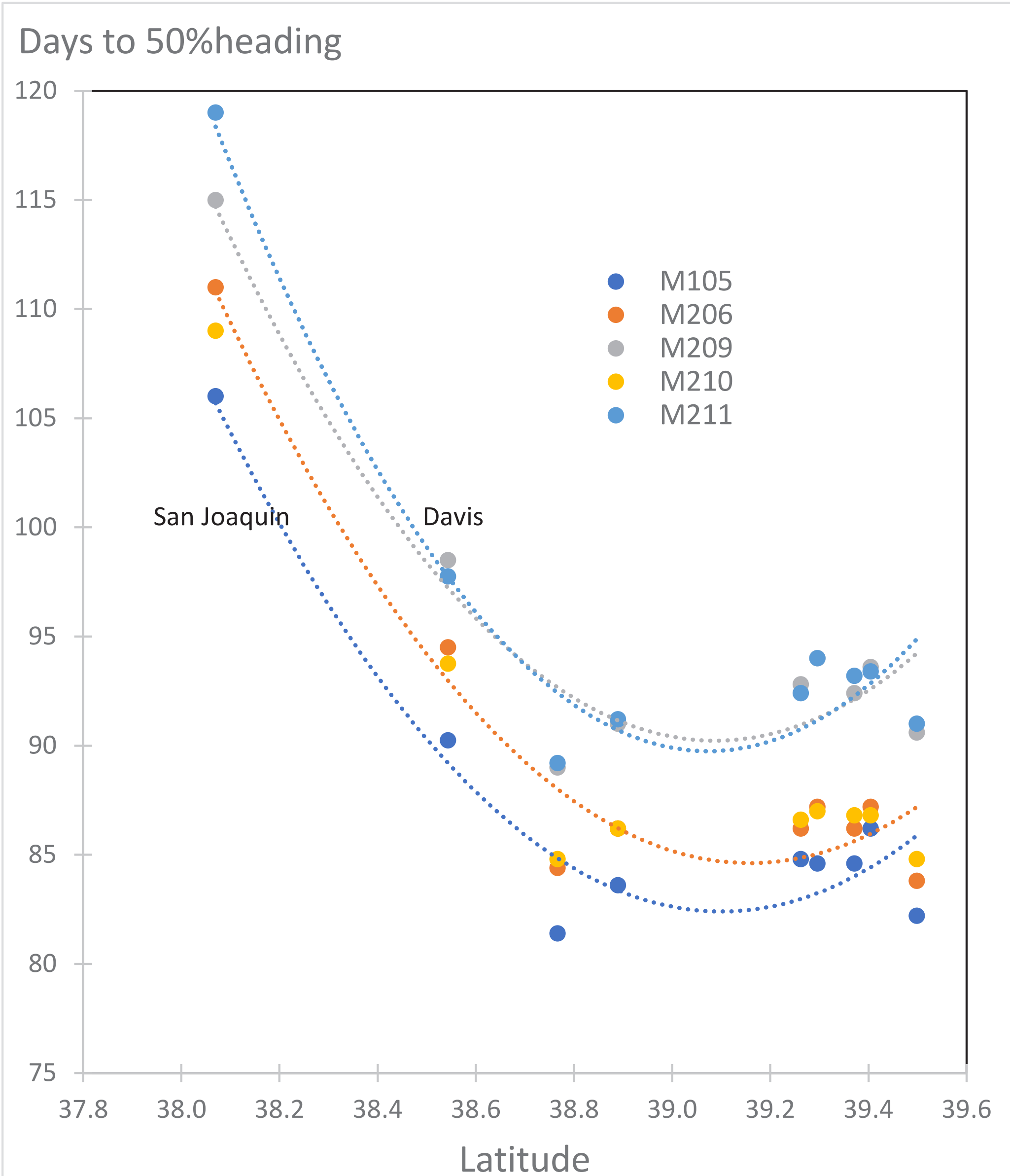


Figure 7. Days to 50% heading for common California medium grains. Data are from state wide variety trials and are averaged from 2017 to 2021. The San Joaquin variety trial is drill-seeded which increases the time to heading.

most leaves and developing kernel. The kernel reaches physiological maturity at about 30% moisture. For translocation of stored materials and photosynthesis to remain active, the maturing plant must have adequate soil moisture for a long enough period to ripen late maturing kernels. While it is not possible to increase kernel weight above the genetic potential of the variety, it is possible to lower kernel weight by soil drying too soon. Thus, decisions about when to drain the field are critical. Early draining facilitates harvest but may allow the field to dry too soon to complete grain filling, thus reducing both kernel weight and milling quality. This decision is often a tradeoff between a smooth harvest and lower head rice or "mucking" out the harvest to achieve higher head rice.

Table 3. Tiller, panicle and yield responses to seeding rate. Data from a 2015 study at the RES using M-206. Data represent the mean of two planting dates.

Seed rate	seeding stand	height	Tiller density	Panicle density	tillers	panicles	yield (lb/ac)
seeds/ft2	seedlings/ft2	cm	tillers/ft2	panicles/ft2	tillers/plant	panicles/plant	lb/ac
5	3	98.8	41	36	15.9	14.0	7491
15	12	99.6	61	52	5.3	4.5	8829
25	17	97.8	67	58	4.0	3.5	9575
35	20	99.1	65	56	3.3	2.8	9311
45	25	97.1	76	66	3.0	2.6	9881
55	31	96.6	79	66	2.6	2.1	9744

Table 4: Days from planting to panicle initiation, heading and R7 (when at least one grain on panicle has yellow hull) for different California rice varieties and planting dates. Note that these data are from a greenhouse pot study where average daily temperatures were warmer than typical. Thus, the actual time to each stage are shorter than typical.Data represent the mean of two planting dates.

Variety	Planting Date	Panicle initiation	50% heading	PI to 50% heading	R7	50% heading to R7
		(days)	(days)	(days)	(days)	(days)
CM-101	1-May	48	73	25	94	21
S-102	1-May	44	71	27	90	19
M-104	1-May	48	73	25	92	19
M-105	1-May	44	71	27	92	21
M-202	1-May	44	76	32	94	18
M-205	1-May	48	78	30	101	23
M-206	1-May	48	76	28	98	22
M-401	1-May	50	108	58	125	17
L-206	1-May	44	71	27	87	16
CM-101	15-May	41	69	28	92	23
S-102	15-May	41	71	30	92	21
M-104	15-May	41	66	25	84	18
M-105	15-May	41	71	30	92	21
M-202	15-May	41	73	32	92	19
M-205	15-May	41	76	35	92	16
M-206	15-May	41	69	28	87	18
M-401	15-May	45	94	49	113	19
L-206	15-May	41	71	30	87	16
CM-101	29-May	43	78	35	94	16
S-102	29-May	43	70	27	91	21
M-104	29-May	43	70	27	87	17
M-105	29-May	43	73	30	87	14
M-202	29-May	43	78	35	94	16
M-205	29-May	43	78	35	94	16
M-206	29-May	45	70	25	91	21
M-401	29-May	48	94	46	115	21
L-206	29-May	43	73	30	85	12

Table 5. Average days to 50% heading for major CA medium rice varieties grown at the RES. Data are from variety trials conducted at the RES from 2017 to 2021.

M-105	M-206	M-209	M-210	M-211
Average days to 50% heading				
75	77	81	76	83
Range of days to 50% heading				
67-80	70-83	77-84	71-80	80-86

Developmental rate

The rate of rice development and progress from one growth stage to another is largely based on the accumulation of growing degree days (or heat units). Some rice varieties are photo-period sensitive and their flowering will depend on changes in day length. In California, it is thought that M-401 is at least partially photo-period sensitive, but most of the other commercial varieties flower based on growing degree day units (heat units) accumulated.

The accumulation of average daily temperatures is calculated as 'growing degree days (GDD)'. At its simplest it includes an average daily temperature [(Tmax-Tmin)/2] and a minimum development threshold that must be exceeded for growth to occur. This is the base temperature (Tbase) and below this temperature the plant does not continue to develop. For California rice varieties this temperature is 50°F. The equation is:

GDD = [(Tmax+Tmin)/2] – Tbase.

Additional modifications exist for high temperature cutoffs. (The growth rate rice does not increase as temperature increases above a certain point.)

Understanding how temperature affects crop development helps explain a number of factors why there is variation in time to heading for the same variety.

1. In Table 5 we see that for the same variety the time to 50% heading can vary by over a week, even if the rice is planted on the same day of the year. This is just due to differences in temperature during the growing period.

2. Planting early in the season (late April or early May, tends to result in a longer growth duration because rice is being planted at a cool time of the year and hence growth is slower during this period.

3. It also explains why rice grown in the southern part of Sacramento Valley and in the Delta region where it is cooler, take a longer time to reach 50% heading (Figure 7).

4. It explains why dry-seeded rice takes about 5-7 days long to reach 50% heading than water seeded rice. Water temperatures early in the season are warmer than air temperatures and thus rice seedlings progress faster in a water seeded system where plants (especially the growing points of the rice) are under the water.

HARVEST INDEX: How much grain, how much straw?

The remarkable increases in California and world rice yields in the 1970's and 1980's were the result of major plant breeding programs to develop semi-dwarf or short statured varieties to more efficiently use the sun's energy. Agronomists refer to the measure of this trait as Harvest Index (HI) which is the ratio of grain to total plant biomass or biological yield (grain + straw). Harvest index is a measure of the partitioning of the sun's energy between the grain and the vegetative part of the plant (which eventually becomes the straw).

Harvest index (HI) is the ratio of grain weight to total plant weight and can be expressed as:

HI = GW/ GW + SW

Where: HI = Harvest Index

GW = Grain Weight

SW = Straw Weight

(GW + SW) = Biological Yield

NOTE: Root weight is not considered in the calculation of HI

Tall varieties are now grown in California only as specialty rice types. They exhibit lower HI than the modern short varieties commonly grown on most of California acreage. Short statured varieties have the advantage that they remain standing at higher nitrogen (N) levels. This is largely because their short stature provides less leverage to fall over due to a large grain weight on the top of the plant. As a result, N applications can be increased by about 30 lbs/acre relative to the taller types; and because higher N is important for photosynthesis, grain yield potential is increased. So what impact has this had on the amount of straw left after harvest? Some have suggested that by reducing the plant height by 30% we have also reduced straw remaining after harvest by 30%. This is not the case. We conducted several studies comparing short and tall varieties across different N rates. Figure 8 shows that Biological Yield (GW + SW) was similar for both tall and short varieties across all N levels. However, Figure 9 shows that grain yield for the short varieties was higher across all N rates. Of course, whether tall or short, rice varieties of both types will reach a plateau in yield at some level of N after which both will produce less rice due to lodging or blanking. Yields extrapolated from N rates of 120 lb/a typical for tall varieties and from N rates of 150 lb/a for short varieties were 6273 lb/a and 7262 lbs/a respectively with an increase in grain yield of 16%. Figure 10 shows that straw yields at these N rates are 7396 lb/ac for tall varieties and 7124 lbs/ac for the shorter types or a decrease of only 3.6%. Therefore, the adoption of short varieties has not likely reduced straw levels by all that much. These figures represent averages for many field trials over several years. However, grain and straw yields will vary by field and yields have increased since these data were taken with the original short types such as M- 7, M-9 and M-201. Importantly, however, is that tall variety HI should be used when calculating carbon conservation credits for returning straw to the soil. Using the HI for short varieties would show less straw than is actually produced. Figure 11 shows how HI varies over N level for both tall and short varieties.

SUMMARY

Yield components are the product of the number of panicles per unit area, the number of spikelets per panicle, the % filled spikelets and the kernel weight. Generally, a seeding density of 20 to 25 established seedlings/ft^2 result in an adequate density of 60 to 70 fertile panicles/ft^2. Management practices have the biggest influence on final yield during the vegetative stage when the panicle number is determined. This yield component is completely formed in the first 45-60 days of the season and cannot be changed after that time. The number of spikelets per panicle and the percentage of filled kernels are determined at, and shortly after PI. The panicle size and spikelet number cannot be increased, but good management of water to reduce exposure to cold temperatures can minimize excessive blanking. Similarly, kernel weight cannot be increased over the genetic potential of the variety, but management practices such as field draining for harvest can affect grain filling. Rice man-agement practices are described in detail in the following sections of this workbook. It is im-portant to think about when these occur in the life of the rice plant and what effect they might have on specific yield components. The knowl-edge of yield component formation can also help in diagnosing problems after the fact.

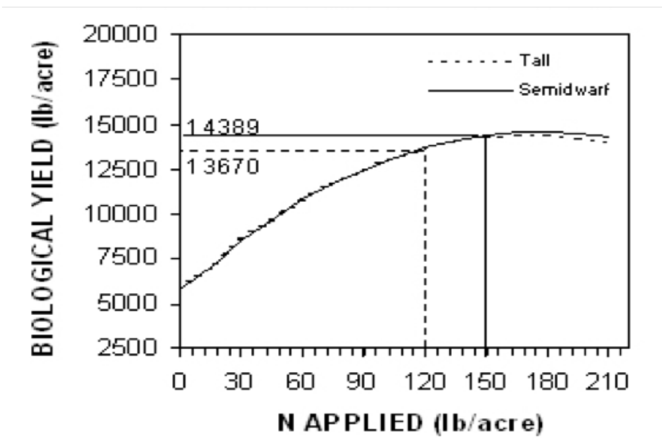


Figure 8. Biological yield (grain + straw) at N rates for tall (120 lb/ac) and short (150 lb/ac) varieties

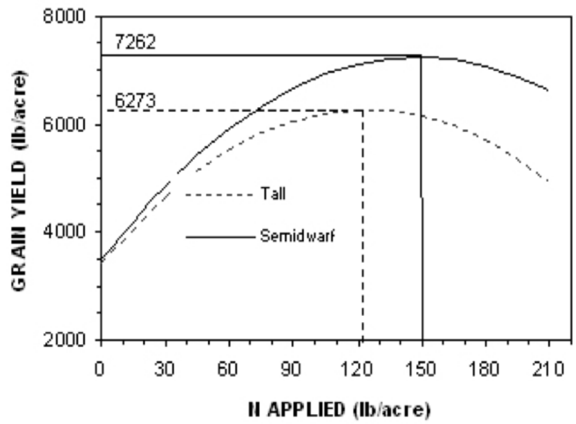


Figure 9. Grain yield at N rates for tall (120 lb/ac) and short (150 lb/ac) varieties

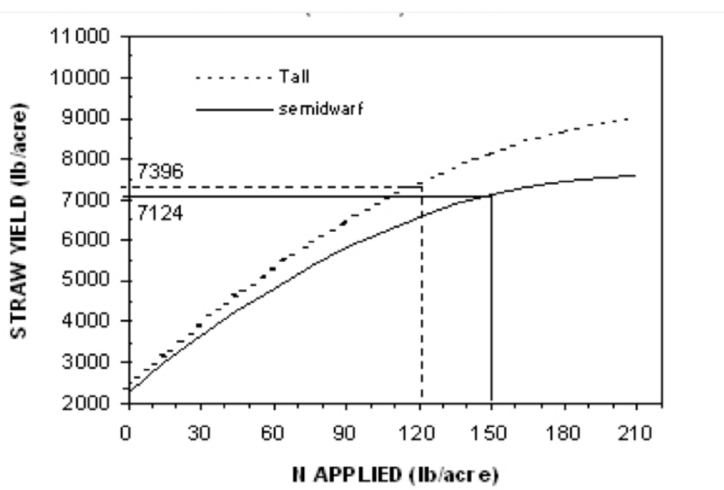


Figure 10. Straw yield at N rates for tall (120 lb/ac) and short (150 lb/ac) varieties

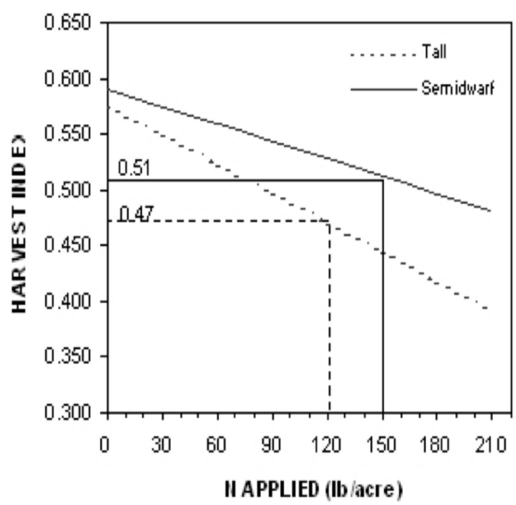


Figure 11. Harvest index at N rates for tall (120 lb/ac) and short (150 lb/ac) varieties

Field Development

Field development is the configuration of the field shape and surface slope as well as the installation of water control structures to optimize water management and crop production, conserving resources and improving operational efficiency. Most important to rice is accurate and easy management of water application, depth, and drainage so that crop growth is improved, and weeds are controlled. Also important is water conservation—through increases in water use efficiency and by minimizing the likelihood of accidental drainage. Another goal is more efficient use of land, tillage, and harvest equipment. This can be achieved by reducing the number of levees, straightening the levees, or making them smaller.

History

Much of the Central Valley is naturally fairly level, ranging from two to five feet of fall per mile (Willson 1979), so not much leveling was done in the early days of the rice industry. Consequently, most early efforts towards field improvement were in clearing native vegetation and building irrigation water structures such as canals, drains, weir boxes, and levees. The prevailing belief at the time was to leave the soil surface between the levees alone because rice grew poorly in cut areas and rank in fill areas. By the mid-1920s, growers began to see the economic benefits of leveling, although the first heavy earth movers and landplanes capable of major land formation were not available until 1935 (anonymous, 1948). Leveling became widespread after WWII, with a sharp increase in the 1960s. A key concern was whether to maintain the natural contours, which was cheaper, or to make the slope uniform so straight levees could be used, but at a higher cost (Figure 1). Wick (1970), estimated an equipment efficiency gain of 12-15%, 10% higher yield, faster initial flooding, more precise depth management, gain in productive land, and increased land value by leveling for parallel levees. The leveling system most commonly used depended on installing a matrix of grade stakes, based on a detailed survey map, which guided the equipment drivers.

Figure 1. Typical contour levees required in unleveled land, above. Land leveled to uniform slope with parallel levees, below.

Accuracy was dependent on the skill of the operator to match cuts and fills with specifications. In the early 1970s, laser-guided equipment (Figure 2) revolutionized land accuracy, automating some equipment operations and eliminating the need to set a complex matrix of grade stakes. With the adoption of the laser and its exceptional accuracy, growers changed their view of how flat fields could be.

Slopes decreased to zero with laser leveling, allow- ing for wider levee spacing and bigger basins. In addition, in those areas where rice is

Figure 2. Typical scraper for leveling equipped with laser receiver that guides position of cutting blade. Signal is received from laser beam on stand in foreground. Scrapers may be equipped with single, dual or satellite guided receivers

the only crop, fields were specifically developed for rice using permanent levees and little or no slope. Today, a high percentage of rice fields are laser leveled and have parallel levees. Those which do not are usually in areas where rice is rotated with other crops.

More recently, Global Positioning Systems (GPS) have been used for precision leveling, because GPS systems can be used to map field elevation in three dimensions, with an accuracy of up to 0.1 inches. This is more accurate than laser leveling, and it is easier to set up, as GPS leveling does not require the laser towers that are required for laser leveling. GPS leveling is less troublesome than laser leveling, as it is not hampered by dust and wind, whereas laser leveling can be negatively affected by both.

The necessary equipment is a tractor equipped with surveying software, a GPS receiver, and a base reference point. The scraper (which levels the soil) can be adjusted based on the field elevation map and can be controlled from inside the cab with the software.

Site Selection

Rice fields require the ability to pond water, so soils with low infiltration rates are necessary to prevent excessive water use. Desirable rice soils are those with high clay content (35 to 60%) in the topsoil or subsoil, or which have a cemented layer or hardpan in the subsoil. The most productive rice soils have deeper topsoils although good rice yields may come from shallower soils if crop nutrition needs are adequately met. Fields developed along the edges of the Sacramento Valley and near streams often have more variable soil types across short distances, which should be factored into the development plan. Fields formed from naturally flat topography benefit from less disturbance of topsoils compared to fields developed on steeper land where less fertile subsoils are exposed during leveling. It is especially difficult to farm rice when a calcareous or sodic subsoil is brought to the surface. Such soils often have soil chemistry problems that are difficult to correct.

Leveling

Land leveling allows maintenance of a uniform water depth within the basin (the area between the levees, also called a paddy) and greatly facilitates subsequent management practices for stand establishment, weed control, and field drainage for harvest. When a new field is developed or an old one is improved, an engineering plan is usually developed that includes all the features of the new field such as the placement of levees and whether they are straight or contour. It also includes the position of roads, landings, irrigation intakes, canals, drains, and other necessary structures. Often, several leveling options may be prepared and the producer decides which best fits his situation.

How a field is leveled depends on the crops grown, irrigation method, field configuration, soil type, and cost. About two-thirds of rice fields in the Sacramento Valley are set up to grow rice only, while the others grow row and field crops in a rice rotation. Fields growing rice only often have little or no slope while those in a crop rotation usually have slopes of 0.05 to 0.1%.

Fields may have a uniform slope across the whole field or the slope will vary because the natural contour of the land varies. Soil type will affect how a field is leveled, primarily as it relates to whether or not a soil can economically support crops other than rice. Although good for rotational crops, inclusions of well-drained soil in a rice field should be avoided if possible to minimize the volume of water needed to maintain a flood.

Cost is frequently the primary determinant of how a field is leveled. Very steep ground is most economically leveled into a series of 'benches,' each separated by a levee. This avoids the need to cut down large hills and fill in deep valleys and it leaves more topsoil in place. The area between the levees in benched fields is essentially a small field with its own uniform slope.

There are consequences to leveling, which is that moving the soil can cause changes in fertility (discussed in the next section), as well as possibly bringing up weed seeds that were buried deeper in the soil profile. The year after a new leveling event, growers may see weed species that were previously thought to be eradicated, as well as weeds in different locations throughout the field.

Soil Fertility

Leveled fields frequently have infertile and fertile spots related to the cuts and fills. Since most nutrients in the soil are concentrated in the plow layer, and subsoils are usually alkaline and may have infertile cemented hardpans, the effects of leveling on crop nutrition should be a primary consideration during the planning stage. The leveling plan should consider the depth to infertile subsoil and try to avoid it. The National Resources Conservation Service has irrigation land leveling specifications: "In cut areas, when highly permeable or otherwise un- suitable subsoil conditions are encountered, the cuts shall be over excavated and the topsoil replaced. In the fill areas, if specified, the topsoil will be stripped, the fills partly made and the topsoil replaced." (NRCS 2000). While more expensive, this method will help reduce the damage from deep cuts and help maintain uniformity of soil fertility.

Levees

Levees can be either permanently installed or taken down annually and reinstalled each spring. Permanent levees predominate in rice-only areas while annually installed temporary levees are common in mixed cropping areas or where a rotation crop may be grown occasionally. Construction of permanent levees should be integrated with the leveling plan because they are larger and require more soil. Temporary levees are built by pulling a large disk ridger or levee squeeze across the prepared field, gathering soil from a width of 11 to 13'. To prevent seepage, temporary levees often require the construction of two parallel levees with a borrow pit (indentation) between them. When the levees are knocked down and the field worked, the soil returns to its original position. In some rice-only fields, the individual basins are large (>25 ac) and the levees around them are wide enough for roads, which gives complete access for management. The benefits of permanent levees include freedom from annual installation, road access, no borrow-pits, and roll-overs. Roll-overs are flattened areas at the ends of levees for equipment to cross over from basin to basin. The disadvantages of permanent levees are that perennial weeds grow which may contaminate the crop and rodents establish and cause leaks. Some annual repair work is necessary to keep weeds and rodents under control, using herbicides, rodent baits, traps, and discs to repair holes.

Temporary levees take extra work to build and may require a fresh map or survey of the levee locations each year. Fields in a rotation usually need a fresh levee survey when coming back into rice. Temporary levees are usually free of perennial weeds and rodents. The big advantage to temporary levees is that they can be constructed after soil preparation, making it easier to quickly prepare a large field. Irrigation boxes for temporary levees are usually reinstalled each year, although some growers leave the boxes in from year-to-year and just remove the levee. Temporary levees are built on the prepared field, first marking their location, then pulling the levee. A large rice ridger can work in unplowed soil, but takes several passes to gather sufficient soil for the levee. A squeeze or crowder requires that the ground be loosened first by plowing and drying, then a single pass will create the levee. Both types leave a borrow pit, which means there is unproductive land.

All three levee types, temporary, permanent, and roads, use approximately the same amount of land. A typical leveled field usually has 3-5% of the land in levees. An unleveled field with contour levees may have as much as 10% of the land in levees.

The orientation of levees relative to wind direction can be an important consideration during the planning stages, particularly if the basins are long. Strong winds blowing across the surface of long basins will ‘pile’ the water on the downwind side, which may cause erosion damage to field sides and levees, and sometimes breaches in levees. In addition, the deeper water may impact rice growth and possibly uproot plants. Levees that are crosswise to the wind help reduce the damaging effects. Larger basins are more susceptible to the effects of wind but are more efficient in many respects, so some compromises are necessary.

Grade

Grade refers to the slope of the land surface. This means small elevation changes across the field, called either the ‘slope’ or ‘fall’. Because rice needs fairly shallow and uniform water depth large variations in elevation cannot be tolerated. Slope is usually expressed in tenths of a foot per hundred feet of distance or as a percentage. For example, a slope of 0.1’/100’ is the same as 0.1%. A 0.1% fall is equivalent to one foot every thousand feet. One foot is too great a fall for high-yield rice production so levees are necessary to break up the field and make sure that water depth will vary no more than 3-4”, and preferably no more than 2.5”. Many fields are leveled to much less than 0.1%, often 0.02 to 0.05%, allowing for wide levee spacing and greater efficiency. Many fields that are used only for rice have no slope at all and are completely flat. Others have compound grades so that levees are set at an angle to the edges of the field. Many fields have more than one grade, so that levee spacing is not uniform across the field. This is usually related to the cost of leveling which may make it impractical to establish a uniform grade.

Two goals of leveling and setting levees are to space them far enough apart to minimize their number, but close enough together so that the fall between, which affects water depth, does not exceed what the crop can tolerate. Two examples in the shaded box deal with these primary goals.

The point of the first example is that you choose your levee spacing consistent with the slope of the land and the needs of the crop. Usually, when the leveling plan is developed based on the criteria discussed above, you can determine levee spacing on the map. If the field falls in two directions, the calculation is the same although the levees will not be perpendicular to the side of the field. In practice, levee positions can be done with a laser transit simply by finding those spots in the field that represent the desired fall.

The second example is really the corollary of the first. This may be useful if you know the slope and levee spacing, but the water on the low side is too deep and you want to move the levees.

Irrigation Systems

Water delivery and distribution must be considered in the development of the field. While the levees are the primary means of controlling and containing water, other structures are necessary to regulate and distribute it. The method of water management is also integrated into the field development plan. Several irrigation system design options are discussed in the section on Water Management.

Irrigation boxes

Weir boxes in each levee are the primary means of regulating water flow and depth. Several materials have been used to build weir boxes, including wood, steel, cement, plastic, and fiberglass. Figure 3 is a typical wooden rice box. Redwood is cheap and easily repaired and is useful in fields where levees and boxes are removed annually. Fields with permanent levees often use more durable materials such as corrugated plastic pipes connected to steel drop boxes. All have common properties including a flume or pipe to move water from one side of a levee to the other, and removable 'flash boards' which hold water back to a given depth and let the excess flow over the top. Water level in the basin above the box is regulated by adding or removing boards. Weir boxes are usually placed near the ends of levees, often on both ends, and sometimes opposite ends in adjacent levees to promote water circulation. The size and number of rice boxes are dependent on the required capacity to move water from one basin to another. Rice boxes, as in Figure 3, are typically 18" high, 48" long, and 24-48" wide. The pipe diameter in permanent rice weirs is usually 12-18".

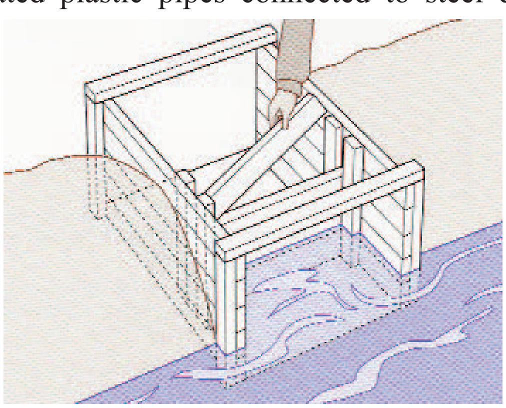


Figure 3. Typical wooden rice box. From: Hill et.al. 1991.

VARIETY SELECTION & MANAGEMENT

Introduction and History

Since its beginning in 1912, California's rice industry limited its production and marketing largely to a few short and medium grain japonica varieties, developed from stocks originating in Japan and China. These varieties produced good yields of quality rice in the dry, temperate climate of the Sacramento and San Joaquin Valleys. For the grower, the choice of variety to plant was relatively simple because the few varieties available were similar in performance, yield potential and milling quality when properly managed. Included were Colusa, Caloro, and Calrose, all released from the grower owned and funded Rice Experiment Station (RES) at Biggs, CA in 1918, 1921 and 1948, respectively, and Earlirose, a productive, early maturing, proprietary variety, released in 1965 which soon became a popular variety for cold areas and/or late plantings. These were the major rice varieties grown in California until the early 1970's.

Then, the variety picture began to change significantly. A powerful impetus for this was the enactment of the California Rice Research Marketing Order that established the California Rice Research Board in 1969. This grower initiative provided significant and regular funding to hasten development and release of new varieties. The medium grain variety CS-M3 was released in 1970 and the short grain variety CS-S4 in 1971, from rice hybridizations made in 1946 and 1957 at the RES. CS-M3 gained wide acceptance and competed with the older Calrose for acreage. But CS-S4, though an improvement over Caloro, was not widely grown because of its susceptibility to low temperature induced sterility. The last tall stature variety from the RES breeding program, M5, was released in 1975.

In 1976, Calrose 76, the first short stature (semidwarf) California rice, was released. This late maturing medium grain variety was a radiation induced mutant selected by the USDA in Davis in 1971. It was soon followed by the semidwarf M9, developed by hybridizing the tropical "green revolution" variety IR-8 by the RES. Thus began the era of short stature rice in California, which was to have enormous consequences. Subsequently, numerous varieties have been released in a range of maturity groups with different grain shapes and culinary characteristics.

Acreage

Publicly developed and introduced rice varieties are grown annually on over 90% of the planted acreage and more than 40 introduced proprietary varieties are grown on the rest (See Tables 1 & 2). Most of the varieties grown in California are classified as "temperate japonicas," adapted to the cooler rice growing areas and temperate latitudes of the world. This is contrast to "tropical japonicas" (grown in the Southern US) or indicas that constitute the majority of the world's rice production. About 80% of the acreage is planted to 'Calrose' type medium grain varieties destined for a host of purposes including table rice and manufactured uses. California short grains and as well as introduced and proprietary varieties are also temperate japonica. Long grain varieties are tropical japonicas. California short and long grain varieties are also planted on two to three percent of the acres. Premium quality medium and short grain rice is grown on about 10% of acres, and is destined for higher priced table rice markets. Additional small acreages of specialty varieties are also planted, such as sweet rice (also called mochi, glutinous or waxy), arborio types (large or bold grain), and aromatic long grains including conventional, basmati, jasmine, and colored bran types.

Publicly developed and introduced rice varieties are grown annually on about 96% of the planted acres.

Table 1. Outline of the RES rice variety naming system and varieties offered in 2023. Grain type letter(s) are combined with a numeric descriptor. The first digit is the maturity group, the others are in the order of release.

Grain Type	Very Early (100-199)	Early (200-299)	Intermediate (300-399)	Late (400-499)
Short (S)	S-102 S-202	-	-	-
Medium (M)	M-105	M-206 M-209 M-210 M-211	-	M-401
Long (L)	-	L-205 L-208 L-207	-	-
Calmochi sweet rice (CM)	CM-101	CM-203	-	-
Aromatic (A)	-	A-202	A-301*	-
Calhikari short premium (CH)	-	CH-201 CH-202 CH-203	-	-
Calmati basmati type (CT)	-	CT-202	-	-
Calaroma jasmine type (CJ)	-	CJ-201	-	-
Calamylow (CA)	-	CA-201	-	-

**seed production discontinued.*

Table 2. Rice acreage estimates for Rice Experiment Station varieties in 2021 and 2022.

Variety	2021			2022		
	Seed Acres†	Percentage	Estimated Acres‡	Seed Acres†	Percentage	Estimated Acres‡
Medium Grain						
M-105	2,945	12.1	48,808	2,645	13.8	35,279
M-206	8,172	32.4	131,382	5,332	27.9	71,119
M-209	4,665	20.5	82,957	2,506	13.1	33,429
M-210	2,053	8.4	33,944	1,725	9.0	23,013
M-211	1,542	6.5	26,232	2,729	14.3	36,401
M-401	1,136	4.6	18,790	407	2.1	5,428
Total RES-Medium	20,513	84.5	342,113	15,343	80.3	204,669
Non-RES Medium	1,400	5.2	20,887	999	5.2	13,331
Total Medium Grain	21,913	89.6	363,000	16,343	85.5	218,000
Short Grain						
CA-201	1	0.04	143	7	0.1	170
CH-201	50	0.2	707	46	0.4	1,126
CH-202	145	0.5	2,067	232	2.2	5,622
CM-101	484	1.9	7,525	106	1.0	2,569
CM-203	346	1.5	5,889	193	1.8	4,689
S-102	198	0.7	2,816	256	2.4	6,206
S-202	16	0.1	221	2	0.02	54
Total RES -Short	1,238	4.8	19,368	842	8.0	20,436
Non-RES Short	613	3.9	15,632	394	3.8	9,564
Total Short Grain	1,851	8.6	35,000	1,236	11.8	30,000
Long Grain						
A-201	241	0.5	1,987	206	0.6	1,476
A-202	220	0.4	1,814	214	0.6	1,540
CJ-201	79	0.2	652	276	0.8	1,984
CT-202	17	0.0	140	18	0.1	129
L-205	20	0.0	167	46	0.1	331
L-207	207	0.4	1,707	155	0.4	1,114
L-208	10	0.0	78	19	0.1	134
Total RES -Long	794	1.6	6,545	934	2.6	6,710
Non-RES Long	1	0.0	455	40	0.1	290
Total Long Grain	795	1.7	7,000	974	2.7	7,000
USDA-NASS Acres						
Medium			363,000			218,000
Short			35,000			30,000
Long			7,000			7,000
TOTAL			405,000			255,000

† Seed acres represent the number of approved seed acres in the California Crop Improvement seed certification program.

‡ Estimated acres were determined by using the percent acres in seed production and the total reported USDA-NASS acres.

Naming System for Public Varieties in California

In 1979, the California rice industry developed a uniform naming system for new RES developed rice varieties, based on grain type, maturity group and order of release. This was necessary to avoid confusing the large number of varieties to prevent mixing of different type grains and to avoid inappropriate planting dates. Varieties should be referred to by their complete letter, numerical and descriptive name because deleting any component may lead to serious errors.

The name of a new variety contains a prefix letter designating its grain type as long (L), medium (M) or short (S). Specialty rice will carry a descriptive word prefix, such as Calmochi for waxy or sweet rice, Calmati for basmati-like rice, Calhikari for premium quality short grain rice, Calamylow for low amylose (≈7%) type rice, A for aromatic long grains, and Calaroma for jasmine long grains. Immediately following the letter or name descriptor is a three-digit number separated by a dash (-) from the letter or name. The first digit in the number designates the maturity group as either 1 (very early), 2 (early), 3 (intermediate) or 4 (late). The last two digits indicate the order of release of this type, from 01 to 99, starting in 1979 when this system began. For example, M-105 indicates a very early maturing medium grain variety which was fifth in order of release.

Proprietary and Introduced Varieties

In addition to the publicly developed varieties, some varieties of Japanese origin are also grown and retain their Japanese name, such as Akitakomachi and Koshihikari. Several companies also introduce or develop varieties for California while others have introduced varieties with unique characteristics such as colored bran, aroma, and special culinary properties. The 2020 list of all rice varieties in California approved for production, their commercial impact designation and tier is provided in Table 3a, 3b and 3c for medium, short and long grain varieties, respectively.

Grain and Plant Characteristics Important for Management

Successful production and marketing of rice requires knowledge of plant and grain characteristics. Since a rice grower's first concern is usually the market for which the crop is intended, primary consideration must be given to grain shape, appearance and culinary characteristics. Second, yield performance is usually an important criterion for variety selection, although for certain varieties, market quality outweighs yield. Varieties should also be chosen on the basis of their relative maturity so they can fit the cropping schedule of a particular farming operation or are suitable to a particular climatic condition. For example, late maturing varieties fit early planting schedules; cold tolerant varieties are needed for cooler areas. Agronomic characteristics, such as lodging and nitrogen response may also be considered in addition to straw quantity and quality and pubescence (rough or smooth leaf and hull). Currently, no California varieties have insect or herbicide resis-

Table 3a. Medium Grain Rice varieties approved for production in California and commercial impact and tier designation.

Variety	CI	Non-CI	Tier
02-PY-014		✓	
02-PY-021		✓	
85-101-10		✓	
91-130-02		✓	
94-158-01		✓	
Amber (formerly00-117)		✓	
Arborio (incl CA Arborio)	✓		1
Black Japonica (LBJ-489)	✓		2
Black Rice – SWF	✓		2
Black Rice (SunWest)	✓		2
Calriso	✓		1
Carnaroli (all subtypes incl MH-1)	✓		1
Crystal (formerly 04-116)		✓	
Farah (formerly 02-121-03)		✓	
FRC #11		✓	
FRC #22		✓	
Frances	✓		2
Guadiamar		✓	
Hong Kong Black (HKB-102)	✓		2
Jade (formerly 07-122)		✓	
Kokuho Rose		✓	
LBJ-115	✓		2
LMR-206	✓		2
M-103 (not in seed production)		✓	
M-104		✓	
M-105		✓	
M-201		✓	
M-202		✓	
M-204 (not in seed production)		✓	
M-205		✓	
M-206 (formerly 98-Y-242)		✓	
M-207 (formerly 00-Y-805 not in seed production)		✓	
M-208		✓	
M-209		✓	
M-210		✓	
M-211		✓	
M-401		✓	

Table 3a. Continued

M-402		✓	
Millrose		✓	
NFD181		✓	
Riz Rouge Camargue	✓		2
Rojito (SunWest)	✓		2
Royce (formerly 95-164-01)		✓	
RRI -226		✓	
RRI-321		✓	
Shasta (formerly 98-102)		✓	
SP-211		✓	
SP-311		✓	
SP-411		✓	
Trisha (formerly KR4)		✓	
Wehani LWE-218 (Lundberg)	✓		2
Winsor (formerly 02-120)		✓	
WRM-3538		✓	
Remy		✓	
Royal		✓	
Jemma		✓	
Imperial		✓	

Table 3b. Short Grain Rice varieties approved for production in California and commercial impact and tier designation.

Variety	CI	Non-CI	Tier
A-17		✓	
A-20	✓		1
Akita Komachi		✓	
Asuka (formerly 04-302)		✓	
BL-2 (not in production)	✓		1
Calamylow-201 (formerly BL-1)	✓		1
Calhikari 202		✓	
Calhikari-201		✓	
Calmochi -101	✓		1
Calmochi --203	✓		1
Caloro		✓	
Calpearl	✓		1
Carnaroli (all subtypes incl MH-1)	✓		1

Table 3b. Continued

Variety	CI	Non-CI	Tier
Himenomochi (formerly PI 504474)	✓		1
Hitomebore		✓	
Kogane Mochi	✓		1
Koshihikari		✓	
NFD 108	✓		1
NFD 109	✓		1
S-102		✓	
S-201 (not in seed production)		✓	
S-202		✓	
S-6		✓	
Sasanishiki		✓	
SP-2	✓		1
Surpass	✓		1
Vialone Nano	✓		1
WRS-4431	✓		1
Yamada Nishiki		✓	

Table 3c. Long Grain Rice varieties approved for production in California and commercial impact and tier designation.

Variety	CI	Non-CI	Tier
A-201	✓		1
A-202	✓		1
A-301	✓		1
Aromatic Long Grain Red Rice	✓		2
Calaroma	✓		1
Calmati-201	✓		1
Calmati-202	✓		1
Donana		✓	
L-202 (not in production)		✓	
L-203 (not in production)		✓	
L-204 (not in production)		✓	
L-205 (not in production)		✓	
L-206		✓	
L-207		✓	
L-208		✓	
Long Grain Red Rice	✓		2
P-2 Denosa		✓	
P-3 Isla		✓	

Table 4. Approximate size and shape classifications for California rice varieties, brown basis.

	Length (mm)	Width (mm)	Length/ width	Kernel wt. (g/1000 kernels)
Premium short	5.2	2.8	1.8	20.2
Short	5.5	3.3	1.7	27.6
Premium medium	6.7	3	2.2	23.9
Medium	6.1	2.9	1.9	23.8
Arborio	6.3	3.3	1.9	25.3
Long	7.8	2.2	3.5	21.5
Aromatic	8.2	2.1	3.9	23.1
Basmati type	7.5	2.1	3.6	21
Mochi	5.3	3	1.8	23.9

tance, but will in the future, which may become a primary selection criterion. For those blast prone areas, a blast resistant variety would be consideration (M-210). Rice plant and grain characteristics are discussed below.

Grain Quality

Milling, market and cooking/culinary qualities are mentioned here because they are influenced by varietal selection and management methods. For example, genetic characteristics influence milling quality, which will influence choice of variety. In addition, many quality components of Japanese premium short grain varieties are influenced by production practices.

Grain Starch Content

Amylose is a straight chain glucose molecule, as contrasted to amylopectin, a larger highly branched glucose molecule. In general, the more amylose a variety has, the less sticky it is. The majority of California rice is Calrose type medium grain and has low amylose content which tends to make it soft when cooked and the grains tend to stick together. “Calrose” is a marketing term that refers to all non-premium quality medium grain rice varieties with cooking/culinary characteristics similar to the original Calrose variety. Demand for Calrose varieties remains strong, and they occupy over 80% of the state’s acreage. California non-premium short grain rice also has low amylose and cooks similarly to Calrose and is used as table rice, brown rice, and rice cakes.

Long grain rice in California has higher amylose than medium and short grain which imparts a firm, dry characteristic when cooked. Calaroma-201 has a low amylose content similar to medium grains and is softer cooking.

Scent: Aromatic and Basmati Types

A few California varieties, such as A-202, are known as aromatic and have a distinctive scent, similar to popcorn, particularly when cooked. The scent is also discernible in the field. It is from a high 2-acetyl-1-pyrroline content compared to non-aromatic varieties. In addition to aroma, Basmati-type varieties (Calmati-202) also have a cell wall arrangement in the grain that results in grain lengthening during cooking as compared to other varieties which tend to expand uniformly when cooked. Otherwise, they have amylose starch content similar to other long grain varieties. Aromatic and Basmati type rice sells in a unique market. Calaroma-201 is also aromatic but has different cooking properties. The presence of aroma makes it very important to maintain identity preservation of aromatic varieties to avoid mixtures with non-aromatic types.

Arborio/Chalky Types

Arborio is the name of a short grain variety from Italy and a market type for similar varieties grown in California. This type is characterized by having a very large kernel, and an excessive amount of chalkiness which is the presence of white, opaque areas within the milled kernel, as contrasted to the translucent whiteness of most varieties. Chalk is a heritable defect and is one of the first things rice breeders eliminate in most varieties because it results in low milling yields and poor appearance.

Chalk is referred to as white belly and other names, depending on the position of the chalk on or in the milled kernel. But for Arborio, chalk is associated with superior culinary properties for specific dishes, primarily risottos. Other than genetics, chalkiness is caused by high nighttime temperatures during grain fill, high harvest moisture, uneven ripening, and cultural practices that result in uneven ripening and presence of immature kernels at harvest.

Specialty varieties currently grown include aromatic rice (conventional, basmati type), arborio type (large, chalky grain), mochi (which has no amylose), and colored bran (red or nearly black). The latter has little or no amylose.

Plant Characteristics

Relative Maturity

Maturity of California rice varieties is classified by the number of days from planting to 50% heading in the warmer areas of the state. Four categories are used (Table 5). Maturity differs primarily in the length of the vegetative stage. Beyond 50% heading, California short and medium grain varieties normally require another 40 to 55 days for grain maturity in warm areas, and 5 to 15 days more in cool areas. Long grain varieties usually ripen 5 to 10 days faster after 50% heading than medium grain varieties. Maturity is relative and can be advanced or delayed by planting date, nutritional status, temperature and other environmental factors.

Very early varieties are commonly grown in cooler areas and for late planting when later varieties are not well-suited. An increasing practice is to plant them early in warm areas to advance harvest to allow more time for straw management and to shorten the water season. Maintenance of milling quality can be more of an issue when very early varieties are planted early.

Table 5. Variety maturity group and days to 50% heading at RES.

Maturity Group	Days to 50% heading
Very Early	< 80
Early	81-90
Intermediate	91-99
Late	> 100

Early varieties occupy roughly 70-75% of the acreage. They are predominately Calrose type and are generally higher yielding varieties. Early varieties provide flexibility because they are suited to a wide range of planting dates.

Intermediate maturity varieties were intended to provide a more timely harvest sequence.

However, there are few representatives in this category because of the industry preference for earliness.

Late maturity varieties were also intended to provide options for harvest sequencing. However, most late varieties currently grown are used because they have particular characteristics, such as premium quality, rather than for their value in scheduling harvest. They are generally planted before May 1. About 4% of the acres are typically planted to late maturing varieties.

Seedling Vigor

Seedling vigor refers to early growth and includes rapid leaf emergence through the water, stand density, growth rate after emergence, leaf droopiness, and leafiness. Vigor is an important component in variety evaluation because it helps improve stand establishment. For the grower, vigorous varieties make water management easier and may improve competition against weeds. California varieties vary in their vigor over a fairly narrow range, with the long grains having less vigor than medium and short grains.

Plant Height

Plant height is the distance between the soil surface and the tip of the erect panicle. Height is important because of its relationship to plant physiological processes and lodging which affects harvestability and yield. Height classifications include short, intermediate and tall. Short stature varieties at average soil fertility are less than 95 cm; intermediate stature varieties are 95-105 cm; and tall varieties are taller than 105 cm. Prior to 1976, all California varieties were tall and tended to lodge, particularly under high nitrogen fertility. Beginning with the release of Calrose 76, all varieties from the public program have been short stature. Since full adoption of short stature varieties from 1976 to about 1980, statewide average yields rose dramatically.

Pubescence of Hulls and Leaves

The predominant hull trait important to producers is the presence or absence of hairs. Pubescent/hairy/rough varieties have numerous hairs called trichomes distributed over the flower, seed covers and leaf surfaces. Glabrous/smooth varieties have a few hairs on the keel of the hull and the margin of the leaves, but are otherwise smooth. Before heading, smooth and rough varieties can be distinguished by running a leaf blade between thumb and finger and noting whether its surface (not edge) is rough. Of importance to producers is the fact that smooth varieties have a higher bulk density (test weight) than hairy varieties and result in heavier trucks which can be easily overloaded; and tighter packing in bin driers requires more pressure to move air compared to rough varieties. Smooth varieties are also less dusty during harvest and drying, resulting in less discomfort for harvest and drier personnel. With the exception of CM-101, CH-201, CH-202, CT-202, CJ-201, and S-102, all public California varieties are smooth. Both Koshihikari and Akitakomachi are rough hulled.

Awns

Varieties may have long, medium, or short awns, or may be awnless. The characteristic is under genetic, and to some extent, environmental control. The importance of awns for producers is in harvesting. Awns on some varieties may be difficult to remove resulting in lower bulk density and difficulty in unloading harvesters due to bridging, especially pubescent varieties.

Photoperiod Response

Some rice varieties respond to the length of the day, the time between sunrise and sunset. This is the photoperiod. The transition from vegetative to reproductive growth is triggered by day length in photoperiod sensitive varieties which are mostly grown in the tropics. However, with the exception of M-401, most rice grown in temperate zones, including California, is generally insensitive to photoperiod, and responds primarily to temperature.

Tolerance to Low Temperature Sterility

Low temperatures during formation of the pollen mother cell (microsporogenesis) is a primary cause of panicle sterility (blanking). This physiological stage coincides with the time when the collar of the flag leaf is adjacent to the penultimate leaf (next to the last leaf), and when the panicle is still entirely inside the boot. The cause is low temperature for a sufficient duration, particularly if it occurs for several successive nights. While many combinations of time and temperature can cause blanking, an overnight low of 55°-60° or lower can be used as an alert that temperatures may be low enough to cause damage. All varieties are screened for tolerance to blanking. Table 6 gives approximate ranking of varieties by their general level of low temperature sterility tolerance.

Pest Resistance

Resistance to diseases is a long-term goal of rice plant breeding. To date M-208 and M-210 are the only blast resistant varieties in California. Relative levels of stem rot resistance are given in the Agronomy Fact Sheets, and all fall within a fairly narrow range. Efforts are continuing to try improve resistance to stem rot and blast. Resistant lines are being used but the problem continues to be in recovering good agronomic characteristics.

Characteristics of Varieties

UC Cooperative Extension produces Agronomy Fact Sheets annually. The brochure "Characteristics of Public California Rice Varieties" gives a comparison of RES varieties in production. There are individual brochures for varieties that are prepared when they are released as well.

Table 6. Relative ranking of RES rice varieties for cold temperature sterility tolerance. The + sign indicates better tolerance for the group.

Low	Fair	Good	Excellent
Calmati 202 Calaroma 201+ M-401 A-202+	M-205 M-209 L-206+ L-207+ L-208+	S-102 S-202 M-206+ M-105+ M-210 M-211 Calmochi 203 Calhikari 201- Calhikari 202- Calhikari 203 Koshihikari- Akitakomachi	Calmochi 101

The brochures can be found online on the Rice Experiment Station Website (www.crrf.org) under the publications tab.

Management of Rice Varieties

Planting Date

Suggested planting dates for public varieties are given in Table 7. These suggestions assume average weather conditions will prevail. Within the preferred planting date range the variety should perform well if other conditions are optimum. Planting outside these ranges increases risk of weather-related damage. Planting dates are not rigid and many growers accept the risk and successfully plant outside these ranges. They are meant only as a guideline. Warm areas in Table 7 refer to the Sacramento Valley north of Highway 20 and west of Highway 99. Cool areas include south of Highway 20 and east of Highway 99. Cold areas include south Natomas and Escalon areas.

Seeding Rate

Short stature rice varieties perform well at uniform densities of 10 to 20 vigorous plants per square foot. However, many rice fields have plant populations over 30 plants. Plant density can be quite variable and still produce optimum yield. For example, approximately 40 productive tillers per square foot, each giving 100 grains, will produce about 10,000 lbs/ac. The rice plant responds to different populations. Low density planting increases tillering, whereas high density reduces tillering so that the number of panicles per square foot remain fairly constant across a wide range of planting rates. In addition, the number of kernels per panicle also increases or decreases, depending on the density of the panicles. Modern rice fields are usually sown heavily to provide quick cover, weed competition and insurance against catastrophic stand loss. Research has shown that seeding rate, within a wide range, does not dramatically affect yield, assuming normal growing conditions. At all sowing rates, the number of seeds is much higher than needed for healthy stands if all the seeds made strong seedlings. However, the consequence of too dense planting is primarily cost although some data suggests that stem rot severity may increase in dense stands. While seed cost remains low in California, growers may continue to use high seed rates without great penalty.

Nitrogen Rates for Different Varieties

Varieties differ in their nitrogen (N) requirements, particularly when comparing short stature Calrose and short grain types to taller premium short and medium grain types, and certain proprietary tall varieties, such as Kokuhorose. The yield of grain + straw (biological yield) is similar for tall and short varieties. However, with short varieties, more of the biological yield is grain, due to more efficient partitioning of plant energy (photosynthates). In addition, they do not lodge as easily under high N fertility. Both higher efficiency and less lodging result in higher yield than tall varieties. Recent field trials have demonstrated small differences in N requirements among common short stature varieties. Nitrogen rate fertilization testing of new releases has not been a research priority in the decades since the shift to semidwarf varieties. Over fertilization increases the risk of lodging, disease, low temperature sterility, and is inefficient economically. Lower rates of N are used in the premium quality short grains or specialty varieties because of lodging is characteristic of these types. Varieties with good lodging resistance (M205 and M-209) may receive slightly a higher application of N.

Table 7. Suggested planting date ranges for public varieties.

Variety by Maturity Group	Preferred Date Range	Optimum	Comments
Very Early			
S-102	May 1 - May 25	May 10	Avoid planting early in warm areas with all early varieties. Advance all dates by 5- to 10-days in cool areas. CM-203 is early to flower but slow to fill grain.
Calmochi-101	May 1 - May 20	May 5	
Calmochi-203	May 1 - May 20	May 5	
Early			
M-206	April 20 - May 25	May 5 - 10	Adapted to most areas.
M-209	April 20 - May 25	May 5 - 10	Best used in warm areas.
M-210	April 20 - May 25	May 5 - 10	Adapted to most areas and areas prone to blast.
M-211	April 20 - May 25	May 5 - 10	Best used in warm areas and harvested at higher moistures.
L-205	April 20 - May 20	May 5 - 10	Best used in warm areas.
L-207	April 20 - May 20	May 5 - 10	Best used in warm areas.
L-208	April 20 - May 20	May 5	Best used in warm areas.
Calhikari 201	April 25 - May 20	May 5	Avoid cool areas and excess nitrigen.
Calhikari 202	April 25 - May 20	May 5	Avoid cool areas and excess nitrigen.
Calihikari 203	April 25 - May 20	May 5	Avoid cold areas.
A-201	April 25 - May 20	May 5	Avoid cold areas.
A-202	April 25 - May 20	May 5	Avoid cold areas.
Calmati 202	April 25 - May 20	May 5	Avoid cold areas.
Akitakomachi	April 20 - May 20	May 5	Avoid cold areas.
Koshihikari	April 20 - May 20	May 5	Avoid cold areas.
Late			
M-401	April 20 - May 10	May 1	Avoid cold areas.

Variety and Harvest Considerations

Short and medium grain rice typically produce higher head rice yields (HRY) than does long grain rice. This is due to the more rounded, thicker, and harder kernels of medium grains. Additionally, earlier-maturing varieties may yield less head rice than later-maturing varieties, which is thought to be a result of grain filling processes.

Flowering patterns with the panicle vary somewhat between varieties. Anthesis (flower opening) begins at the top of the panicle and proceeds downward, a characteristic present in all California varieties and referred to as nonsynchronous flowering. The number of days required for flower opening ranges from 4 to 8 depending on the variety (Figure 1). The delay in anthesis from the top to the bottom also means that all flowers do not reach the stage of development that is sensitive to low temperature induced pollen sterility at the same time. Brief periods of low temperature result in sections of the panicle being "blank".

Correspondingly, the range of moisture content of individual kernels within a panicle can vary from 15 to 30 percent moisture content even though the average may be around 24 percent (Figure 2). Research has shown that the kernels at 15 percent moisture or less are likely to fissure when exposed to several hours of dew. Rice harvested at a moisture content of 18 percent may contain a large portion of individual kernels with moisture contents as low as 10 percent. There is inherent risk if standard harvesting procedures are adopted that uses an average moisture content of 18 percent as the time to harvest a given field.

The range of maturity (i.e. harvestable moisture content) can be further accentuated by within field variability in plant growth and development. Such variation is attributable to such

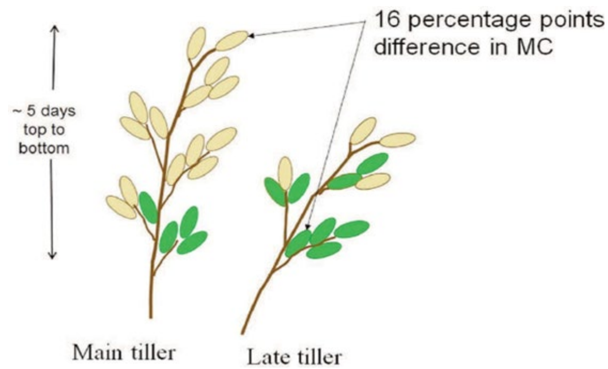


Figure 1. The moisture content of individual kernels varies due to the pattern of flowering within a panicle.

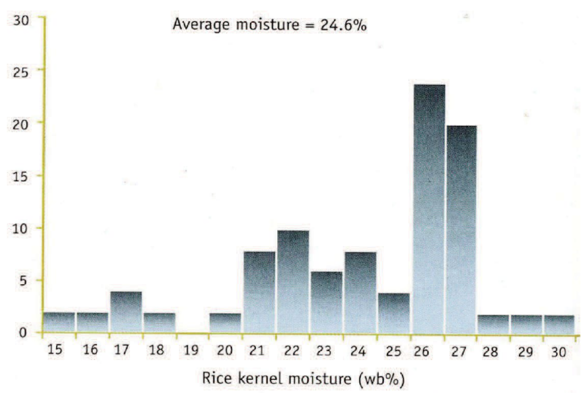


Figure 2. The range of kernel moisture content in a sample may be 15 perecnt or more

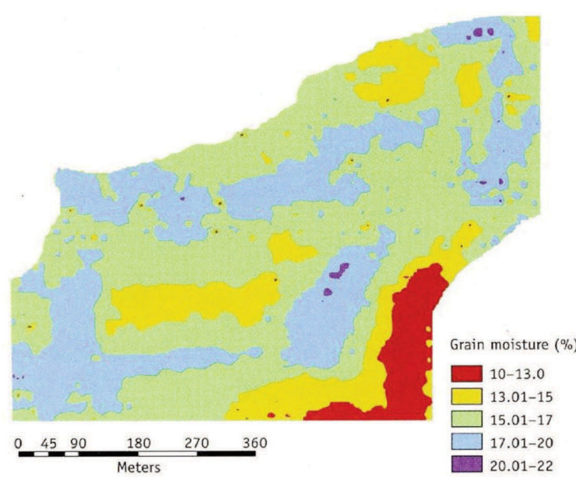


Figure 3. In field moisture content at harvest can vary widely due to management and soil type.

things as variable water depth, the uneven application of nitrogen fertilizer, water temperature, or soil type. Research showed that the moisture content in a California rice field can range from 10 to 22 percent under routine farm management practices (Figure 3). Without prior knowledge of specific field, a simple “nosing in” of the combine to check moisture content can be misleading.

Environmental Effects on Head Rice Yield

Rice harvested at low moisture content often does not produce low head rice quality if it has not been exposed to rehydrating conditions. During the dry north wind periods that commonly occur during harvest, rice can dry to quite low moisture contents and still produce good milling quality because dry conditions prevent dew formation.

However, when the north wind ceases and dew forming conditions return, head rice yield drops. In weather conditions with high dew point temperatures, rice can rehydrate to fairly high moisture contents, levels that normally associated with high head rice yield (Figure 4). Rice that rehydrates after a north wind can produce poor head rice quality even though it is harvested at the recommended moisture content. The history of rice moisture content is an important aspect of understanding the head rice yield produced in a particular field. Soil type also influences the time course of head rice loss. For example, a more rapid decline in head rice yield would be expected on light-textured soils exposed to dry, windy conditions.

In 2003 and 2004 at RES, harvest moisture content dropped 6.2 and 8.2 percentages points by the end of the windy period (Figure 5). During the north wind head rice yield declined by over 8 points in both years. Interestingly, growers’ return per acre decreased by only $0.08 and $0.17 per cwt in 2003 and 2004, respectively (Table 8). During the dry weather, reduced drying costs offset most of the head rice yield loss. Typically, the west side of the Sacramento Valley experiences more north wind days than areas on the east side (Figure 6). The number of windy days during harvest ranges from a low of 1.0 around Nicolaus to around 4 near Orland.

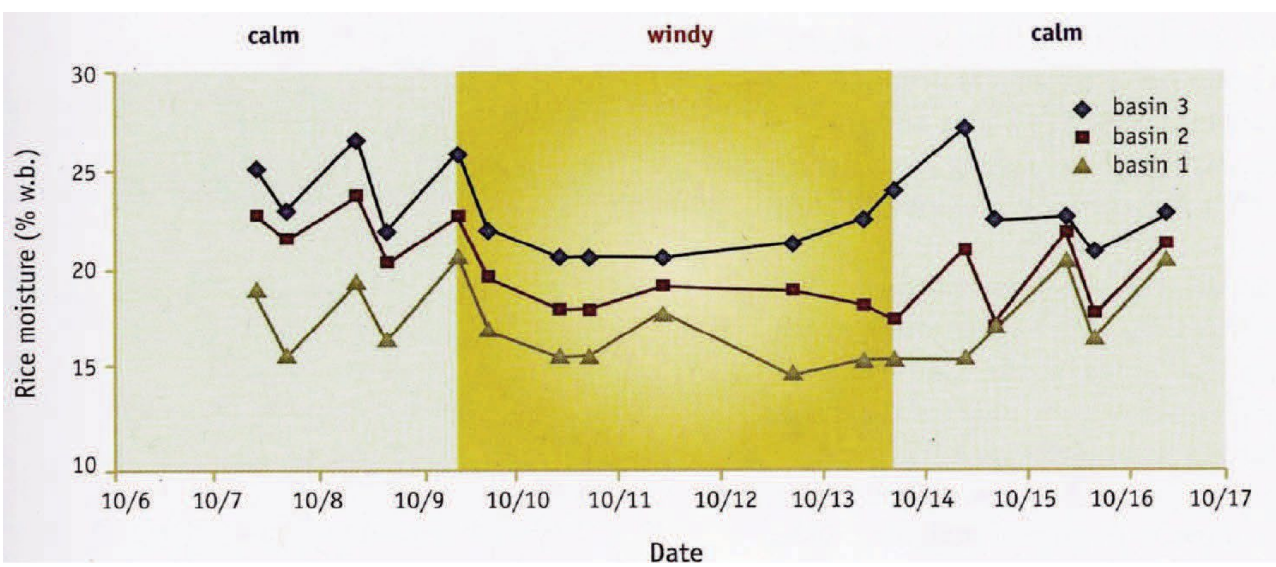


Figure 4 . Diurnal fluctuation in rice grain moisture before, during, and after a north wind period.

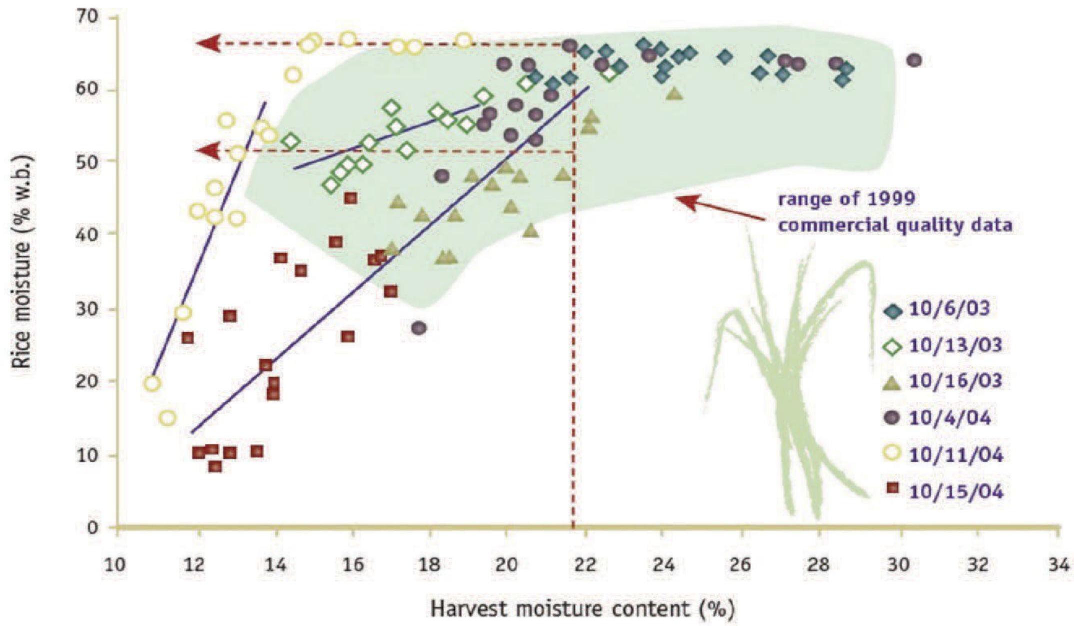


Figure 5. Head rice yield as related to harvest moisture content before, during, and after a dry north wind period in 2003 and 2004, Biggs, CA.

Table 8 . Rice quality and value before, during, and after a dry north wind period in 2003 and 2004 for M-202, Biggs, CA.

Harvest date		Moisture content (%)	Head Rice yield (%)	Grower Return ($/cwt)
2003	Oct. 6	24.3	63.8	5.63
	Oct. 13	18.1	55.6	5.55
	Oct.16	19.6	45.8	5.01
2004	Oct. 4	22.8	58.2	5.46
	Oct. 11	14.6	49.7	5.29
	Oct. 15	14.3	25.3	4.04

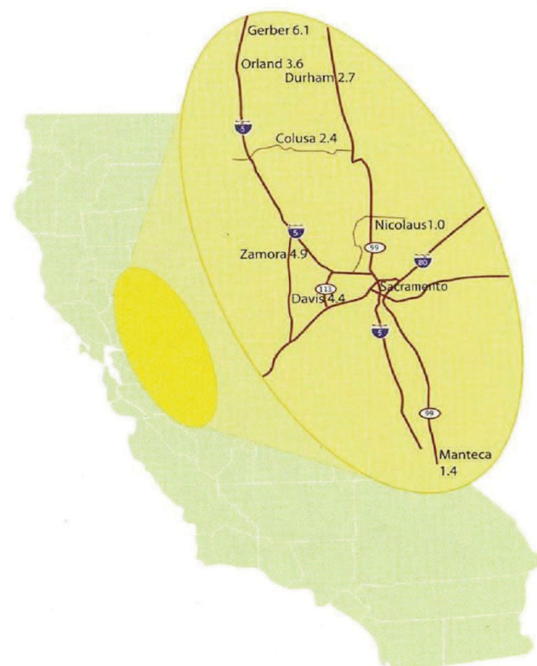


Figure 6 . Average number of north wind days at selected locations in the Sacramento Valley. Data based on 10-year averages.

Sampling for Harvest Moisture Content

Rice moisture content may fluctuate by 5 or more percentage points during a 24-hour period before and after a north wind period. When evaluating a field in preparation for harvest, it is important to sample at a consistent time of day, such as around noon. By doing so the moisture samples are comparable between days and provide a clearer picture of the dry down rate of the rice. Rice will generally dry down at a rate of about 0.5 percent per day, north wind and high temperatures notwithstanding. For best accuracy, use a harvester to cut the sample to provide the best representation of the true moisture content. Alternatively, one can hand strip heads from random locations. Be sure to take some of the sample from the lower, less-mature panicles. Avoid taking just the ripe grains from the topmost panicles; this will produce a sample with a lower moisture reading as compared to a combine cut sample.

Harvest Moisture Range by Variety

As a general rule most newer Calrose varieties (i.e. M-105, M-205, M-206, and M-210) with the exception of M-211 and M-209, can be harvested at a lower moisture content than the older varieties (i.e. M-104, M-202, and M-401). Head rice yields are fairly stable in the newer varieties down to a harvest moisture content of around 18 to 19%. M-209 and M-211 are not as stable as the other new varieties and harvest at low moisture should be avoided (Figure 7). Good milling returns below this moisture content are both variety and weather dependent. Fissuring of rice can be caused by repeated cycles of rice grains absorbing moisture during dew or rainfall events followed by quickly drying out again. These fissures are generally weaker and tend to break during the milling process. The drier the rice the more susceptible it is to fissure and results in lower milling yields. Rice varieties like M-211 and M-401 are more susceptible to fissuring and resulting in reduced milling at low harvest moistures (Figure 7). The potential for varieties to have reduced milling at lower moisture contents in some years but not others is often related to long periods of dew during dry down observed in those years. For example, during the 10-year period from 2003 to 2012, seven years had relatively few dew events of eight hours or longer (Table 9). During the 2011 harvest season there were only two in nights with extended periods of dew and none in 2012.

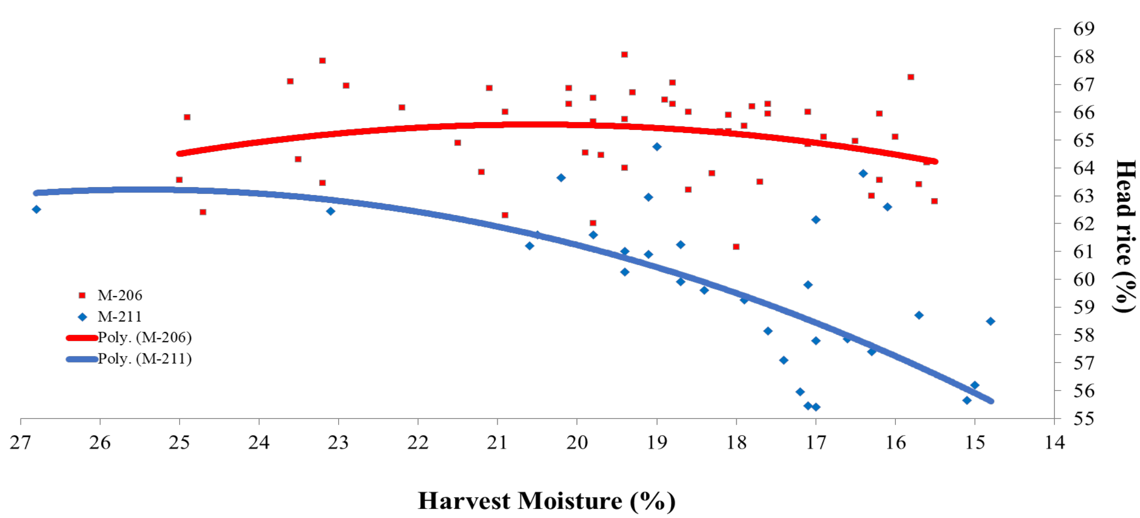


Figure 7. Effect of harvest grain moisture on head rice yield of M-211 and M-206.

Table 9.wwwW Total number of hours of dew at the Rice Experiment Station during harvest season , 2003 – 2012.

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
21-Sep	16	14	2							
22	16	14	4		11	2		2		
23	14	14			12					
24	11	14		2	8					
25	16	15			5				11	
26	16	11								
27	16	14	5	2	2					
28	11	12		5	13					
29	17	11			8					
30	16	14		3	6					
Oct.1	17	14		5	1					
2	16	14	3	6	2	9				
3	14	14	6	7	4	18			16	
4	13	12	2		6	10		4	4	
5	16	10			4	12				3
6	16	14		13	2	11		3		5
7	15	8		11	4	4				
8	16	10							1	
9	14				10		1		6	
10	1				13				4	
11	12			2	16		2			4
12	15			1	16		3			2
13	3	5		4	12		14			
14	15	8	2	8	12		7			3
15	16		8	10	17	2	12			
16	16			5	16	3			3	
17					5	2	10	8		
18				1	5		9	9		
19			8		13	6	9	8	6	
20			8			4			4	4
21							8	1		6
22					7		11	3		
23					7	1		4		

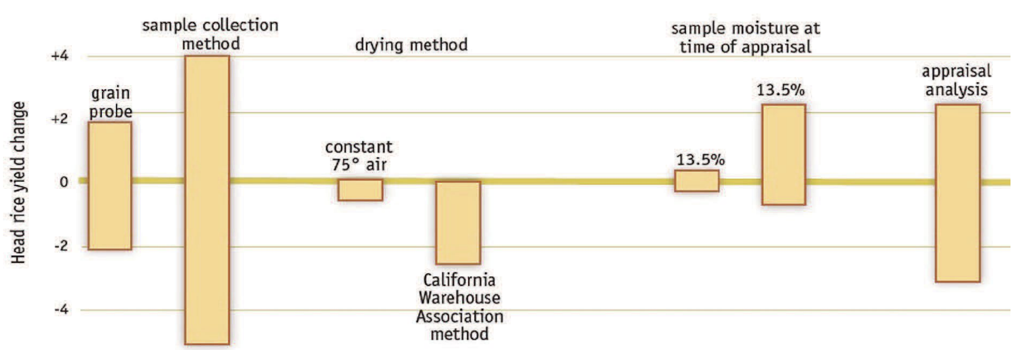


Figure 8. Variability and error in head rice yield results associated with appraisal sample collection, sample drying method, and sample analysis.

However, there were 7 continuous days of heavy dew during peak harvest in 2007.

Reducing Variability in Quality Appraisal Samples

- Variability and error in appraisal samples can be minimized by:
- collecting a representative sample; do not use a single catch can sample,
- drying samples with room temperature air to maximize head rice quality,
- drying samples to the same moisture content, because lower moisture samples have slightly, higher head rice quality than samples at 14 percent moisture content,
- using a standard multi-sample vacuum probe and a splitter to obtain the needed amount.

Analysis of replicated head rice samples appraisals by the CDFA showed that results fall within a range of 4.8 percent (± 2.4 percentage points). Variability was greater when the samples were appraised within a few days of drying but did not change after longer periods of storage (Figure 8).

Sample Drying

Air temperature used for sample drying can affect head rice quality. Maximum quality is achieved by using air at a constant room temperature of 75°F or lower (Figure 8). If the air is heated, the rice should be exposed to warm air only periodically and allowed to temper between exposures. For example, the California Warehouse Association recommends heated air at 100°F followed by a 4-hour tempering before the next 30-minute exposure. This procedure produces head rice yields about 2.5 percentage points lower than the room temperature air method.

Sample Moisture

Sample moisture content at milling appraisal affects head rice yield. For example, medium grain rice gains about 2 percentage points of head rice when the sample moisture drops from 13.5 to 12 percent. Short grain rice is less affected by sample moisture. In contrast, long grain rice may have a 6-point spread over this range of grain moisture content.

Rice Certification Law

California's complex market and variety situation requires procedures to ensure that different types of rice do not get mixed. Transgenic varieties with unique production and quality traits are not currently grown commercially in California. While biotechnology has enormous potential to create rice varieties with a wide variety of nutritional, medicinal and industrial uses, it is important to prevent commingling with other, similar looking varieties that are not transgenic. Processors are demanding assurances of purity in response to the consumer reaction to transgenic crops, particularly in export markets. Hence, the California rice industry sponsored the California Rice Certification Act of 2000 to ensure consistently high quality of California rice, maintain consumer confidence, and enhance and protect California's reputation as a provider of high-quality rice.

The Rice Certification Act of 2000 (Assembly Bulletin 2622) was signed into law on September 22, 2000 and its provisions went to effect in the 2003 crop year. This legislation contains both mandatory and voluntary identity preservation (IP) components allowing for the certification of any verifiable attribute of rice. The California Rice Commission (CRC) recognized that "There is a growing need to maintain the identity of various types of rice to satisfy increasing consumer demand for specialty rice varieties. This demand requires providing the industry with the ability to establish the terms and conditions for the production and handling of rice in order to minimize the potential for the commingling of various types of rice, and in order to prevent commingling where reconditioning is infeasible or impossible." All rice varieties for commercial production in California possessing "traits of commercial significance" will be required by statute to be produced within an IP certification system. The cost of the mandatory program will be borne by the growers of the specialty rice seed and grain. The CRC is empowered to collect fees, receive and investigate complaints, provide notice of action regarding alleged violations, and seek injunctive relief and other legal means to prevent violation of the Act. The Rice Certification Act is an example of a product-based IP system.

Any characteristics that may adversely affect the marketability of rice if mixtures occur are defined as having "commercial impact." Included are those that can be visually identified (e.g., bran color, grain shape, grain size, etc.) or that require specialized equipment to determine their identity or composition (e.g., lab cooking tests, taste panels, DNA or specific protein tests). For example, if rice with red bran were mixed with Calrose type medium grain, the mixture would have lower value, and hence be commercially impacted. All rice grown, sold or processed in California will be evaluated for characteristics of commercial impact, including rice brought into California for processing or sale, and IP protocols can be required for production, handling, transportation and storage of a given variety to prevent contamination of other rice. Several specialty varieties currently being grown and successfully segregated in California (e.g., sweet, scented, basmati, arborio, and colored bran varieties) may eventually be identified as having commercial impact. IP procedures for these varieties are already in place.

An advisory committee will recommend regulations to the Secretary of the California Department of Food and Agriculture pertaining to rice identified as having characteristics of commercial impact. The advisory committee will consider each variety separately and render a judgment, using science, economics and market experience, as to whether a given attribute has the potential for commercial impact. If it does, the committee will then establish terms and conditions of production, transportation, drying and storage to segregate the commodity from other rice types. These may include the method of seed application to prevent contamination of neighboring fields, buffer zones between fields, handling requirements to prevent mixtures, and other IP requirements.

An expressed intent of the Act is to encourage research and development of new types of rice. However, to prevent contamination and introduction of exotic pests, the committee must approve research protocols to ensure that the research will not have negative commercial impact. Researchers will be required to submit their research protocols, location of the research and acreage to the advisory committee and follow required procedures. Specific attributes of the rice for research do not have to be revealed. "Research" is limited to 50 or fewer acres of a single type of rice or rice that is intended for commercial use. The advisory committee also reviews procedures for rice brought into the state from other states or countries for research purposes. Current state or federal regulations for bringing such rice into California will apply unless the committee can justify that they are not acceptable. This Act does not apply to rice research conducted by the University of California except when such rice enters the channels of trade.

Separate from the work of the advisory committee, the Act allows the CRC to establish a voluntary program to certify any verifiable attribute of rice although it has not been used to any extent to date. Certified rice may be labeled with the words "This lot of rice certified (specified attribute) in accordance with the California Rice Certification Act of 2000." Certifiable attributes include any of those characteristics that can be verified, such as origin, scent, colored bran, mochi quality, variety, etc. One may certify, with the appropriate documentation and procedures, that a given lot of rice has or does not have a particular attribute. Hence, rice could be certified as non-transgenic or free of colored bran. Rices with and without commercial impact and seed, rough, and milled rice can all be certified. The Act does not certify rice as organic, although specific attributes of organic rice could be certified.

Regulations on Varieties and Rice Seed

Rice seed can only be introduced into the US through a USDA APHIS approved quarantine permitted greenhouse protocol. A similar quarantine protocol is also required to bring seed rice into California from the rice producing states in the southern US. All rice varieties grown in California must be reviewed by Rice Certification Committee of the California Rice Commission for determination of commercial impact (CI) and approved for commercial production.

Varieties are classified as;

1. No commercial impact (standard medium, short and long grains).
2. Tier 1 premium short grains, waxy or mochi, bold grains, or aromatics.
3. Tier 2 colored bran, or genetically modified (currently none in the US).
4. Tier 1&2 have requirement for identification, handling, planting and harvest to prevent contamination.
5. Testing for the presence of the transgenic "Liberty Link" event that contaminated southern US long grains will only continue on "foundation" seed for all commercial varieties.
6. Beginning in 2019 all commercial rice planting in California must use a class of certified seed, (see California Crop Improvement Association) or an approved seed program for varieties not able to be certified or proprietary (e.g. Quality Assurance (QA) seed).

Intellectual Property Protection

Since the unauthorized export of RES rice varieties to Spain in 1989, rice varieties released by the California Cooperative Rice Research Foundation's (CCRRF) Rice Experiment Station have been protected under the US Plant Variety Protection Act (Title 5 to be sold as a class of certified seed only and not for export) and since 2000 all releases have been protected with US Utility Patent. Use of these varieties for breeding or genetic research requires a material transfer agreement. Beginning in 2018 all seed producers of RES rice varieties will be licensed by CCRRF that includes registering with complying with the requirement of the California Crop Improvement Association and the California Department of Food Agriculture.

Appendix A
story of California Rice Varieties

The short grain varieties, predominantly Caloro and Colusa, occupied essentially all of California's production until the late 1950's. The state's production shifted to Calrose following its release in 1948. California's short grain acreage continued to decline due to the success of Calrose and its progeny that currently occupy more than 80 percent of the rice acreage. Long grain, waxy short grains, aromatic long grains have been developed but have never occupied a large percentage of California's rice production. A detailed review of California's rice history from it's beginnings to 1980 had been prepared by J. H. Willson (Willson 1979).

The accelerated rice breeding program initiated in 1969 began delivering new rice varieties to growers beginning in 1976. The successful development of semidwarf Calrose mediums grains was accomplished by Rugter et al. (1977) through induced breeding and Carnahan et al. (1978) through backcrossing. These founding semidwarfs formed the germplasm pools that have allowed the development and release of 19 improved medium and short grain California varieties. The medium grain decedents of Calrose were selected to have Calrose cooking and processing characteristics and are predominantly commercially commingled in drying, storage, and utilization.

The California breeding program began to develop adapted long grains from different parentage for California. Tseng et al. (1984) released the well adapted and productive L-202. L-202 has been a successful parent in the development of recent long grain varieties Cypress and Cocodrie developed in Louisiana. L-202 seed was also exported to Spain and renamed "Thaibonnet" and it has become the major long grain variety grown in that region. Additional long grains were released by Tseng et al. with improvements in agronomic, milling, and cooking quality; however, long grain production still occupies <5% of California's rice acreage.

California's traditional short grain acreage has remained small in recent years after losing a major market in Puerto Rico. Premium quality short grains, primarily the Japanese varieties Koshihikari and Akitakomachi, developed in the late 1990s in response to the opening of the Japanese market to rice. Satisfying the quality requirement for the Japanese market has proven to be a significant challenge at the commercial level with the Japanese varieties. Developing high yielding adapted varieties with premium quality characteristics has proven to be an even more difficult task. Premium short grain production seems to have become established in California, but the acreage is fluctuating being subject to trade and marketing issues.

California has an established premium quality medium grain production. These types cook similar to the Japanese premium short grains with a similar texture appear very shiny and remain soft after cooling. They trace their ancestry back to the proprietary tall late maturing medium grain varieties Terso and Kokuhorose. M-401, an induced semidwarf of Terso, is the predominant variety.

Specialty rice varieties occupy a small acreage. They include Calmochi-101, waxy short grain, aromatic long grains, Mediterranean bold grains, and colored bran. They are grown under contract and include proprietary lines and introductions.

The Calrose market type grown in California may include several medium grain varieties. M-206 has been the predominant variety produced in the state over the last several years. Table I contains a summary some of the major physicochemical characteristics of several Calrose medium grains. They have a low apparent amylose content and low gelatinization temperature. The kernel size and shape are identifiable features of these varieties. Cooking and processing characteristics including desirability for breakfast cereals are recognized in the marketplace but not well characterized in standard laboratory testing methods. Environmental factors like climate and temperature in the California rice production region also contribute to grain quality.

Traditional California short grains have low amylose and low gelatinization temperature. The kernels are relatively large and may have some chalkiness. This chalky spot or region being whiter than the surrounding endosperm and these short grain types were referred to as "pearl" rice. In addition to table rice these short grains like S-102 are often used in production puffed rice cakes. Table A-II also contains the physicochemical characteristics for premium quality short grains grown in California. These short grains have a smaller very translucent kernel and produce very high whole kernel milling yields. Koshihikari, a Japanese short grain variety released in the 1950's, is the established standard for Japanese premium quality. The breeding, production, and quality of Koshihikari have been recently reviewed by Iwate (2001). Other premium short grains grown in California include Akitakomachi, a very early maturing variety developed in Japan, and 3 California developed semidwarf varieties Calhikari-201, Calihikari-202, and Calihikari-203. Eating quality is considered one of the most important traits of rice in Japan and has been the focus of extensive research as well as evaluation of rice for use and sale in the marketplace. Near infra-red based "Japanese taste machines" that measure components like amylose, protein, moisture, K and Mg, and fatty acid content correlated with taste panel results are used to analyze samples and issue a taste score for commerce in Japan. A review of rice grain quality from a Japanese perspective is available from Matsuo et al. (1997).

Development of long grains for production in California faces both the agronomic challenge of cold tolerance and the need to achieve the milling, cooking, and processing properties found in long grains grown in the southern US. Breeding efforts have been directed toward developing adapted long grains that cooked firmer and less sticky because of the soft cooking tendency of California grown conventional long-grain rice. As part of this approach, L-205 was developed with the Newrex quality that is characterized by having 2 to 3% higher amylose content and a stronger viscogram profile than conventional long grains. Because of these characteristics, Newrex types cook dry and exhibit minimal solids loss during the cooking process and are regarded as a superior type for canned soups, parboiling, and noodle making. Considerable improvement in whole kernel milling yields have also been achieved in the more recent California long grains. Table A-III contain quality characteristics for California long grains.

Specialty types include the waxy short grains Calmochi-101 and Calmochi-203; the long grain aromatics A-201and A-202; and the aromatic basmati type Calmati-202; and the jasmine type Calaroma-201. These special purpose varieties are usually grown under contract and some of their physicochemical characteristics can be found in Table A-I, A-II, A-III. There has been a significant increase in interest in these and other specialty types including the Jasmine, basmati, Mediterranean varieties like Arborio, and colored bran types in recent years in both the public and private sector. Some common features of these types are that they are generally ethnic foods, have low agronomic productivity, may present milling or handling challenges, and a lack of established quality evaluation criteria that make them a particularly challenging target for rice breeding or marketing.

Table A-I. Characteristics of California medium grain varieties.

Variety	Type	AC[1]	% Protein[2]		Gel Temp.[3]	Brown Rice Kernels[4]			
		%	Brown	Milled	High/Int/Low	Length	Width	L/W	Weight
M-104	Calrose	17.8	7.8	7.0	Low	6.3	2.8	2.3	24.1
M-202	Calrose	16.5	7.5	6.6	Low	6.1	2.9	2.1	23.9
M-205	Calrose	17.8	7.1	6.3	Low	6.4	2.7	2.3	24.4
M-206	Calrose	17.7	6.7	5.9	Low	6.2	2.8	2.2	24.6
M-208	Calrose	17.3	6.2	5.6	Low	6.6	2.9	2.3	24.9
M-209	Calrose	17.1	6.8	6.0	Low	6.23	2.8	2.2	24.6
M-210	Calrose	15.7	7.3	6.4	Low	6.31	2.8	2.2	23.1
M-211	Calrose	14.1	5.8	5.1	Low	6.33	3.0	2.1	26.1
M-401	Premium	18.1	5.9	5.2	Low	6.4	2.8	2.3	25.6

[1]Apparent amylose content. [2]N%x 5.95 dry basis. [3]Gelatinization temperature type: High, Intermediate, low
[4]Kernel dimensions in mm, L/W, length width ratio, and 1000 kernel weight in g.

Table A-II. Characteristics of California Short Grain Varieties.

Variety	Type	AC[1]	% Protein[2]		Gel Temp.[3]	Brown Rice Kernels[4]			
		%	Brown	Milled	High/Int/Low	Length	Width	L/W	Weight
Akitakomachi	Premium	17	7.2	6.4	Low	5.3	2.9	1.9	21.3
Koshihikari	Premium	17.6	6.5	5.5	Low	5.1	2.9	1.8	20
Calhikari-201	Premium	18.2	6.7	5.7	Low	5.1	3.0	1.7	20.3
Calhikari-202	Premium	16.9	6.2	5.7	Low	4.9	2.9	1.7	19.2
Calhikari-203	Premium	19.8	6.5	5.8	Low	4.9	2.9	1.7	19.2
S-102	Short	18.6	7.0	6.4	Low	5.8	3.2	1.8	27.5
S-202	Short	14.4	8.2	7.5	Low	6.3	3.3	1.9	25.2
Calmochi-101	Glutinous	0.1	6.8	6.1	Low	5.3	2.9	1.8	22.7
Calmochi-203	Glutinous	0.0	6.2	5.7	Low	5.4	3.2	1.7	24.5
Calamylow-201	Low amylose	6.3	6.5	5.7	Low	4.8	2.9	1.6	18.5

[1]Apparent amylose content. [2]N%x 5.95 dry basis. [3]Gelatinization temperature type: High, Intermediate, low
[4]Kernel dimensions in mm, L/W, length width ratio, and 1000 kernel weight in g.

Table A-III. Characteristics of California Long Grain Varieties.

Variety	Type	AC[1]	% Protein[2]		Gel Temp.[3]	Brown Rice Kernels[4]			
		%	Brown	Milled	High/Int/Low	Length	Width	L/W	Weight
L-205	Newrex	24.1	8	7.7	Intermediate	7.3	2.3	3.2	21.7
L-206	Long	23.1	6.9	6.2	Intermediate	8.0	2.2	3.6	23.2
L-207	Long	24.3	6.5	5.6	Intermediate	8.0	2.2	3.6	23.5
L-208	Long	23.9	6.4	5.4	Intermediate	7.8	2.2	3.6	22.5
A-201	Aromatic	23.7	8.0	7.7	Intermediate	7.9	2.2	3.6	23.0
A-202	Aromatic	22.4	6.6	5.6	Intermediate	7.9	2.4	3.3	24.7
Calmati-202	Basmati	24.8	8.0	7.5	Intermediate	8.0	2.1	3.9	22.2
Calaroma-201	Jasmine	15.7	6.4	5.8	Low	8.0	2.1	3.7	22.8

[1]Apparent amylose content. [2]N%x 5.95 dry basis. [3]Gelatinization temperature type: High, Intermediate, low
[4]Kernel dimensions in mm, L/W, length width ratio, and 1000 kernel weight in g.

Table A-IV. *Grain shape, year of release, maturity category and parentage of California public rice varieties.**

Cultivar	Grain	Year	Maturity	Parents
Caloro	S	1917	L	Early Wateribune
Colusa	S	1921	L	Chinese
Calrose	M	1948	L	Caloro/Calady*2
CS-M3	M	1971	L	C6 Smooth/Calrose
CS-S4	S	1972	L	Caloro/Smooth No. 3//Caloro/3/Caloro
M5	M	1975	L	CS-M3 natural mutation selections
S6	S	1975	E	Colusa/CS-M3
Calrose 76	M	1976	L	Induced mutant of Calrose
M7	M	1978	L	Calrose 76/CS-M3
M9	M	1978	E	IR-8/CS-M3*2//10-7*2
Calmochi-201	S	1979	E	Induced mutant of S6
L-201	L	1979	E	CI 9701/3/R134-1/R48-257//R50-11
M-101	M	1979	VE	CS-M3/Calrose 76//D31
M-301	M	1980	M	Calrose 76/CS-M3//M5
S-201	S	1980	E	Calrose 76/CS-M3//S6
Calmochi-202	S	1981	E	R57-362-4/D51//Calmochi-201
M-302	M	1981	M	Calrose 76/CM-M3//M5
M-401	M	1981	L	Induced mutant of Terso
M-201	M	1982	E	Terso/3/IR-8/CS-M3*2//Kokuhorose
L-202	L	1984	E	723761/ 7232278//L-201
Calmochi-101	S	1985	VE	Tatsumi mochi//M7/S6
M-202	M	1985	E	IR-8/CS-M3*2//10-7*2/3/M-101
A-301	L	1987	M	IR-22/R48-257//5915C35-8/3/Della
M-102	M	1987	VE	M-201/M-101
M-203	M	1988	E	Induced mutant of M-401
S-101	S	1988	VE	0-6526//R26/Toyohikari/3/M7/74-Y-89//SD7/73-221
M-103	M	1989	VE	SD7//Earlirose/Reimei/3/M-302
S-301	S	1990	M	SD7/73-221/M7P-1/3/M7P-5
L-203	L	1991	E	L-202/83-Y-45
M-204	M	1994	E	M-201/M7/3/M7//ESD7-3/Kokuhorose
A-201	L	1996	E	L-202/PI 457920//L-202
L-204	L	1996	E	Lemont//Tainung-sen-yu 2414/L-201
S-102	S	1996	VE	Calpearl/Calmochi-101//Calpearl
Calhikari-201	SPQ	1999	E	Koshihikari/(Koshihikari/S-101)*2
Calmati-201	LB	1999	E	82-Y-51/83-Y-45//L202/PI373938/3/83-Y-45/PI457918
L-205	L	1999	E	M7/R660//M7/R1588/3/82-Y-52/4/Rexmont/83-Y-45
M-402	M	1999	L	Kokuhorose/4/M7*2/M9//M7/3/M-401/Kokuhorose
M-104	M	2000	VE	M-103/6/F1(M-102/4/M-201/3/M7/M9//M7/5/M-103)
M-205	M	2000	E	M-201/M7//M-201/3/M-202
M-206	M	2000	E	S-301/M204
M-208	M	2006	E	M-401/3/Mercury//Mercury/Koshihikari/4/M-204
Calmati-202	LB	2006	E	A-201/9543483 (Calmati-201 sib)
L-206	L	2006	E	L-203/4/Lemont/3/R1588/L-201//R1588/Labelle
Calamylow-201	SLA	2006	E	Induce mutant of Calhikari-201
M-105	M	2011	VE	M-206/M-104
Calhikari-202	SPQ	2012	E	Koshihikari*2/S-101//Koshihikari/S-101/3/Hitomebore
A-202	LA	2014	E	03Y551(94Y39//JSMN85 /Della)/02Y045(L204/95Y442)
M-209	M	2015	E	M-205/5/M-201/M7//M-201/3/M-202/4/M-204
Calmochi-203	SWX	2015	E	M7//D51/R57/3/M-302/4/CM-101(87Y259)/5/CM101/6/NFD108/7 / M102/CM101/3/AKENO//CP/CM101
L-207	L	2016	E	F1R32425(05P3310(PI614958)/02Y516)/99Y529
M-210	M	2018	E	M-206*8/97-Y-315vE
Calaroma-201	LJ	2018	E	00KDMX3-3/4/90Y563/3/L202/QUIZHAW/L2O2/5/JES
S-202	S	2019	E	84Y254//M-102/85Y13/3/DENGYU1/88Y013/4/84Y254 /85Y013//Calpearl/ CM-101/3/S-102
M-211	M	2020	E	M-206/4/M203/K397//M205/3/87P1309//M401/M203
L-208	L	2020	E	05P3310/02Y516//99Y529
Calhikari-203	SPQ	2023	E	10Y2049/04Y177/4/Kosh*2/S-101//Kosh/S-101/3/Hitome

Market type: L= long; M=medium; S=short; SPQ=premium short; SLA=low amylose short; SWX=waxy ; LA=Aromatic long; LB=Basmati; LJ=Jasmine

Maturity: VE=very early; E=early; M=medium/intermediate; L=late

PLANTING & STAND ESTABLISHMENT

Tillage

Tillage contributes significantly to rice production costs, time, and effort, including equipment investment and operating costs (Espino et al., 2021). So, it is important to have a good grasp of the objectives of tillage, which include,

- Drying of soil
- Loosening of the soil to allow for subsequent land smoothing operations and application of preplant fertilizer
- Forming a uniform seedbed free of large clods
- Destruction of growing weeds
- Aeration to hasten decomposition of residue
- Release of nutrients in organic matter
- Burial of crop residue to reduce disease inoculum and keep floating residue from accumulating and suppressing crop growth

Typical tillage involves one or two passes with a chisel plow, one pass with a stubble disc, and another pass with a finish disc. Sometimes soil will be very cloddy and require extra work to break down large clods. Fields should be laser leveled with a dual GPS scraper, as necessary. On non-leveling years, a triplane is used to maintain the ground level. After discing and leveling, a corrugated roller is used prior to flooding and planting. The final seedbed in a rice field does not have to be as fine as for direct seeding of row crops, and by comparison is quite coarse. More important is the uniformity of the surface so that there are no off-grade high and low spots and large clods do not protrude from the water after flooding.

Chiselplow. Many growers rely on heavy chiselplows as the first ground breaking operation in the spring. The chisels are usually mounted on a spring or have a coil configuration which helps lift the soil. Some are rigid chisels and penetrate slightly deeper and produce a more cloddy surface. Chisels have a lifting action and the objective is to loosen, aerate and dry the ground. Drying is important to facilitate subsequent ground work, to allow air to get in pore spaces, and to avoid destruction of soil structure which may be damaged by heavy equipment working on wet soils. Subsequent operations depend on dry soil, so it is important to allow adequate time for drying before proceed-

Figure 1. Fall chisel plow operation incorporating rice straw (left), and typical chisel shank (right).

Figure 2. Heavy-duty single offset disc, called a stubble disc, for use in fall straw incorporation (left). Lighter versions with smaller blades are used for spring tillage. On the right, a schematic overview of a typical single offset disc.

ing. A chisel shank and chiselplow operation are shown in Figure 1.

Discs. Heavy single offset discs are usually used after chiseling to work deeper and mix crop residue with the soil. Such discs have a rigid mainframe that supports two gangs of disc blades that operate at an angle to the direction of travel so that they penetrate the soil and roll it (Figure 2).

The front gang is set to cut in the opposite direction of the rear gang. The round blades may vary from 28" to 32," and may have smooth or scalloped edges. This operation is important to continue drying the soil, facilitate soil contact for residue decomposition and to prevent residue from rising to the surface where it may be a problem.

One or two passes each with a stubble disc and finishing disc are usually necessary. These operations also destroy growing weeds to prevent them from getting a head start on the crop. As air enters the pore spaces, organic matter begins to decay more rapidly, which results in conversion of nutrients from their organic forms to mineral forms, called mineralization. Greater availability of nutrients, particularly nitrogen, is an important benefit of tillage. Rice soils which never dry and aerate are generally less fertile.

Plowing

Deep tillage with a moldboard plow (Figure 3) or disc plow is less commonly used because of higher cost and disturbance of the smoothness of the field. However, plows may be useful because they invert the soil and can completely bury residues and weed seeds. They also, however, leave the ground very rough and possibly out of level. Since they cut deeply, plows are not appropriate in fields with shallow surface layers or cacareous subsoils, where they may bring soil chemistry problems to the surface. Plowing is more common in row crop areas, but some growers may plow about every third year in rice-only areas. Over the long term, deeper tillage will deepen the plow layer and should benefit soil fertility and root growth.

Figure 3. Typical two-way moldboard plow.

Depth of Tillage

Tillage depth should be consistent with the overall objectives of land preparation, drying and loosening the soil, and burying residue. Typically, 6” to 8” is sufficient. Some shallow soils limit tillage depth while others have deeper topsoil. Rice roots are shallow and do not respond to deep tillage as some deep-rooted crops do. The supply of nutrients is more important than depth. Deeper soils tend to have a thicker layer of nutrient rich soil, so rice on such soils often performs better compared to performance on shallow soils.

Spring Residue Management

Most straw management work is done in the fall, but despite best efforts, there is often abundant straw in the typical spring seedbed, which must be managed. Good practices in the fall will help spring operations, particularly chopping, which assists with incorporation and decomposition. Uncovered straw will float and drift into corners, edges or high spots, reduce stand, and increase disease, so a goal of spring work is to cover as much straw as possible. Chisels and discs will partially cover straw but have the tendency to also bring some back up again. The only remedy is to do extra ground work if there is abundant straw still on the surface. It is probably not economical to continue to work the ground past one or two extra operations.

Land Planing

A land plane is simply a long, rigid rectangular (four wheels) or ‘A’ frame (three wheels) in the center of which a scrapper blade or bucket is set (Figure 4). As the operator pulls the plane across the field, soil fills the bucket and simultaneously spills forward out of the bucket, creating a churning action that breaks up the clods, improves their uniformity and fills in ruts from previous groundwork. The depth of cut of the scraper blade can be adjusted, but it typically cuts no more than an inch deep into the tilled soil. The smooth surface is ideal for fertilizer application because it facilitates uniform depth of placement. Typically, one pass with a plane is sufficient; although, some growers make a second pass at an angle to the first. Landplaning is a relatively slow and expensive operation. Planing only smooths the surface; it is not a substitute for leveling. However, land planing is important for maintaining the integrity of the leveling job and to fine tune it for the current season. With prevailing shallow water management, off grade spots and large clods represent potential weedy sites. Planes do not work well in wet soil since the soil must flow freely in and out of the bucket. Land planing packs the soil, and if it is moist, will stimulate early weed growth. Therefore, once the field is planed, subsequent operations must be done promptly. Preplant fertilizer is usually applied to the smoothed soil; although, some growers plane after fertilizer application.

Figure 4. Typical three wheel land plane.

Corrugated Rollers

Heavy corrugated rollers are commonly used as a final field operation to eliminate large clods and pack the soil, providing a more uniform surface compared to a disced seedbed (Figure 5). To some extent, the corrugations help keep seed evenly distributed. Seed planted in corrugated fields often settles into the bottom of the grooves, resembling drill seeded rice. Corrugated rollers are 15’ to 24’ wide and have ridges at 6” to 7” spacing around their circumference. This tool is consistent with shallow water management because large clods are either broken or pressed down in the seedbed. Liquid and dry fertilizer and herbicide applicators may be attached to the roller frame and allow growers to perform simultaneous operations. Rollers require dry soil for good operation. Moist soil will cake on the surface, and clean corrugations will not form in the soil.

Corrugated rollers are fairly cheap to operate unless additional operations are combined with them. These combined operations require additional controls in the tractor cab, and a skilled operator is important.

Alternative Tillage Systems

Examples of alternative systems include dry seeding, stale seedbed, and no-till. Dry seeding involves sowing unsoaked seed on the soil surface and shallowly covering it with soil using a corrugated roller or light harrow, or drill seeding as one would plant wheat. The seedbed in a drill-seeded field is prepared as for water seeding, except the goal is a finer, well-packed seedbed to precisely control seed depth. A smooth roller may benefit this operation. The stale seedbed method involves limited tillage in the fall or spring to help germinate weeds and provide alternative weed control strategies. There is more information about drill seeding and stale seedbed systems later in this chapter. Rarely, growers may drill directly into the field without otherwise tilling the soil, called ‘no-till.’ Growers use no-till to reduce tillage costs, get an earlier start and discourage weeds, which tend to be less severe when the soil is not disturbed. A heavier, specialized drill is usually needed to cut through residue and packed soil. This is rarely done because there is often some damage to the soil surface from harvesting or spraying equipment that must be repaired.

Seed Soaking

Most California rice fields are sown with soaked, pregerminated rice seeds. Soaking accomplishes two purposes. First, water replaces air inside the seed coat so that the seed is less buoyant and sinks more readily, helping to keep the seed from drifting and ‘bunching.’ Second, germination processes are started so that the seed will have a headstart when it is planted compared to dry-sown seed. A flooded rice field is an inhospitable environment, habitat for numerous pests and competitors of rice seed. During soaking, vital physiological processes begin, which are precursors to growth. Allowing the most vulnerable period of a seed’s first hours of growth to take place in the relatively benign environment of a soaking tank helps assure its success in the field. Dry seeds sown into water tend to be more

Figure 5. Corrugated roller (left) and closeup of roller surface showing ridges that form corrugations (right).

susceptible to midge, shrimp and disease attack. Research has shown that the duration of soaking is roughly equivalent, in terms of plant growth, to sowing earlier by the same amount of time as the soaking (Grigarick et al. 1984).

Pregerminated seeds sprout quicker and anchor their roots into the soil, reducing the time of exposure to the different pest and environmental problems that affect early seedling development.

Water absorption and growth.

A rice seed absorbs moisture rapidly once it is placed in water and continues to increase its water content well beyond the time when it is ready for sowing (Figure 6). Early growth processes were observed at a steady 68ºF, somewhat cooler than the typical environment of a rice soaking tank (Williams, unpublished data). Water was absorbed rapidly during the first three

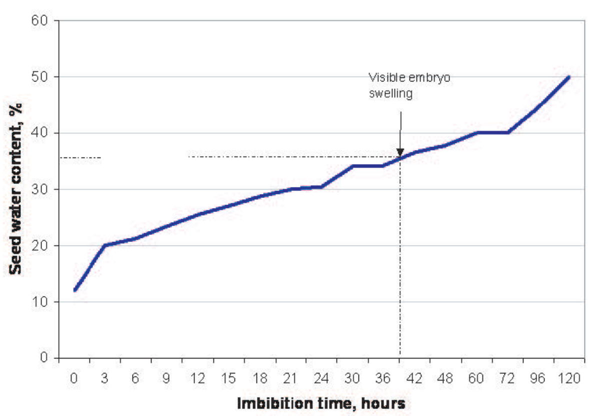


Figure 6. Rice seed water uptake at 68ºF. Visible embryo swelling first seen at 42 hours at seed water content of 36.5%, dry weight basis. (Williams unpublished data)

hours, and then the rate of absorption declined to a relatively steady rate thereafter. At 12 hours after imbibition, the seeds had a 'hydrated' look and moisture content over 25%, about doubling water content. The first visual sign of growth was swelling of the embryo and a change to a translucent character at 42 hours and moisture content of 36.5%. By 48 hours, the embryo was just beginning to split the hull, and by 60 hours the first shoots were breaking through.

Soaking

Soaking is typically done in steel bins (Figure 7), with dimensions of approximately 48" wide, 48" deep, and 51" high, and a volume of 62 to 64 cubic feet. Sodium hypochlorite or a similar disinfectant is usually added to the soaking water to help control bakanae, a fungal disease that causes seedling elongation and yellowing. (For more information on bakanae control measures, including soaking, see the Diseases chapter.) The bins have indentations at the bottom for forklifts to lift, invert and dump the seed into trucks. A full bin will hold up to about 2300 lbs of dry seed, and contains about 230 gallons of water (seed just covered). In other words, ten gallons of water is required for every hundredweight (cwt) seed, plus an additional gallon/cwt as the seed absorbs water. The exact amount of water for initial filling depends on the grain type, with medium grains requiring slightly more water than long grains. The bins are usually fitted with drains so that water can be drained.

Some seed soaking is also done in the same trucks that deliver the seed to the airstrip before

Figure 7. Typical rice seed soaking bins

planting. The advantage is reduced handling, no need for bins or forklifts and less labor. The disadvantage is that the large volume will generate more heat than small bins if seeding is delayed, and it is difficult to refill and cool the seed. Sprinklers are sometimes put on the trucks for cooling if seeding is delayed.

The metabolic activity of growth creates heat which will accumulate in the enclosed soaking bin. High outside air temperature will increase the rate of heat accumulation. As temperature rises, respiration rate increases, up to about 90ºF, and then starts to drop off. Oxygen levels also decline as the seed oxygen demand increases. If soaking proceeds too long, the combination of high, sub-lethal temperature and low oxygen will cause poor seedling vigor and delay in stand establishment. Loss of seedling vigor may lead to stand loss from pests and weather damage. Lethal temperatures for wet rice seeds have been reported from 104 to 113ºF.

Damaging temperatures can easily be reached if soaking is not done properly, and is regulated mainly by time of soaking and drainage. Recommended soaking guidelines are 24 hours in the soak water and 24 hours of draining, for a total pregermination time of 48 hours. Seed does not have to remain in the water for the entire duration of pregermination for early growth to begin. The seed should be sown promptly after 48 hours to avoid heat accumulation and oxygen depletion; however, some growers' practices vary significantly from these guidelines. There is some safety built into the guidelines, but problems with heat begin when 48 hours is greatly exceeded. When sowing is delayed by north wind or flooding delays, growers should attempt to cool the seed by refilling the soak tanks with fresh, cool water. Trucks with seed in them should be taken to a shady area, tarps removed and sprinklers put on top.

Adequate drainage is necessary to prepare the seed for sowing. During drainage, while pregermination continues, excess moisture drains away so the seed will more easily flow from the trucks and the aircraft spreaders. Poorly drained seed will stick together and resist flowing, resulting in poor seed distribution in the field.

Planting

Direct sowing requires soaked seed be flown directly onto the flooded field so that it comes to rest on the soil surface. It is important that the seed remain on the soil surface. Seed that is buried more than a centimeter in the soil will have low vigor or won't germinate because of inadequate oxygen. Rice seed needs a ready oxygen supply to sprout. Flood water replaces air in the soil and greatly reduces diffusion. Figure 8 shows how oxygen levels in the water and soil differ. Research by UC scientists and others showed that the oxygen level in a rice field drops to nearly zero within 6 to 10 hours of when a dry soil is flooded. In addition, the flood water reduces oxygen diffusion into the soil by a factor of over 10,000 times. (Patrick and Mikkelsen 1971).

The top centimeter of soil contains some oxygen which declines rapidly with depth. Burying seed severely reduces germination and emergence.

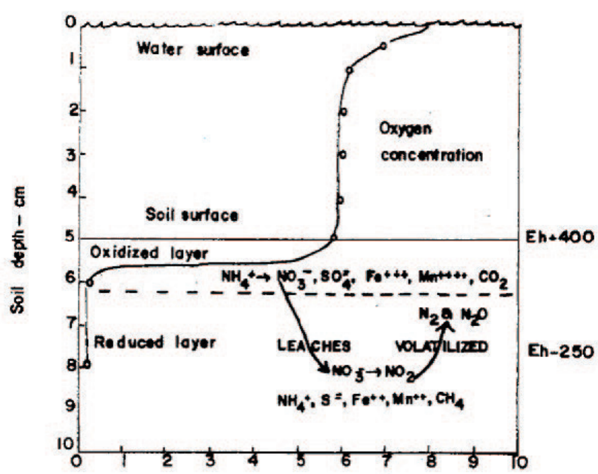


Figure 8. Oxygen levels in soil and water of a typical rice field. From: Plant Nutrient Behavior in Flooded Soils. (Patrick & Mikkelsen 1971)

Stand assessment

Minimum seedling population for maximum yield is dependent on many factors--sowing method, water management, planting date, variety, soil type and others. In 2015, a trial was conducted to determine optimal seed and plant density for maximum yield, using variety M.206 (Linquist, 2016). The results showed that plant density (plants/ft²) was about half of the seed density (Figure 9). In other words, only about half of the planted seeds germinated. Furthermore, maximum yields were achieved with about 25 plants/ft² (Figure 10). At half of that plant population (12.5 plants/ft²), yield potential declined to approximately 90%. While optimum seed and plant density may vary with different varieties and across years, these results provide guidance for stand assessment. UC Cooperative Extension has developed an online seeding rate calculator to assist with determining seeding rate based on variety and the desired stand density. The calculator is located at the UC Rice Online website.

Assessment of the stand soon after sowing is very important to ensure that pests (diseases, midges, shrimp) and burial have not wwreduced the stand to an unacceptable level. In cool weather, rice will germinate and grow slowly and less uniformly, and as temperatures warm the reverse is true. Optimum temperatures for germination and early seedling growth are in the range of 77 94ºF. Minimum temperature for germination is 54 56ºF, and maximum temperature is 104ºF. Seedling pests also respond to temperature, with diseases tending to be more damaging in cool weather, partially a result of poor growth and prolonged exposure of the rice.

Shrimp and midges, on the other hand, tend to be more severe during warm periods.

Early identification of insufficient stand is essential to successful reseeding. The longer the delay, the lower the success of replanting. Stand evaluation must be made within the field. A useful tool for looking at small plants is a sampling cylinder (Figure 11). Carefully push it slightly into the soil to avoid stirring up sediment, and observe the condition of seeds within the cylinder. By making it a known size, such as one square foot, one can make a count of healthy seedlings. Another version is a box fitted with a Plexiglas bottom. By pressing the box to the soil surface, seeds can be easily seen without mud obscuring them. Close examination of individual seedlings is necessary, so it is very helpful to have a hand lens. More information

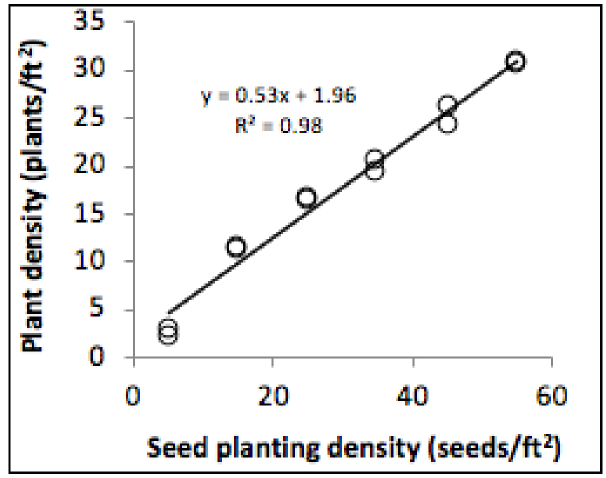


Figure 9. The relationship between seed density and plant density. Results are combined for the two planting dates, May 25 and June 1, and are for variety M.206.

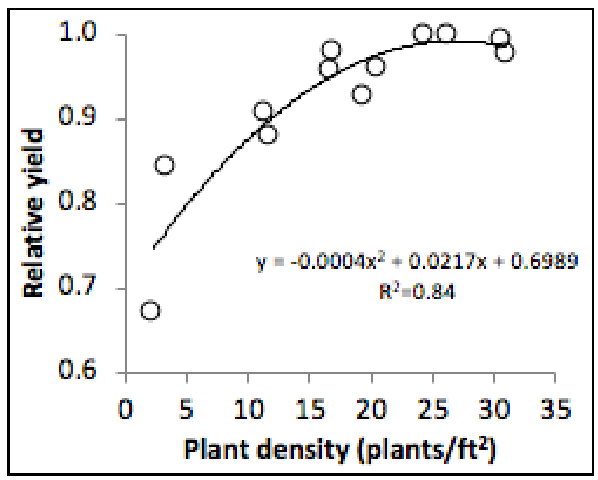


Figure 10. Relative yield versus plant density. Results are combined for the two planting dates, May 25 and June 1, and are for variety M.206.

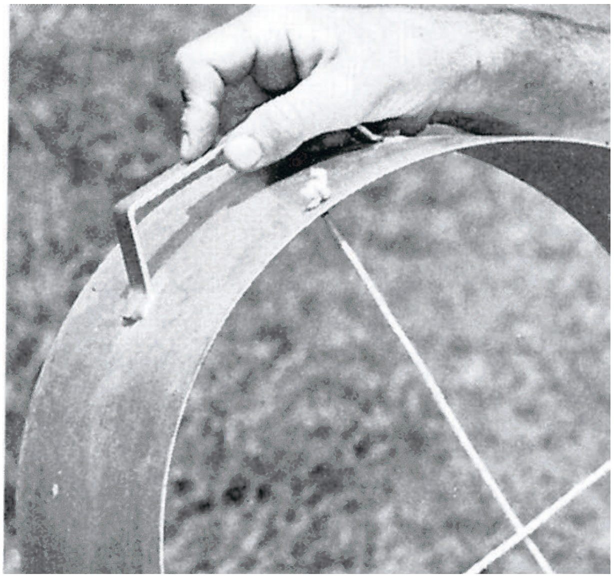


Figure 11. Sampling cylinder.

on stand establishment pests can be found in the sections on diseases and invertebrates.

Wind burial can reduce plant population, and bunching can leave large open areas, both of which may necessitate reseeding. Assessing a buried or bunched stand is difficult. Buried seeds may eventually succeed but finding them is difficult. A coarse screen with mesh just smaller than the seed can be fitted in a frame and pulled across the surface. Sluicing with water will reveal the seed, although it does take some work. A bunched stand leaves many areas under populated, while other areas having too thick a stand.

Reseeding

The decision to replant if stand density is less than optimal is an economic decision that growers will have to make based on their planting costs and expected lost revenues from reduced yield. If the decision to reseed has been made, identify and manage the possible impediments to success. Over the first few days of flooding many organisms establish in the field algae, crustaceans, insects, microorganisms some of which are potentially damaging to the rice. In addition, a layer of detritus composed of dead algae and diatoms may form on the soil surface which can deter root growth. To the extent possible, one should manage these problems with appropriate measures. As stated above, early diagnosis is important and the most important component of successful reseeding. Depending on the density of the stand, the reseeding rate can be from 50 to 100% of the original rate. Normal soaking procedures should be used so the new seed will start quickly. Depending on the time difference between first and second seeding, one may consider using an earlier maturing variety of the same market category to help with uniform maturity. Soaking of the new seed should be done according to standard guidelines (i.e. 24 hours soak, 24 hours drain). The new seed will perform better if the field is drained. However, drainage must be balanced against the potential loss of weed control.

Rice seed has dormancy inhibitors in the hull when it is first harvested. Currently-used varieties naturally lose their dormancy with time, and it is not necessary to do any special treatments prior to planting at normal dates. In the past, seed treatments had been beneficial to increase uniformity and rate of germination, both of which are affected by dormancy. Dormancy has been associated with chemical germination inhibitors in the hull and impermeability of the hull and seed coat to water. Sodium hypochlorite has been used in the soak water, at the rate of one gallon of 5.25% sodium hypochlorite per hundred gallons of water, a 1% solution, to alter the chemical germination inhibitors in the hull to improve speed of germination and early growth. Percent germination is not affected.

Wet seedbeds and delayed planting

Late spring rain may make it impossible to adequately dry the seedbed for optimum stand conditions. The result can be lower soil fertility, difficulty in land planing and rolling, precocious weed growth, difficulty in placement of aqua fertilizer, more algae, and delayed planting. If time permits, rework the ground, using a chisel-plow to speed drying. If the ground has not been worked, and there is a stand of vetch or other vegetation, let it grow as long as possible, and it will help dry the soil. If the ground is worked wet, expect some of the problems cited above and manage accordingly.

Drill Seeding

Drill seeding is used by some to reduce costs and manage herbicide resistant weeds. It is also the typical planting practice in the Sacramento-San Joaquin Delta region where dry seed is drilled into moist soil (as one might do with wheat). The light-weight, high organic matter soils of the region make water seeding less successful because the soil can bury the seed and prevent germination. High winds in the region may also impact seedling root anchoring under water seeding.

The primary issues in drill seeding are depth of seed placement and management of moisture for germination. Rice seedlings may not emerge well from deep planting. Studies in 1985 (Gunnell et al.) demonstrated reduced emergence as planting depth increased from ½ to 3”. Emergence percentage for M.202 was 100%, 100%, 92.5% and 20%, at ½”, 1”, 2”, and 3”, respectively. Deeply planted seeds took much longer to emerge and often came up twisted and bent. For current varieties, plant no deeper than 1 ½” to 2”. Growers who drill seed can plant to moisture or plant dry and irrigate the field to bring up the plants. The former is better to reduce weeds in the rice, but there is the risk of missing the moisture. Drill seeding into a dry seedbed and flush irrigating reduces that risk if done properly, but weeds are usually more of a problem. Either way, the permanent flood is established about a month later when the rice is at the 3 to 4 leaf stage.

Alternative Stand Establishment Methods for Weed Management

Continuously farmed rice affords few options for breaking weed population cycles. Consequently, the number of aggressive herbicide resistant weeds has built up over time. In heavily infested rice fields, conventional weed control strategies are ineffective and costly. The weed seed bank in the soil becomes increasingly dominated by resistant biotypes in these fields. Alternative stand establishment methods can reduce the resistant weed seed bank in the absence of traditional crop rotation.

These methods do pose some risk. However, with careful management, good yields are possible. Keep in mind that the primary objective is to reduce the population of resistant weeds and then return the field to a conventional water seeded system where weed control is once again cost effective. UC studies concluded that integrating cultural and chemical weed control practices is effective without significant reductions in yield (Figure 12). Integrating reduced tillage and a stale seedbed in rice systems will reduce herbicide resistant weed populations, delay the evolution of herbicide resistance, and reduce weed seed banks. Establishment techniques such as reduced tillage, stale seedbed or dry seeding may be used to manipulate weed species recruitment and expand herbicide options.

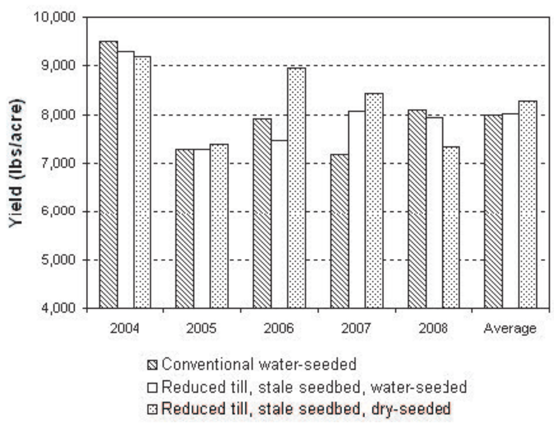


Figure 12. Grain rice yields under conventional and reduced till, stale seedbed waterand dry-seeded systems, 2004-2008, Biggs, CA

Planting into a Stale Seedbed

A stale seedbed is one where rice is planted into undisturbed soil. A stale seedbed approach encourages weeds to germinate by using irrigation prior to planting. Once the weeds are established, they are killed with non-selective herbicides, such as glyphosate (Roundup). In dry seeded rice, pendimethalin (Prowl) may be used for soil residual control of many grass species. These herbicides provide alternative mechanisms of action to control resistant species.

Fall Tillage versus Spring Tillage

A stale seedbed can be established with either fall or spring tillage. The preplant irrigation and weed control with a non-selective herbicide is the same for both circumstances. Fall seedbed preparation requires that the straw is well incorporated; an additional pass with a disc may be necessary. Flood the field for decomposition as usual. A prolonged winter flood should “melt” the clods to a relatively smooth soil surface by spring. If the field is cultivat ed in spring, apply P and K fertilizer during the cultivation operations pri or to irrigation, weed germination, and herbicide application. Phosphorus left on the soil surface promotes algae growth. If it is inopportune to apply them during cultivation, they can be applied into the water 20-30 days after seeding.

Key points to remember for stale seedbed method

- Cultivate the field in the fall in the usual fashion.
- In the spring, flood the field to germinate weed seeds, preferably during warmer periods to encourage rice weed germination.
- Water grass and other grass seeds: maintain flood or saturated soil for 4 to 5 days.
- Sedge and broadleaf seeds: maintain flood or saturated soil for about 10 days.
- Dry-up the ground. Apply glyphosate to kill germinated weeds approximately 10 to 14 days after drain.
- Do not apply the herbicide until the rice weeds are vigorously growing. Applying too early will compromise control. Be patient.
- Do not disturb the soil after glyphosate treatment to avoid bringing more weed seeds to the surface.

Table 1. Example operations for planting rice using water seeded or dry seeded stale seedbed alternative stand establishment methods.

REDUCED TILL, STALE SEEDBED, WATER SEEDED	REDUCED TILL, STALE SEEDBED, DRY SEEDED
Preplant Weed Control • Flood the field to germinate weed seeds • Drain, then apply non-selective herbicide after the weeds are vigorously growing • Introduce flood for planting 2 days after herbicide application.	**Preplant Weed Control** • Flood the field to germinate weed seeds • Drain, then apply non-selective herbicide after the weeds are vigorously growing
Seeding, fertility and water management • Apply N at 20-60 lb /ac to soil surface (optional). a. Use ammonium sulfate if you typically see a benefit from sulfur. b. Use urea if you can flood quickly. c. Consider applying P and K in the fall. • Flood field. • Seed with pre-germinated seed at a heavier rate than usual (~200 lb/ac). There are two options following seeding 1. Drain field for stand establishment (especially if ground was not dried and soil oxygen concentration may be low) • Apply bulk of N (150 lb/ac) as urea immediately prior to permanent reflood • Top 1” of soil must be dry so that flood water will drive urea into soil and prevent N volatilization losses. 2. Maintain a continuous flood and raise water depth as seedlings develop. • Apply bulk of N (150 lb/ac) as ammonium sulfate at the 3-4 leaf stage of rice or when rice roots are well-developed.	**Seeding, fertility and water management** • Pre-plant application of 1/3 total N. a. ~30-50 lb N/ac as ammonium sulfate. b. N may be applied with drill. c. Total N requirement may be a little higher than in a conventional water seeded system. • Seed at a rate of about 100 lb/ac. a. 5-7” spacing. b. Depth < 1” • Flush/drain to promote rice germination. a. Rice seed may not germinate in low spots with standing water. b. Rapid water movement in fields with lighter textured soils may bury the seeds in some areas and thin the stand. • May need to flush again prior to permanent flood, depending on the weather. Hot, windy weather can cause the soil to crust before the seedlings emerge. • Apply remaining 2/3 total N just prior to permanent flood. a. 100 to 120 lb N/ac as urea. b. Top 1” of soil must be dry so that flood water will drive urea into soil and prevent N volatilization losses. • Apply permanent flood when rice plants are large enough to be above water; typically between the 4 leaf and tillering stage.
Weed management Weed management options when draining for stand establishment 1. Pre-plant glyphosate (Roundup). 2. Foliar herbicide application at 3 leaf stage of rice. 3. Into the water application after reflooding, or foliar application with rice 3-4 leaf stage to tillering and water lowered for 70% exposure of weed foliage. Weed management options with continuous flooded system 1. Pre-plant glyphosate (Roundup). 2. Into the water herbicides. 3. Foliar herbicide options at 1-3 tiller rice with water lowered if needed for 70% exposure of weed foliage	**Weed management** 1. Pre-plant glyphosate (Roundup). 2. Herbicide options: a. A pre-emergent herbicide application after the first flush of irrigation followed by a foliar application prior to permanent flooding. b. A foliar herbicide in tank mixture with a soil residual herbicide applied when rice is the 2-4 leaf stage. 3. Come back with a foliar herbicide application after permanent flood if needed to control a new flush of weed emergence. Water should be lowered for 70% weed foliage exposure to the herbicide.

WATER MANAGEMENT

Most California rice is produced by direct seeding into standing water with permanent flood for most of the season. Limited acreage is drill seeded which also uses a permanent flood after stand establishment. The origins of this system have much to do with weed control, nitrogen management, and productivity, discussed in other sections.

Typically, a shallow flood is established over the field and pre-germinated seed is sown by airplane into the water. The seed comes to rest on the soil surface and establishes in that spot. The water is kept on the field throughout the season except for short-term drainage, permanently removing it only at the end of the growing season to prepare the field for harvest. Rice growers spend much of their time managing the water and there are numerous variations on this simple theme which makes water management more complicated than it first appears. A previous section dealt with leveling and water management structures. This section deals with water management during the season.

Purposes of Water Management

The general goals of water management are:

- Supply water to the crop
- Establish an optimum plant population
- Suppress weeds
- Provide for pesticide applications
- Conserve nutrients
- Protect against cold weather
- Protect water quality
- Manage salinity

Each will be discussed later in the chapter.

Seasonal Water Use

Seasonal water delivery for California rice varies a great deal depending on soil type, management, and seasonal length (Table 1). The average delivered use is approximately 5 to 5.5 acre-feet per acre (af/a), but varies from about 4 to 8 af/a, or more, depending on soil properties and water management.

Evapotranspiration (Et, crop use, consumptive use) is the amount the crop itself takes up through the roots and transpires from leaf surfaces into the atmosphere. Et varies with seasonal length, so an easy way to save water in rice is to grow shorter season varieties. There is also some seasonal variation in Et due to annual weather fluctuations and differences due to planting dates. The climatic factors important to crop use are solar radiation, wind, and temperature.

Percolation is controlled by soil texture and impervious subsoils. Most rice soils have clay and/or hardpan in the subsoil, so water does not percolate rapidly compared to deep loamy or sandy soils. In general, percolation losses throughout a growing season in California clay soils are less than 4” per growing season. If deep per-

Table 1. Approximate seasonal water use by use component for rice in California. Note, this table does not account for leaks in levees and outlets.

Seasonal Water Use	Acre feet per acre
Evapotraspiration (Et)	2.75 - 3.25
Percolation/seepage	0.2 – 1.0
Drainage	0 - 2.0
Total	2.95 – 6.25

colation is excessive, rice may be a poor crop choice. In New South Wales, Australia, where water shortage is chronic, rice soils are tested for infiltration rate, and if excessive, rice cannot be grown.

Seepage is the lateral movement of water out of the field, usually through levees. Seepage occurs in all soils but is more of a problem in course textured soils which have high hydraulic conductivity. Seepage rates are also determined by the height of water on the other side of the levee. Seepage is lower (or even reversed) when there is a water supply canal or another flooded rice field on the other side of the levee. Studies have shown that seasonal water losses due to seepage are less than 2” per growing season.

Drainage during and at the end of the season accounts for the balance of delivered use. This number has gone down with the widespread use of laser leveling, which allows for less spillage, and mandated water holding required for pesticide use.

Water Management Systems

Different water management system designs are used for ease of management, water conservation, and maintenance of tailwater quality. Each is discussed below.

Flow Through System

The most common system is the flow-through system, also called the conventional system. Water supplied to the topmost basin sequentially floods each successive basin as it makes its way to the lowermost basin. The water is regulated by weirs or rice boxes. Excess water is allowed to spill over the last box into a drain. By continually supplying water to the top, and allowing a small amount to spill out the bottom, with the boxes adjusted properly, the water level is automatically maintained, hence the name “flow-through system.” The advantages of this system include low installation cost, the ability to flush salts from the field, easy installation and removal, and adaptation to irregular slopes. The disadvantages include substantial management, difficulty in preventing excess water in lower basins, and slow response to adjustments. This system is not well adapted to holding water as required by regulations (discussed later in this section). Holding water is contrary to the intended purpose of the system. Figure 1 is a schematic of a conventional flow-through system.

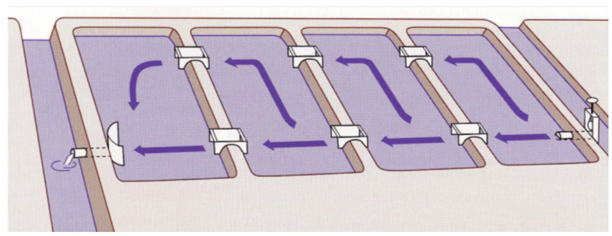


Figure 1. Conventional flow through system showing serial application of water from top (right) to the bottom of the field (left). Double box system reduces restrictions on water flow and may improve circulation. From: Hill et al. 1991.

Recirculating Tailwater Recovery System.

These systems capture tailwater in a sump and pump it back to an inlet for reuse in the same or other fields. They are useful for water conservation and keeping pesticide residues out of public waterways. Numerous recirculation systems have been installed although many have fallen into disuse because of maintenance and operation cost. These systems are adaptable to single fields, whole farms, and whole irrigation districts. Only a few single-field systems are in use. Figure 2 is a schematic of a single field with a recirculation system. The concept applies to various scales. All systems in use help stretch the limited supply of expensive water and allow growers to comply with less restrictive holding requirements. In-field water management is the same as for the flow-through system. The major management challenge is balancing the intake

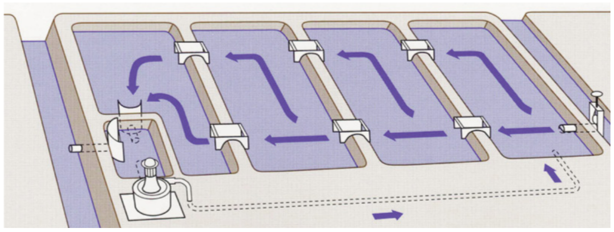


Figure 2. Single field recirculation system. This concept can be scaled up to multiple fields, multiple farms or whole irrigation districts. From: Hill et al. 1991

of fresh water with recirculated water, which is more difficult as the system increases in size. The advantages of this system are the ability to keep pesticide residues out of public waterways, good flexibility of management relative to regulations, reduction of cold water effects, conservation of water, and lower water expense. Disadvantages are the cost of installation and maintenance, extra land out of production, and a higher level of management.

Static Water Irrigation System

This system was developed specifically to keep pesticide residues out of public water. The key features include multiple water inlets from a canal along the side of the field so that each basin is irrigated in parallel but separate from the others (Figure 3). The inlet acts as the drain at the end of the season and the goal is for zero drainage. Some saline fields have convention-

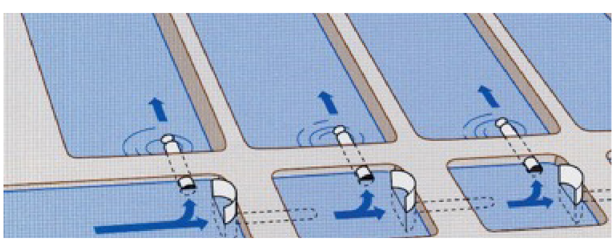


Figure 3. Static water irrigation system. From: Hill et. al.,1991

al drains at the end opposite the intakes which allow for flushing of salts at the start of the season. Once water goes into the field it stays until the end of the season, with additional water added as needed. To accomplish this, inlet pipes are installed below grade at the low side of each basin. Each pipe has a flap valve that is opened by the pressure of inflowing water, and closes as the inflow declines, keeping water in the field. Water levels are managed by changing the levels in the supply ditch. Opposite each inlet pipe is an in-ditch weir to adjust water levels. To drain the basins, water in the supply ditch must be drained and the flaps opened. Advantages include an excellent capability for water holding, water conservation, independent control of levels in each basin, easier management, and no need for a return pump. Disadvantages include higher cost of installation and maintenance of the system, land out of production, reduced flushing of salts, and the unsuitability of permanent installations for rotation crops (although temporary static systems have been used in row crop areas).

Cold Water Effects

It is common knowledge that yields are low near a cold water intake. Re cent research has shown that the cold water and the associated reduction in rice productivity extend well beyond the area where the effects are readily visible. The distribution of cold water can extend throughout the intake check and bleed into the adjacent check (Figure 4). The infrared image taken in early June showed that the water temperature warmed by only about 5 degrees as it passed through the 15-acre check. The intake water temperature was 56° F when it entered the field. Plant development throughout the growing season was delayed as a result (Table 2). Interestingly, the gradient in developmental delay was accentuated with time. For example, there was an 11-day difference in the time to first tiller between the cold and warmer parts of the check. The differential increased to 21 days by panicle initiation and 32 days at boot. The cold water effects are accumulative. Similar relationships were observed in the yield components (Table 3). Head size and seeds per panicle decreased

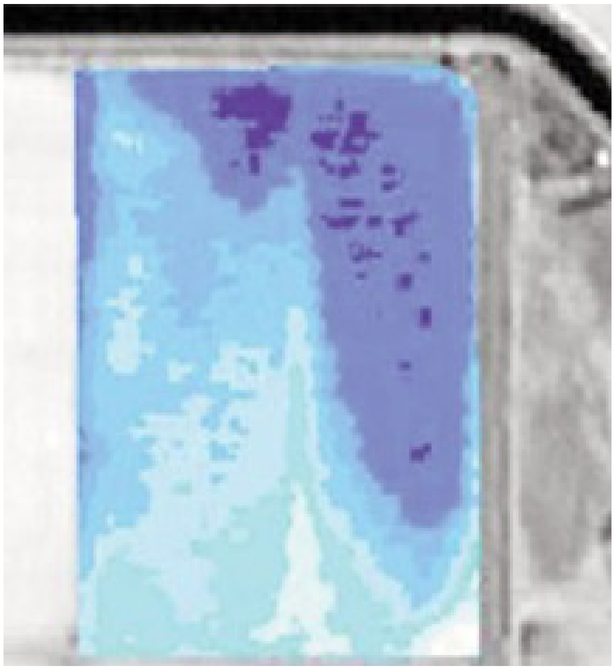


Figure 4. An infrared image showing the water temperature gradient in an intake check in early June 2001. In coming water = 56° F. There a temperature gradient of about 5° F across the check.

from the warm to the cold areas of the check. There was a corresponding increase in blanking and a reduction in yield. Notice that the yield loss is not restricted to just the area surrounding the intake box. It appears that the potential yield reduction due to cold temperature is comparable to a dose-response function.

In that, the longer the crop is exposed to cold water the more pronounced the impact. Figure 5 uses a threshold water temperature of 65° to illustrate the concept. The longer the plants were exposed to water temperature of less than 65° during the day for the first six weeks the greater the yield loss. For example, only 20 percent of the yield potential was observed in the areas of the field that experienced water temperature under 65° for 250 hours (i.e. 80 percent reduction). In contrast, at 150 hours of exposure, 60 percent of the yield potential was realized. If you farm ground with cold water, you may want to consider modifying the water delivery channel when laying out your irrigation system to minimize this effect.

Flow Rates

Flow rates determine the speed of initial flooding and, if necessary, re-flooding. Speedy flooding is desirable for earlier planting and to prevent weeds and other pests, such as seedling disease, shrimp, and midge, from getting ahead of the rice. Precision leveling, flat fields, and corrugated rollers have made initial flooding quicker compared to earlier years, given simi-

Table 2. Days after planting (DAP) to reach different stage of development in a cold water intake check.

	1st Tiller	PI	Boot	50% Heading
	-------------------------------- DAP --------------------------------			
North	43	85	120	---
(inlet)	34	69	104	114
	31	64	90	104
South	32	64	88	96

Table 3. Yield components as effected by water temperature gradient across an intake check.

	Head (cm)	Seeds per panicle	% Blanks	Yield (lb) @ 14% MC
North	14	0	98	402 (green)
(inlet)	13	10	53	2288
	16	45	29	5924
South	17	53	12	9138

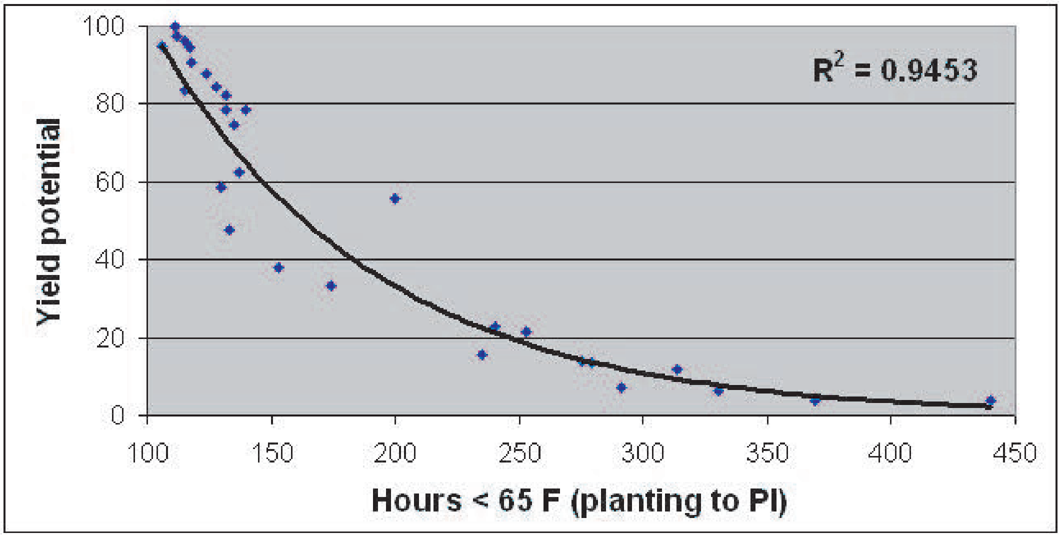


Figure 5. The potential yield reduction in rice when exposed to water temperatures < 65° F for different periods of time.

lar flow rates. Increasing competition for water and greater reliance on pumps may reduce flow rates in the future, so it is important to have an appreciation for what is needed for the various stages of crop production.

Flow rate guidelines appear in Table 4, and can be used to estimate the time to flood with a given quantity of water or the desired flow rate for a given size field. The calculations in Table 4 are for a delivery of four acre-inches per acre, which assumes that this is sufficient to just cover the field for seeding, but not to establish a depth of flood water. About two inches are assumed to go into the soil and the balance will be on top. The amount required for initial flooding is really quite variable and depends on the amount of water already stored in the soil, the slope of the field and how the grower floods. 'Acceptable' flooding times are in the shaded area and are selected to help avoid problems that develop with increasing time. During cool spells, a longer flooding period may be acceptable because growth of pests is slower. Acceptable time is arbitrarily set at 96 hours in Table 4, although it is not a disaster if the field takes a day or two longer to flood. When fields take longer than a week to flood, pest problems start to increase.

Putting it in simple terms, quick flooding requires roughly 28 gallons per minute per acre (gpm/a). Once a flood is established, the amount needed for maintenance is much less, a continuous flow of 5 gpm/a over the course of a season is usually adequate. For design purposes, one should plan on a minimum of 10 gpm/a. The extra capacity allows electric pumps to operate during off-peak periods. Extremely low flow rates may require special management, such as sowing rice in sections of the field as they are flooded, or dividing fields into small units.

Water Management Methods

Initial Flood

When field preparation is completed, boxes installed, and levee ends closed, water is introduced into the top of the field. Additional inlet sites may be used in large fields to speed the process if sufficient water is available. Flow rates determine the rate of flooding. The objective in the initial flood is to get the entire field wet as quickly as possible. In a flow-through system, this may be accomplished by blocking back water in the top basin until it is nearly cov-

Table 4. Approximate hours for initial flood for various field sizes with different flow rates. Shaded area represents acceptable time. Based on delivering 4 acre inches/a.

	Size of Field in Acres			
GPM	**50**	**100**	**150**	**200**
500	181	361	542	722
1000	90	181	271	361
2000	45	90	135	181
3000	30	60	90	120
4000	23	45	68	90
5000	18	36	54	72
6000	15	30	45	60
7000	13	26	39	52
8000	11	23	34	45
9000	10	20	30	40
10000	9	18	27	36

ered by setting the board in the first box to hold the minimum amount and allowing the rest of the water to spill over. Repeat this basin by basin until the last one is covered. It is not necessary to establish final depth at this time, only to get the soil wet to receive the seed. It may take several days to establish the desired depth, but it is not necessary to delay seeding. Flooding from the top of the field helps flood the field faster. If the boxes are all wide open during initial flooding, the water will tend to run straight to the lowest basin, and one must work from the bottom of the field to the top. This is called back flooding and takes much more time because the tendency is to get more water than needed in the lower basins. Increasingly growers are establishing shallow ditches between rice check boxes which allows the checks to flood more uniformly.

Establishing a Stand

Following seeding, the goal of early season water management is to establish a vigorous, healthy, weed-free stand. The management of water during this period is integrated with herbicide use and greatly affected by water supply. For example, early applied foliar materials, such as Clincher, require a drained field. Rapid reapplication of water is important for good weed control and may affect success in some areas because of low flow rate. For materials applied into the water, such as Bolero, the goal of water management is to quickly establish a continuous flood of 4 to 5” which provides a good compromise between rice growth and weed suppression. Shallow water (1-3”) promotes rice growth and root anchorage but also favors weed growth. Deep water (7-8”) delays early rice growth and tillering, but also greatly inhibits grasses and smallflower umbrellasedge, the most competitive weed species. Water management for specific herbicides is discussed in the section on weed management.

Drainage for stand establishment

Many growers use a planned drain period after sowing to help improve stand establishment. This practice is known as the ‘Leathers method,’ after the grower who popularized it. This is a useful practice where rice has difficulty anchoring to the soil or is easily covered or moved during windy weather. When properly used, stand density and uniformity of distribution is usually improved and concerns about the effects of wind are less. Generally, fields are completely drained immediately after sowing and the water is left off until the radicle penetrates the soil and anchors the seedling. In this aerated situation, roots are stimulated to grow more than they are in a flooded, less well-aerated environment. Seedling rice responds to a surplus of air by increasing root growth, while shoot growth is less stimulated. The sequence of events is:

- Sow rice into shallow flood;
- Drain field rapidly and completely, immediately after sowing up to two days after sowing;
- Maintain drained condition for 3 to 5 days, depending on temperature and growth of roots
- Reflood when radicle penetrates soil

This practice must be used only where there are enough outlets for quick drainage and there is an adequate water supply for quick reflooding. Furthermore, the field should be well-leveled so that it will flood and drain quickly. If the field takes too long to drain and reflood, drought stress may kill some of the seedlings and result in a poor stand in portions of the field. Internal drains, either across the basins or around their circumference, help speed water removal and application. Timing of drainage relative to planting is also important. Waiting for more than a day or two reduces the beneficial effects and may jeopardize weed control operations and timing.

Early season water management and weed control: Delayed Pinpoint Flood

While it may be desirable to maintain a 4-5" of water on the field early in the growing season to control weeds, some herbicides (particularly foliar herbicides) require lowering the water in the field to expose weeds and maximize herbicide contact with weeds. This is discussed in more detail in the weed control chapter. The main point of this chapter is that during the first month and a half of the growing season, water management is often driven by herbicide (and other pesticides) use. The usage of these chemicals affects water height in the field, when water is flowing into the field as well as imposing strict limits on when water is flowing out of fields due to water holding periods (discussed in more detail later). When possible, quick removal of water and replacement after spray application is desirable for good weed control. A prolonged drain period promotes weed growth and delayed reflooding may reduce herbicide efficacy.

Alternate wetting and drying (AWD) and mid-season drain

Keeping rice soils permanently flooded has been recommended as a good practice for ensuring optimal weed control and efficient nutrient use efficiency (particularly for nitrogen). However, keeping a field flooded alters soil chemistry and makes the soil anaerobic (without oxygen). While this may be good for conserving nitrogen, anaerobic soils also produce and emit more methane (CH4) and make some heavy metals such as arsenic (As), mercury and lead more bioavailable. Thus, continuously flooded rice fields have higher CH4 emissions and higher concentrations of As (and other heavy metals) in the rice grain compared to fields that are not continuously flooded. Importantly, while California rice fields are high emitters of CH4 (due to water seeding and straw incorporation), the levels of As in the grain are relatively low compared to other areas where rice is produced.

One practice to reduce both CH4 emissions and grain As concentrations, is to let the field dry out one or more times during the growing season. This introduces oxygen back into the soil and can lead to reduction in CH4 emissions of over 40-60% and a reduction in grain As of 30-40%. However, doing this must be done carefully, otherwise there is the risk of yield reduction, fertilizer N losses and high nitrous oxide (N2O) emissions (a more potent greenhouse gas than CH4).

The term alternate wetting and drying (AWD) is used very broadly and covers a wide range of practices where the soil is allowed to dry down (become aerobic) at least two or more times during the season. A mid-season drain is a single drain during the season. Using AWD practices in California rice systems is not very practical because it is hard to find time during the season to implement multiple drains without affecting crop productivity. For example, during the first month or so, water management practices are largely driven by weed management decisions. Furthermore, letting the soil dry during this period will result in fertilizer N losses and N2O emissions because there is a lot of fertilizer N in the soil at this time. Secondly, we do not recommend drying the field during booting as this can lead to blanking if nighttime temperatures get too cold (in fact, we recommend raising the water during this time). Draining during the grain fill period is likely to result in negative grain quality issues. This leaves a window of opportunity during the mid-season for a single draw-down of water. We call this a mid-season drain.

A mid-season drain

Many growers in California apply propanil during the mid-season (30-50 days after planting) as a clean-up herbicide. Propanil is a contact herbicide, so flood water needs to be lowered. A mid-season drain could simply be an extension of this drain. Our research has shown that a short dry-down period (2-3 days) lowers CH4 emissions for a short period but emissions increase again after field is flooded. When the drain is extending to 8-12 days (time depends on the field), CH4 emissions do not increase rapidly after the field is re-flooded and CH4 re-

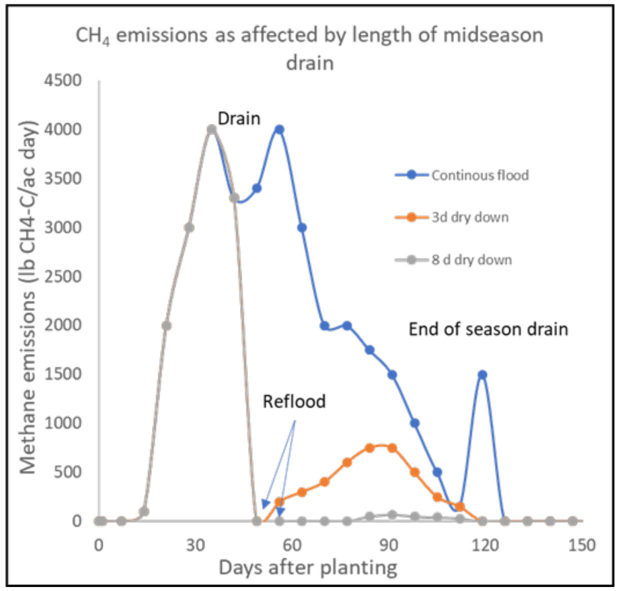


Figure 6. Example of CH4 emissions from continuously flooded fields vs a short or long mid-season drain.

Table 5. Methane emissions and rice grain yields from 2018 trial at the RES comparing continuous flood to a 5and 12-day mid-season drain period (Source: Perry et al., 2022).

Treatment	Methane emissions CH_4-C (lb/ac)	Grain yield cwt/ac
Continuous flood	136	93.5
5 d drain	84	92.4
12 d drain	49	92.7

ductions of 40-60% can be achieved Figure 6. We have done this research for close to a decade and on a number of fields and have found no yield reduction Table 5.

Here are some do's and don'ts:

- Don't let soil dry out during the first 5 to 6 weeks of the season. There are several reasons for this:
    - First, is that in water-seeded systems where the N fertilizer was applied pre-plant, this fertilizer is in the soil until roughly 6 weeks (the rice takes most of it up between 4 and 6 weeks after planting). Letting the soil dry during this period will result in potentially high N losses (nitrification and then denitrification when field is reflooded).
    - Second, due to nitrification and denitrification, high amounts of N2O will also be emitted.
    - Third, before this time the canopy has not covered, thus there is the potential for more weed growth.
    - Finally, early-season drains tend to extend the time a crop takes to reach maturity.
- Ideally, start the drain around 35 to 40 days after planting. This results in fields being reflooded around 45 to 50 days faster planting. By this time, all of the N fertilizer that was applied early in the season has been taken up.
- If you are applying a top dress of N fertilizer, apply it just before reflooding field.
- Monitor field during drain period. In considering the total drain time, account for the time it takes to reflood field.

One question that often arises with this is if this practice conserves water. In a typical year where rice is planted at normal acreage, the savings of this practice is small (about 1 inch we estimate). The reason for this is that most percolation and seepage water losses are very low when a lot of rice is in the landscape. This is because the water table is high. However, when rice is surrounded by fallow fields, upland crops and farmers using well pumps, the water table is lower. Growers often report using a lot more irrigation water in these fields just to keep them flooded. In these situations, having no flood water on the field for a period of time will save more water.

This system can also be used for dryor drill-seeded rice as is done in the mid-south. In this situation, fields are usually fertilized then flooded about 4 weeks after planting. In order to ensure all or most of the fertilizer is taken up, the field should remain flooded for at least two weeks before the dry-down period is started.

Permanent flood, water depth effects

A permanent flood should be established as soon as possible after sowing. The sooner it is done, the more beneficial impact it will have on weed management. Once established, permanent flood is maintained throughout the rest of the season. Maintain a steady depth of 4"-5" through maximum tillering and avoid taking water off the field.

The goal of the permanent flood is to maintain steady pressure on weeds and optimize rice growth. Rice growth response to various depths is demonstrated in Figure 7. Rice growing in shallow water (1-2") begins tillering faster and reaches a higher maximum tiller number earlier than rice growing in medium (4-5") or deep water (7-8"). Rapid establishment of plant cover is the main reason many growers prefer shallow water early in the season. Ultimately, the final tiller number is similar at all depths within this range because excess tillers developed in shallow water die off to a level that the plant can support. Leaf development and plant size (biomass) follow a trend similar to tillering. However, rice plants in deep water tend to be taller and mature earlier com-

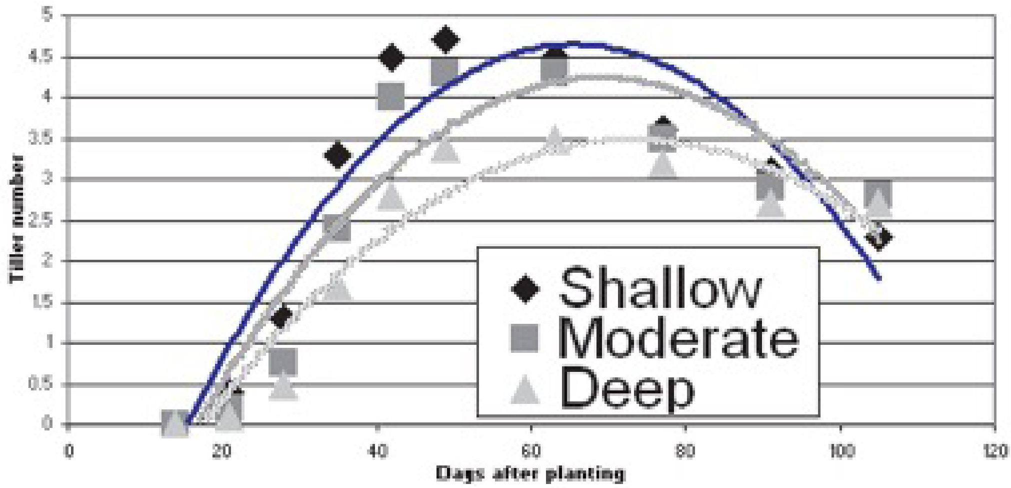


Figure 7. Tillering of M-202 rice at three water depths held season long, 1986. (Williams et al. 1994)

pared to rice growing in shallow water. Growth of rice in deep water suggests it is under stress which slows growth for the first half of the season, even though final growth parameters, except height and maturity, are similar at all three depths. Yield in field-scale trials comparing different depths within the range of 2" to 8" was the same across all depths.

Most growers are reluctant to accept slower crop development and increased management required for deeper water and prefer lower water to ensure that plants perform at their optimum, particularly when environmental conditions are adverse. Some soils, such as alkaline and saline soils, are already stressful to the crop, and deep water is not advisable. In addition, levees holding deep water are more subject to wind damage. The use of some herbicides in deep water is also not advisable. However, some growers have found value in deeper water, 5-7" through tillering, for better weed control where soil conditions permit it. One should avoid very shallow water, 1-3", because weed control will be difficult.

Blanking Protection

Blanking occurs when pollen is damaged by cool temperatures (55-60°F, depending on variety). It is the major temperature-related factor reducing yields in California. It is a potential problem in all areas of the valley but the problem increases as one moves south due to cooler night-time temperatures. Since rice florets are primarily self-fertilized, the loss of pollen is not usually replaced from other nearby florets, so a kernel does not develop. UC research in the early 1970s showed that the position of the panicle when it is sensitive to cool temperature is low in the stem, partially underwater. This is usually 10-14 days before the panicle emerges, and when the collars of the flag leaf and the penultimate leaf are aligned. The sensitive period lasts for about a week for any individual panicle and about three weeks for a field. As the air cools during the night, the air temperature within the canopy also drops. However, the water resists change and its temperature takes longer to drop. The higher water temperature can provide a critical source of heat to protect the rice heads from cool temperature damage. The change in

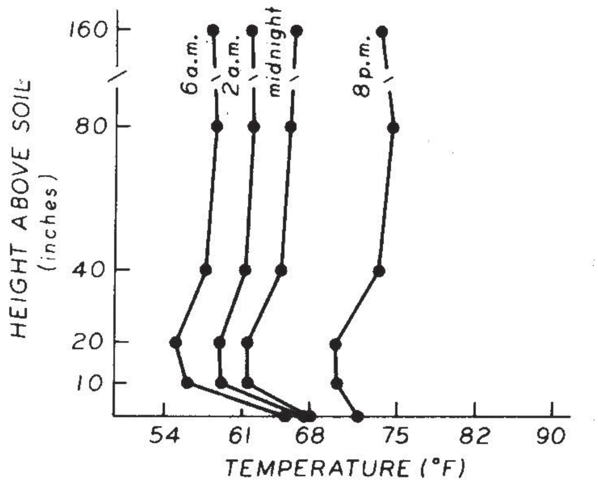


Figure 8. Temperature profile of a rice canopy. Water depth is 6”. From: Board and Peterson 1980.

air and water temperature at different heights above the soil is shown in Figure 8. At 8 pm, the air and water temperature are similar, but by 6 am, there is a large difference. The amount of difference increases with the depth of water and lower temperature. Growers can take advantage of this natural heater by increasing the water 7 to 21 days before heading. The water should be as deep as the levee system in the field will allow, but at least 8”. This depth will partially cover the developing panicles and help protect them from the cooler air above. Since tillering is complete, water depth will not affect growth.

Pre-harvest Water Management

Preharvest drainage requires a compromise between the conflicting needs of harvesting equipment and crop ripening, although certain risk factors can be identified to guide the process. As with many other management practices, the grower’s task is to optimize drain timing.

Typically, water is removed two to four weeks before the anticipated harvest date. Heavy harvesting equipment requires firm soil so it will not cause deep ruts and/or get stuck in the mud. Mud during harvest not only decreases efficiency but may also cause serious damage to valuable equipment and rut the field. The exact timing, to ensure firm soil, depends on:

- surface drainage-accurately leveled fields drain more completely than those with low spots;
- the internal drainage of the soil-soils with deep profiles usually drain quicker although soils with very high clay, such as Willows clay, are slow to drain;
- physiological activity of the rice plants that remain greener will use more moisture than senescent plants; Quadris sprayed fields tend to hang on longer and affect drain time;
- and climate during the drain period--high temperatures and north wind increase evapotranspiration.

Integrating these factors is more art than science and there is no substitute for experience in a particular field. In the end, you want a firm, but not dry, soil surface on which to run harvest equipment. In recent years, many growers have switched from half-track and full-track equipment to rubber tires, increasing the importance of firm soil at harvest.

As important as making sure the ground is dry enough to support equipment is to make sure it is moist enough to finish the crop. Premature drainage will impede ripening and result in more chalk and light kernels. In addition, research has shown that milling quality is improved if the water is left on longer, including up to the time of harvest! Since harvesting in the water is not a practical option, the grower has to decide when to drain to optimize ripening. Rice does not ripen uniformly, especially in different parts of the field, so assessing the entire field is important. The same factors that govern how fast the soil drains pertain to the moisture supply for ripening. Some rough guidelines for determining when the crop is sufficiently ripe to tolerate drainage are:

- grains have filled from the top to the bottom of the panicle;
- color has changed from green to golden;
- tip kernels have become hard;
- lower kernels will have soft dough but not milk.

Water Stress

Drought stress sometimes occurs when a pump shuts off or is on the high side of a poorly leveled field. Some organic growers also use mid-season drainage for weed control which induces drought. Rice grows well under flooded conditions and most varieties that have been bred for flooded conditions are not very tolerant of water stress and yields will be reduced when subjected to water stress. That said, several recent studies on-farm and at the RES (specifically to look at the effects of drying a field briefly to lower arsenic uptake and reduce methane emissions) have demonstrated that yields are not reduced when the soil water content is lowered below saturation between 45 and 55 days (just before PI) after sowing. In these cases, water has been off the surface of the soil for up to eight days.

Signs of water stress include leaf-rolling, leaf-scorching, impaired tillering, stunting, delayed flowering, spikelet sterility, and incomplete grain filling (Yoshida 1981). Drought avoidance is important during expansive growth beginning in the early vegetative stage, the degree of injury from which is related to the intensity and duration of the water deficit (Hsiao 1982). However, if not severe, the addition of water usually leads to complete recovery. The most drought-sensitive growth stage is floral development, starting with microsporogenesis through heading (Boyer and McPherson 1976). Drought stress during this stage leads to blanking and the crop cannot recover from it. During ripening, premature removal of water may lead to incompletely filled kernels and lower test weight.

Managing Salinity

Rice is particularly sensitive to salinity during the seedling and pollination stages. While most irrigation water used on rice in California has low salt (<0.7 dS/m), some water sources that include drain and well water can go much higher (Scardaci et al. 2002). Sacramento River water is low in salt being between 0.13 and 0.37 dS/m.

The type of irrigation system and pattern of flow also affects salinity. In static and conventional systems, salinity increased with distance from the inlet and in areas where water stagnates (Figure 9). Water with much lower salinity will result in higher salinity as salt accumulates and moves through the field so that lower basins typically have higher salinity, which peaks during holding periods. Yield reductions were

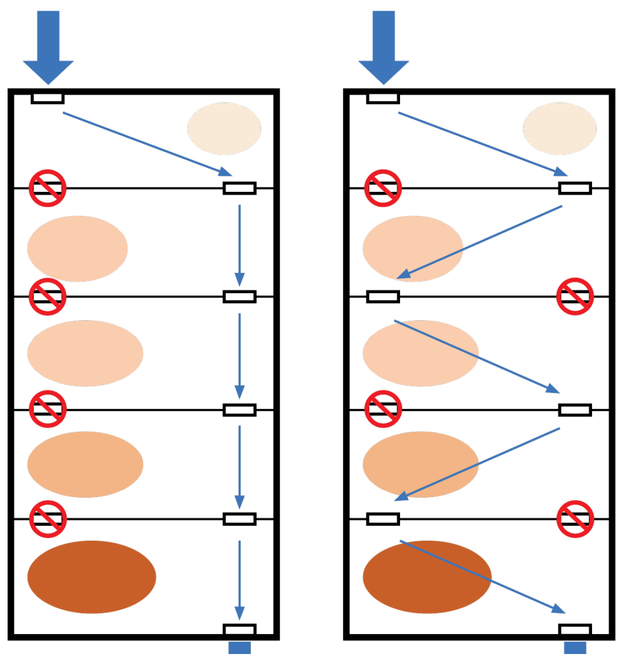


Figure 9. In the diagram above, the left shows a field with water running down one side of the field and how flood water salinity is concentrated on one side of the field (darker colors indicate higher salinity). By changing the water flow path in this field (shown on right) the water flow path is forced through the high salinity areas and helps flush them out.

associated with salinity of >0.9 dS/m .

Below are some steps to consider in order to control salinity:

- Irrigation water should have an EC below 0.6 dS/m – for an averaged-sized field this will help ensure that the field water salinity does not increase beyond the 0.9 dS/m yield threshold at the bottom of a field.
- Change water flow path – Salinity builds up in stagnant parts of the field. Changing water flow path will reduce salinity hot spots from developing (Figure 8).
- Early in the season when salinity is highest, allow for spillage and maintain higher water levels – This may not be possible in drought years or with certain herbicide programs.
- Smaller fields and multiple side inlets – The distance water travels in a field largely determines the build-up of water salinity. Larger fields will have greater water salinity build-up in the bottom of the field. Smaller fields and multiple inlets should be considered in fields with saline soil or receiving irrigation water high in salinity.
- Herbicide selection Growers using saline water should avoid using herbicides that require long-term holding so they can flush the field during the early part of the season.

Maintaining Water Quality

How one manages water not only impacts the growth of rice but also water quality. Since rice tailwater ultimately flows back to public waterways, growers must maintain its quality by using appropriate practices. Chapter 11 on water quality discusses these issues.

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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 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.

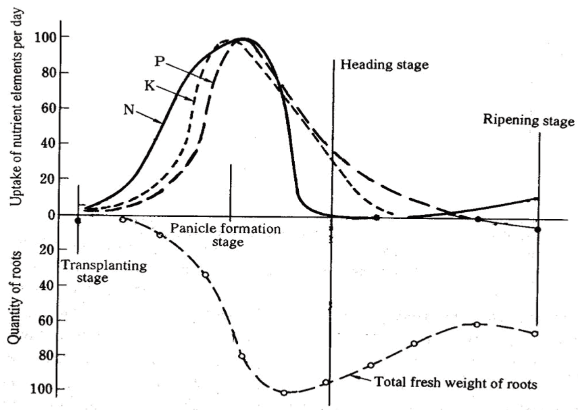


Figure 1. Seasonal uptake rate of selected nutrients and root growth by a rice plant

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.

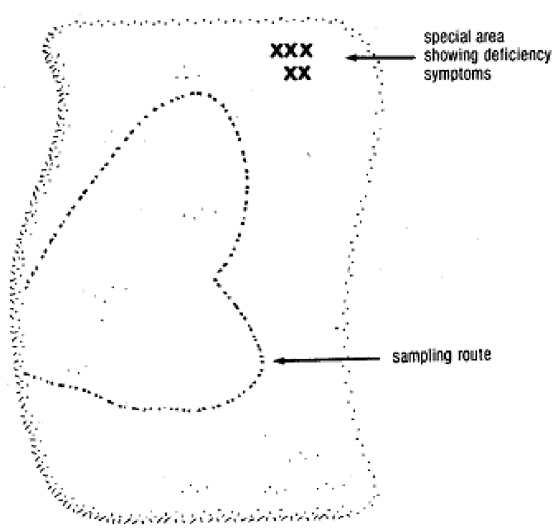


Figure 2. Sampling pattern for taking soil or leaf samples to test for nutrient deficiencies.

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

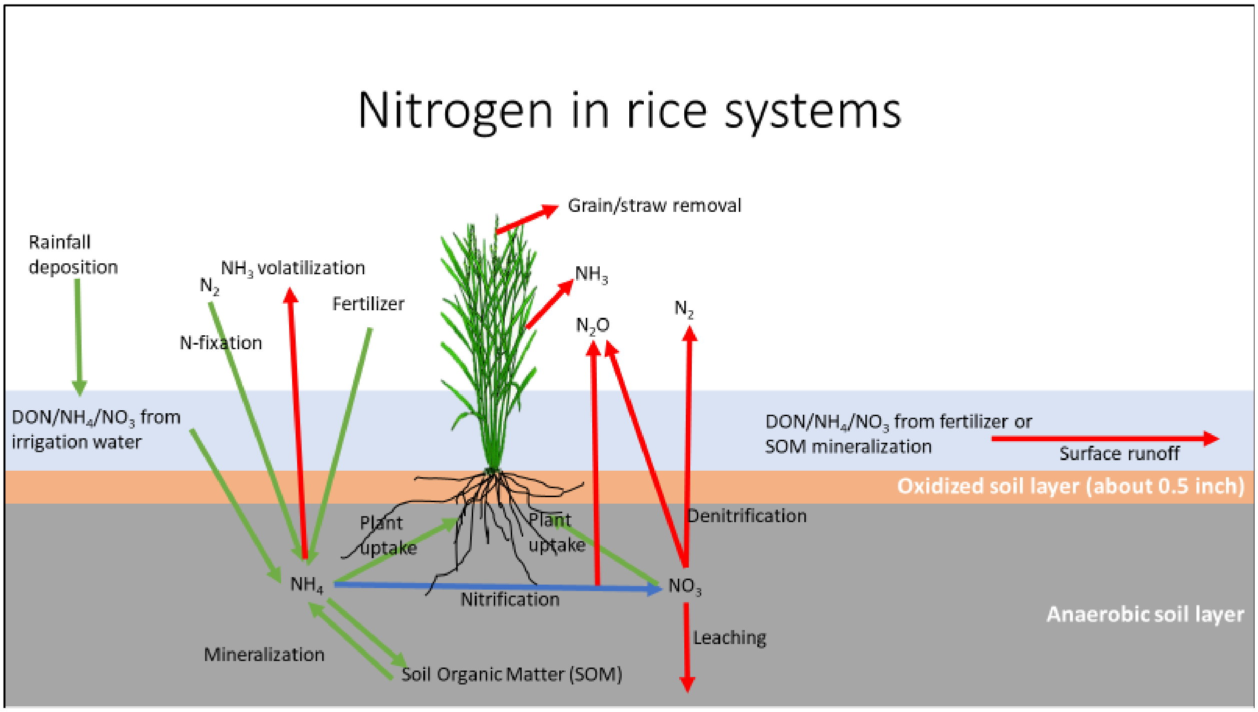


Figure 3. Nitrogen inputs, losses and transformations in rice systems

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

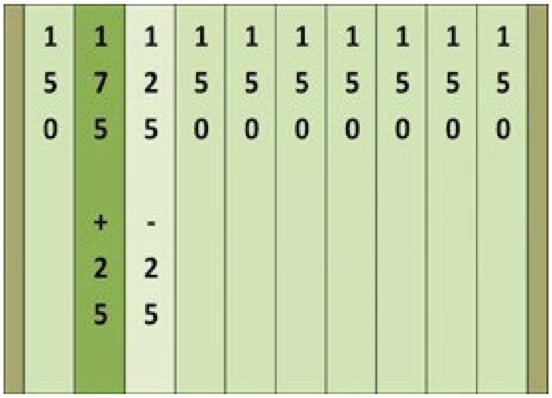


Figure 4. Example of a field with test strips of different N rates

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.

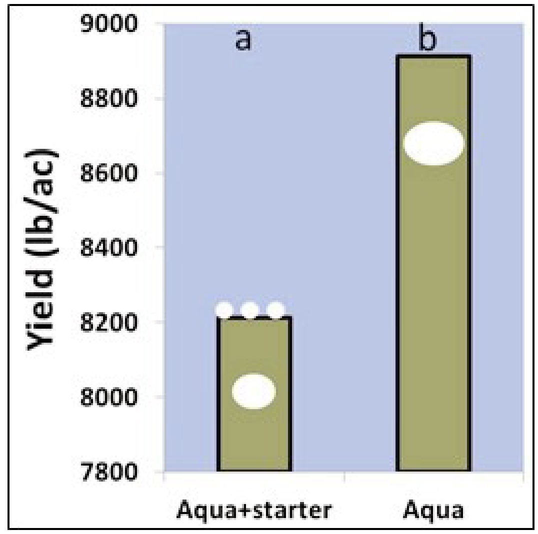


Figure 5. Effect of N source and placement on yields. The N shown here is 100 lb N/ac and the data represent the average response across different fields.

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-

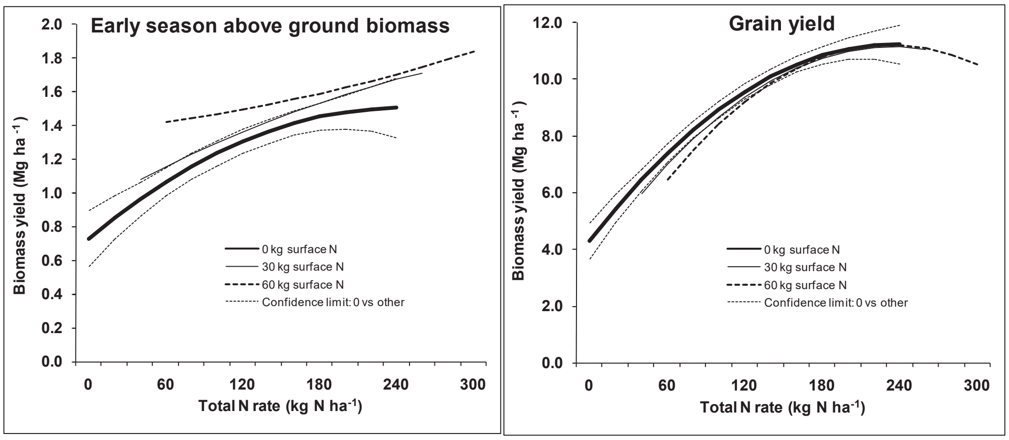


Table 3. Interpretive guide for leaf nitrogen percentage. Total leaf N concentrations are for California medium grain varieties.

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

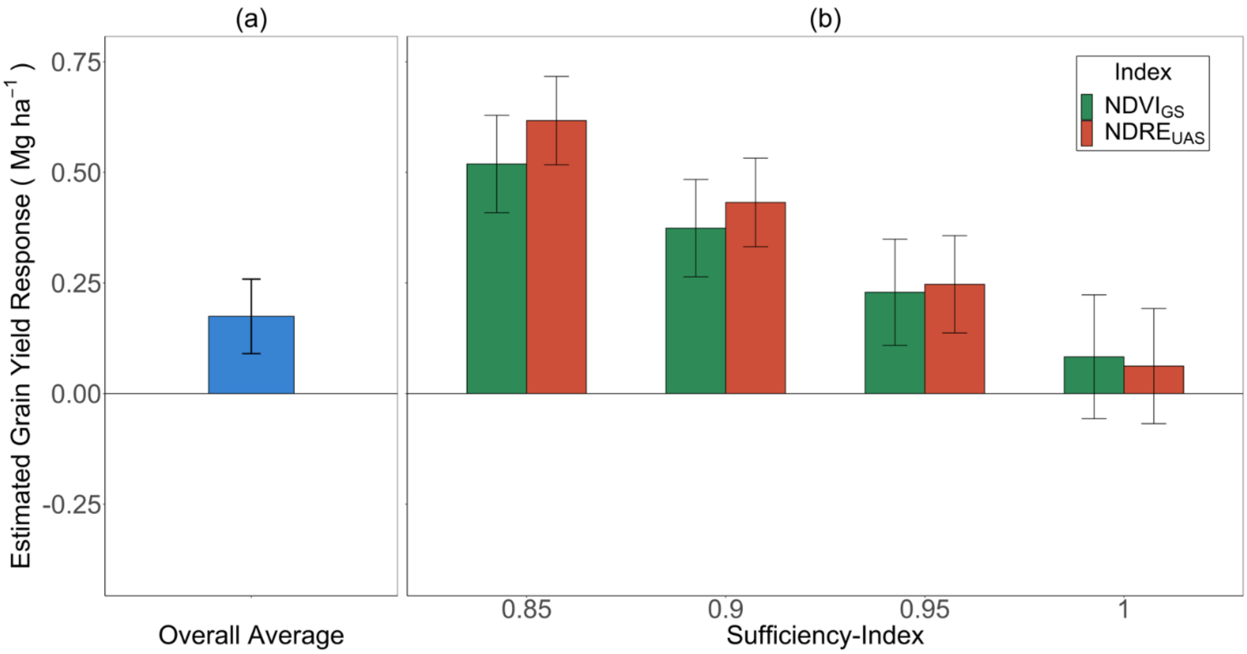


Figure 7. The estimated rice grain yield response (lb/ac=kg/ac X 0.89) to top-dress N applied at the panicle initiation (PI) growth stage at 30 lb N/ac. (a) overall average (averaged across SI 0.85 to 1.00), and (b) for GreenSeeker (GS) Normalized Difference Vegetation Index (NDVIGS) and unmanned aircraft 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

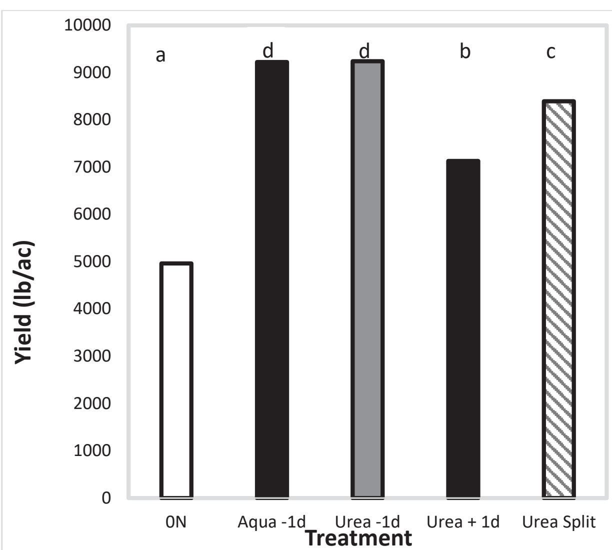


Figure 8. Yield response to aqua and urea applied 1 day before flooding (-1d), urea 1 day after flooding (+1d) and a split application of urea compared to a treatment that received no nitrogen (0N). All treatments received 135 lb N/ac. The split urea was applied at a ratio of 20:30:30:20% at 2, 4, 6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

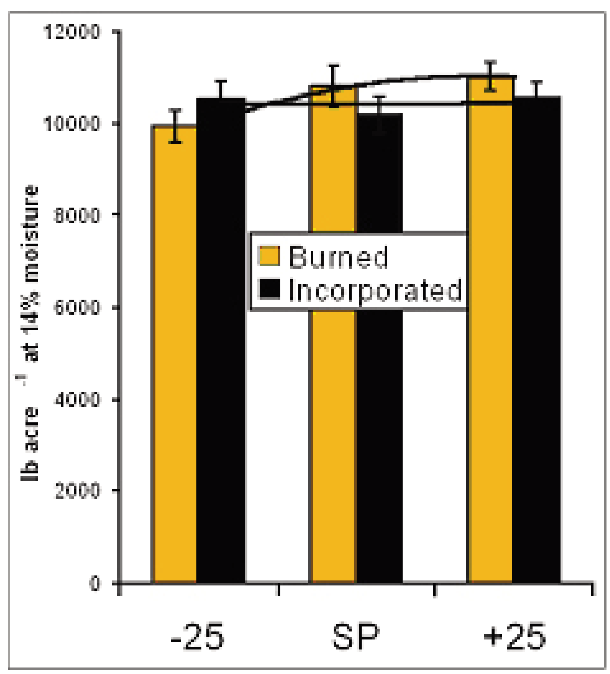


Figure 9. Yield of burned and straw incorporated/flooded fields when fertilized at the standard grower practice (SP) and plus of minus 25 lb.

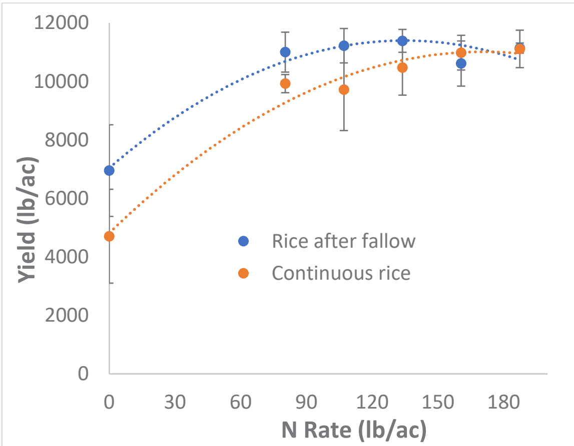


Figure 10. Rice grain yield when the rice crop followed a fallow year versus following a previous rice crop. Data are from 2022 at the Rice Experiment Station.

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

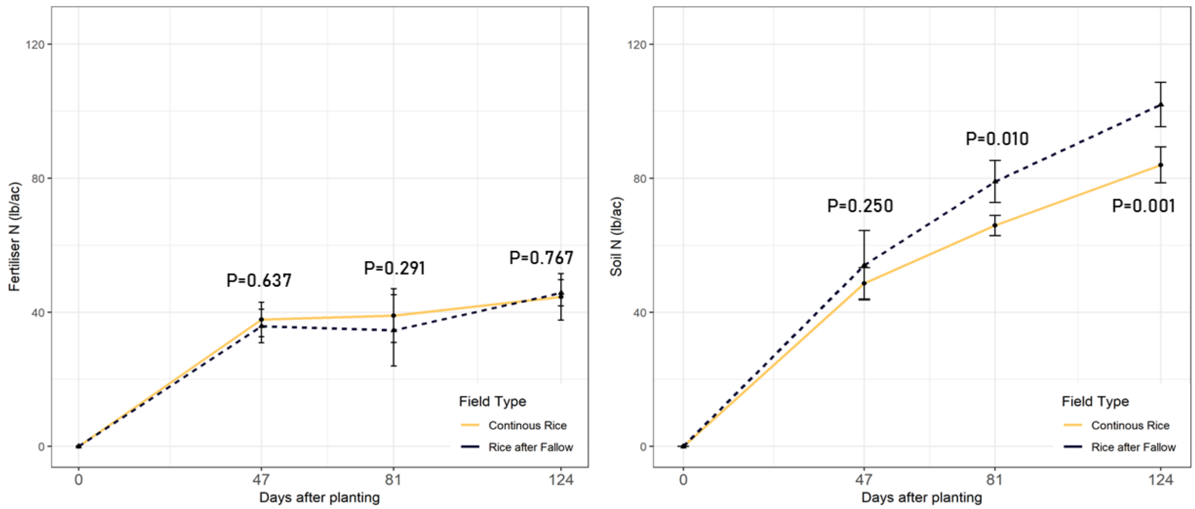


Figure 11. Source of N taken up by the crop in continuous rice systems versus rice following a fallow year determined from 15N labeled N fertilizer applied at a rate of 135 lb Na/ac. The left graph shows the amount of N in the plant that came from fertilizer and the right graph shows the amount coming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

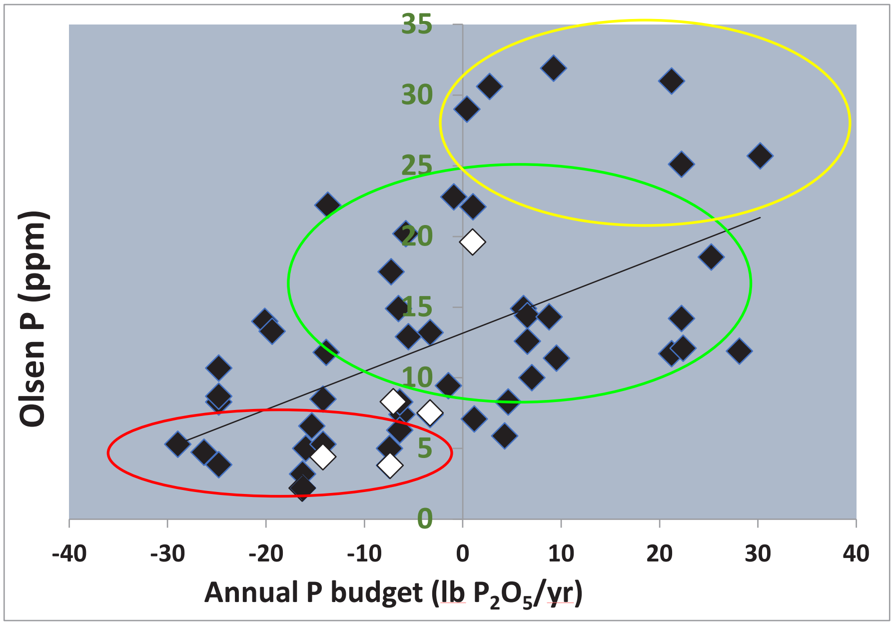


Figure 13. The relationship between soil Olsen-P values, P balance and yield response to P fertilizer (left). Data are from on-farm studies and the P balance reflects the 5 yr average of inputs and outputs. . Circles indicate fields in which different P management strategies need to be used. The open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

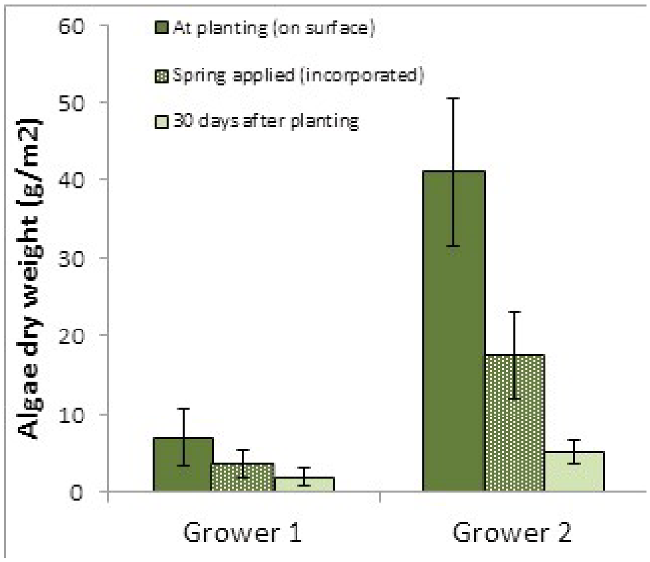


Figure 14. Effect of P fertilizer management (timing and placement) on algal growth in two rice fields

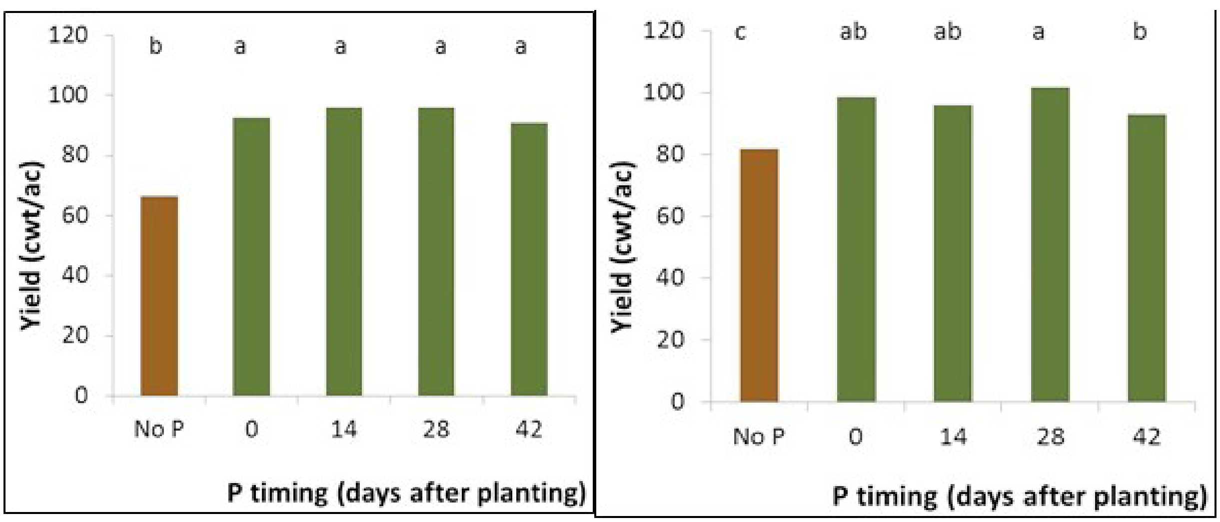


Figure 15. Effect of P fertilizer timing on rice yields in two rice fields

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.

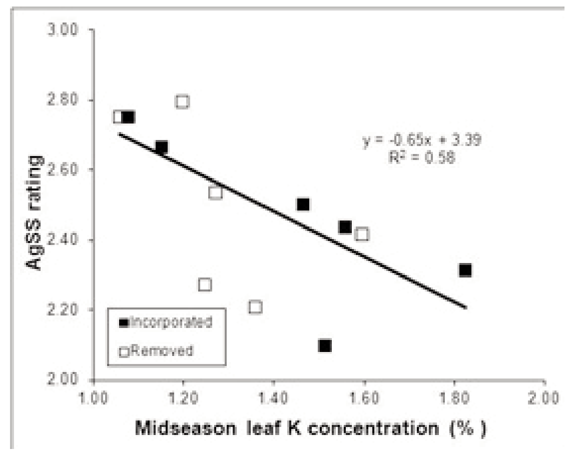


Figure 16. Aggregate sheath spot (AgSS) rating as affected by Y-leaf (at panicle initiation) K concentration in fields where straw was either incorporated or removed.

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

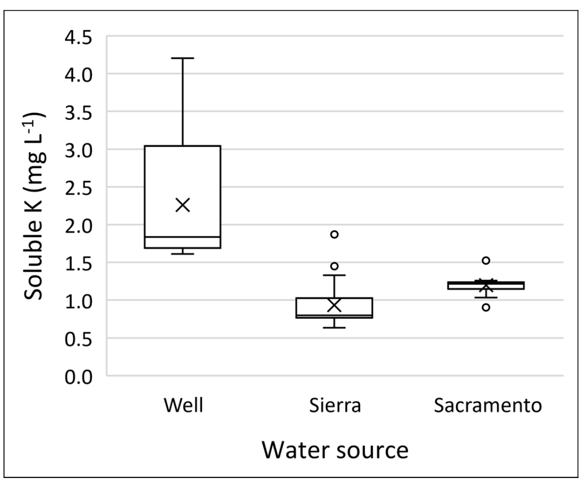


Figure 17. Irrigation water potassium concentrations. Sierra rivers include the Feather, Yuba and Bear rivers.

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 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

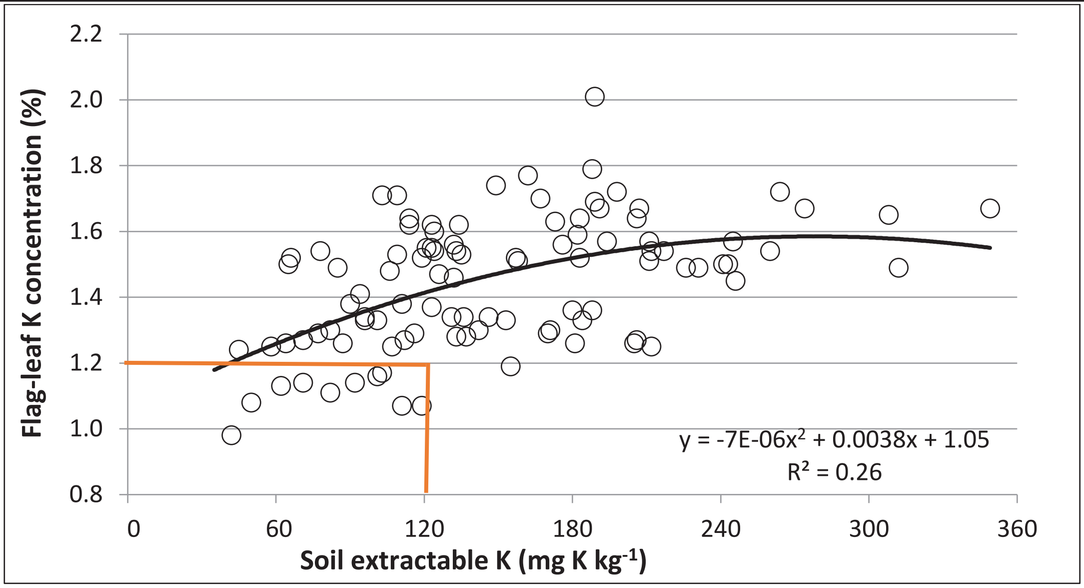


Figure 18. The relationship between soil K and flag leaf K values (taken at flowering) in fields where K fertilizer was not applied.

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

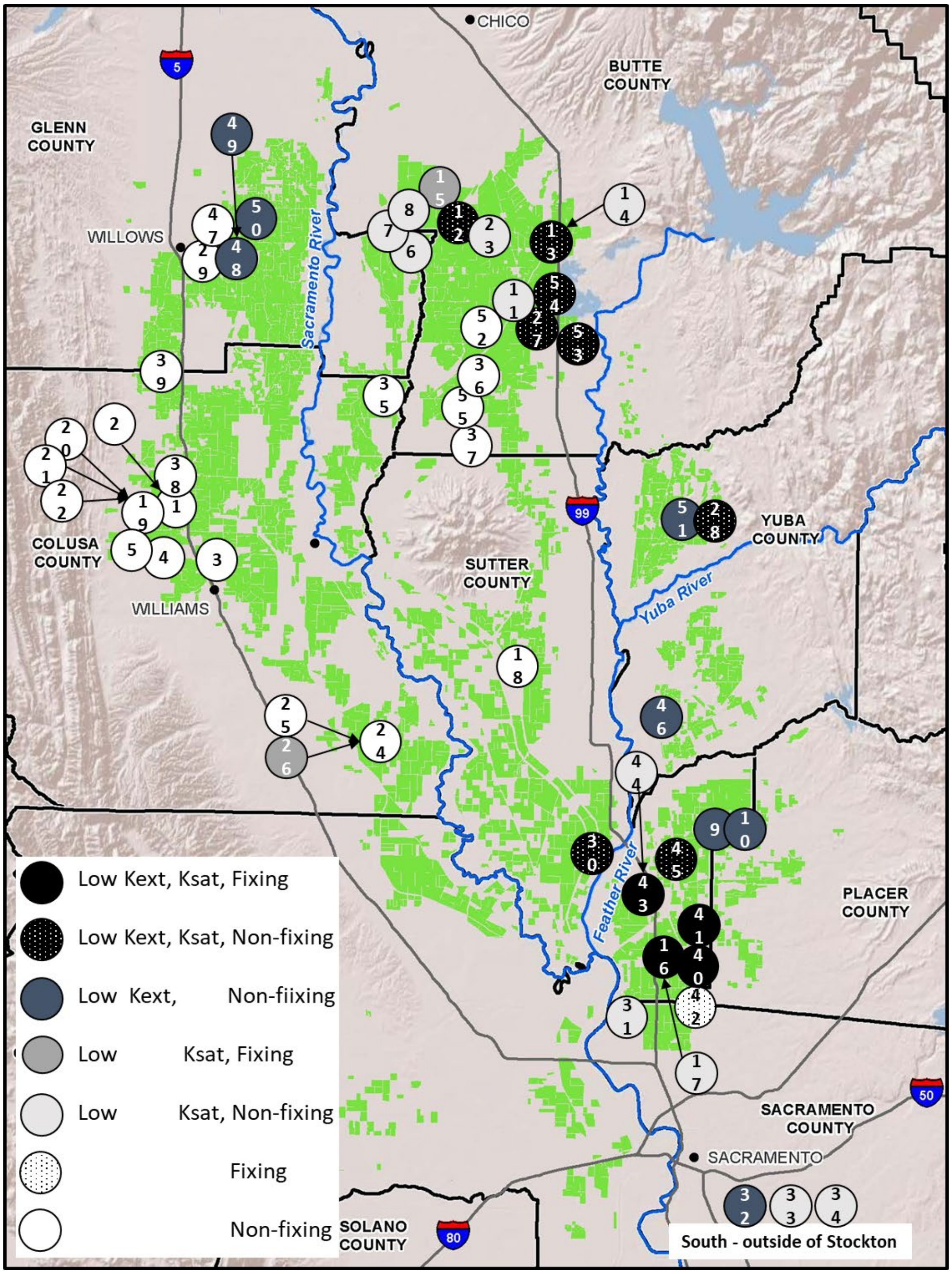


Figure 19. Map showing locations of fields in the Sacramento Valley. The different shade of circles indicate if fields (mean of all samples from the field) have low soil extractable K (Kext<120 mg kg-1) or low K saturation (Ksat<1.6%) and if the soil is a fixing or non-K fixing soil. In all cases where 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

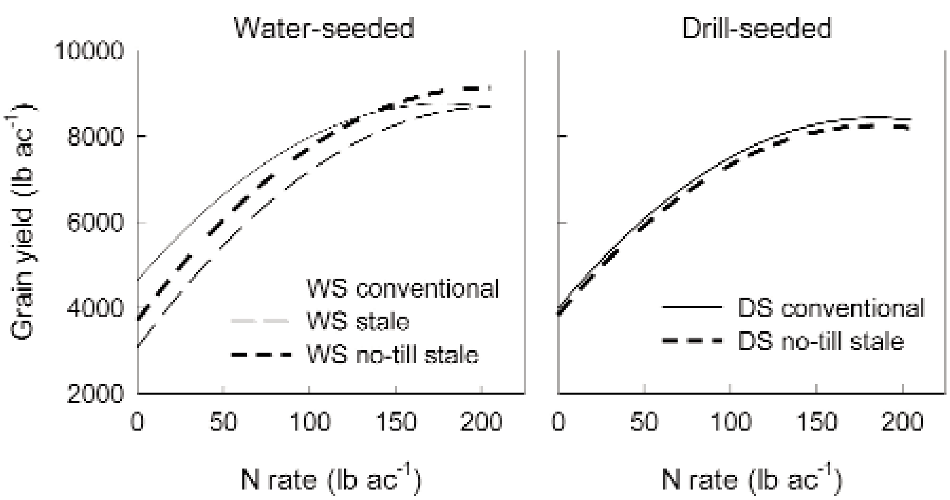


Figure 20. Grain yield response to N fertilizer in water and drill seeded rice when managed conventionally or with a stale seedbed. In the water seeded system both a tilled and no-till stale seedbed system was evaluated.

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 lessions 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.

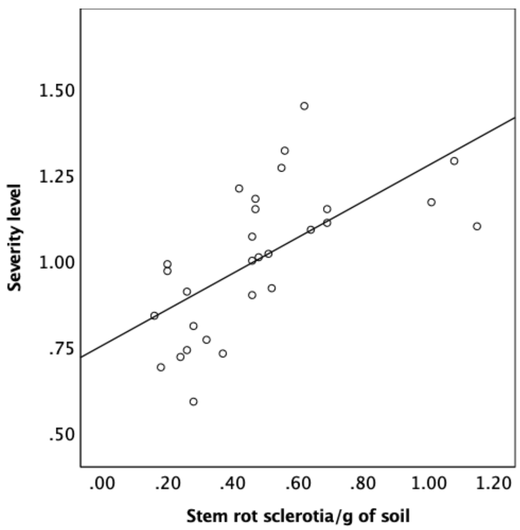


Figure 11. Disease severity (0=healthy, 4=culm rotted through) is positively correlated with the number of sclerotia present in the upper layer of soil prior to planting. From Webster et al., Hilgardia 49 (3), 1981.

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

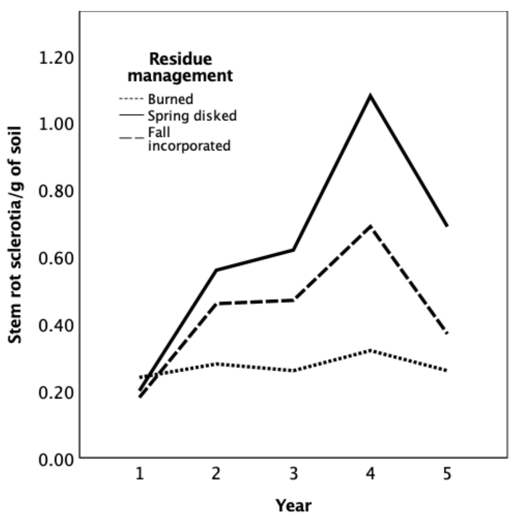


Figure 13. Residue management plays a key role in the management of stem rot. Burning or decomposing straw during wintertime can reduce the number of sclerotia in the soil, resulting in lower disease levels during the season. From Webster et al., Hilgardia 49(3), 1981.

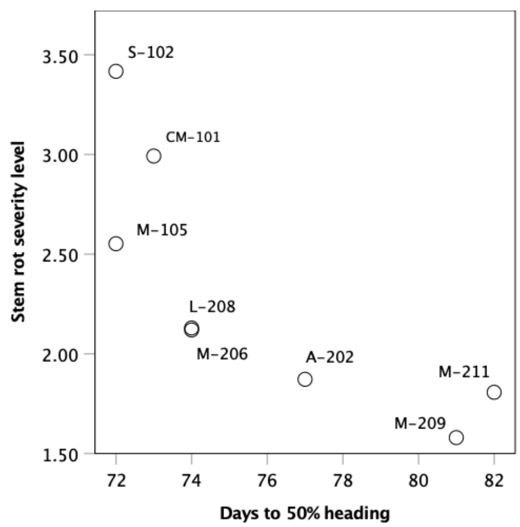


Figure 14. Stem rot severity (0=healthy, 4=culm rotted through) at the end of the season among selected varieties. Varieties with longer periods of development tend to have lower stem rot severity. Richvale, Butte County, 2021.

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 condictions, 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

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

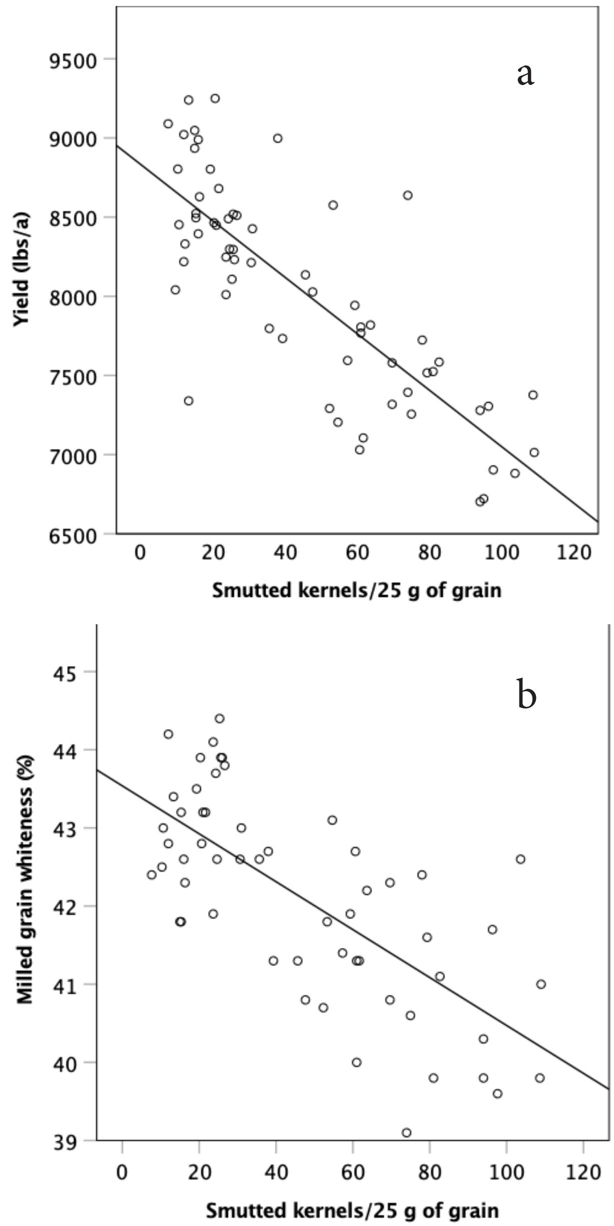


Figure 24. Relationship between kernel smut infection in a long grain variety with yield (a) and milled grain whiteness (b). As the number of smutted kernels increases, both parameters decrease. Richvale, Butte County, 2020.

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.

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.

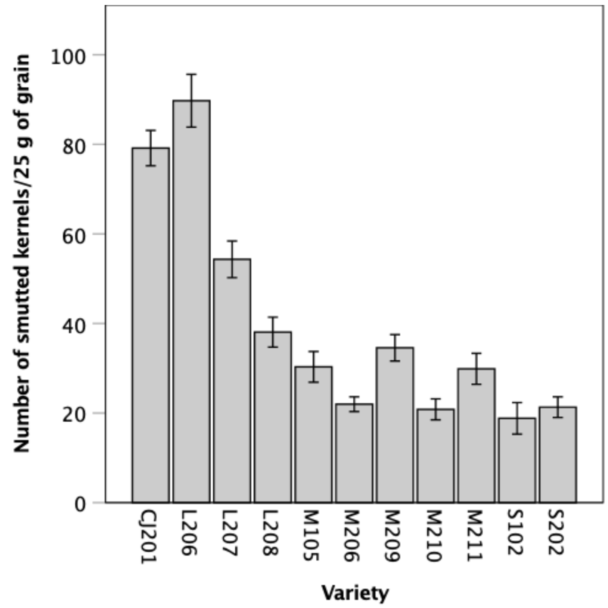


Figure 25. Response of common rice varieties to kernel smut. Short and medium grain varieties are considered less susceptible than long grain varieties. Glenn County, 2018.

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.

INVERTEBRATES

Numerous species of invertebrate animals are found in rice fields. These species are able to utilize the short-term aquatic environments of a typical rice field and are often pre-adapted to this type of agricultural environment. The changing nature of a rice field limits use of this habitat to invertebrates with specific life histories. Rice fields go from dry soil to a flooded aquatic environment, followed by quickly developing plant material, and finally drained soil with senescent plants. Insects, spiders, crustaceans, and other groups constitute the invertebrates in rice fields. In a study conducted in 1990, researchers sampled and identified about 60 different species of arthropods in a survey of a California rice field. More recent efforts in the 2000's again found this level of diversity in California rice fields.

Most of these invertebrates inflict no damage to rice plants, whereas about ten species can hinder rice productivity and yield. Rice is most susceptible to damage during the first six weeks after seeding. A couple of species of insects and crustaceans decrease seedling establishment. During the vegetative growth phase, a few species can potentially be problematic by feeding on foliage, but populations are generally low and damage minimal. Invertebrate pests in California are uncommon during the grain-filling period. The rice stink bug, a pest that severely impacts grain quality of southern U.S. rice, is absent in the California system. Similarly, leafhopper and planthopper species (and associated virus diseases they transmit) that severely hamper Asian rice production do not occur in California rice. Stem borers also do not occur in California rice.

Another segment of the invertebrate complex in rice fields that is of interest is the mosquito population and the natural enemies that feed upon aquatic mosquito eggs, larvae, and pupae. These individuals have no direct impact on rice plant productivity but are important from a "good neighbor" standpoint. Rice production practices can affect mosquito populations and their management. Mosquito management is gaining increased importance with the increased prevalence of mosquito-vectored diseases, i.e., West Nile Virus.

A rice field is a definite "agroecosystem". Management actions intended to facilitate seedling establishment, weed control, plant growth (fertilization), etc. have effects on population levels of invertebrates. These effects could be positive or negative. Discussions of management of invertebrate pests will be divided into three portions of the growing season:

1. Seeding to 4-5 leaf stage (0 to ~30 days after seeding),
2. 5-leaf stage to heading and flowering stage (30 to ~90 days after seeding),
3. Heading to harvest.
4. Management actions... have effects on populations of invertebrates

Seeding to 4-5 leaf stage

Tadpole shrimp, crayfish, seed midge, and rice leafminer all have the capacity to hinder rice seedling establishment and early-season plant growth. In addition, rice water weevil adults feed during this period; however, the primary damage is inflicted later in the growing season by the rice water weevil larvae that develop on roots under the soil. Insecticidal management of this pest is targeted toward the adults so it is appropriate to consider this pest in this section.

Tadpole shrimp

Tadpole shrimp (fig. 1) persist during dry periods in the egg stage (surviving for several years at minimum) and hatch quickly in the spring with the addition of water and sufficiently high temperatures. Eggs in the surface layer of soil hatch primarily two to three days after the flood is initiated, although some eggs will continue to hatch. Just-hatched tadpole shrimp are extremely small, but young tadpole shrimp grow fast, with higher water temperatures leading to more rapid growth. Initially, they feed on algae and other small organisms. Very young shrimp resemble adult shrimp, although they have less pigmentation. When their carapace (primary shell) is about half the length of a rice seed, tadpole shrimp readily feed on germinating rice seeds, preferring the emerging radicle and coleoptile (fig 2, fig. 3). Large tadpole shrimp can cause further damage by uprooting seedlings while digging in the soil. The occurrence of floating seedlings, cast exoskeletons (shed skins produced as the tadpole shrimp molts), and muddy water (from shrimp digging) are indicative of tadpole shrimp infestations. Chewed and pruned roots on the floating seedlings can distinguish drifting seedlings due to tadpole shrimp from seedlings that are floating due to strong winds or other conditions.

Muddy water produced by the shrimp can reduce light penetration and further inhibit seedling growth and establishment. Once seedlings have a well-established root and the prophyll (spike) is emerged, they are less susceptible to tadpole shrimp injury. Mature tadpole shrimp lay eggs along the bottom.

Management of all seedling pests is generally similar. For tadpole shrimp, application of insecticides pre-plant or soon after seeding is typically most effective due to the quick developing nature of the infestations after flooding. Scouting for tadpole shrimp while small followed by rapid applications can still avoid damaging populations however. Actions that facilitate quick establishment of rice seedlings can also mitigate damage from tadpole shrimp. Since they only damage rice seeds and young seedlings, once these stages are past, the potential for damage is low. Quick flooding and timely seeding reduces the risk of injury. Field draining soon after seeding until there is no standing water can assist in managing tadpole shrimp.

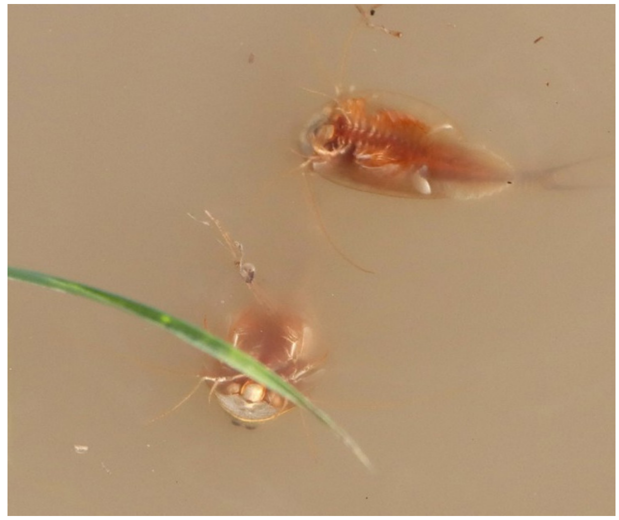


Figure 1. Tadpole shrimp can feed on germinating seeds, uproot seedlings, and muddy water, reducing the amount of light seedlings growing underwater can get.

Figure 2. Small tadpole shrimp look very similar to large shrimp, with a rice grain shown for scale here.

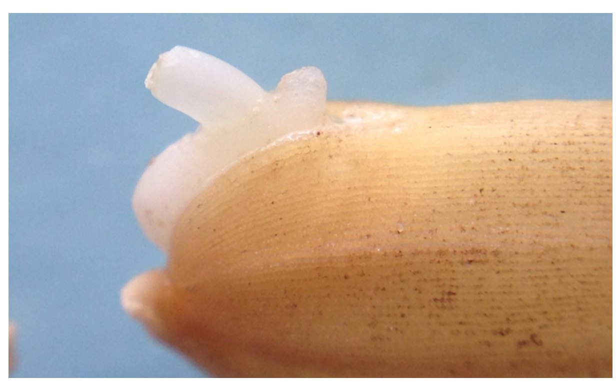


Figure 3. Tadpole shrimp injury to the emerging coleoptile.

Crayfish

Crayfish (fig. 4) make burrows and tunnels in levees near water boxes, compromising the structure of the levee (fig. 5). Crayfish's tunneling activity can cause seepage in levees, which could result in the illegal release of pesticide-treated water. Crayfish feed on dead and decaying matter, insects, and plants.

Their feeding on plants can also be a problem on seedling rice. Muddy water, uprooted seedlings, and reduced stands result from crayfish infestations as they feed on rice and forage along the bottom.

Similar to preventing damage by tadpole shrimp, quick flooding and seeding can prevent damage to seedlings by crayfish. Crop rotation can also help manage crayfish. No insecticides are labelled for crayfish.

Rice seed midge

Rice seed midge also hinders seedling establishment and can damage newly planted rice as larvae. There are several midge species in this pest grouping (Cricotopus sylvestris, Paralauterborniella subcincta, Paratanytarsus spp.). The adults are a small, somewhat mosquito-like fly, although they cannot bite like a mosquito (fig. 6). Adults are extremely mobile. Upon flooding a field, thousands of these adults fly to the field and deposit eggs on the water surface. Swarms of adult midges near fields are often misidentified as mosquitoes. The eggs hatch in one to two days and the larvae feed on the soil surface of the flooded field (fig. 7). Larvae feed on seeds and seedlings as well as on algae. They often destroy the seed before it can germinate in the water (Fig. 8). Once the seedling is 3 to 4" long, it is not susceptible to midge damage.

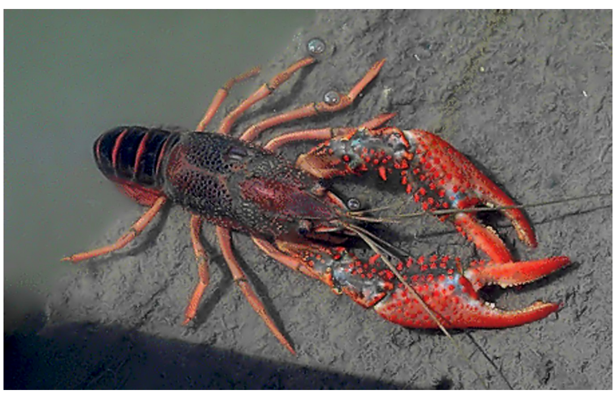


Figure 4. Crayfish can directly affect rice by feeding on the germinating seed

Figure 6. The rice seed midge can produce large swarms under certain conditions.

Figure 5. Holes dug by crayfish may cause unwanted seepage.

Figure 7. Rice seed midge form tubes in sediment.

Management of all these seedling pests is similar. Application of insecticides pre-plant or soon after seeding is most effective due to the quick developing nature of the infestations after flooding. Scouting for tadpole shrimp while small followed by rapid applications can still avoid damaging populations. Actions that facilitate quick establishment of rice seedlings can also mitigate damage from these pests. Since these invertebrates only damage rice seeds and young seedlings, once these stages are past, the potential for damage is low. Quick flooding and timely seeding reduces the risk of injury by these pests. Crop rotation can help manage crayfish, and field draining soon after seeding can assist in managing tadpole shrimp and seed midge.

Figure 8. Developing rice seed midge larvae will feed on germinating seeds, killing them.

Rice leafminer

The rice leafminer was a significant pest of rice in California through the 1970's. During the 1990's, this pest could be found at low levels in most fields. Today, populations of rice leafminer are very low or absent. The adult fly is small, bristly, and brown-grey. Female flies lay single eggs on leaves. The resulting larva (fig. 9) mines between the epidermal layers of the leaf (fig. 10). This injury can resemble that of rice water weevil adults with the difference being that the leafminer larva can be seen in the leaf when it is held up to the sunlight. There are multiple generations of rice leafminers per year (up to 11), but this pest only damages rice before the plants start to grow upright. Leaves laying on the water surface are susceptible to attack. Therefore, slow-growing rice (cool weather and/or deep water) is most susceptible to damage. Biological control by parasitic wasps does aid in managing this pest.

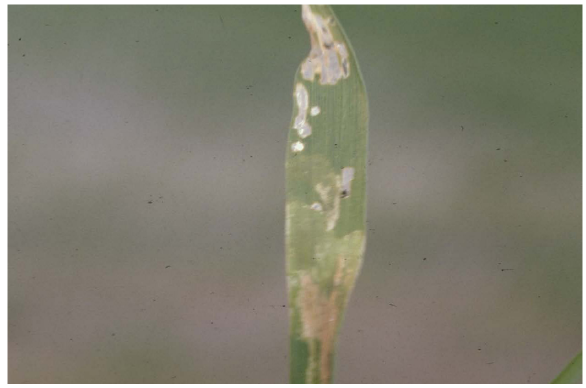


Figure 9. Rice leafminer larvae tunnel within the leaf eating the tissue.

Figure 10. Large rice leafminer numbers can cause browning of the leaf and reduce photosynthesis

Rice water weevil

The rice water weevil (fig. 11) was one of the most damaging insect pests of rice in California after its discovery in the Sacramento Valley in the late 1950s. Currently, noticeable damage by rice water weevil is unusual and limited to areas with a history of rice water weevil pressure. Most likely, the decline in issues with rice water weevil can be explained by the use of new, more vigorous varieties and the intensive use of insecticides to manage tadpole shrimp.

Adult rice water weevils overwinter in a diapause (reduced activity) state in ditch banks, crop residue, and riparian areas. As temperatures increase, adults feed on leaves of grasses and break diapause. Through this, they regenerate their flight muscles such that adults can fly for several miles (hypothesized to up to 20 miles). The spring flight (Apr.-June) occurs days with warm, calm evenings. Adults prefer to infest newly flooded rice fields. Fields with rice plants emerging through the water are most susceptible to infestation. Adults feed on the leaves of rice plants, which result in characteristic longitudinal feeding scars (fig. 12). This feeding has no effects on spring rice growth or yield.

Adults oviposit in rice leaf sheaths just below the water level in plants with 2 to 6 leaves. Eggs hatch in 5-7 days. The first instar larvae feed on leaves for a few days and then drop down through the water and soil to the roots (fig. 13). The remainder of the life cycle is spent in the flooded soil of rice fields. The larvae develop through four instars and feed on rice roots. Rice water weevil larvae root feeding causes reduced plant growth, chlorosis, and reduced tillering. These symptoms become noticeable four to six weeks after seeding. Pupation occurs on rice roots (fig. 14) and new adults emerge in late July. These adults feed to a limited extent on rice leaves and then leave the rice fields for overwintering sites. In California, damaging infestations of rice water weevil larvae are limited to areas up to 50 feet next to borders of fields and levees (fig. 15). Grain losses from larval feeding of up to 45% have been recorded. In California, research results support an economic threshold of about 1 larva per plant.

Management of rice water weevil in California relies on chemical and cultural controls. Biological control of this pest is nonexistent. For cultural controls, removal of levee vegetation in the spring helps reduce rice water weevil den-

Figure 11. The rice water weevil is the most important pest of rice in the US. In California, it only affects areas near borders and levees.

Figure 12. Overwintering adults emerge in the spring to feed on rice leaves

Figure 13. The small, legless larva drop to soil where they feed on the roots.

sities. The additional herbicides required for this and the loss of wildlife habitat on levees are substantial drawbacks of this tactic. Two additional cultural methods assist in reducing rice water weevil densities, but may not fit all production schemes. They include dry seeding rice and delaying seeding dates. The reduced yields that can result from these techniques make them undesirable to growers.

Currently, the need for insecticide applications against rice water weevil rely on grower experience and the history of the field. Several insecticides are available for rice water weevil. In 1999, diflubenzuron (Dimilin) and lambda-cyhalothrin (Warrior) were registered, followed by another pyrethroid, zeta-cypermethrin (Mustang), in 2002. Generic formulations of lambda-cyhalothrin are also available. These insecticides are effective for RWW management in California, although they have limitations. They target adults, and have limited effects on larvae, which is the damaging stage. Dimilin sterilizes adults (i.e., females produce no viable eggs) and the pyrethroid products kill adults, limiting egg laying. Application timing is of utmost importance since control with these products is not possible after a few days following oviposition. These insecticides are recommended to be sprayed at the 2-4 rice leaf stage. Additionally, lambda-cyhalothrin can be applied preflood up to five days before the field is flooded. Applications can be made to field borders and only 50 feet adjacent to the levee. Clothianidin (Belay), a third generation neonicotinoid, was registered in 2014. A post-flood application timing (~2-3 leaf stage) appears to be the optimal timing or this product, although clothianidin can be used as a rescue treatment when larvae are present and feeding on roots at the 5 to 6 leaf stage of rice.

Figure 14. Feeding from the larvae will prune the root system and retard the growth of the plant, resulting in costly yield reductions.

Figure 15. Injury by rice water weevil is observed as a reduction of plant growth, reduction in tillering, and chlorosis. Damage is limited to areas near borders and levees.

5-leaf Stage to Heading and Flowering Stage

Two species of armyworms, true armyworm and western yellowstriped armyworm, are found in rice fields during the summer, although true armyworm is the species most often associated with damage (fig. 16). In recent years, damage from these pests has been more severe than it has been historically.

The armyworm moth lays its eggs in linear masses with the leaf tied around the eggs in a roll on rice or other grass species in and around rice fields. Larvae of both species are striped and vary in body color. Larvae feed predominantly at night or during cloudy days. They grow to full size and pupate in about 3 to 4 weeks in the summer. Pupation normally takes place in the upper surface of the soil or in debris, so many

Figure 16. Armyworm larva with true armyworm on the left and yellowstriped armyworm on the right.

Figure 17. Adult true armyworm.

mature larvae drown in flooded paddies before reaching a suitable pupation site. However, some are able to pupate lodged between leaves or tillers. Adult moths of both species have a wing span of about 1.5 inches and are predominantly silver and gray (western yellowstriped armyworm) or buff colored (true armyworm) (fig. 17).

Damage by armyworms typically occurs during periods of stem elongation (early summer) and grain formation (late summer). Larvae defoliate plants, typically by chewing angular pieces off

Figure 18. Leaf damage is the most obvious sign of the presence of caterpillars. Even large caterpillars can be hard to find, as evidenced by the two caterpillars hiding in the photo on the right.

Figure 19. Severe defoliation can occur when armyworms reach high population levels.

leaves (fig. 18). During outbreaks, defoliation to the water level can occur (fig. 19). Armyworm larvae may also feed on the panicle, specifically on the rachis near the developing kernels causing these kernels to dry before filling. This feeding causes all or parts of the panicle to turn white (fig. 20). The seriousness of armyworm injury depends on the maturity of the plant and the amount of tissue consumed. Significant yield reduction can occur if defoliation is greater than 25% during the early summer infestation or if panicle injury is higher than 10% later in the summer

True armyworm outbreaks occurred in 2015, 2016 and 2017. Pheromone moth trapping is being used to predict activity of armyworm larvae and improve timing of field monitoring (fig. 21). Various natural factors cause mortality of armyworms. Many caterpillars drown or are killed by natural enemies, including predators,

Figure 20. Armyworm injury during heading results in broken panicle branches and empty kernels.

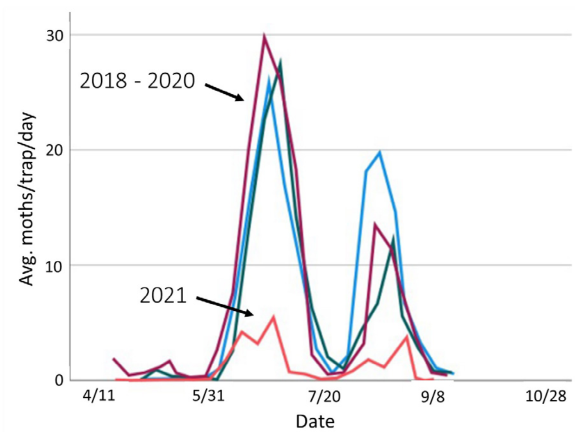


Figure 21. Average number of true armyworm moths trapped across the Sacramento Valley in pheromone traps, 2018-2021. There are typically two peaks in adult moth captures.

pathogenic microorganisms, and parasitoids. Insecticide treatments are justified if, from late June through early July, more than 25% defoliation occurs and armyworms are present on the plants. Treatment for panicle loss is justified if 10% of the panicles in the area sampled are damaged and armyworms are observed.

The pyrethroid insecticides (lambda-cyhalothrin and zeta-cypermethrin) are ineffective for controlling armyworms. The insect growth regulator diflubenzuron (Dimilin) is effective; however, it has an 80 day pre-harvest interval which prevents its use during the heading stage. The biological insecticide Bacillus thuringensis is effective when applied against small armyworms, which can be difficult to find timely in the field. The insect growth regulator methoxyfenozide (Intrepid) has received a Section 18 registration, allowing its use on rice on a yearly basis. Other alternative insecticides are still being evaluated.

Heading to Harvest

A few instances of pecky rice (fig. 22) have occurred in California in recent years. Pecky rice refers to kernels that exhibit a discoloration after hulling and milling. This discoloration can be caused by insects, but can also be caused by pathogens developing on the kernel due to excess moisture from rain or lodged rice. In fields that produced some pecky rice and quality downgrades the previous year, a native stink bug called the redshouldered stink bug (fig. 23) (Thyanta pallidovirens [= T. accerra]) was collected the following year in early September.

Figure 22. Pecky Rice

Figure 23. Redshouldered stink bug

Cage studies showed that this and other common stink bug species have the potential to feed on developing kernels and cause peck. Stink bugs can be common in rice fields with higher levels of weeds, fields near natural/riparian areas, and rice fields interspersed with other crops. Nevertheless, in most fields, stink bugs are present at very low levels and do not constitute a problem.

Additional Information:

The UC Pest Management Guidelines for Rice maintains up-to-date information on management of key invertebrate pests of rice (UC IPM Pest Management Guidelines: Rice, UC ANR Publication 3465; http:// www.ipm.ucdavis.edu/PMG/selectnewpest.rice.html). In addition, the publication entitled, Integrated Pest Management for Rice, 3rd Edition (UC ANR Publication 3280) is a good resource for rice IPM.

WEEDS

Introduction

Weed populations have always been dynamic and the continuous use of almost any management practice alone has resulted in the loss of weed control. About the only certainty in California rice weed management is change. Within a few years after the introduction of rice in 1914, weeds were running rampant in the dry-seeded culture established at the time. Dr. Jenkins Jones wrote in 1924 that "practically all, if not all of the lands—and these represent the major portion of the rice acreage—are quite foul with water grass," and that on these lands it was "practically impossible to grow profitable rice crops." Jones' research led to water-seeding, but large seeded biotypes of water grass better able to emerge through the continuous flood became the dominant weed problem along with a new set of aquatic species. These included the sedge species, the aquatic broadleaf species and the late watergrass biotypes or so-called "mimics" which evolved in Asia from selection pressure of hand weeding. As weeds that looked different from rice were hand pulled the ever evolving survivors looked more and more like rice; hence, the name mimic." Since 1992, several weed species that commonly infest California rice fields have evolved resistance to herbicides. Even multiple resistances, the resistance to more than one type of herbicide action, has evolved. This and the advent of mostly foliar applied herbicides have greatly increased the difficulty of watering and hence weed control. Adding to the complexity of rice weed management are regulatory aspects related to herbicide drift, buffer zones and water holding periods that limit weed control choices and shape decisions. The following discussion and tables provide a framework for decision-making in the increasingly complex of rice weed control.

The Weeds: Species, Recordkeeping and Resistance

Proper identification of weed species is essential to successful weed management in rice. Weed identification is particularly important because many of the rice herbicides control one or only a few species, so incorrect weed identification can lead to poor control. It is not enough to group weeds broadly into sedges, "lilies" and grasses. Rather, we need to know with certainty that the weed is ricefield bulrush instead of smallflower umbrella sedge; or to know with certainty that the weed is California arrowhead rather than ducksalad or some other broadleaf species. Moreover, knowledge of the species and its competitive ability are critical to target the most important and potentially damaging weeds. For example, even though California arrowhead may be the dominant species in a field, will it be the most damaging? Weed species common to California rice are listed in Table 1.

Field history is a valuable tool for understanding the changes in weed populations. Although it is common to keep field records of varieties, yields and quality, it is relatively uncommon to see good records and maps of the weed species present in a field. Records of weeds (complete with field maps) coupled with good documentation of management and herbicide practices provide very useful information about the build-up of certain weed species, weed resistance and other aspects related to weed control (such as whether or not the weed infestations are related to field operations—field equipment, etc.). Furthermore, the ability to use certain herbicides depends on the ability to document resistant weed populations in the field. Most importantly, good field records will likely improve the ability to select management practices and herbicides to minimize weed problems.

Table 1. The common and scientific names of major weeds in California rice.

Group	Common Name	Scientific Name	Weed Type
Grasses	Barnyardgrass	*Echinochloa crus-galli*	annual
	Watergrass (early)	*Echinochloa oryzoides*	annual
	Watergrass (late)	*Echinochloa phyllopogon*	annual
	Sprangletop, bearded	*Leptochloa fusca ssp. fascicularis*	annual
	Sprangletop, Mexican	*Leptochloa fusca ssp. uninervia*	annual
	Weedy Rice	*Oryza sativa*	annual
Sedges	Smallflower Umbrella Sedge	*Cyperus difformis*	annual
	Bulrush, Ricefield	*Schoenoplectus mucronatus*	annual
	Bulrush, River	*Schoenoplectus fluviatilis*	perennial
	Cattails	*Typha spp.*	perennial
Broadleaf	California Arrowhead	*Sagittaria montevidensis*	annual
	Gregg’s Arrowhead	*Sagittaria longiloba*	perennial
	Ducksalad	*Heteranthera limosa*	annual
	Marshweed	*Limnophilia spp.*	perennial
	Pickerelweed	*Monochoria vaginalis*	annual
	Pondweed, American	*Potamogeton nodosus*	perennial
	Redstems	*Ammannia spp.*	annual
	Common Waterplantain	*Alsima triviale*	perennial
	Waterhyssop	*Bacopa spp.*	annual
	Winged Primrose Willow	*Ludwigia decurrens*	annual

Record keeping is even more important with the advent of herbicide resistance. It is now not enough just to identify a particular species, but whether or not it exhibits herbicide resistance is of paramount importance to selecting the correct herbicide, combination or sequence. Currently, the only diagnostic services to determine whether or not weeds are resistant are provided by UC Davis Weed Science Program at the Rice Experiment Station at Biggs or by the companies whose products are involved. Submitting samples to the UC weed program requires specific records related to field history, cultural management, water delivery system and farming operations. Thus, such diagnosis depends on the records of field history. Aside from diagnostic confirmation of weed resistance, the best indicator is whether or not properly applied herbicides are able to control the weeds. If not, the chances are good that the species may be resistant. However, other possibilities should be eliminated before concluding that the weed is resistant. One telltale sign, assuming that all conditions such as weed growth stage, weather and management practices were ideal, is the survival of a single, normally susceptible species while all others are controlled. The survival of a single species year after year when it was previously controlled is also a reasonable indicator of resistance. However, allowing weeds to reproduce over time eliminates the option of prevention to keep resistant weed seed banks at low levels in the soil. Certainly, the early identification of weed resistance and even draconian efforts to reduce weed seed production are essential to combat resistant weeds—especially on a farm scale where resistant populations could be restricted to single fields rather than be allowed to spread.

Weed Management: Prevention

Prevention can be an important part of rice weed control. Prevention sounds good but unfortunately is not practiced as much as it should be. The use of certified seed is probably the best example of weed prevention in California. By comparison to most other areas of the world, California has one of the highest percentages of planted acres in certified seed — nearly 100% at its peak, but with economic downturns this has been somewhat lax at a time when resistant watergrass should have made it imperative. Certified seed standards do not permit weedy (red) rice or noxious weed seeds and have eliminated red rice from California. The maximum allowable is 0.10 weed seeds by weight, and further limits watergrass and barnyardgrass seeds to less than 0.01 by weight. Irrigation water and farm machinery frequently transport weed seeds or other plant propagules into the field. The introduction of weed seed, tubers, and rhizomes can be reduced by cleaning farm implements when they are moved from field to field.

Weed Management: Cultural Methods

The value of good cultural practices cannot be underestimated in their importance to weed management. Although they are generally not enough by themselves, good practices can greatly suppress weeds and enhance the effectiveness of herbicides used in combination with them. Most, if not all of these cultural methods will be a necessary part of crop management anyway, so in controlling weeds, they become extremely cost effective. For example, good water management can be the most efficient method available to suppress weed species such as sprangletop, barnyardgrass, and even watergrass, to the point that herbicides can control them more effectively.

Tillage and Field Preparation

Tillage, land leveling, and preplant fertilizing all influence weed germination and growth. These management practices are covered in other chapters of this workbook and will be discussed here only in reference to weed management. Tillage and field preparation have changed dramatically with the advent of rice straw incorporation and winter flooding. Generally, the soil is wetter for longer periods and thus drying of over wintering rhizomes and corms of perennial weeds is not possible unless heavily infested fields are specifically targeted for dry tillage. Additionally, straw incorporation by wet rolling and especially discing or plowing in the fall incorporates weed seed, creating an over wintering seed bank that cannot be reduced by bird and small mammal depredation. In the spring, inadequate grading or planing of the field can leave high spots for weed germination or low areas where weeds remain under the floodwater during the application of foliar-active herbicides.

Water Management

Proper water management is the most important factor in controlling weeds in rice. Careful land grading and seedbed preparation before planting help maintain uniform water depths in rice fields. Ideally, fields should be flooded continuously to a depth sufficient to suppress weeds, particularly the grasses and smallflower umbrella sedge—generally 4-8” deep. However, this works only if the herbicides are effective when applied into the water. The advent of weed resistance to many of the into-the-water herbicides has necessitated a change to foliar-active

Table 2. Waterholding requirements, pre-harvest intervals (PHI) and restricted entry intervals (REI) for rice herbicides (by trad name and active ingrident). Note: Rice herbicides waterholding requirements, pre-harvest intervals (PHI) and restricted entry intervals (REI) from product labels. Please read and follow label directions and contact your county agricultural commissioner for label interpretations and permit conditions.

COMMON TRADE NAME	ACTIVE INGREDIENT	WATERHOLD TIME	PRE-HARVEST INTERVAL (PHI)	RESTRICTED ENTERY INTERVAL (REI)
Solution Water Soluble	2,4-D	0-days	60-days	48 hours
Londax®	Bensulfuron-methyl	7-days static	80-days	24 hours
Butte®	Benzobicyclon + Halosulfuron	20-days	82-days	12-hours
Shark®	Carfentrazone-ethyl	5-days static 30-days release: less close system	60-days	12-hours
Cerano® MEG	Clomazone	14-days	120-days	12-hours
Clincher® CA	Cyhalofop-butyl	0-day	60-days	12-hours
Loyant® CA	Florpyrauxifen-benzyl	0	60-days	12-hours
Sandea®, Sempra®	Halosulfuron-methyl	0-days	69-days	12-hours
Strada®	Orthosulfamuron	0-days	90-days	12-hours
Granite® SC & GR	Penoxsulam	0-days	60-days	12-hours
Stam® 80 EDF SuperWham!®	Propanil	7-days: Less closed system	60 days	24-hours
Abolish® 8EC Bolero® UltraMax League® MVP	Thiobencarb	See appendix 1	See appendix 1	7-days
Grandstand® CA	Triclopyr TEA	20-days: less closed system	60-days	48-hours

or contact herbicides. Foliar herbicides require good coverage on the weed, thus if used early in the season when weeds are small, the field must be drained. Rapid reflooding for weed suppression and to prevent a new flush of germination is also necessary. This will be next to impossible on fields that take several days to flood or where water is insufficient to reflood rapidly. Adequate canals, drains, and water control structures are necessary to provide for efficiently regulating the flow of irrigation water. Where irrigation structures or water availability do not allow for rapid drainage and reflooding, it may be necessary to reduce field size. Large fields may be made smaller, or each basin managed independently with separate inflows and outflows to achieve the necessary water precision to optimize foliar herbicides. Land leveling, grading, and efficient irrigation management are equally important to meet state man- dated water holding regulations (Table 2) following herbicide applications. Inefficient irrigation may allow too much water in the lower end of a field with no recourse but to hold deep water.

Rotation

Not all rice soils can be rotated to other crops. However, rotation out of rice can greatly reduce weed populations in subsequent rice crops. Rotating to crops for which effective weed controls are available, such as tomato, safflower, cereal crops, or sunflower, is one of the best ways to manage weeds that cannot be selectively controlled with herbicides and cultural practices in rice. Non-flooded conditions, seedbank decay and alternative herbicides in the rotation crop all contribute to reducing future weed infestations. In fields where perennial weeds with tubers, rhizomes, or large rootstocks such as cattail, pondweed, Gregg's arrow-head, and bulrush, a dry fallow rotation out of rice may be necessary. Plowing the rice field to a depth of 8 to 12 inches (20 to 30 cm) during the fallow season can add to these benefits. In rice-only soils, a rice-rice rotation of the cultural method such as flooding one year and dry seeding or stale seedbed techniques the next, coupled with non- selective preplant herbicides, may help in controlling weed species resistant to normally used rice herbicides.

The Herbicides

When Londax dominated the California market for weed control in water-seeded rice in the early 1990s, there was relatively little interest in new products. With the onset of widespread weed resistance, many old and new products have entered, or are about to enter the market (Table 3).

While all the new products hold promise for improving weed management in rice, they add to the puzzle of information needed to use them safely and efficiently. For example, if a foliar applied herbicide is translocated in the plant, it may not be necessary to completely drain the field to provide enough foliage above the water; but in combination with a foliar herbicide that does not translocate (contact), weed control could be greatly compromised by not having the field completely drained to fully expose the weeds. If the field is completely drained, of course, there is the very real possibility for a new flush of weeds such as sprangletop. Thus, it is extremely important to know the behavior of each herbicide in the plant and the environment. Most of the California rice herbicides are somewhat limited in the spectrum of weeds controlled, requiring the proper selection either alone, in combination or in sequence to give adequate weed control. The weed spectra and water management regimes for the currently available herbicides are shown in Figure 1a and 1b. Potential weed control given in the tables is based on both company and UC Davis research and represents the control that could

Table 3. The common and trade names of current herbicides for rice in California.

Common	Trade Names
Bensulfuron	Londax
Benzobicyclon + halosulfuron	Butte
Bispyribac	Regiment
Carfentrazone	Shark
Clomazone	Cerano
Cyhalofop	Clincher
Florpyrauxifen	Loyant
Halosulfuron	Sempra, Sandea
Orthosulfamuron	Strada
Pendimethalin	Prowl
Penoxsulam	Granite
Propanil	Stam, SuperWham!
Thiobencarb	Abolish, Bolero
Thiobencarb + imazosulfuron	League MVP
Triclopyr	Grandstand

be consistently expected of a particular product, assuming that the weed species are not resistant. Different uses of the same product, application timing, field management and environmental conditions (weather) may all increase or decrease control. For example, SuperWham or Stam (propanil) work better at or above 75º F and with eight or more hours of sunlight following application. Light is required because propanil blocks photosynthesis. Shark into-the-water may control a broader range of species than indicated in Figure 1 if used as a foliar applied herbicide, but higher rates are required. For best control, carefully read and follow the label which will state the rates, adjuvants, combinations and other requirements of the product. By mixing and matching the herbicides in Figure 1 a complete spectrum of weed control may be possible. However, in addition to the weed spectrum, it is important to know how the herbicide is taken up by the weed, if it is translocated in the plant, the range of application timings for weed control and crop safety, if the herbicide has residual activity, whether or not the weeds are resistant and if tank mixes or sequences are antagonistic.

Herbicide Combinations

Tank mixtures may be used when two or more herbicides are compatible. This requires that not only must they be chemically compatible, but best management practices for their application such as timing and water depth are the same. Tank mix combinations can reduce the cost of application and often reduce the rates of one or more herbicides. The purpose of combinations is to broaden the spectrum of weed control such that each herbicide in the mix will control the weeds missed by its partner (Figure 2). Even though some herbicides complement each other in timing and weed spectrum, they cannot be mixed because of antagonism. Antagonism can be manifested in either injury to rice or as a lack of weed control—that is one herbicide increasing the injury to rice by the other or reducing the normal effect of the other on weed susceptibility. It is important to follow the label of each herbicide with regard to tank mixes.

Herbicide sequences

To achieve good broad-spectrum weed control, most herbicides must be used in sequence rather than as tank mixes. This is because of differences in the behavior of the herbicides with respect to timing, water management, antagonism, translocation and other factors. Probably the most important aspect of these sequences is to protect against the buildup of weed resistance by using different modes of action. For example, a sequence of Clincher followed by propanil will take out any remaining watergrass with resistance to Clincher. Figures 3, 4 and 5 show the weed susceptibility of herbicide sequences with Regiment, Cerano and Clincher, respectively. Unlike herbicide tank mixes, sequences can be complicated by the need to raise and lower water depths to meet the requirements of each herbicide in the sequence. Water management requirements for the different herbicide sequences are also shown in Figures 3, 4 and 5.

Behavior of Herbicides

Table 4 provides additional information on the behavior of current and future herbicides respectively.

Table 4. Behavior of currently used herbicides(lsr = rice leaf stage; mt = mid-tillering; ** = both foliar & soil activity)

1. Foliar Activity. Herbicides that must be directly sprayed on the plant to be effective are said to be foliar active and often require fields to be drained before they are applied so the weeds are adequately exposed to the spray.
2. Applied in Water. Herbicides that are formulated as granules (e.g., Bolero Ultramax) are active through the soil and do not require field draining. Herbicides marked with an asterisk (*) are formulated as a spray for foliar contact but are also adsorbed to the soil when sprayed into the water so that plants take them up through the roots as well.
3. Translocation Index. The translocation index provides a measure of how much the herbicide moves within the plant: numbers above 7 indicate highly mobile, numbers below 4 mean little movement. This index is important for water management when applying an herbicide. For example, if a foliar-applied herbicide is translocated in the plant, it may not be necessary to completely drain the field. If it is used in combination with a foliar herbicide that does not translocate (i.e., a contact herbicide), weed control would be compromised by not having the field drained fully to expose the weeds.
4. Timing Window. Application timing is important to minimize rice injury and optimize weed control. Timing is stated in relation to the rice crop development: lsr=leaf stage of rice and mt = mid-tillering. Because several herbicides also work best when timed to the weed's stage of development, the timing window may be further reduced.
5. Residual Activity. Residual activity is the length of time that the herbicide remains active in the soil and is generally determined by the amount and strength of soil adsorption and by the rate of degradation of the herbicide. Residual activity is important in herbicides that are applied early in the season because it helps to prevent reinfestation by subsequent germination of a new flush of weeds before the rice canopy is large enough to shade them out.
6. Mode of Action. Weeds are resistant to the

mode of action that kills them, not to the herbicide per se; consequently, once the weeds become resistant to a particular mode of action, all other herbicides with similar modes of action will likely fail to control the weed. To distinguish between herbicide modes of action, group numbers, assigned by the Weed Science Society of America (WSSA), are listed. Weeds with the same group number have the same mode of action. Although weeds may exhibit multiple resistance (resistance across many groups), mode-of-action numbers are useful in planning mixtures or sequences of herbicides. For more information, see http://wssa.net

7. Weed Resistance. In fields where herbicide resistance has been identified, it is critically important to implement the herbicide resistance management strategies outlined below.
8. No resistance has been confirmed for benzobicyclon, but there is resistance to halosulfuron.

Foliar or Soil Activity

Most of the newer herbicides are active only as foliar sprays. However, Abolish, Bolero, Cerano, Butte, Granite, and Londax have soil activity. Generally, when the product is formulated and used as a granule such as Bolero, Butte or Granite, the activity is through the soil. Abolish, which is the same active ingredient as Bolero, is also active through the soil, but the product is designed as a spray which improves foliar uptake for pinpoint flood management. Like Abolish, Londax is also soil active when sprayed into the water. Generally, rates can be lower when used as a foliar spray than when applied into the water, but each chemical varies so the manufacturer's label should be followed. Products that are effective when applied into the water are weakly adsorbed and concentrated by the soil from where they are released and taken in through the plant roots. Field drainage to expose the weeds is very important for most foliar-only herbicides.

Contact or Translocated

Another important factor affecting the proper use of herbicides is whether or not they move in the plant. Two herbicides may be foliar active but are used quite differently with respect to field management. Translocated herbicides, such as Grandstand and Loyant move from the site of uptake to other parts of the weed to kill the growing point. Contact herbicides move very little from the point of impact, and kill only that part of the plant covered by the spray. Shark, SuperWham or Stam (propanil) hardly move at all, whereas Clincher and Regiment move small distances. Cerano moves, but only upward in the translocation stream, so it will not move down from a foliar application. The translocation indices given in Table 4 are indicators of the relative movement of rice herbicides in the plant. Numbers above seven mean that the herbicide is highly mobile and below four generally means little movement. Matching water management to the translocation characteristics of the herbicide is extremely important to the success of the application. For example, the labels for Grandstand and Loyant, a translocated herbicide, specifies that only 70% of the foliage need be exposed, whereas some contact-only herbicides may require complete drainage.

Window of Application

Herbicides vary widely in their ability to kill weeds of different sizes and in their safety to rice at different stages of growth. The application timing on the product label is given to minimize rice injury and optimize weed control and is the "application window." Abolish and Bolero (thiobencarb) and Cerano have the smallest ap-

Table 4. Behavior of currently used herbicides(lsr = rice leaf stage; mt = mid-tillering; ** = both foliar & soil activity)

Herbicide	Foliar activity [1]	Applied in water [2]	Translocation index [3]	Timing window [4]	Residual (days) [5]	Mode of action [6]	Weed resistance[7]
Bensulfuron (Londax)	Yes	Yes *	4	0–5 lsr	35–40	2	Yes
Benzobicyclon/ Halosulfuron (Butte)	Yes	Yes	4	0–5 lsr	30	27/2	see comment [8]
Bispyribac (Regiment)	Yes	No	4	5 lsr–mt	0	2	Yes
Carfentrazone (Shark)	Yes	Yes *	2	4 lsr–mt	5–8	14	No
Clomazone (Cerano)	No	Yes	6	0–1 lsr	5 (water)	13	Limited
Cyhalofop-butyl (Clincher)	Yes	No	4	2 lsr–mt	0	1	Yes
Florpyrauxifen (Loyant)	Yes	No	8	2 lsr to 60 days before harvest	0	4	No
Halosulfuron (Sandea)	Yes	Yes *	4	0–5 lsr	30	2	Yes
Orthosulfamuron (Strada)	Yes	Yes *	4	2–4 lsr	12–24	2	Yes
Pendimethalin (Prowl)	No	No	0	soil cracking	5 (water) 20 (dry soil)	3	No
Penoxsulam (Granite)	Yes	Yes	4	2 lsr–mt	0	2	Yes
Propanil (Stam, SuperWham)	Yes	No	3	3 lsr–mt	0	7	Yes
Thiobencarb (Abolish)	Yes	Yes *	3	1–2 lsr	20–25	8	Yes
Thiobencarb (Bolero)	No	Yes	3	1–2 lsr	20–25	8	Yes
Thiobencarb/ imazosulfuron (League MVP)	No	Yes	3	1–2 lsr	20–25	8/2	Yes
Triclopyr (Grandstand)	Yes	No	8	5 lsr–mt	0	4	No

1 Foliar Activity. Herbicides that must be directly sprayed on the plant to be effective are said to be foliar active and often require fields to be drained before they are applied so the weeds are adequately exposed to the spray.
2 Applied in Water. Herbicides that are formulated as granules (e.g., Bolero Ultramax) are active through the soil and do not require field draining. Herbicides marked with an asterisk (*) are formulated as a spray for foliar contact but are also adsorbed to the soil when sprayed into the water so that plants take them up through the roots as well.
3 Translocation Index. The translocation index provides a measure of how much the herbicide moves within the plant: numbers above 7 indicate highly mobile, numbers below 4 mean little movement. This index is important for water management when applying an herbicide. For example, if a foliar-applied herbicide is translocated in the plant, it may not be necessary to completely drain the field. If it is used in combination with a foliar herbicide that does not translocate (i.e., a contact herbicide), weed control would be compromised by not having the field drained fully to expose the weeds.

4 Timing Window. Application timing is important to minimize rice injury and optimize weed control. Timing is stated in relation to the rice crop development: lsr=leaf stage of rice and mt = mid-tillering. Because several herbicides also work best when timed to the weed's stage of development, the timing window may be further reduced.
5 Residual Activity. Residual activity is the length of time that the herbicide remains active in the soil and is generally determined by the amount and strength of soil adsorption and by the rate of degradation of the herbicide. Residual activity is important in herbicides that are applied early in the season because it helps to prevent reinfestation by subsequent germination of a new flush of weeds before the rice canopy is large enough to shade them out.
6 Mode of Action. Weeds are resistant to the mode of action that kills them, not to the herbicide per se; consequently, once the weeds become resistant to a particular mode of action, all other herbicides with similar modes of action will likely fail to control the weed. To distinguish between herbicide modes of action, group numbers, assigned by the Weed Science Society of America (WSSA), are listed. Weeds with the same group number have the same mode of action. Although weeds may exhibit multiple resistance (resistance across many groups), mode-of-action numbers are useful in planning mixtures or sequences of herbicides. For more information, see http://wssa.net
7 Weed Resistance. In fields where herbicide resistance has been identified, it is critically important to implement the herbicide resistance management strategies outlined below.
8 No resistance has been confirmed for benzobicyclon, but there is resistance to halosulfuron.

plication windows. Abolish and Bolero require rice to be at least 1 ½ leaf but watergrass not greater than two leaf. Cerano also has a narrow window of application from just before planting to the 1 leaf stage of rice but watergrass must be less than 1 ½ leaf for most effective control. Many of the new herbicides have relatively broad windows of application timing both with respect to crop safety and weed control. Some, like Whip, require rice to be in early tillering before the crop is safe. Regardless of the window, it is important to remove weeds before competition reduces yield. Most research shows that the onset of weed competition is about twenty days after seeding, depending on the severity of the weed pressure and rate of growth. Competition notwithstanding, the new herbicides offer the opportunity to remove weeds where applications have been delayed by weather or to cleanup where weeds have been missed by earlier applications.

Residual Activity

Residual activity is an important attribute in preventing re-infestation by subsequent germination of a new flush of weeds. Residual activity is generally determined by the amount and strength of soil adsorption and by the rate of degradation of the herbicide in the environment. Carfentrazone, for example, has a half-life of only about five days and hence a short residual activity, whereas Londax residual is 35 days. Residual activity is much more important for early applications before the rice canopy is capable of shading out weeds. Mixing a residual herbicide with early applications of foliar herbicides such as propanil can sustain control long enough for the rice canopy to cover. It is, however, a double-edged sword in that selection pressure for weed resistance continues as long as the herbicide remains active in the soil.

Mechanisms of Action

It is essential to know which herbicides have similar mechanisms of action because weeds are resistant to the mechanism that kills them, not to the herbicide per se. Once the weeds become resistant to a herbicide with a particular mechanism of action, all other herbicides with a similar mechanism of action will likely fail to control the weed. Table 5 shows the current rice herbicides grouped by mechanism of action. Thus, it would not be a good idea to use Granite where resistance to Regiment has been documented. To prevent the further buildup of resistant weed seed banks, herbicides with different mechanisms of action should be rotated or used in sequence or combination to prevent resistant species from setting seed.

Table 5. Herbicides mechanism of action

Group	Active Ingredient	Mechanism of Action
Thiocarbamates	thiobencarb (Abolish, Bolero)	VLCFA (Very long chain fatty acids)
Aryloxyphenoxy-propionates	cyhalofop-butyl (Clincher)	ACCase inhibitors
Amide	propanil (SuperWham, Stam)	Photosystem II inhibitor
Sulfonylurea	bensulfuron (Londax) halosulfuron (Sempra) Orthosulfamuron (Strada) Imazosulfuron (component of League)	ALS inhibitor
Phrimidinyl-thiobenzoates	bispyribac (Regiment)	ALS inhibitor
Triazolopyrimidines	penoxsulam (Granite)	ALS inhibitor
Dinitroaniline	pendimethalin (Prowl)	Tublin inhibitor (mitosis.)
Isoxazolidinone	clomazone (Command)	Carotenoid biosynthesis
Pyridine-carboxylates	florpyrauxifen-benzyl (Loyant)	PPO inhibitor
Pyridyloxy-carboxylates	triclopyr (Grandstand)	Synthetic Auxin
Unclassified	benzobicyclon (Butte)	HPPD inhibitor

CALIFORNIA RICE WEED HERBICIDE SUSCEPTIBILITY CHART

Mode of action	Product name (active ingredient)	Grasses: Barnyardgrass	Grasses: Early watergrass	Grasses: Late watergrass	Grasses: Sprangletop	Sedges: Ricefield bulrush	Sedges: Smallflower umbrella sedge	Broadleaf weeds: Ducksalad	Broadleaf weeds: Monochoria	Broadleaf weeds: Redstem	Broadleaf weeds: California arrowheads
ACCase inhibitor ►	Clincher® CA (cyhalofop)	■🔴R	■🔴R	■🔴R	■🟡R	□	□	□	□	□	□
Pigment synthesis inhibitor ►	Cerano® 5 MEG (clomazone)	■🟡R	■🟡R	■🟡R	■🟡R	□	□	□	□	□	□
Lipid synthesis inhibitors ►	Abolish® 8 EC	■🔴R	■🔴R	■🔴R	■	□	■	□	□	□	□
	Bolero® Ultramax (thiobencarb)	■🔴R	■🔴R	■🔴R	■	□	■	□	□	□	□
Photosystem II inhibitors ►	RiceShot® 48 SF, Stam® 80 EDF CA, SuperWHAM!® CA (propanil)	■🔴R	■🔴R	■🔴R	□	■🟡R	■🔴R	▨	▨	▨	▨
ALS inhibitors ► Three classes of ALS inhibitors ►											
Protox inhibitor ►	Shark® H_2O (carfentrazone)	□	□	□	□	■	■	▨	▨	■	■
Auxin mimics ►	Grandstand® CA (triclopyr)	□	□	□	□	■	□	□	□	■	□
	Loyant® CA (florpyrauxifen-benzyl)	▨	▨	▨	□	■	■	■	■	■	■
Cell divison inhibitor ►	Prowl® H_2O (pendimethalin) Drill-seeded rice only	■	■	■	■	□	□	□	□	□	□

TSA = Triazolopyrimidine sulfonamide POB = pyrimidinyl oxybenzoate SU = sulfonylurea

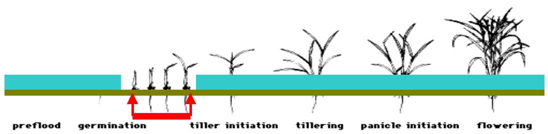
Mode of action	Product name (active ingredient)	Grasses: Barnyardgrass	Grasses: Early watergrass	Grasses: Late watergrass	Grasses: Sprangletop	Sedges: Ricefield bulrush	Sedges: Smallflower umbrella sedge	Broadleaf weeds: Ducksalad	Broadleaf weeds: Monochoria	Broadleaf weeds: Redstem	Broadleaf weeds: California arrowheads
SU	Londax® (bensulfuron)	□	□	□	□	■🔴R	■🔴R	■	■	■🔴R	■🔴R
SU	Halomax® Sandea® (halosulfuron)	□	□	□	□	■🔴R	■🔴R	■	■	■🔴R	■🔴R
SU	Strada® CA (orthosulfamuron)	▨🔴R	▨🔴R	▨🔴R	□	■🔴R	■🔴R	■	■	■🔴R	■🔴R
POB	Regiment® CA (bispyribac)	■🔴R	■🔴R	■🔴R	□	▨🔴R	▨🔴R	■	■	▨🔴R	■🔴R
TSA	Granite® GR (penoxsulam)	■🔴R	■🔴R	■🔴R	□	▨🔴R	▨🔴R	■	■	▨🔴R	■🔴R
TSA	Granite® SC (penoxsulam)	■🔴R	■🔴R	■🔴R	□	■🔴R	▨🔴R	■	■	■🔴R	■🔴R
Lipid synthesis inhibitor + ALS inhibitor (SU)	League® MVP (thiobencarb + imazosulfuron)	■🔴R	■🔴R	▨🔴R	■	■🔴R	■🔴R	■	■	■🔴R	■🔴R
HPPD inhibitor + ALS inhibitor (SU)	Butte® Herbicide (benzobicyclon + halosulfuron)	▨	▨	▨	■	■	■	■	■	▨	■

UC RICE

For additional information visit http://rice.ucanr.edu

■ Control ▨ Partial control / Suppression □ No control ■🔴R ▨🔴R No control of resistant plants. The resistance is already widespread. ■🟡R No control of resistant plants. The resistance is spreading.

Abolish
(Pin-point Flood)

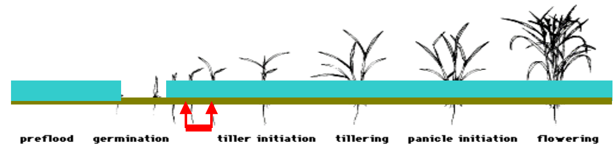


Emrg. shoot, 1st. lf.	Yes
Appl'd in water	No
Translocated	Little
Timing	1-3 lsr
Resistance	Yes

Application timing

1.0 to 3.0 lsr (4 lb ai/ac)

Bolero
(Leathers' Method)

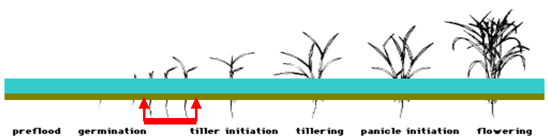


Emerg. shoot	Yes
Appl'd in water	Yes
Translocated	Little
Timing	2 lsr
Resistance	Yes

Application timing

2.0 lsr (4.0 lb ai/ac)

Bolero
(Permanent Flood)

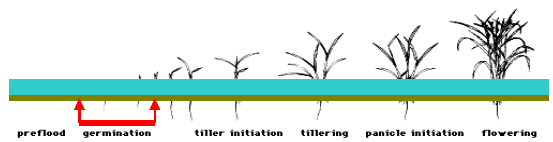


Emerg. shoot	Yes
Appl'd in water	Yes
Translocated	Little
Timing	1-2 lsr
Resistance	Yes

Application timing

1.0 to 2.0 lsr (4 lb ai/ac)

Cerano
(Permanent Flood)

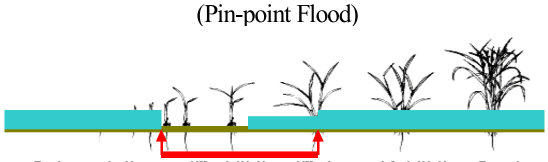


Roots, emerg. Shoots	Yes
Appl'd in water	Yes
Translocated	Yes
Timing	preseed-lsr
Resistance	Yes

Application timing

Preseed to 1.0 lsr (0.6 lb ai/ac)

Clincher
(Pin-point Flood)

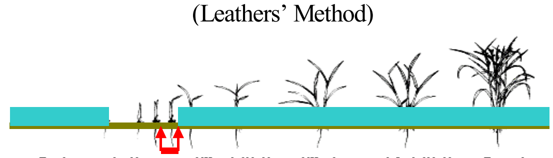


Foliar	Yes
Appl'd in water	No
Translocated	Yes
Timing	2 lsr-midtil
Resistance	Yes

Application timing

2.0 lsr to til (0.25 to 0.31 lb ai/ac)

Clincher
(Leathers' Method)



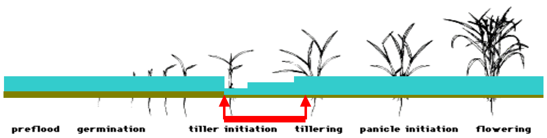
Foliar	Yes
Appl'd in water	No
Translocated	Yes
Timing	2 lsr
Resistance	Yes

Application timing

2.0 lsr (0.25 lb ai/ac)

Grandstand

(Pin-point Flood)



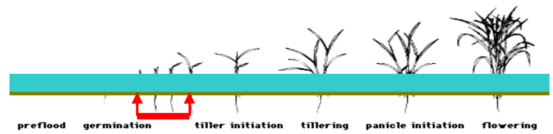
Foliar	Yes
Appl'd in water	No
Translocated	Yes
Timing	1 till-maxtil
Resistance	No

Application timing

1.0 til to maxtil (0.25 to 0.375 lb ai/ac)

Londax, Sandea

(Permanent Flood)



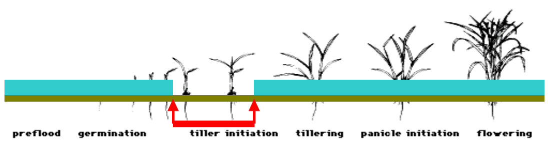
Foliar and roots	Yes
Appl'd in water	Yes
Translocated	Yes, moderate
Timing	0-5 lsr
Resistance	Yes

Application timing

1.0 to 3.0 lsr (0.06 lb ai/ac)

Londax, Sandea

(Pin-point Flood)



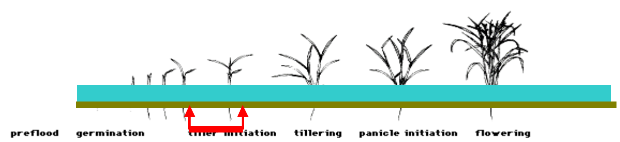
Foliar and roots	Yes
Appl'd in water	Yes
Translocated	Yes, moderate
Timing	0-5 lsr
Resistance	Yes

Application timing

3.0 lsr to 1-2 til (0.06 lb ai/ac)

Granite GR

(Continuous Flood)



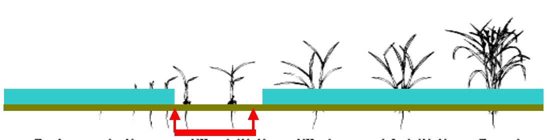
Foliar and roots	Yes
Appl'd in water	Yes
Translocated	Yes, moderate
Timing	2-3 lsr
Resistance	Yes

Application timing

2-3 lsr (0.04 lb ai/ac)

Granite SC

(Pin-point Flood)



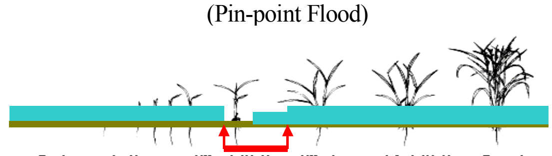
Foliar and roots	Yes
Appl'd in water	No
Translocated	Yes, moderate
Timing	2 lsr to 1 Till
Resistance	Yes

Application timing

2 lsr to 1-2 til (0.035 lb ai/ac)

Regiment

(Pin-point Flood)



Foliar and roots	Yes
Appl'd in water	No
Translocated	Yes, moderate
Timing	5 lsr-1 til
Resistance	Yes

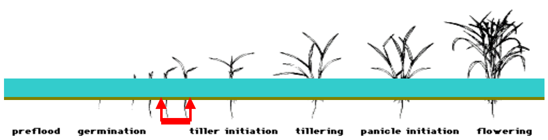
Application timing

1.0 til to midtil (15 g ai/ac) (18 g ai/ac*)

*** For resistant late watergrass**

Shark

(D.D.A./D.S.A.)
(Permanent Flood)



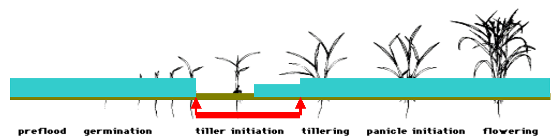
Foliar	Yes
Appl'd in water	Yes
Translocated	No
Timing	2-3 lsr
Resistance	No

Application timing

2.0 to 3.0 lsr (0.20 lb ai/ac)

propanil

(Pin-point Flood)



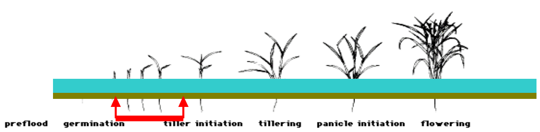
Foliar	Yes
Appl'd in water	No
Translocated	No
Timing	3 lsr-midtil
Resistance	No

Application timing

3.0 lsr to midtil (3 to 6 lb ai/ac)

Butte

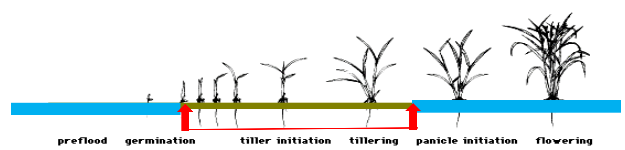
(Permanent Flood)



Roots, emerg. Shoots	Yes
Appl'd in water	Yes
Translocated	Yes
Timing	preseed-lsr
Resistance	No

Day of seeding to 2 to 9 lb product), at l inches water depth

Loyant



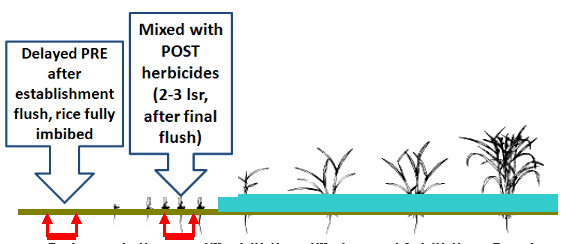
FoliarAppl'd	Yes
in water	No
Translocated	Yes
Timing	2 lsr
Resistance	No

Application timing

2.0 lsr to 60 days before harvest (0.035 lb ai/ac)

Prowl

(Dry-seeded)

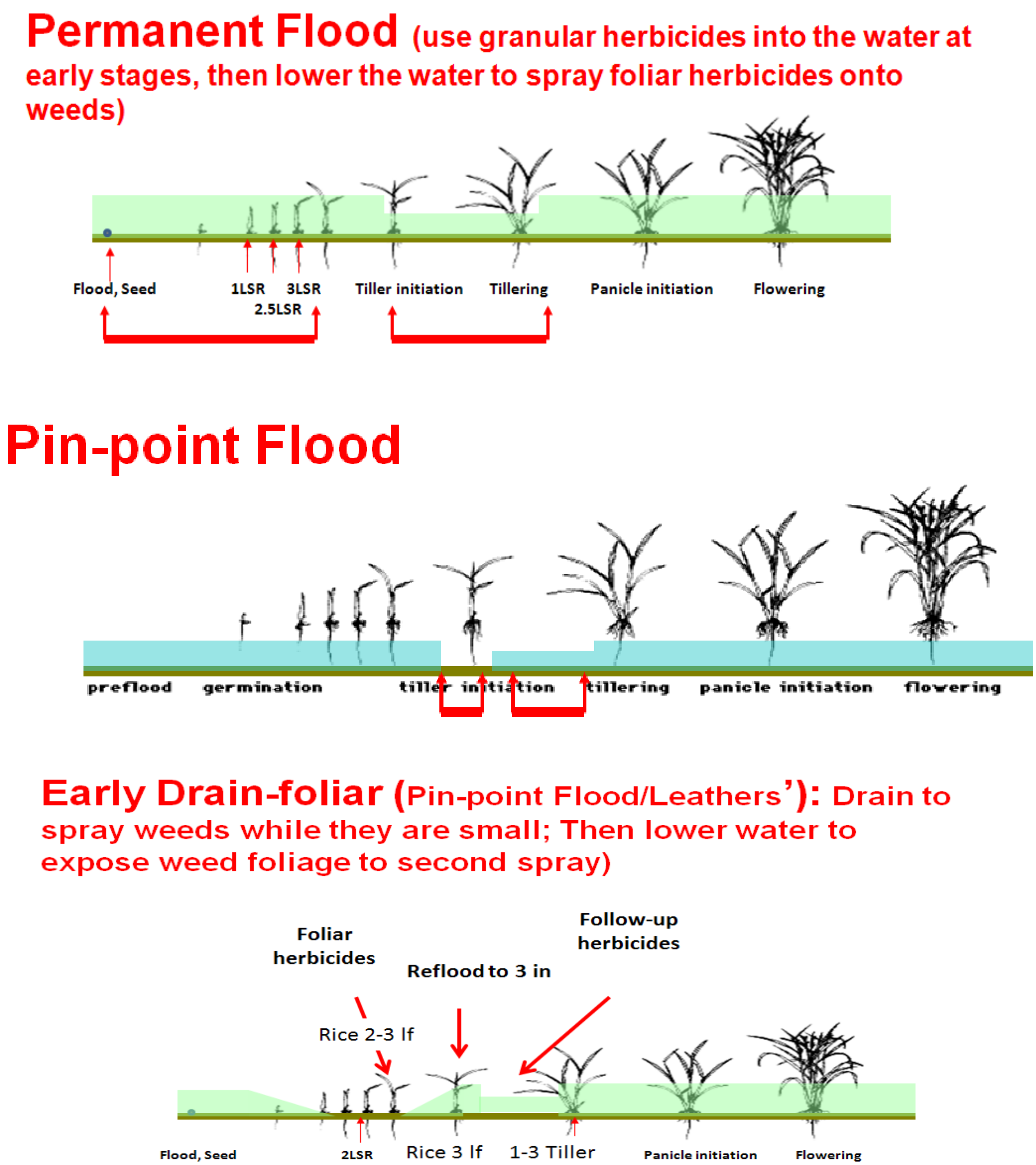


Foliar	No
Appl'd in water	No
Translocated	No
Timing	Delayed PRE or 2-3 lsr (as PRE)
Resistance	No

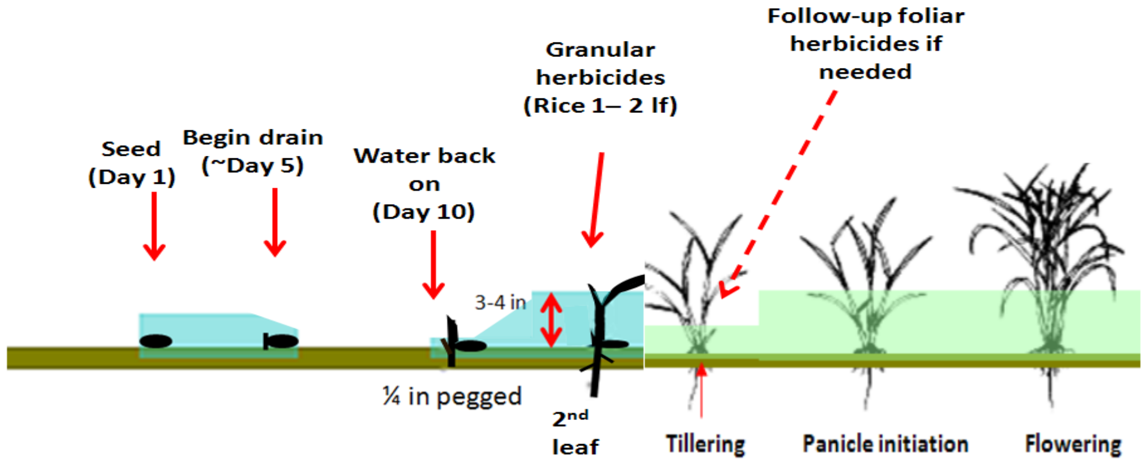
Application timing

DPRE (1 lb ai/ac)

Figure 1b. Major herbicide-based weed control systems for rice in California



Early Drain-granule: for granular herbicides into the water after reflood (requires ability for rapid reflood)



Drill-seeded (field is initially dry and then is gradually flooded deeper)

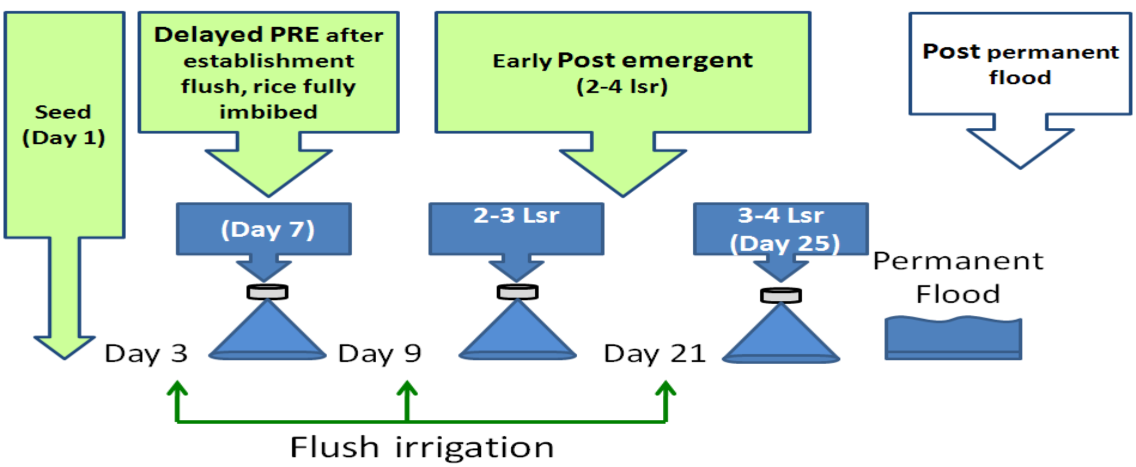
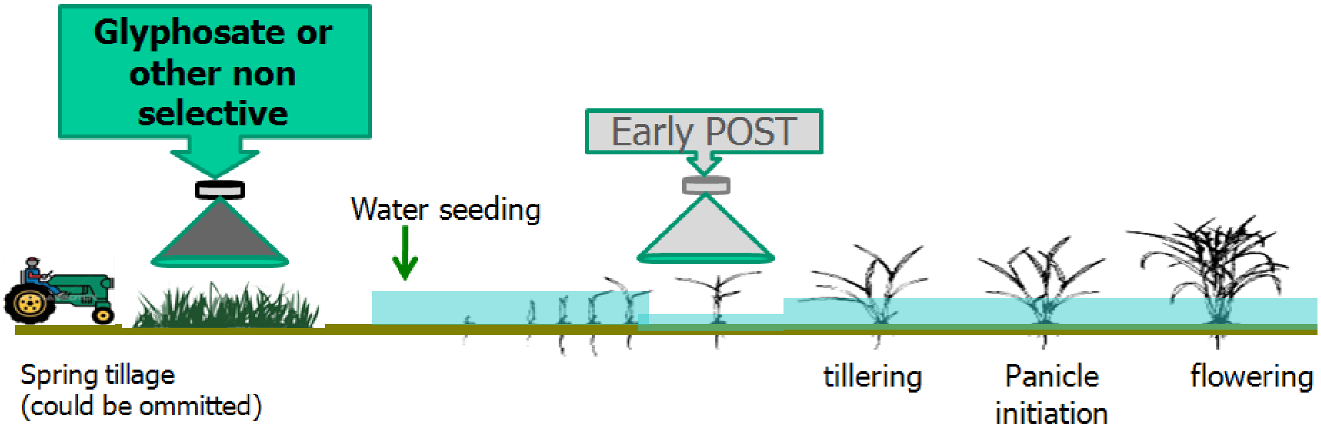


Figure 1b (continued). Major herbicide-based weed control systems for rice in California.

Stale seedbed control of multiple-herbicide-resistant late watergrass ("mimic")



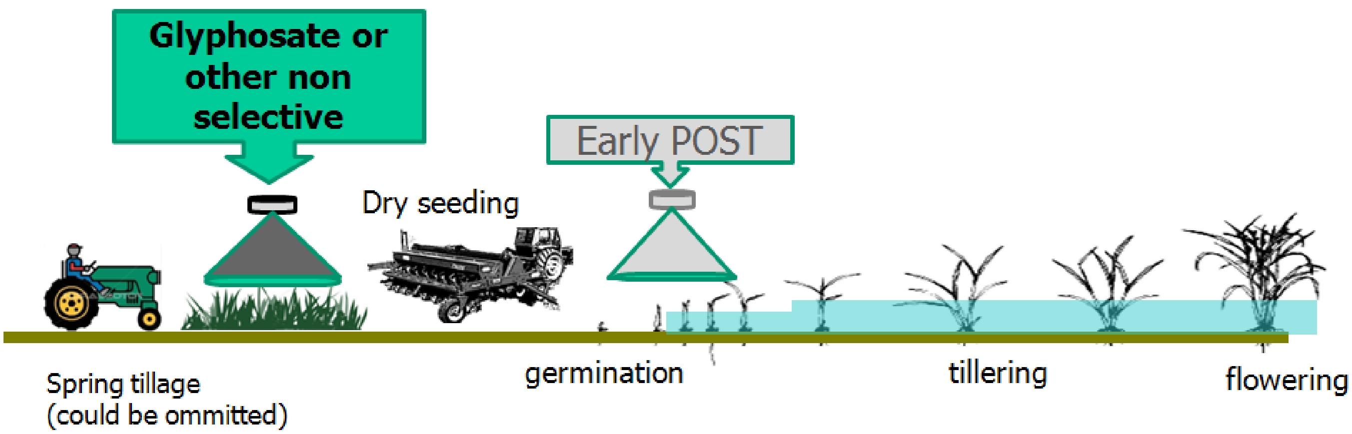


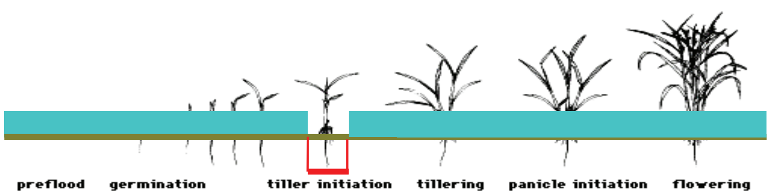
Figure 2. Weed susceptibility, application timing and water management regimes for tank-mixed herbicides in California rice

	Barnyardgrass	Watergrass	Sprangletop	Smallflower Umbrella	Ricefield Bullrush	CA Arrowhead	Gregg's arrowhead	Ducksalad	Redstem	Monochoria
Stam or Superwham	+	+	-	+	+	±	-	±	±	±
Abolish	+ / R	+ / R	+	+	-	-	-	-	-	-

- + Control
- - No Control
- ± Suppresion
- R Resistant

Propanil + Abolish

(Pin-Point Flood)



2-3 lsr (3 lb ai/ac + 3.0 lb ai/ac)

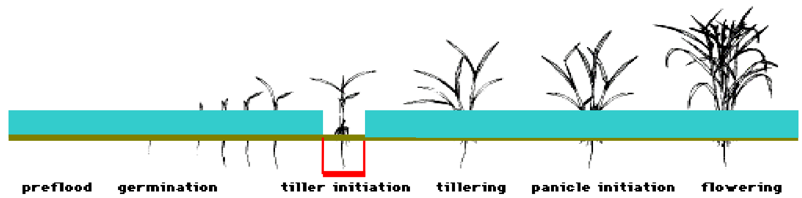
	Barnyardgrass	Watergrass	Sprangletop	Smallflower Umbrella	Ricefield Bullrush	CA Arrowhead	Gregg's arrowhead	Ducksalad	Redstem	Monochoria
Regiment	+ / R	+ / R	-	-	+ / R	+ / R	-	±	-	±
Abolish	+ / R	+ / R	+	+	-	-	-	-	-	-
Shark	-	-	-	+	+	+	-	±	±	±
Whip	+ / R	+ / R	+	-	-	-	-	-	-	-

- + Control
- - No Control
- ± Suppresion
- R Resistant

Figure 2. (continued) Weed susceptibility, application timing and water management regimes for tank-mixed herbicides in California rice

Regiment + Abolish

(Pin-Point Flood)



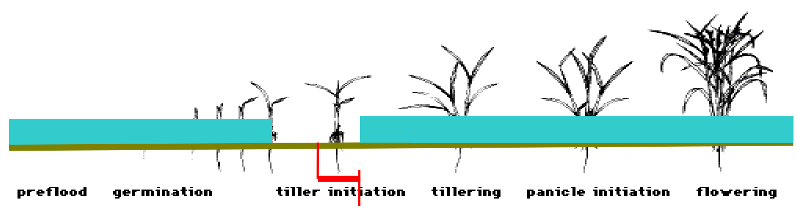
Synergistic mixture intended only for late water grass

5-6 lsr (10-15 g ai/ac + 2.0-3.0 lb ai/ac)

Can also be effective on smallflower and bulrush

Regiment + Shark

(Pin-Point Flood)



Broad-spectrum

4-5 lsr (12-15 g ai/ac + 0.20 lb ai/ac)

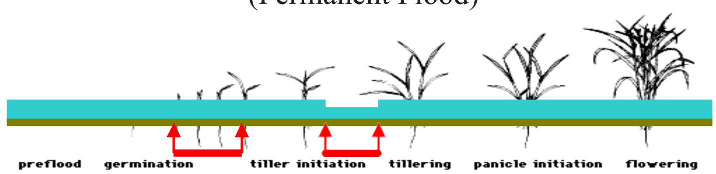
Figure 3. Weed susceptibility, application timing and water management regimes for herbicide sequences with Regiment.

	barnyardgrass	watergrass	sprangletop	smallflower umbrella	ricefield bulrush	CA arrowhead	Gregg's arrowhead	ducksalad	redstem	monochoria
Bolero	+ R	+ R	+	+	-	-	-	-	-	-
Followed by										
Regiment	+ R	+ R	-	-	+ R	+ R	-	-	-	±

+ control
- no control
± suppression
R resistant

Bolero fb. Regiment

(Permanent Flood)



1.0 to 2.0 lsr (4.0 lb ai/ac)

Application timing

Fb.

1-3 til (15 g ai/ac)

	barnyardgrass	watergrass	sprangletop	smallflower umbrella	ricefield bulrush	CA arrowhead	Gregg's arrowhead	ducksalad	redstem	monochoria
Regiment	+ R	+ R	-	-	+ R	+ R	-	-	-	±
Followed by										
Stam or Superwham	+	+	-	+	+	±	-	±	±	±

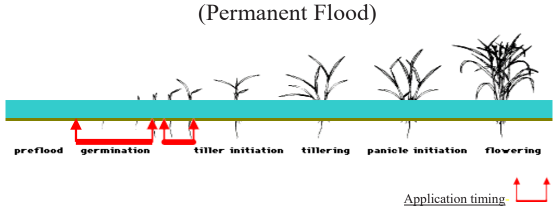
+ control
- no control
± suppression
R resistant

Figure 4. Weed susceptibility, application timing and water management regimes for herbicide sequences with Cerano in California rice.

	barnyardgrass	watergrass	sprangletop	smallflower umbrella	ricefield bulrush	CA arrowhead	Gregg's arrowhead	ducksalad	redstem	monochoria
Cerano	+	+ / R*	+ / R	-	-	-	-	-	-	-
Followed by:										
Londax	-	-	-	+ / R	+ / R	+ / R	-	+	+ / R	-
Regiment	+ / R	+ / R	-	± / R	±	+ / R	-	±	-	±
Shark	-	-	-	+	+	+	-	±	±	
Stam or Superwham	+	+	-	+ / R	+ / R	±	-	±	±	±
Grandstand	-	-	-	-	+	-	-	-	+	-

Cerano fb. Londax

(Permanent Flood)



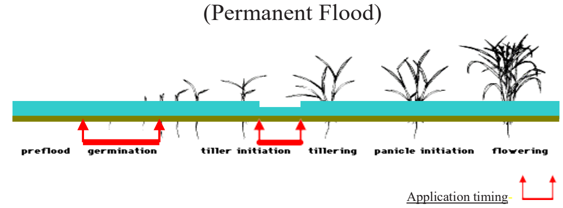
Preseed to 1.0 lsr (0.6 lb ai/ac)

Fb.

2-3 lsr (0.06 lb ai/ac)

Cerano fb. Regiment

(Permanent Flood)



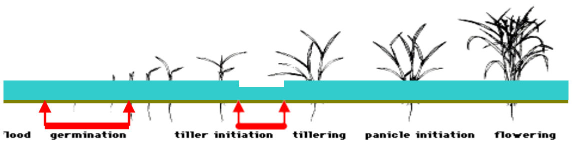
Preseed to 1.0 lsr (0.6 lb ai/ac)

Fb.

2-3 Tiller (15 g ai/ac)

Cerano fb. propanil

(Permanent Flood)



Application timing-

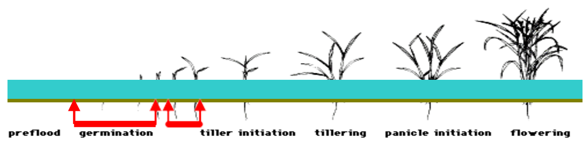
<u>Preseed to 1.0 lsr (0.6 lb ai/ac)</u>

<u>Fb</u>.

<u>1-3 til (6 lb ai/ac)</u>

Cerano fb. Shark

(Permanent Flood)



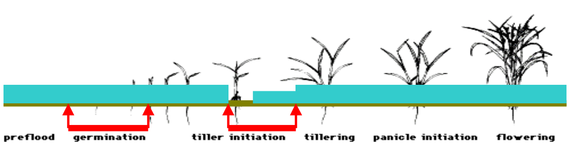
Application timing

<u>Preseed to 1.0 lsr (0.6 lb ai/ac)</u>

<u>Fb</u>.

<u>2-3 lsr (0.2 lb ai/ac)</u>

Cerano fb. propanil + Grandstand



Application timing-

<u>Preseed to 1.0 lsr (0.6 lb ai/ac)</u>

<u>Fb</u>.

<u>1-3 til (6.0 lb ai/ac + 0.25 lb ai/ac)</u>

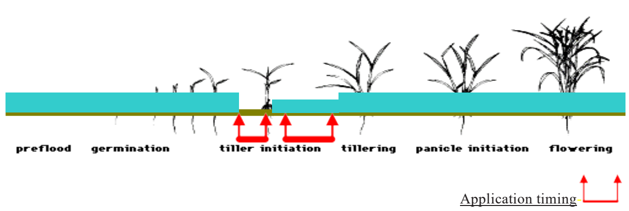
Figure 5. Weed susceptibility, application timing and water management regimes for herbicide sequences with Clincher in California rice.

	barnyardgrass	watergrass	sprangletop	smallflower umbrella	ricefield bulrush	CA arrowhead	Gregg's arrowhead	ducksalad	redstem	monochoria
Clincher	+ / R	+ / R	+ R	-	-	-	-	-	-	-
Followed by:										
Londax	-	-	-	+ / R	+ / R	+ / R	-	+	+ R	-
Regiment	+ / R	+ / R	-	± R	+ / R	+ / R	-	±	-	±
Stam or Superwham	+	+	-	+ R	+ R	±	-	±	±	±
Shark	-	-	-	+	+	+	-	±	±	

\+ control - no control **R** resistant ± suppression

Clincher fb. Londax

(Pin-point Flood)



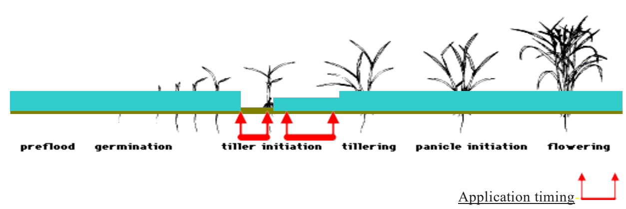
3.0 to 6.0 lsr (0.25-0.28 lb ai/ac)

Fb.

2-3 til (0.06 lb ai/ac)

Clincher fb. Regiment

(Pin-point Flood)



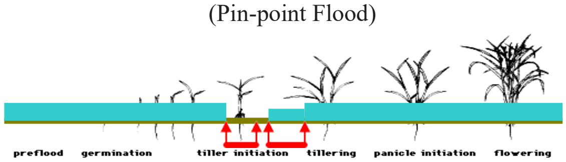
3.0 to 6.0 lsr (0.25-0.28 lb ai/ac)

Fb.

2-3 til (15 g ai/ac)

propanil fb. Clincher

(Pin-point Flood)



Application timing

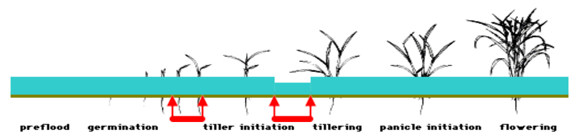
5-6 til (6.0 lb ai/ac)

Fb.

1 to 3 til (0.28 lb ai/ac)

Shark fb. Clincher

(Pin-point Flood)



Application timing

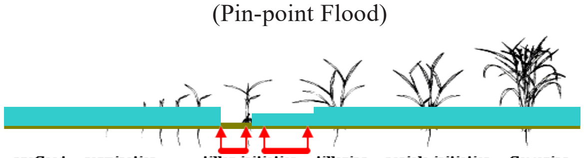
2-3 lsr (0.2 lb ai/ac)

Fb.

1 to 3 til (0.28 lb ai/ac)

Clincher fb. propanil

(Pin-point Flood)



Application timing

3.0 to 6.0 lsr (0.25-0.28 lb ai/ac)

Fb.

2-3 til (6.0 lb ai/ac)

Figure 6. Weed susceptibility, application timing and water management regimes for herbicide sequences with Granite. In the case of watergrass, resistance is strongest with late watergrass ("mimic"); resistance to ALS inhibitors may or may not involve all herbicides in that group.

	barnyardgrass	watergrass	sprangletop	smallflower umbrella	ricefield bulrush	CA arrowhead	Gregg's arrowhead	ducksalad	redstem	monochoria
Granite	+	+ / R	-	+ / R	+ / R	+	-	+	+	-
Followed by										
Stam or Superwham	+	+	-	+ / R	+ / R	±	-	±	±	±

\+ control

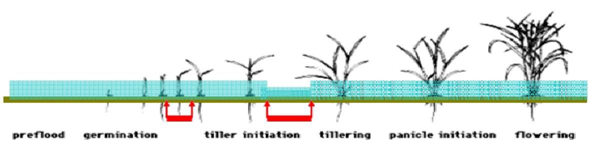
\- no control

± suppression

R resistant, poor control

Granite (GR) fb Propanil

(Permanent Flood)



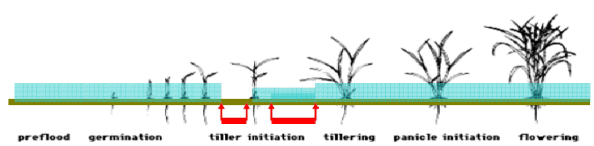
Application timing-

- If the WG population is already widely R to Granite, this sequence will not protect propanil

2.5 lsr (0.04 lb ai/ac)
Fb.
1-3 til (6 lb ai/ac)

Granite (SC) fb Propanil

(Pin-point Flood)



Application timing-

- Will not control sprangletop
- But Granite can be mixed with Clincher

3.0 to 4.0 lsr (0.031 lb ai/ac)
Fb.
2-3 til (6 lb ai/ac)

HERBICIDE RESISTANCE STEWARDSHIP IN RICE

University of California
Cooperative Extension
June 2018

What is Weed Resistance?

- The ability of a weed biotype to survive treatment with a given herbicide to which the weed species is normally susceptible
- Herbicide-resistant biotypes are present within a weed species' population as a part of normal genetic variation
- Repeated use of the same herbicide or mode of action (MOA) will select for herbicide-resistant biotypes
- In California, we have two types of herbicide resistance: 1) **Target-Site** resistance and 2) **Non-Target Site** resistance
- Certain weed biotypes can be simultaneously resistant to herbicides that differ chemically and in their MOA
- Weeds that are not on the label will tolerate the herbicide, but are not resistant biotypes

Symptoms of Weed Resistance in the Field

Resistance needs to be ultimately confirmed by a specific test. Failure to control weeds can occur due to factors such as faulty spraying, incorrect dose or timing, weeds too large, subsequent weed germination after treatment, very large infestations, poor coverage, and other factors. The presence of resistance in the field is characterized by the following:

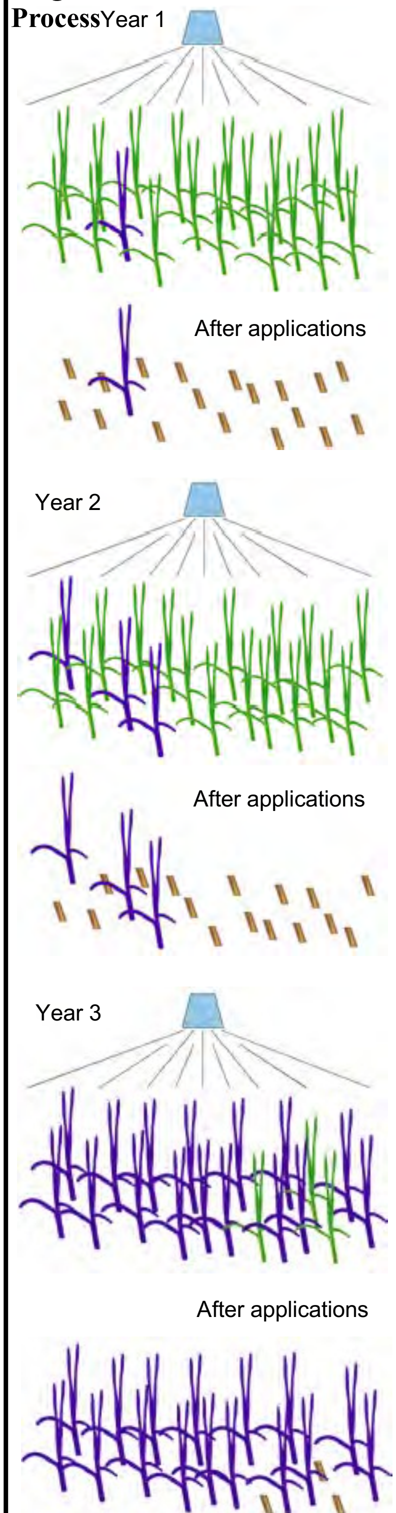
- There are healthy looking plants alongside dead plants of the same species after treatment
- One susceptible species is poorly controlled, while other adjacent susceptible species are well controlled
- The species was previously well controlled by the same herbicide and rate but a gradual decline in control has been noticed over time
- The same herbicide (or herbicides with the same MOA) has been used repeatedly on the same site
- Discrete patches of the target weed persistently survive treatment with a given herbicide(s)
- Resistance in the same weed species and herbicide occurs in neighboring field

What Factors Favor the Evolution of Resistance?

- Excessive reliance on chemical control and repeated sequential use of the same MOA
- A monoculture of continuous rice production
- Weeds that that have annual growth habit and produce lots of seeds with little dormancy
- A herbicide that has high efficacy on a specific wee species
- A herbicide with prolonged residual activity

Endorsed by the California Rice Commission and the California Rice Research Board

Stages of Herbicide Resistance Evolutionary Process



Elimination of the most sensitive genotype

The only survivors, if the application is done correctly, will be the resistant plants which will grow and set seed.

Now there are more resistant individuals in the population. Application of the same herbicide or products with the same MOA will increase these individuals even more.

The remaining resistant population will then set seed.

Eventually, the population becomes mostly resistant individuals.

At this point the herbicide is no longer effective.

Weed Identification Pictures

Grasses

Barnyardgrass & Watergrass

Barnyardgrass and watergrass can easily be distinguished by the absence of a ligule around the collar region, or the region where the leaf blade encloses the stem, as compared to the presence of a membranous ligule with rice.

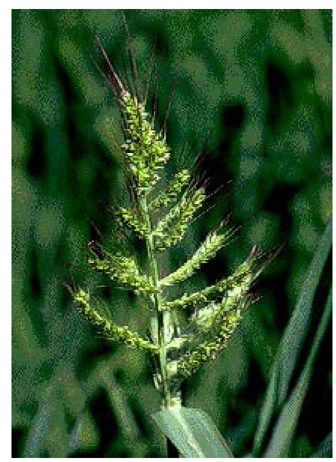
Left: Barnyardgrass and watergrass – no ligule
Right: Rice – membranous ligule present

Barnyardgrass

(Echinochola crus-galli)

Seedling

Tillering plant



Seedhead

Early Watergrass

(E. oryzoides)

Seedhead

Late Watergrass

(E. phyllopogon)

Seedhead

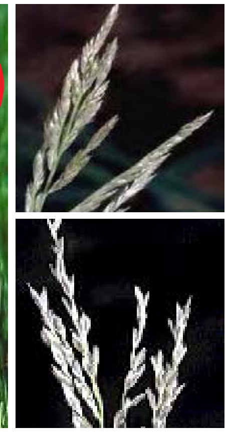
Bearded Sprangletop

(Leptochloa fusca ssp. fascicularis)

Ligule

Seedling

Tillering



Flowering structures

Sedges

Ricefield Bulrush

(Schoenoplectus mucronatus)

Seedling: Side-view

Seedling: Above-view

Flowering

Smallflower Umbrella Sedge

(Cyperus difformis)

Seedling

3-4 leaf stage

Flowering Sedge

Close-up: flowering structures

Broadleaveves

California and Gregg's Arrowheads

California and Gregg's arrowheads have similar seedling as shown to the left. They can not be distinguished until they have put on their first true leaf.

California Arrowhead

(Sagittaria montevidensis)

Leaf

Flowering Plant

Gregg's Arrowhead

(S. longiloba)

Leaf

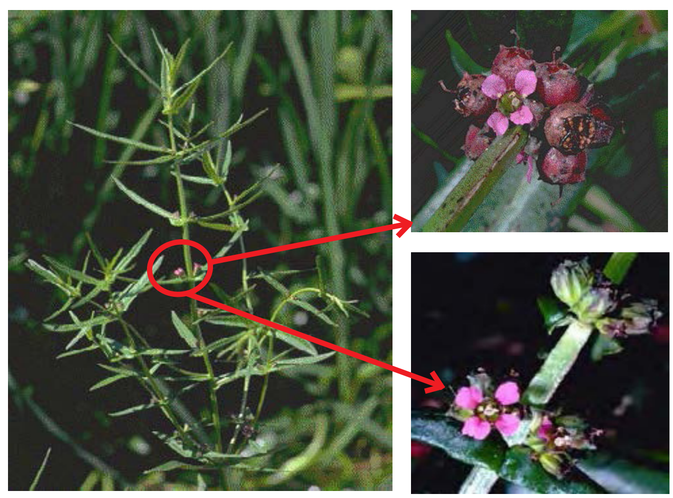
Flowering Plant

Redstem

(Ammannia species)

Emerging seedling

Seedling



Flowering redstem

Flowering structures

Waterhyssop

(Bacopa rotundifolia)

Seedling

Mature Plants

Flowering Plant

Ducksalad

(Heteranthera limosa)

Emerging seedling

Mature plants in flower. The flowers may also be blue.

Ducksalad infestation

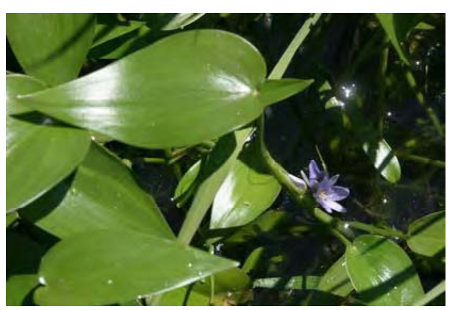
Common Waterplantain

(Alisma plantago-aquatic)

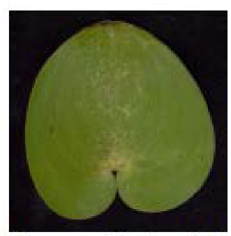
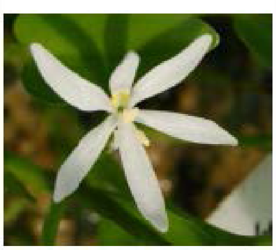
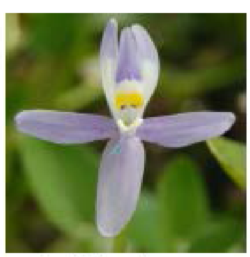
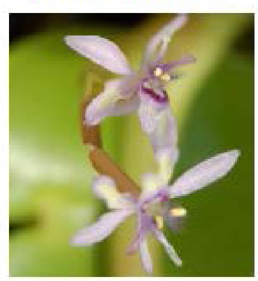
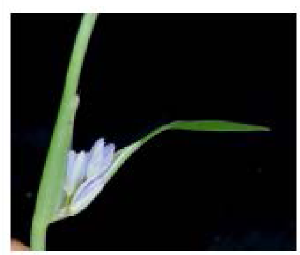
Seedling

Monochoria

(Monochoria vaginalis)



Ducksalad species found in Sacramento Valley rice fields

White-flowered *Heteranthera limosa* (Sw.) Willd.	Blue-flowered *Heteranthera rotundifolia* (Kunth) Griseb.	Bouquet mudplantain *Heteranthera multiflora* (Griseb.) Horn	Monochoria *Monochoria vaginalis* (Burm. F.) Kunth
			
Adult plant	Adult plant	Immature and adult leaves	Adult plant
			
Seedling	Seedling	Seedling	Monochoria seedling
			
Leaves with rounded tips	Leaves with rounded tips	Adult Leaves with deep lobes at petiole attachment	Leaves with pointed tips
			
Single white flower	Single blue flower	Multiple blue-purple flowers	Cluster of blue flowers

James Eckert, University of California, Department of Plant Science, Davis, CA

Weedy or "Red" Rice

Type 1:

- Short grain
- No color on nodes

Seeds:

- Awnless
- Straw-hulled seed
- High shattering
- High dormancy

Type 2:

- Medium grain
- No color on nodes

Seeds:

- Awnless
- Bronze-hulled seed
- High shattering
- Low dormancy

Type 3:

- Medium grain
- No color on nodes

Seeds:

- Awned
- Straw-hulled seed
- High shattering
- High dormancy

Type 4:

- Medium grain
- No color on nodes

Seeds:

- Awned
- Black-hulled seed
- High shattering
- High dormancy

Type 5:

- Medium grain
- Purple bands on nodes

Seeds:

- Awnless
- Straw-hulled seed
- High shattering
- Low dormancy

All California weedy rice types have the following characteristics:

- Red pericarped (red-branned)
- Light green leaves
- Pubescent (fuzzy) leaves
- Taller in height than Calrose varieties


Solitary weedy rice plant at mid-season


Weedy rice leaf collars


Patch of weedy rice next to levee prior to heading


Weedy rice ligule & auricles

Appendix 1.

Rice Pesticides Water Management Requirements Summary

Water must be held for the indicated number of 24-hour periods on the treated field, or within the containment area specified below before release into State waters.		Thiobencarb		Thiobencarb Plus Imazosulfuron	
		Bolero® UltraMax	Abolish® 8 EC	League® MVP	Malathion
		Hold	Hold	Hold	Hold
NORTH SAC VALLEY	Single treated fields.	30	19	30	4 (b)
	Release into tailwater recovery system or ponded onto fallow land or contained in other systems appropriate for preventing discharge.	19	19	19	
	System controlled by one permittee, then water may be discharged into the system in manner consistent with product labeling.	14	14	14	
	System includes drainage from more than one permittee, then water must be retained on site.	6	6	6	
	Water on fields within bounds of areas that discharge negligible amounts of drainage onto perennial streams. Commissioner must evaluate such sites and verify the hydrologic isolation of the fields.	6	6	6	
	CAC may authorize emergency release of tailwater.	19	19	19	
SOUTH SAC & SJ VALLEY (a)	All water on treated fields must be retained on the treated fields.	19	19	19	4 (b)
	Release into tailwater recovery system or ponded onto fallow land or contained in other systems appropriate for preventing discharge.	19	19	19	
	System controlled by one permittee, then water may be discharged in manner consistent with product labeling.	14	14	14	
	System includes drainage from more than one permittee, then water must be retained on site.	6	6	6	
	Water on fields within bounds of areas that discharge negligible amounts of drainage onto perennial streams. Commissioner must evaluate such sites and verify the hydrologic isolation of the fields.	6	6	6	
	CAC may authorize emergency release of tailwater.	19	19	19	

(a)- South Sacramento & San Joaquin Valley defined as: South of the line by Roads E10 and 116 in Yolo County and the American River in Sacramento County

(b) Volunteer hold.

VERTEBRATES

Rice fields provide excellent habitat for some bird and rodent species. The Norway rat is probably the most serious vertebrate pest of rice, feeding on newly planted seed, seedlings, or ripening grain. Muskrats burrow in rice levees, damaging drainage systems and irrigation structures. Waterfowl and blackbirds may also cause yield losses in some localized areas.

The most successful vertebrate pest management program is one that manages pest populations at levels at which significant damage never occurs. This requires knowledge of the biology and behavior of the potential pests and regular monitoring for them in and around fields. Historical records of pest population levels, control measures implemented, economics of control procedures and the success of methods used, can be used to help determine the best management approach.

Consideration also should be given to the presence of non-pest species and the potential risks of a control method. The methods and materials available for vertebrate control are constantly changing. Check with your County Agricultural Commissioner on laws and regulations concerning the status of wildlife species and the methods and materials available to control them.

Waterfowl

Annually, large numbers of waterfowl (ducks, geese, coots) migrate along the Pacific flyway to and from their northern breeding grounds and may spend from a few weeks to months in fall and winter in California's Central Valley. Flooded rice fields provide an ideal habitat for waterfowl and have an important role in the conservation of these birds (fig. 1). Because most rice in California is harvested prior to the arrival of migrating waterfowl and planted after their departure, damage to rice is usually kept to a minimum. Most problems occur where waterfowl become 'resident'. Ducks and geese cause the

Figure 1. Large numbers of waterfowl migrate along the Pacific flyway and spend time in California rice-growing region.

most serious losses in rice by feeding on maturing grain and sometimes causing lodging. Coots may sometimes damage newly planted fields.

Management guidelines

All species of waterfowl are migratory game birds that are protected by federal and state laws. Waterfowl cannot be lethally controlled without a depredation permit. Damage can usually be alleviated using frightening (hazing) techniques. Propane cannons (fig. 2), electronic

Figure 2. Air cannon used for frightening waterfowl.

noise makers, pyrotechnics, Mylar tape and other sound and visual scare devices may be used to frighten waterfowl from areas where they are causing damage. Waterfowl may habituate to these techniques so they might only have short-term effectiveness. Persistence in applying the methods and alternating frightening devices are important in achieving success.

Figure 3. Electronic noise maker.

Blackbirds

Blackbirds may damage ripening rice, especially during the milk and dough stages (fig. 4, 5). Losses may be quite high in some fields that are close to important roosting areas.

Figure 4. Redwing blackbird.

Figure 5. Damage to rice panicle caused by blackbirds.

Management guidelines

Frightening techniques are most commonly used to manage blackbirds. Unfortunately, these techniques are even less effective for blackbirds than waterfowl. To be effective, you must instigate these controls as soon as birds appear in the field. A permit is not needed to lethally remove blackbirds that are causing or threatening to damage rice crops. To date, repellents have not proven to be effective in reducing blackbird damage to rice in California.

Norway rats

The Norway rat (Rattus norvegicus) is responsible for most rat damage in rice fields (fig. 6). Rat damage to growing rice is usually most serious shortly after planting when the water is temporarily lowered for seed germination and stand establishment. This can be especially severe where fields are not leveled and high spots are exposed to air. The rats pull up the sprouting plants and eat the seeds (fig. 7). Rats may also consume ripening grain as the cereal heads come into the milk stage, but losses are generally not as serious.

Norway rats have a bulky appearance and a tail that is shorter than the length of their head and body combined. Rats are mainly active at night, but if their numbers are high, activity may be observed during the day. They are omnivorous and feed on a wide variety of plant and animal materials. Norway rats dig burrows and burrow systems are frequently found along levees beside rice fields (fig. 8). These burrows can also weaken levees systems and affect irrigation.

Norway rats are prolific breeders. They are capable of breeding year-round under optimal conditions but most breeding is in spring and fall. Females produce about 4 litters per year. Average litter size is about 6, and the young are weaned at 3 weeks and become sexually ma-

Figure 6. Norway rat.

Figure 7. Germinating rice seeds damaged by Norway rats.

Figure 8. Norway rat burrow

ture at 2 to 3 months of age. These reproductive characteristics enable rat populations to rapidly increase and become widespread in response to onset of optimal environmental conditions. Populations typically undergo cycles of abundance. Problems are most likely to occur following mild winters and when food supply is abundant.

Management guidelines

Norway rats are non-native mammals and may be taken at any time and in any manner when they are causing damage to crops or other property. Where possible, non-crop habitats should be managed year round to reduce shelter and food supply for rats. Good weed control on levees is essential. Ground vegetation in areas adjacent to rice fields should be kept to a minimum by grazing or mowing.

When rat populations continue to be high despite habitat modification, rodenticides may be used. Currently (2023), registered rodenticides for Norway rat control on levees and adjacent non-cropped areas include the acute toxicant zinc phosphide and the anticoagulants diphacinone and chlorophacinone. The rodenticide and application method should be chosen with regard for potential non-target hazards. Consult your Agricultural Commissioner for specific information.

Zinc phosphide is an acute toxicant that is metabolized quickly within the target animal, and has minimal (if any) secondary poisoning risks. However, because of its fast action, rodents might only ingest a sublethal dose of bait before becoming sick. This may result in rodents becoming 'bait shy'. Consequently, it is best to wait at least 3 months, and preferably 6 months between applications. Zinc phosphide bait is placed according to label instructions in active burrows or in places frequented by rats but inaccessible to livestock, poultry, non-target wild-

Figure 9. Tube used to decrease non-target exposure of rodenticides.

life, pets and children (fig. 9). When possible, prebait with clean grain several days before bait application to determine if rats are taking the bait and to overcome any bait shyness. Prebaiting is especially important where other foods are abundant.

Anticoagulant baits act by reducing the clotting ability of the blood. The target animal must consume a number of doses of bait over a period of several days to obtain a lethal dose. Because a residue of the anticoagulant bait may remain in the target animal (primarily in the liver), predators or scavengers may also be at risk of consuming a lethal dose of bait. Risk increases where treated rat populations levels are extremely high (i.e., high availability of carcasses containing anticoagulant) and in areas where and at times when predator and scavenger populations are especially abundant. Risk also increases when too much bait is applied. As with all rodenticides, follow the label carefully and use as little bait as possible to bring the population under control.

Anticoagulants may be applied in bait stations, by spot application, or in paraffinized bait blocks. Bait stations protect bait from rain and prevent non-target species feeding on the bait. To achieve control, keep the stations well-supplied until feeding ceases. Bait blocks made from paraffin may be placed in areas of rat activity. These blocks aren't as readily accepted as loose baits but are relatively waterproof and eliminate the need for bait boxes. Replace blocks as necessary and discard of uneaten bait when the control program is completed.

Muskrats

Muskrats (Ondatra zibethicus) are semi-aquatic rodents named for their conspicuous odor resulting from secretions from musk glands at the ventral base of the tail (fig. 10). They sometimes inhabit water supply canals and drainage ditches near rice fields. Their burrowing, especially around headgates can cause breaks in levees and dikes. Significant yield loss may occur before repairs can be completed. Muskrats also occasionally cut and eat rice plants.

Muskrats have dense fur, a long, laterally flattened tail and partially webbed feet. Adults are about 18 inches long and weigh from 1.5 to 2.5 pounds. Their native range in California was along the Colorado River by the Arizona border and in scattered locations on the eastern side of the Sierra Nevada from Mono to Lassen County. Construction of irrigation canals in the early 1900's enabled them to expand their range into southern California. A high demand for muskrat fur during the 1920's resulted in the release of muskrats elsewhere. Muskrats now occupy canals, ponds, and irrigation ditches throughout most of California.

Muskrats are very prolific. Most females have two or three litters per year, with an average of about 6 or 7 kits per litter. Most births occur in spring. The gestation period is between 25 and 30 days. The young become active and able to swim within 14 days, and are weaned at 28 days. Most become sexually active the spring after their birth.

Depending on the environment and season, muskrats construct either houses or dig burrows into banks. Unless the population is very dense, muskrats prefer to burrow into banks rather than build houses. Soil type and slope of the bank determine the permanence and complexity of a burrow system. Burrows often begin in the water, from 6- to 8-inches below the surface, and penetrate the embankment on an upward slant. Burrows are not typically found when banks are less than 0.2 meters high, slope is less than 10 degrees, or when combined sand/gravel content is less than 90 percent. Burrows may extend 20 feet or more into banks. Houses are usually constructed from the dominant emergent plants in the area. They are built at water level with several underwater tunnels or “leads” for entrances.

Muskrats are primarily herbivorous although animal matter like crayfish may occasionally be consumed. Muskrats feed on aquatic vegetation growing in the vicinity of their dwellings. Characteristic signs of muskrat feeding activity include food platforms and feeding houses. Most activity occurs at night, with peaks at dusk and dawn.

Management guidelines

Muskrats are classified as furbearers but can be taken at any time when they are causing damage to crops or other property. Management of vegetation to reduce muskrat food sources on levees and on ditch banks can help minimize muskrat problems. In some situations however, lethal control of muskrats is necessary. Trapping can be very effective in reducing muskrat populations and damage. Conibear traps are probably the most effective but it is important to note that while they can be

used to remove muskrats causing damage, they cannot be used to trap muskrats for fur (see Fish and Game Code).

Anticoagulant baits (diphacinone and chlorophacinone) may also be used. Bait can be placed in floating bait boxes or bait blocks (also used for Norway rat control) may be placed in muskrat feeding areas on levees and banks.

Figure 10. Muskrat.

WATER QUALITY

Water is essential to agriculture. Without it, farmers could not grow crops or produce live-stock. Fertilizers and crop protection chemi-cals are also essential to agriculture and their application needs to be carefully controlled to prevent contamination of water. People are be-coming increasingly concerned about environ-mental issues and the safety of their water for drinking. Since some of the water used in rice irrigation passes through the field and is reused downstream, often for urban domestic purposes or for recreation, it is critical that rice growers and chemical applicators maintain the quality of drainage water. In the 1980s fish kills in the Sacramento River and off tastes in Sacramento drinking water (Fig. 1) due to pesticides in the waterways highlighted the importance of being good stewards of water resources.

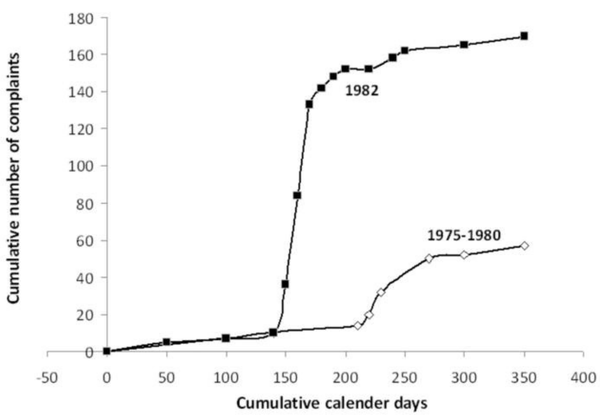


Figure 1. Water taste complaints received by the City of Sacramento prior to (1975- 1980) and during the use of thiobencarb (1982).

This chapter discusses current water quality regulations, what are potential problems regard-ing water quality for rice growers and how can we best manage rice systems to maintain high water quality standards.

Definitions

What is a "discharge"? A discharge would occur when any amount of wastewater that leaves your property enters surface waters of the State. The dis-charge does not have to be directly to surface water. For purposes of this program, it may first flow over a neighbor's property or through a toe drain along the edge of the field.

Who is a "discharger"? A discharger may include persons, individuals, corporation cities, special dis-tricts, farm owners, tenant farmers who release waste that could affect the quality of the water of the State.

What is "waste"? Waste is broadly defined in the California Water Code to include any and all waste substances that may include, but are not limited to soil, silt, sand, clay, rock, metals, salts, boron, sele-nium potassium, nitrogen, pesticides and fertilizers.

What are "waters of the State"? Waters of the State include any surface or groundwater with- in the boundaries of the Slate. Waters of the State include, for example natural streams, irrigation ditches or ca-nals, ponds, agriculturally- dominated waterways, and constructed agricultural drains.

Water quality regulation in California's rice systems

The Clean Water Act (CWA) is the source for water quality regulation in California and the United States. In California, additional water code requirements, enacted by the Porter-Co-logne Water Quality Control Act are found in California Water Code, Division 7. The Cal-ifornia Water Code provides a broad scope in regulating waste or proposing to discharge waste within any region that could affect the quality of waters of the State. The term "waste" is a broad definition, and the term "waters of the state" includes all surface water and ground wa-ter within the State. The California Water Code applies to point and non-point sources. Regula-tion occurs in several ways to dischargers: pro-hibition of discharge, waste discharge require-ments (permit), or a waiver of waste discharge requirements.

The California agricultural community received a waiver from a permit for discharging waste into waters of the State. The waiver expired on December 31, 2002. Since, 2003, all agriculture in California must comply with an agricultural discharge program referred to as the Ag Waiver. In 2008, the pro- gram was renamed the Irrigated Lands Regulatory Program (ILRP) because the word "waiver" implied that agriculture was exempt from regulation. Instead, agriculture is exempt from a permit as long as there is compliance with ILRP conditions to monitor pesticides and other constituents of concern (waste) discharged from the land into waters of the State. Current requirements allow for development of management plans when a certain number of exceedances occur. The California Rice Commission (CRC) manages the only commodity specific, general program under the waiver of waste discharge requirements (or ILRP program)

Constituents of concern

There are many constituents of concern listed in the ILRP as this program is for all irrigated lands. The constituents of concern for the rice industry are listed in Table 1. These constituents have been monitored by the CRC or during a two-year UC Davis study. While many of these constituents will be discussed in more detail later it is important to understand the effect of rice systems on these constituents. Natural waters do not contain pesticides and it is through the process of growing rice that pesticides are introduced into the water. Water does, however, contain carbon, nutrients, and metals. Results from the UC Davis study found that water leaving rice fields (tailwater) had generally higher concentrations of dissolved organic carbon (DOC), total suspended solids (TSS), total dissolved solids (TDS) and to a lesser extent ammonium and potassium (Fig. 2) throughout the year than the inlet water. Also, in the winter, phosphorus concentrations were higher in tail water than in the inlet water. This indicates that rice systems contribute to increases in these values.

Pesticides

California rice growers receive regulations under a prohibition of discharge program, the Rice Pesticides Program (RPP). The RPP began in the late 1970's, early 1980's and was officially adopted into regulation under the Basin Plan in 1990. Under the RPP, rice growers must follow approved management practices and monitor specific pesticides to meet performance goals in agricultural drains. The five pesticides under the RPP include two herbicides thiobencarb, molinate (cancelled and no longer monitored after 2009), and three insecticides no longer monitored: carbofuran (cancelled and no longer monitored on rice), malathion and methyl parathion (little or no use on rice).

Monitoring for thiobencarb in 2008 found that there were 37 detections of thiobencarb in water from the main rice drains and the Sacramento River. However, only two of these samples had thiobencarb concentrations above the performance goal of 1.5 ug/L (1.5 ppb). Monitoring results at the city intakes show two detections at Wes Sacramento, and one detection at Sacramento with no exccedances of the secondary maximum contaminant level (MCL) for off taste of 1.0 ug/L (1.0 ppb). During this same period there were only three detections of molinate and no exceedances (greater than 10 ppb).

Propanil is an important herbicide in the rice industry. It was reintroduced in the rice industry after being cancelled for drift issues in 1969. Propanil was never a consideration for the RPP because the product never caused any water quality impairments. The water board currently has concerns only because propanil is used a lot. The majority of locations sampled by the CRC had no detectable levels of propanil; however,

Table 1. Constituents of concern monitored by the CRC or evaluated in a 2006/07 study.

Constituent of Concern	Water quality objective	Comment
Herbicides		
Carfentrazone-ethyl (Shark)	ne*	
Clomazone (Cerano)	ne	
Cyhalofop-butyl (Clincher)	ne	
Fenoxaprop-p-ethyl (Whip)	ne	
Propanil (Stam)	ne	
Triclopyr TEA (Grandstand)	ne	
Thiobencarb (Bolero/Abolish)**	1.5 ug/L	Basin Plan performance goal under prohibition of discharge
Insecticides		
Diflubenzuron (Dimlin)	ne	
(s)-cypermethrin (Mustang)	ne	
Lambda cyhalothrin (Warrior)	ne	
Fungicides		
Azoxystrobin (Quadris)	ne	
Trifloxystrobin/ Propiconazole (Stratego)	ne	
Physical parameters		
pH	6.5-8.5	
Electrical conductivity (EC)	700 umhos/cm	CVRWQCB threshold
Dissolved oxygen (DO)	7 mg/L	Basin Plan water quality objective for lower Sacramento R.
Temperature	68° F	Basin Plan water quality objective for lower Sacramento R.
Color	ne	
Turbidity	ne	
Total disolved solids (TDS)	ne	
Dissolved organic carbon (DOC)	3 mg/L	CALFED drinking water control program
Nutrients		
Total N	ne	
Nitrite-N	ne	
Nitrate-N	10 mg/L	EPA standard
Ammonia-N	25 mg/L	
Total phosphorus	ne	
Soluable phosphorus	ne	
Potassium	ne	
Metals		
Copper	10 ug/L	
Biological		
E. coli	235 CFU	

* ne=not established ** City intakes have a thiobencarb maximum contamination level (MCL) of 70.0ug/L (toxicity), and a secondary MCL of 1.0 ug/L (off taste)
CVRWQCB=Central Valley Regional Water Quality Control Board

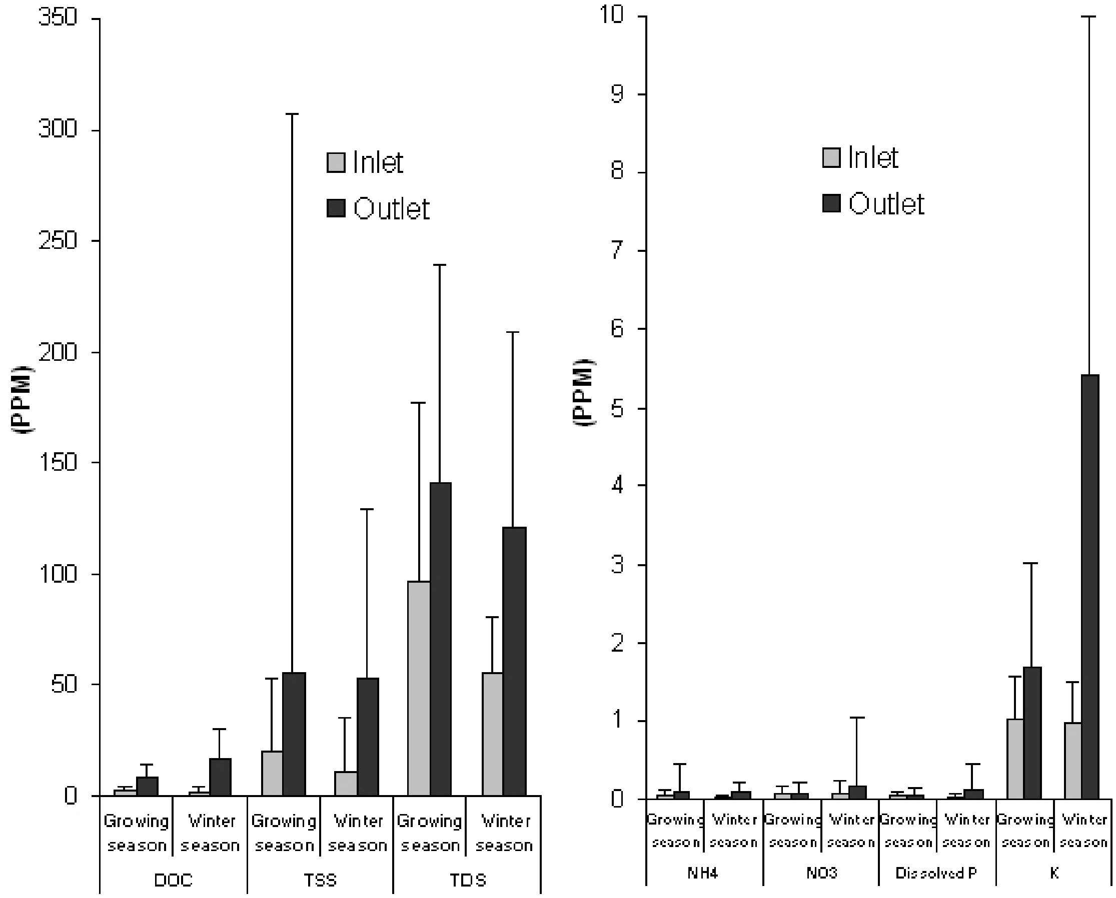


Figure 2. Concentrations of dissolved organic carbon (DOC), total suspended solids (TSS), total dissolved solids (TDS), ammonium (NH4), nitrate (NO3), dissolved phosphate and potassium (K) from rice field water inlets and outlets averaged over two growing and winter seasons. Error bars are standard deviations of all of the fields and sampling events within that period.

it was detected during a one- to two-week period from the mid to end of June. This highlights the importance of all growers to adhere to the hold times for all pesticides as indicated on the label. This will be discussed later.

Physical parameters

Dissolved oxygen (DO): DO is the amount of gaseous oxygen (O^2) dissolved in water. Oxygen diffuses into water from the surrounding air, by aeration (rapid movement), and as a waste product of photosynthesis. Adequate DO is necessary for good water quality as oxygen is a necessary element to all forms of life. Natural stream purification processes require adequate oxygen levels to provide for fish and other aerobic life forms.

Factors that contribute to low DO values are biological oxygen demand from the decomposition of organic matter. Low DO may also be caused by high levels of algae in the water (and the resulting diurnal oxygen depletion resulting from nighttime algae uptake), and/or flow of water that limits natural aeration. Warm water temperature can also contribute to low DO values. As temperatures increase oxygen solubility decreases. Due to the above factors (primarily temperature) low DO values were found in some of the major rice drains between June and September.

pH: The pH of water is a measure of the concentration of hydrogen ions. The pH determines the solubility (amount that can be dissolved in the water) and biological availability (amount that can be utilized by aquatic life) of chemical constituents such as nutrients and heavy metals (i.e. lead, copper, cadmium). In the case of heavy metals, the degree to which they are soluble determines their toxicity. Metals tend to be more toxic at lower pH because they are more soluble. The water quality objective is to maintain water pH values between 6.5 and 8.5. Sampling the main rice drains in 2008 found no water samples outside of this range.

Electrical conductivity (EC): EC estimates the amount of total dissolved salts, or the total amount of dissolved ions in the water. The salt content of water has a large impact on aquatic life and can have a negative impact on rice. The threshold cited by the CVRWQCB for reporting is 700 umhos/cm (NOTE: this value is for monitoring purposes only and should not be adopted as a salinity water quality objective). The 2008 sampling season yielded three samples above this critical level. These were all during storm events which occurred outside of the growing sea- son.

Total Suspended Solids (TSS): Total suspended solids include all the particulates suspended in water. In a two-year UC Davis study TSS ranged from almost 0 to over 500 mg/L; however, in most cases it was less than 100 mg/L (Fig. 3). High TSS is most likely the result of wind or storm events that stir up the water. Also, high TSS values are found when the flash boards are first removed and the high volume of water flowing out of the outlet churns up the soil around the outlet.

Total Dissolved Solids (TDS): TDS is an expression for the combined content of all inorganic (minerals and salts) and organic substances in water. Although TDS is not generally considered a primary pollutant (e.g. it is not deemed to

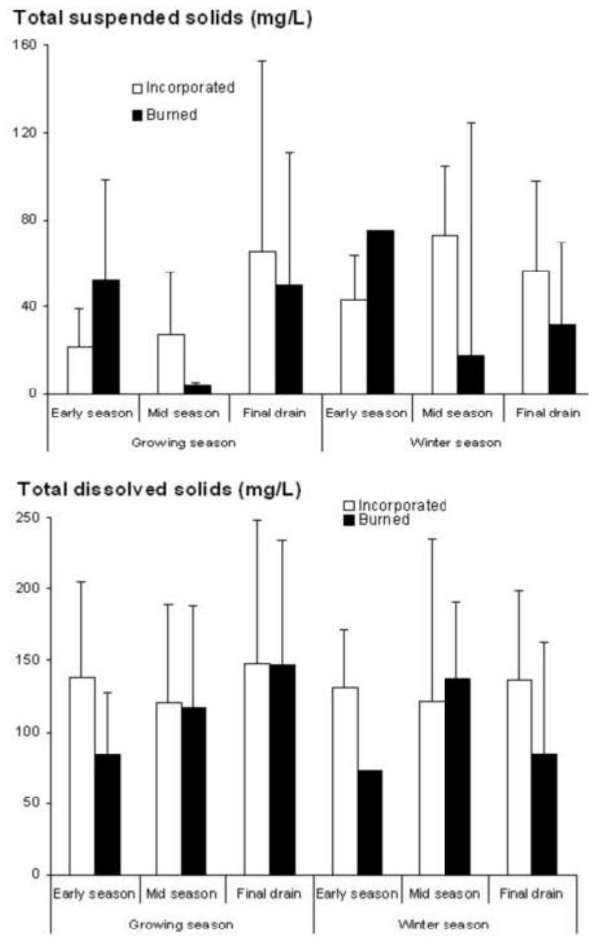


Figure 3. Total suspended solids and total dissolved solids in water leaving rice fields. Data are averaged over two growing seasons.

be associated with health effects), but it is rather used as an indication of aesthetic characteristics of drinking water and as an aggregate indicator of presence of a broad array of chemical contaminants. The Sacramento River typically has TDS values less than 100 mg/L and agricultural watersheds are generally between 250 and 500 mg/L. A UC Davis study found only one water sample with a TDS greater than 500 mg/L. Most of the values were less than 200 mg/L (Fig. 3).

Dissolved organic carbon (DOC): The amount of dissolved organic carbon (DOC) in water is often used as a non-specific indicator of water quality. Organic carbon is a precursor to the formation of harmful disinfection byproducts

(DBPs) in municipal water supplies when water is treated with chlorine. For example, trihalomethanes are one DBP that is considered to be a potential carcinogen. Source water with high DOC concentrations requires additional treatment steps to remove DOC and this increases the cost of treatment. Since the tap water of 22 million Californians originates in the Delta, DOC is an important public health concern. The CALFED Drinking Water Quality Program has the goal of achieving an average TOC concentration of 3 mg/L.

A UC Davis study found that the DOC in rice tail water was higher than that entering the field (Fig. 2). On average the water entering the rice fields had DOC concentrations of 2.4 (+/- 2.4) mg/L which is low because none of the fields in the study used recycled water. While the average is below the 3 mg/L water quality objective, there were samples that were above 3 mg/L. On average, the DOC of the tailwater was 8.6 (+/- 5.4) mg/L. There were seasonal and straw management effects on DOC concentrations (Fig. 4). During the winter and early part of the growing season straw incorporated fields had higher DOC levels than burned fields. This difference was most pronounced at the onset of the winter flood period. During the growing season straw incorporated fields had slightly higher DOC levels at the beginning of the season. Best management practices (BMP) could be developed from this study; however, until critical levels of DOC are established for drainage waters from agricultural fields it is not necessary to adopt management strategies to control it.

Nutrients

Nutrients occur naturally in water as is shown in Figure 2 but they are also added to the water such as when fertilizers are applied. Good management of fertilizers will help ensure that nutrient levels remain low in rice field tailwater. Nitrogen (N), phosphorus (P) and potassium (K) are applied to farm fields as fertilizers but become a problem only when precipitation or flood water washes nutrients off the land and into waterways.

Nitrogen (N): High levels of N in water can produce algae blooms. When the algae blooms die and decompose, oxygen in the water is depleted which causes problems for many aquatic plants and animals that require oxygen.

Some nutrients may pose a health risk to humans. Nitrates, a byproduct of N, are especially dangerous. In drinking water for instance, babies under 6 months of age can develop blue

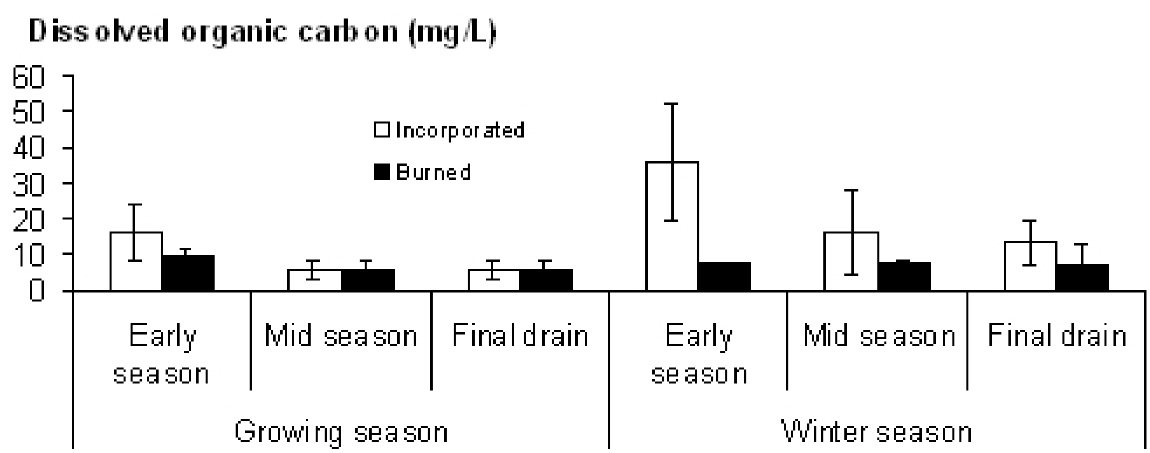


Figure 4. Dissolved organic carbon in water leaving rice fields. Data are averaged over two growing seasons.

baby syndrome. Nitrates in the infant are converted by the body to nitrites that oxidize blood hemoglobin to methemoglobin. The altered blood cells can no longer carry oxy- gen, which can result in brain damage or suffocation. Epidemiological studies also show a correlation between high nitrate levels and gastric and stomach cancers in humans. The risk is so serious that the environ- mental protection agency (EPA) tightly regulates the levels allowed in drinking water. The upper limit for nitrates in drinking water is 10 mg/l as N which is about 45 mg/l of the nitrate ion.

In a two-year study, NO^3-N water concentrations ranged from almost 0 to 2 mg/L, however, 85% of the waters sampled had NO^3-N levels less than 0.1 mg/L (Fig. 5). During the growing season the highest NO^3-N values were at the beginning of the season and may relate to fertilizer management practices-especially the application of starter fertilizers to the soil surface. In the winter, NO^3-N values varied throughout the sea- son. High values in the winter may relate to waterfowl. However, these values are well below 10 mg/L which is the drinking water quality standard.

Ammonia-N values were less than 1 mg/L in our study (Fig. 5). These values are very low and there was not a large affect of season or straw management.

Phosphorus (P): Phosphorus is one of the principle causes of algal blooms in waterways. In rice fields high concentrations of P in the water also lead to algae problems. In a two-year study, P concentrations in the outlet water was always less than 1.0 mg/L with the

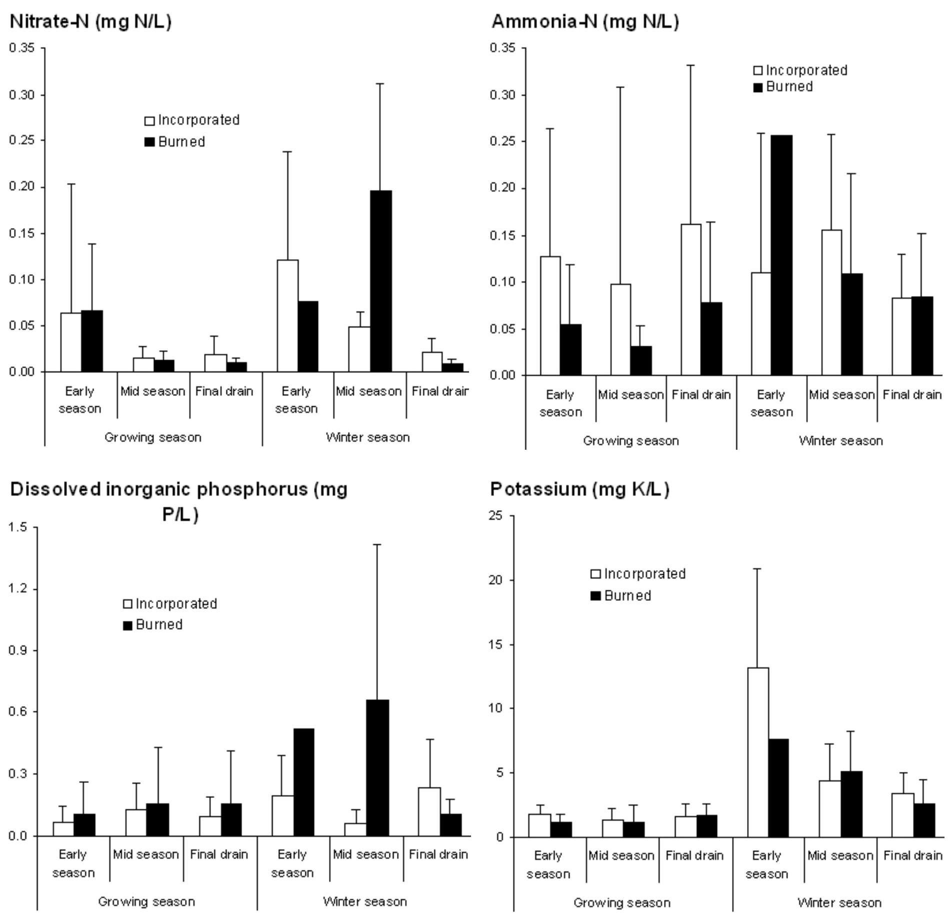


Figure 5. Nitrate-N, ammonia-N, phosphorus and potassium concentrations in water leaving rice fields. Data are averaged over two growing seasons.

exception of one sample (Fig. 5). 77% of the samples had P values less than 0.1 mg/L which was the average P concentration of the inlet water. The highest P values were recorded during the winter from fields where the straw had been burned. The ash following burning is high in soluble P and may have accounted for the high P values found in water leaving these fields.

Potassium (K): Potassium is not normally considered a water quality problem and it is present in most irrigation water. The highest water K concentrations were during the early part of the winter season in fields where straw was incorporated (Fig. 5). Rice straw has a high amount of K in it which can be readily leached out into the flood water. K concentrations were also high in burned fields during the winter period. The rice straw ash contains a high amount of soluble K. The ash and remaining rice stubble are likely the source of water K from these fields.

Metals

Copper (Cu) is the only metal being monitored from rice fields. The source of copper is from the pesticides that are used at the beginning of the growing season primarily to control algae and other pests. In 2006 almost 200,000 rice acres were treated with copper sulfate. In a two-year study, Cu in rice tailwater was not detectable, however, copper sulfate was not used on any of the study fields.

E. coli

E. coli is a type of fecal coliform bacteria that comes from human and ani- mal waste. Elevated levels of E. coli is an indicator that disease-causing bacteria, viruses and protozoans may be present. The water quality limit is 235 CFU (coliform forming units). Water was sampled from rice field inlets, outlets and drains over a two-year period were conducted to determine if E. coli may be a concern. Importantly, the sample size in this study was very small, however, there are some trends worth discussing. First, E. coli levels were generally higher in the winter than during the growing season (Table 2), possibly due to the presence of waterfowl. Second, water entering and leaving rice fields was generally low in E. coli. In one rice field outlet sample the E. coli levels were above the 235 CFU limit. Third, the drains accepting rice field outflows is higher than the rice outlet water and in four cases exceeded the 235 CFU

Table 2. E. coli (CFU – coliform forming units) in water samples from rice field inlets, outlets and drains.

Sample	Season	Total number of samples	Fields sampled	Range	Mean	Number of samples above 235 CFU
				CFU		
Inlet	Growing	5	5	0-49	16	0
	Winter	3	3	22-80	44	0
Outlet	Growing	5	5	0-62	21	0
	Winter	5	6	0-551	133	1
Drain	Growing	3	1	82-3460	1410	2
	Winter	6	4	4-351	139	2

limit. High E. coli values in the drain may be the result of waterfowl and other animals that live in and around the drains.

Management methods to maintain water quality nutrients

Nutrients

There are currently no water quality guidelines for nutrients, TDS, TSS, and DOC; therefore, we will not discuss in detail management options for these constituents. However, we can provide some general guide- lines to reduce the levels of some of these constituents from rice field tail- water.

DOC: DOC concentrations are lower in burned vs incorporated fields during the onset of the winter flood period. Flooding is necessary when straw has been retained in rice fields to encourage straw decomposition. The primary way to reduce the amount of DOC leaving rice fields during the winter is to restrict the flow of water leaving the field.

Phosphorus: While P levels were generally low, levels can be high when P fertilizer is left on the soil surface prior to flooding for planting. Water P levels are greatly reduced by incorporating fertilizer or applying the P fertilizer at a different time (i.e. before fall straw incorporation, before spring tillage, or up to 30 days after sowing). These practices reduce P levels in water and also reduce algae growth in fields. Reductions in algae will reduce the amount of copper applied to fields which is another constituent of concern.

Alternative establishment systems can reduce herbicide use. California rice systems have more herbicide resistant weeds than any other single crop or geographic area in the US. In an effort to control these weeds growers may apply multiple applications or additional herbicides. Applying more herbicides increases the possibility of increasing resistant weed populations and increases the potential for herbicide drift which can end up in surface waters even if hold times are adhered to.

No spring tillage, combined with a stale seedbed, offers new opportunities to control herbicide-resistant weeds and use less and more environ- mentally friendly herbicides. A stale seedbed refers to the practice of flushing or flooding a field with water to induce weed seed germination and then killing the weeds (usually with glyphosate) before planting. The choice between flushing or maintaining the soil surface fully saturated depends on whether or not the field is infested with aquatic obligate weeds which require water saturation to germinate. The soil is then left undisturbed (no tillage) to ensure that buried weed seeds are not brought to the surface to germinate. This practice can be effective for controlling all types of herbicide-resistant weeds in rice systems because they are not resistant to glyphosate. In some studies, conducted at the California Rice Experiment Station the single application of glyphosate was the only herbicide needed season-long.

Holding periods for pesticides.

The primary water quality concern of the California rice industry is residue from pesticides applied to the fields. In 1984, state regulations began which required rice growers to hold pesticide-treated waters on their fields. Long term water holding following application is the primary management method for reducing pesticide concentrations in rice tailwater. This allows for degradation of pesticides within the field (Fig. 6). Different pesticides have different rates of degradation and thus different lengths of required holding periods (Tables 3 and 4).

Water holding requirements exist for most rice pesticides – not only the ones monitored in the

Rice Pesticides Program. Table 4 shows rice pesticide water-holding requirements and was developed from product labels. These do not supersede any additional requirements. Please contact your county agricultural commissioner for label interpretations.

Current regulations provide for emergency release if a written request documents the crop is suffering because of the water management requirements. Emergency release will only be granted for problems related to rainfall, high winds, other extreme weather, or salinity.

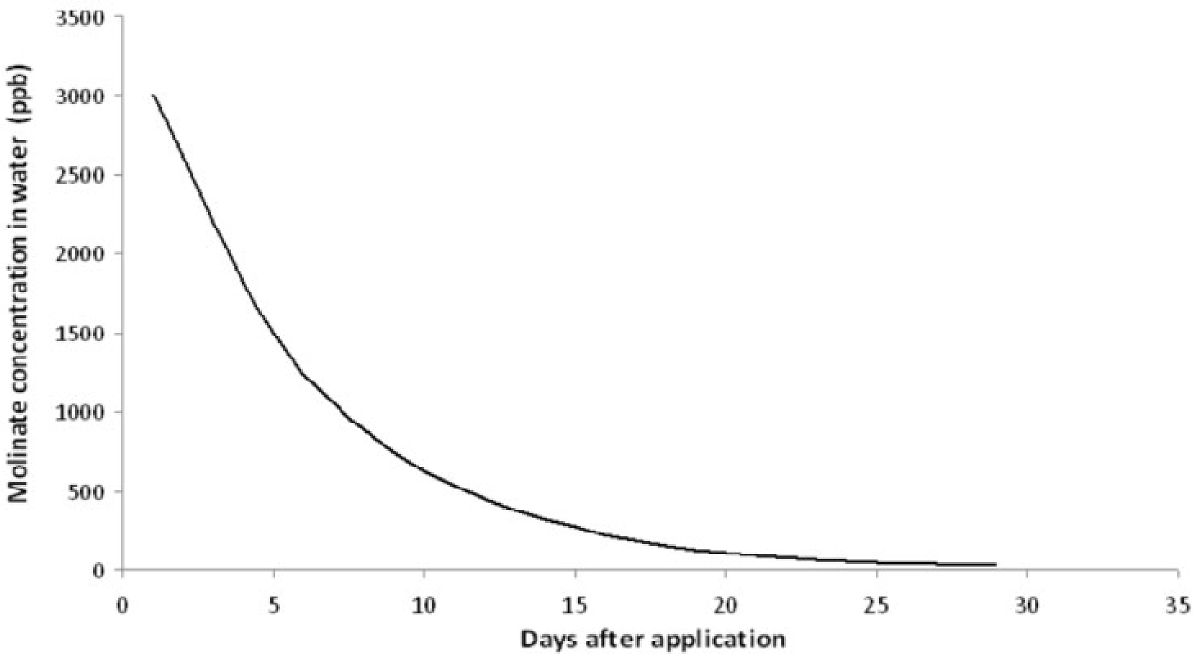


Figure 6. Typical dissipation curve of molinate (Ordram®) in a typical commercial rice field. While molinate is no longer used in rice systems, such dissipation curves lead to the required holding period for molinate shown in Figure 7.

Table 3. Rice pesticide group number per active ingredient, water holding requirements, pre-harvest interval (PHI) and restricted entry interval (REI) from product labels. Please read and follow label directions and contact your county agricultural commissioner for label interpretations and permit conditions.

COMMON TRADE NAME[1]	GROUP NO./ ACTIVE INGREDIENT	WATER HOLD TIME	PRE-HARVEST INTERVAL (PHI)	RESTRICTED ENTRY INTERVAL (REI)
INSECTICIDES:				
Belay® Insecticide	**4A** Clothianidin	14-days	Up to 3rd leaf	12-hours
Mustang® Max Insecticide	**3A** (s)-cypermethrin	7-days	14-days	12-hours
Dimlin® 2L Insect Growth Regulator	**15** Diflubenzuron	14-days	80-days	12-hours
Warrior® Insecticide (various names)	**3A** Lambda cyhalothrin	7-days	21-days; 27-days at the higher rate	24-hours
Malathion 8 (various names)	**1B** Malathion	4-days	4-days: propanil 15-days: bispyribac	12-hours
Intrepid® 2F Section 18	**18** Methoxyfenozide	7-days	14-days	4-hours
FUNGICIDES:				
Quadris® Flowable Fungicide	**11** Azoxystrobin	14-days	28-days	4-hours
Tilt® (propiconazole) Stratego® Fungicide	**3** Propiconazole/ **11** Trifloxystrobin	7-days	35-days	12-hours
HERBICIDES:				
Londax® Herbicide	**2** Bensulfuron-methyl	7-days static	80-days	24-hours
BUTTE® Herbicide	**27** Benzobicyclon/ **2** Halosulfuron-methyl	20-days	82-days	12-hours
Regiment® CA/Arroz 80®	**2** Bispyribac-sodium	0-days	15-days: malathion	12-hours
Shark® Herbicide	**14** Carfentrazone-ethyl	23-days	60-days	12-hours
Cerano® 5 MEG	**13** Clomazone	14-days	120-days	12-hours
Clincher® CA/RebelEX®	**1** Cyhalofop-butyl	0-days	60-days	12-hours
Loyant® CA w/ Rinskor	**4** Florpyrauxifen-benzyl	0-days	60-days	12-hours
Sandea® Herbicide	**2** Halosulfuron-methyl	0-days	69-days	12-hours
Harbenger®/Prowl®	**3** Pendimethalin	0-days		24-hours
Strada® CA Herbicide	**2** Orthosulfamuron	0-days		12-hours
Granite® SC/GR/RebelEX®	**2** Penoxsulam	0-days	60-days	12-hours
Stam® 80 EDF/ SuperWham!	**7** Propanil	7-days: less closed system	60-days	24-hours
Abolish® 8EC/Bolero® UltraMax/League® MVP Willowood Thio Ultramax	**8** Thiobencarb	Table A. DPR Permit Conditions		12-hours
Grandstand®CA Herbicide	**4** Triclopyr TEA	20-days: less closed system	60-days	48-hours

[1]Restrictions apply to all rice pesticides sharing the same active ingredient and are not exclusive to the common trade name.

Trade name	Active ingredient	Water-hold time	Provisions
INSECTICIDES			
Dimlin® 2L Insect Growth Regulator	Diflubenzuron	14 days	None
Mustang® 1.5 EW Insecticide	(s)-cypermethrin	7 days	None
Warrior® Insecticide	Lambda cyhalothrin	7 days	None
FUNGICIDES			
Quadris® Flowable Fungicide	Azoxystrobin	14 days	None
Stratego® Fungicide	Trifloxystrobin/ Propiconazole	7 days	None
HERBICIDES			
Shark® Herbicide	Carfentrazone-ethyl	5-days static 30-days release	Less if closed system
Cerano™ 5 MEG	Clomazone	14 days	None
Clincher™ CA	Cyhalofop-butyl	7 days	None
Whip® 360 Herbicide	Fenoxaprop-p-ethyl	14 days	Applies to use of irrigation water to other crops
Stam™ 80 EDF	Propanil	7 days	Less if closed system
Grandstand™ CA Herbicide	Triclopyr TEA	20 days	Less if closed system

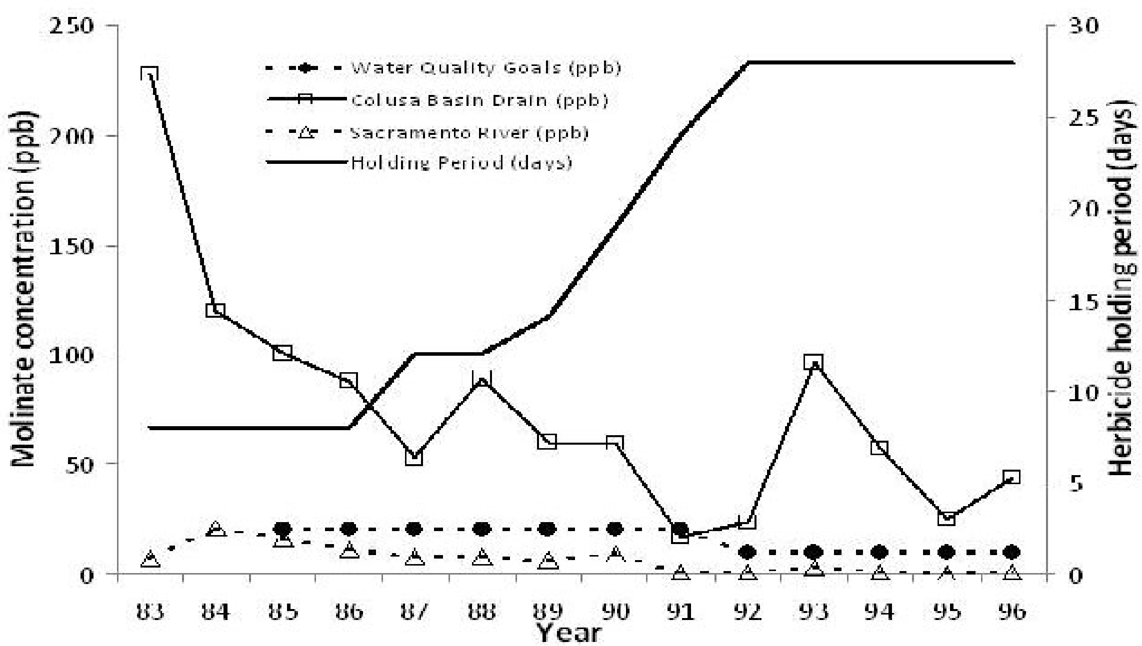


Figure 7. Maximum concentrations of molinate (Ordram®) in the Colusa Basin Drain and the Sacramento River. While molinate is no longer used on rice this figure shows the effect of holding periods on water quality.

Adoption of other rice irrigation systems for tailwater management

Mandatory holding periods have made it difficult for rice growers with conventional irrigation systems to maintain flexibility in managing their irrigation water. Two systems are discussed in this section that will pro- vide greater management flexibility and reduce or eliminate the possibility of spillage during water holding periods.

Gravity tailwater recapture irrigation system. The gravity tailwater recapture irrigation system utilizes pipes and gravity flow to divert tailwater from field to field thereby keeping drain water and pesticide residues out of public waterways. The water flows by gravity, eliminating tailwater pump and sump. Bypass drainpipes in upstream fields are installed in bottommost basins (checks) for maximum effectiveness. The pipe can enter the downstream field at any point, although entry into the upper portion of the field allows the greatest flexibility. The advantages of this system include improved tailwater and pesticide residue containment, management flexibility during water holding periods, and low construction and operation cost. The disadvantages are: when many basins are interconnected, the large water surface area may make quick and precise water management difficult; requires coordination of water among many fields; the system is not completely closed and may allow some tailwater and pesticide residue to enter public waterways.

The float valve rice box. The conventional irrigation system can be improved by replacing the conventional rice weir with a “smart box”. A smart box operates on the same principle as a toilet tank or a horse-trough valve. The plastic container or float of a smart box is adjusted so that it opens and closes a vertically hinged butterfly valve. When the water in the downstream basin is low, the plastic container floats downward and opens the flap gate, allowing water into the basin. When the water depth reaches the set level (adjustable by adding or removing water from the hollow plastic float) the container floats upward, closing the valve: water cannot enter the basin. As long as a source of water is available to the topmost basin, the series of basins is regulated. Each basin takes in water as needed and shuts off when the desired water depth is reached, thereby eliminating much of the day-to-day management associated with traditional flashboard weirs. Once smart boxes are properly adjusted, no spill should occur from the bottommost basin.

Seepage water management

Seepage is the lateral movement of irrigation water through a rice field levee or border to an area outside of the normally flooded production area. Seepage can occur through levees into adjacent dry fields or into existing drains and canals. Leakage caused by crayfish and rodent bur- rowing is not considered seepage but can also result in the movement of irrigation water off rice fields. Seepage will be readily apparent later during the growing season as water accumulates and by green weedy growth along the edge of the field. Occasionally, seepage appears as a wet area that can damage a perimeter road.

Seepage water that contains high concentrations of pesticides can hinder efforts to comply with California’s water quality goals. Efforts to meet these goals depend on long holding periods, which allow pesticides to dissipate almost completely in rice fields before release. Nevertheless, the concentrations of rice pesticides found in many agricultural drains exceed the levels found in tailwater released from rice fields after an adequate holding period. Therefore, seepage and off-target applications (for example, drift) are believed to be the source of the high concentrations currently found in agricultural drains. As holding periods for rice pesticides increased during the last decade, and the contribution of tailwater runoff to pesticide loading of surface waters declined, the relative contribution of seepage to such loading was recognized. Currently, seepage is regarded as an important contributor to pesticide loading in Sacramento Valley waterways.

Rice pesticides that do not strongly adsorb to soil particles, for example, molinate can move with seepage water from treated fields into agricultural drains or other nontarget areas. This seepage water will contain approximately the same concentration of certain rice pesticides as in the field.

In an effort to determine if rice pesticides, particularly molinate, can move with seepage water, the Department of Pesticide Regulation undertook a study to determine the extent of molinate movement from treated commercial rice fields through levee banks into adjacent ditches or fallow fields. In 1992, two sites, located in commercial rice fields in Colusa County, were chosen because they were known to have seepage problems in previous years. Prior to the application of molinate, the suspected seepage areas were covered with heavy plastic tarps to prevent contamination from aerial drift and kept covered throughout the study. At the first site, on a Willows clay, the molinate concentration in the seepage water peaked two days after application at 205 parts per billion (ppb). At the second site, on a Wikoda silty clay, concentrations at six days after sampling were as high as 720 ppb. At the time of the study the water quality goal for molinate was 10 ppb for all public waterways. While this study was not able to determine the extent of seepage throughout the Sacramento Valley, it did show that molinate can move with seepage water through levees to nontarget areas. Other studies conducted by the Central Valley Regional Water Quality Control Board found that both molinate and carbofuran are present in seepage water in ditches adjacent to treated fields. The concentration of these pesticides is likely to be present in the seepage water soon after the field has been treated.

Recognizing seepage and what causes it as well as when and where it occurs can be the first step to good seepage or leak control. For a more complete discussion, see “Seepage Water Management, Voluntary Guidelines for Good Stewardship in Rice Production”, UC Division of Agriculture and Natural Resources Pub. 21568.

UNIVERSITY OF CALIFORNIA AGRICULTURE AND NATURAL RESOURCES
COOPERATIVE EXTENSION
UC DAVIS DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS

2021
SAMPLE COSTS TO PRODUCE RICE

SACRAMENTO VALLEY
Rice Only Rotation, Medium Grain

Prepared by

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Sample Costs to Produce Rice

Sacramento Valley- 2021

Rice Only Rotation, Medium Grain

STUDY CONTENTS

INTRODUCTION

Sample costs to produce medium grain rice in the Sacramento Valley are presented in this study. It is intended as a guide only, and can be used to make production decisions, estimate potential returns, prepare budgets and evaluate production loans. Practices described are based on production practices considered typical for the crop and area, but these same practices will not apply to every farming operation. The sample costs for labor, materials, equipment and custom services are based on June 2021 figures. A blank column titled "Your Cost", is provided in Tables 2 and 3 for your convenience.

For an explanation of calculations used, refer to the section titled Assumptions. For more information contact Donald Stewart, Department of Agricultural and Resource Economics, UC Davis at 530-752-4651 or destewart@ucdavis.edu. To discuss this study with a local county extension farm advisor, contact your county cooperative extension office. ucanr.edu/County_Offices/.

Sample Cost of Production studies for many commodities are available and can be downloaded from the Department website: coststudies.ucdavis.edu. Archived studies are also available on the website.

Costs and Returns Study Program/Acknowledgements. A cost and returns study is a compilation of specific crop data collected from meetings with professionals working in production agriculture from the region. The authors thank farmer cooperators, UC Cooperative Extension, and other industry representatives who provided information, assistance, and expert advice. **The use of trade names and cultural practices in this report does not constitute an endorsement or recommendation by the University of California nor is any criticism implied by omission of other similar products or cultural practices.** *The University is an affirmative action/equal opportunity employer.*

ASSUMPTIONS

The assumptions refer to Tables 1 through 7 and pertain to sample costs to produce medium grain rice in the Sacramento Valley. The cultural practices shown represent production operations and materials considered typical of a well-managed farm in the region. Costs, materials, and practices in this study will not apply to all situations. Timing and types of cultural practices will vary among growers within the region and from season to season due to variables such as weather, soil, insect, and disease pressure.

Farm. The hypothetical farm consists of 840 non-contiguous acres. The grower owns 10 acres and rents 830 acres. Medium grain rice (Calrose) is grown on 800 acres and 40 acres are roads, irrigation systems, equipment and shop area, and homestead. Typically, a grower with this amount of rice acreage will have several non-adjacent fields and the cultural practices will vary among fields. Additionally, extra costs may be incurred moving equipment between fields, (which can be in different irrigation districts). Such costs are not included in this study. No other crops are grown in rotation with rice. All operations are done on 100 percent of the acres unless noted otherwise.

This study assumes the grower owns 10 acres, valued at $12,500 per acre, and rents 830 acres at $475 per acre. This study assumes 100 percent of farmed land is rented. For more details about owned and rented land, please refer to the "Cash Overhead" and "Non-Cash Overhead" sections.

Cultural Practices and Material Inputs

Pre-Plant Land Preparation. Most of the primary tillage, including chiseling, discing, land leveling, laser leveling, and rolling, is normally done from March through May. The permanent levees, which comprise 5 percent of the acres, are reworked, and drainage ditches are maintained as necessary. Environmental regulations may affect the way the drains and levees are maintained and additional costs may be incurred, which are not accounted for in this study.

All fields are chiseled two times to open the ground and dry the soil. This is followed by one discing to break up large clods with a stubble disc, and then disced once more with a finish disc, which increases the soil's drying surface. Precision, laser leveling is done to 50 percent of the acreage annually. The grower tri-planes the other 50 percent of the acreage to maintain even ground for water flow.

Aqua ammonia fertilizer is custom applied by ground, using an aqua rig. The starter fertilizer and zinc are custom applied with a ground rig. The ground is rolled by the grower with a corrugated roller prior to flooding and planting.

Fertilizer. Aqua ammonia is applied pre-plant at 130 pounds of N per acre with an aqua fertilizer injector ground rig, 3 to 4 inches deep. A starter fertilizer, 12-23-20 at 200 pounds per acre, is applied by ground and incorporated using a corrugated roller (can also be applied by air). Zinc sulfate is applied with the starter and is incorporated with those operations. In July, 75 percent of the acres are top dressed by air with 31.5 pounds of N, or 150 pounds of ammonium sulfate per acre.

Planting. Water seeding, in contrast to drill-seeding or dry-seeding, is the primary seeding method in California. The field is flooded and the seed is soaked in water, (see Pest Management, *Disease*) to begin germination and drained. The seed is broadcast by air into a few inches of water on the fields at a rate of 175 lbs./acre. Seeding rates vary from field to field and by variety. Most planting is done from April 20 to May 20.

Irrigation. The grower purchases the irrigation water from an irrigation district; however, growers may also use well water, (ground water) which will incur extra costs from pumping. The grower pays the water costs on the farmed land, which varies widely between irrigation districts in the Sacramento Valley. The total seasonal-cost of irrigation water for this study is $150.00 per acre. Typically, four to six acre-feet of water are applied during the growing season. This does not include the water needed for straw management.

Pest Management. The pesticides and rates mentioned in this cost study are listed in *UC Agronomy Research and Information Center, Rice,* rice.ucanr.edu. **Pesticides mentioned in the study are not recommendations, but those commonly used in the region**. For information on other pesticides available, pest identification, monitoring, and management visit the UC IPM website at ipm.ucdavis.edu.

For additional information and pesticide use permits, contact the local county Agricultural Commissioner's office. **The owner/manager who applies pesticides to his or her property may need to hold a valid private applicator certificate that is issued by the agricultural commissioner's office**. Pesticides with different active ingredients, mode of action, and sites of action should be rotated as needed to combat species shift and resistance. Adjuvants and crop oils are recommended for use with many pesticides for effective control.

Pest Control Adviser/Certified Crop Advisor, (PCA/CCA). An individual who is licensed as a PCA and/or a CCA may monitor the field for pests and disease, collect samples for nutrient analyses, and complete surveys and paperwork for regulatory compliance. A CCA emphasizes fertilizer and plant nutrient management issues. Growers may hire private PCA's or receive the service as part of a service agreement with an agricultural chemical company. Pesticide costs may vary by location and grower volume. In this region, a written recommendation for fertilizer applications is currently not required.

Weeds. Grass weeds and broadleaf weeds are controlled with separate aerial and ground applications. Herbicides, (e.g. Butte, Clincher, Bolero, Granite GR, or a combination) to control grass weeds are applied to 100 percent of the rice shortly after planting. This study assumes that Butte is applied to 100 percent of the acres by air in May. Tank mixes of two foliar active herbicides are often used for the second herbicide application.

This study assumes that a Propanil (Super Wham) and Grandstand tank mix is applied by ground, as stated above, on 100 percent of planted acres. Final weed control is a cleanup herbicide (e.g. Regiment) application in late June that is applied using a ground rig on 80 percent of the acres. Weed material programs vary amongst growers due to management of herbicide resistant weeds or other production circumstances. However, material costs per acre are within similar ranges.

Algae. After planting in May, Copper Sulfate is custom applied by air on 30 percent of the acres.

Insects. Seedling arthropod pests (rice water weevil/tadpole shrimp and rice seed midge) control begins in May after planting, by treating 30 percent of the acres, which includes the field borders or edges and levees with Lambda cyhalothrin insecticide. Armyworms are controlled with one insecticide application of Dimilin in July, on 25 percent of the acres.

Diseases. Rice seed is pre-soaked before planting in either a fungicide or chlorine treatment for control of bakanae diseases. Stem rot, aggregate sheath spot and blast are controlled July through August with one application by air of azoxystrobin on 75 percent of the acres.

Vertebrate Pests. Cannons, also known as zon guns are used to scare birds away from the crop, if needed. The guns run on propane and must be monitored daily. No charges are shown.

Endangered Species. It is important to know if your farm is located in an area where endangered species reside. Trapping and killing endangered species can result in fines. Contact your County Agricultural Commissioner for additional information.

Harvest, Yield, Revenue and Assessments

Harvest. The rice crop is harvested at 20 percent kernel moisture (green rice) using a combine with a cutter-bar header. The grower also owns a pull-type grain cart/bankout wagon. The combine can unload grain (while still harvesting) into the grain cart. The grain is transported out of the field, to bulk grain trailers for transport to the drying facility.

*Transportation***.** The grower pays the transportation of green rice from the field to the dryer. Hauling grain from the dryer to storage may be considered a processing or marketing expense, but is a cost and is reflected in the price returned to the grower. The cost of transporting the rice from the field to the dryer is included, but the hauling cost between the dryer and warehouse is not. The cost of transporting rice is based on a green weight of 102 hundredweight (cwt) per acre and a $0.50 per cwt field pickup and hauling charge. Green weight is the calculated weight of the harvested rice at 20 percent moisture, including 'invisible shrink'.

Table A. Average California Yields and Prices.

Year	Yield/Acre (cwt) (Medium Grain)	Revenue/Acre ($/cwt) (Medium Grain)
2005	75.50	10.10
2006	78.80	13.00
2007	85.00	16.20
2008	85.50	27.40
2009	87.40	19.50
2010	82.00	20.80
2011	85.00	18.40
2012	83.50	18.40
2013	86.70	20.70
2014	88.00	21.50
2015	91.00	18.40
2016	90.00	14.30
2017	86.20	20.30
2018	88.10	21.30
2019	85.90	21.80
2020	89.20	18.90

Drying and Storage. Drying charges increase with moisture content. Most dryers use a rate schedule that reflects the loss of moisture plus other 'invisible' losses in the system associated with immature kernels, dockage and dust. The non-moisture factor varies among dryers, but usually ranges from two percent to six percent. Together, these losses are called 'shrink'. Rice is assumed to be dried to 14 percent moisture. The drying rate charge is based on a green weight of 102 cwt. The current cost of drying the rice is $0.95 per cwt. Storage is charged at $0.78 per cwt on the dry weight and is similarly increased to estimate future power costs. Most of the drying cost is related to natural gas prices, and the storage cost is related to electricity prices.

Yields. The crop yield used in this study is 9,000 pounds (90 cwt) per acre at 14 percent moisture. Yields vary over the years in California, see Table A.

Revenue. A selling price of $21.50 per cwt. of grain rice (with an assumed loan value of $7.00, or $14.50 above loan value) is used to estimate market income. A range of yields and prices are presented in Table 4.

The Agriculture Improvement Act of 2018 (the 2018 Farm Bill) amended the Agricultural Improvement Act of 2014 (2014 Farm Bill) and reauthorized the Agriculture Risk Coverage (ARC) and Price Loss Coverage (PLC) programs with modifications. usda.gov/farmbill.

The 2018 Farm Bill requires a unanimous election to obtain PLC or ARC-CO on a covered commodity-by-commodity basis that will remain in effect for the 2019 through 2023 crop years. An election of ARC-IC in any year will apply to all covered commodities on the farm. Starting with the 2021 crop year, and each crop year thereafter through 2023, the producers on a farm may change the election of PLC or ARC on a year-to-year basis. fsa.usda.gov/programs-and-services/price-support/commodity-loans/non-recourse-loans/rice-program/index

The PLC Program provides payments when the effective price for a covered commodity falls below its effective reference price, which is $14.50 per cwt for Temperate Japonica, as of 2020.

ARC Program is an income support program that provides payments when actual crop revenue declines below a specified guarantee level. The ARC-CO program provides income support tied to historical base acres, not current production, of covered commodities. ARC-CO payments are issued when the actual county crop revenue of a covered commodity is less than the ARC-CO guarantee for the covered commodity. These programs are administered by the United States Department of Agriculture's (USDA), Farm Service Agency (FSA). A single limit of $125,000 for each "person…actively engaged in farming" (as defined by the ACT) applies to all payments under these programs.

Payments are tied to a farm's historical rice and other commodity base acres and yields, and are not available to producers whose average adjusted gross income exceeds $900,000. The study assumes that a grower selects the PLC program; however, selection criteria should be based on individual farm analysis. For more information on these and other programs, or on meeting minimum requirements to comply with the programs, please contact the USDA FSA, or visit the website: fsa.usda.gov/programs-and-services/arcplc_program/index.

Net Revenue. A grower will achieve a positive cash flow when net returns above cash costs (gross returns minus operating costs) are positive. This means that returns are sufficient to cover annual operating expenses (material inputs, labor costs, harvest, fuel, lube and repairs, and interest on operating loans). However, a positive cash flow does not include consideration of a return on investment in owned capital, also called non- cash overhead expenses. Nor does it include loan payments on capital investments such as equipment, irrigation system, and buildings. Net returns over total cost (gross return minus total costs) include both cash costs and non-cash costs. If net returns above operating costs are positive but net returns above total costs are negative, over time, gross returns will be insufficient to replace equipment and other investments necessary for production.

Ranging Analysis. Table 4 has a range of return prices used for calculating net returns per acre at different yields. The yield range used for this study is 7,500 to 10,500 pounds (75-105 cwt) per acre with the price range from $15.50 - $27.50 per 100 pound sac (cwt).

Straw Management. Post-harvest operations for straw decomposition are usually done using a single or a combination of commonly used methods, including: 1) chopping, discing, and flooding, 2) chopping and flooding, 3) chopping, flooding and rolling (stomping) and 4) chopping and discing, then rolled (stomped).

The rice straw is chopped, disced, and then rolled (stomped) on 100 percent of the acres. The winter water availability and costs for single and continuous flooding vary by district, and may be rain-fed. Water for straw decomposition is commonly used, but is not used in this study.

Bailing. Swathing, bailing and hauling to a cogeneration plant (recycled energy) is done by growers that live within the region of the plants that make this method economically feasible.

Burning. Rice straw burning is becoming increasingly rare in the Sacramento Valley. The cost of burning stubble, burn permits and addition fees associated with this method are not included in this study.

Assessments. Producers pay two assessment fees.

California Rice Research Board (CRRB). Under a state marketing order a mandatory assessment fee is collected and administered by the CRRB. This assessment of $0.07 per dry cwt pays for rice research funded by the CRRB. carrb.com/

The California Rice Commission (CRC). This commission assesses each rice grower $0.07 per dry cwt. Rice millers and marketers also contribute an equal amount of $0.07 per dry cwt. This provides the CRC with a total budget based on $0.14 per cwt for all California rice produced to work on a variety of issues facing the California rice industry. calrice.org/

Labor, Equipment and Operating Interest

Labor. Labor Rates are $27.93 per hour for machine operators, $22.05 for non-machine, hand labor and $44.09 for an assistant supervisor irrigation labor. These rates include payroll overhead of 46.98 percent. The basic hourly wages are $19.00 for machine operators, $15.00 for non-machine, hand labor and $30.00 for assistant supervisor irrigation labor. The overhead includes the employer's share of federal and California state payroll taxes (14.85%), workers' compensation insurance (15.71%) for field crops, and a percentage for other possible benefits (16.42%). These costs are based on the average industry final rate as of June, 2021.

Wages for management are not included as a cash cost. Any revenue above total costs is considered a return to management and risk. However, growers wanting to account for management may wish to add a fee. The manager makes all production decisions including cultural practices, action to be taken on pest management recommendations, and labor.

Equipment Operating Costs. Repair costs are based on purchase price, annual hours of use, total hours of life, and repair coefficients formulated by American Society of Agricultural & Biological Engineers (ASABE). Fuel and lubrication costs are also determined by ASABE equations based on maximum Power Take Off (PTO) horsepower, and fuel type. Average prices for on-farm delivery of red-dye diesel and gasoline, based on grower cooperator information and, June, 2021 data from the Energy Information Administration, are $2.80 and $3.90 per gallon, respectively. The cost includes a 13.0 percent sales tax on diesel and 2.25 percent sales tax on gasoline. Federal and state excise taxes on diesel ($0.36/gal) and gasoline ($0.473/gal) are refunded for on-farm use when filing the farm income tax return.

Fuel/Lube/Repairs. The fuel, lube, and repair costs per acre for each operation in Table 1 is determined by multiplying the total hourly operating cost in Table 6 for each piece of equipment used for the selected operation by the hours per acre. Tractor time is ten percent higher than implement time for a given operation to account for setup, travel and down time.

Owned Equipment. For a list of equipment included in the farms inventory and operating costs, see Tables 5 and 6.

Harvest/Header. The total revenue of the 840 acre farm does not support the purchase and operating costs of a new combine. The new combine could harvest as much as 1,200 acres in a season. The combine would be leased as a custom operation by neighboring farmers, creating additional income that would pay for the annual maintenance and repair costs. The grower could also own a used combine purchased at a much cheaper price.

Rented Equipment. A 325 HP, 4WD tractor is rented for one month (250 hours). The tractor is used for ground preparation tillage operations over the 800 acres.

Pickups. Business use of 30,000 miles per year is assumed for the ¾-ton pickup and 20,000 miles per year for the ½-ton pickup. The charges are shown under cultural operations.

Back Hoe/Road Grader/Implement Carrier/Truck 5-Ton. This equipment is listed under investments, "Non-Cash Overhead" section at replacement value. They are used sparingly for various tasks around the farm with no assigned costs. Some of this equipment would have been purchased previously and would be fully depreciated. Only operating and maintenance costs would be shown.

Interest on Operating Capital. Interest on operating capital is based on cash operating costs and is calculated monthly until harvest at a nominal rate of four percent per year. A nominal interest rate is the typical market cost of borrowed funds. The interest cost of post-harvest operations is discounted back to the last harvest month using a negative interest charge. The interest rate will vary depending upon various factors. The rate is this study is considered a typical lending rate by a farm lending agency as of June, 2021.

Risk. The risks associated with crop production should not be underestimated. While this study makes every effort to model a production system based on typical, real world practices, it cannot fully represent financial, agronomic and market risks, which affects profitability and economic viability of agricultural production. Moreover, Table 4 reflects a ranging analysis of returns based on various assumptions which is therefore, hypothetical in nature. **It is important to realize that actual results may differ from the returns contained in this study**. Any returns above total costs are considered returns on risk and investment to management (or owners).

Cash Overhead

Cash overhead consists of various cash expenses paid out during the year that are assigned to the whole farm and not to a particular operation. These costs can include property taxes, interest on operating capital, liability and property insurance, sanitation services, equipment repairs, and management.

Property Taxes. Counties charge a base property tax rate of one percent on the assessed value of the property. In some counties special assessment districts exist and charge additional taxes on property including equipment, buildings, and improvements. Property taxes applied in this study are calculated as one percent of the average value of the property and are not influenced by the Williamson Act or additional county taxes. Average property value equals new cost, plus salvage value divided by two on a per acre basis.

The Williamson Act. California Land Conservation Act has helped preserve agricultural and open space lands since 1965. Local governments and landowners enter into voluntary contracts to restrict enrolled lands to agricultural and open space uses in exchange for property tax reductions. The impact of the Williamson Act on property taxes will vary from year to year and property to property. This is due to how it is annually calculated and then compared to its Proposition 13 (factored base year value). The lower of the two is used for the annual assessment.
boe.ca.gov/proptaxes/pdf/lta19029.pdf
boe.ca.gov/proptaxes/faqs/changeinownership.htm

Insurance. Insurance for farm investments varies depending on the assets included and the amount of coverage.

Property Insurance. This provides coverage for property loss and is charged at 0.886 percent of the average value of the assets over their useful life.

Liability Insurance. A standard farm liability insurance policy fee of $1,461 is included as a cost for the entire farm. This is the cost of the basic policy and paperwork. Additional coverage will incur additional costs. A standard farm liability insurance policy will help cover the expenses for which the owner becomes legally obligated to pay for bodily injury claims on owned property and damages to another person's property as a result of a covered accident.

Crop Insurance. Crop insurance is a tool that some growers use to help offset revenue loss risk. This study assumes that all acres in the farm are eligible for Prevented Planting (PP) coverage, which is available under catastrophic (CAT) crop insurance and buy-up insurance policies. A buy-up insurance policy offers growers more coverage and flexibility to tailor a crop insurance plan to a specific operation. Yield and revenue insuranceare the most common buy-up policies and offer coverage levels between 50 to 85 percent.

The United States Department of Agriculture Risk Management Agency (USDA RMA) sets crop insurance policies and costs, which are administered by private insurance companies. Various crop insurance policies are offered for rice growers in the Sacramento Valley, including revenue protection, revenue protection with harvest price exclusion and yield protection. Depending on the crop insurance policy, the USDA RMA will subsidize between 38 and 67 percent of the grower premium cost, as of July 2018.

The grower, in this study, is assumed to purchase a 75 percent yield protection policy, with an additional 55 percent PP coverage level, assumed to cost $18 per acre. For more information on crop insurance, visit the Risk Management Agency website: rma.usda.gov/, and for more information on Prevented Planting coverage, refer to the RMA Handbook: *Prevented Planting Loss Adjustment Standards Handbook* (FCIC- 25370 [10-2006]).

Rent. Cash rents range from $350 to $550 per acre with surface water rights attached to the land, but water is not paid for by the landowner. The cost of water is borne by the grower renting the land. A rental price of $475 per acre is used in this study. All farmed acres are assumed to be rented, and considered a cash cost. This study assumes all farmed acres are rented to account for the current cost of farming on rice land.

Regulatory Compliance and Administrative Costs. Compliance and administrative costs are estimated to be $25 per acre. This includes expenses such as managing paperwork for regulatory compliance of water quality programs such as waste discharge requirements. This would also include farm evaluation (USDA surveys) and nitrogen management plan reporting as well as miscellaneous administrative costs that accompany the compliance paperwork. These tasks can be performed by the grower, or contracted to a consultant.

Office and Business Expense. Office and business expenses are estimated at $50 per acre. These expenses include office supplies, telephone/internet, bookkeeping, accounting, and office utilities.

Investment Repairs. Annual repairs on investments or capital recovery items that require maintenance are calculated as two percent of the purchase price. This includes repair on all investments except for land.

Non-Cash Overhead

Non-cash overhead is calculated as the capital recovery cost for equipment and other farm investments.

Capital Recovery Costs. Capital recovery cost is the annual depreciation and interest costs for a capital investment. It is the amount of money required each year to recover the difference between the purchase prices and salvage value (unrecovered capital). It is equivalent to the annual payment on a loan for the investment with the down payment equal to the discounted salvage value. This is a more complex method of calculating ownership costs than straight-line depreciation and opportunity costs, but more accurately represents the annual costs of ownership because it takes the time value of money into account (Boehlje and Eidman). The formula for the calculation of the annual capital recovery costs is [(Purchase Price – Salvage Value) x Capital Recovery Factor] + (Salvage Value x Interest Rate).

Salvage Value. Salvage value is an estimate of the remaining value of an investment at the end of its useful life. For farm machinery (tractors and implements) the remaining value is a percentage of the new cost of the investment (Boehlje and Eidman). The percent remaining value is calculated from equations developed by the American Society of Agricultural & Biological Engineers (ASABE) based on equipment type and years of life. The life in years is estimated by dividing the wear out life, as given by ASABE, by the annual hours of use in this operation. For other investments including irrigation systems, buildings, and miscellaneous equipment, the value at the end of its useful life is zero. The salvage value for land is the purchase price because land does not depreciate.

Capital Recovery Factor (CRF). The CRF can be interpreted as the amount of equal (or uniform) payments to be received for (n) years such that the total present value of all these equal payments is equivalent to a payment of 1 dollar at present, if interest rate is (i) (Boehlje and Eidman).

CRF is the amortization factor for an asset and is calculated as; $[i * (1 + i)^n]/[(1 + i)^n - 1]$ where *(i) is the interest rate and (n) the number of years the asset is held.

Interest Rate. An interest rate of 4.75 percent is used to calculate capital recovery. The rate will vary depending upon loan amount and other lending agency conditions, but is the basic suggested rate by a farm lending agency as of June 2021.

Land. Rice land values range from $11,000 to $14,000 per acre. This study uses a value of $12,500 per acre. Environmentally important rice land is valued in excess of the amount that growers can profitably afford to pay because environmental associations or government agencies may be willing to pay more to acquire the land, however such land represents a small portion of total rice land. In this study, ten acres of land is assumed to be owned by the grower and not shown as an investment.

Irrigation System. The property has surface water delivered to the fields by a water district via a canal system from water stored in reservoirs. The fields have systems of lateral ditches and drainage ditches, and irrigation boxes in the fields to maintain water flow and depth. Pumping of ground water for irrigation is not used in this study.

Building. The metal building is on a cement slab with an attached pole barn with a fenced equipment yard.

Shop Tools. This includes shop machinery and tools.

Fuel Tanks. One 1,000-gallon diesel and one 500-gallon gasoline, fuel tanks, using gravity feed are on metal stands. The tanks are setup in a cement containment pad that meets federal, state, and county regulations.

Global Positioning Systems, (GPS). The stationary GPS sending unit is mounted so that it can receive and send data to the tractors operating in the fields. The receiving units are mounted so that they are removable and interchangeable with several tractors.

Equipment. Farm equipment is purchased new or used, but the study shows the current purchase price for new equipment. The new purchase price is adjusted to 60 percent to indicate a mix of new and used equipment. Annual ownership costs for equipment and other investments are shown in the Whole Farm Annual Equipment, Investment, and Business Overhead Costs, Table 6. Equipment costs are composed of three parts: non-cash overhead, cash overhead, and operating costs. Both of the overhead factors have been discussed in previous sections. The operating costs consist of repairs, fuel, and lubrication and are discussed under operating costs.

Table Values. Due to rounding, the totals may be slightly different from the sum of the components.

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UC COOPERATIVE EXTENSION
AGRICULTURAL AND RESOURCE ECONOMICS, UC DAVIS
Table 1. COSTS PER ACRE TO PRODUCE RICE
Sacramento Valley- 2021

	Equipment	Cash and Labor Costs per Acre						
Operation	Time (Hrs./Ac)	Labor Cost	Fuel	Lube & Repairs	Material Cost	Custom/ Rent	Total Cost	Your Cost
Ground Preparation:								
Irrigation: Maintain laterals/Boxes/Drains	0.13	4	2	1	0	0	7	
Irrigation: Maintain Interior Levees	0.12	4	6	3	0	0	13	
Chisel 2x	0.28	9	16	5	0	16	46	
Stubble Disc	0.12	4	7	2	0	16	29	
Finish Disc	0.13	4	7	3	0	0	15	
Land Level: Tri-plane 50% Ac	0.13	5	7	3	0	0	15	
Land Level: GPS Laser 50% Ac	0.00	0	0	0	0	50	50	
TOTAL GROUND PREP COSTS	0.92	31	45	17	0	82	175	
Pre-Plant:								
Fertilize: NH_4OH @ 130lbs. N/Ac	0.12	4	6	2	72	25	109	
Fertilize: 12-23-20/Zinc Sulfate	0.00	0	0	0	50	20	70	
Finish Roll	0.12	4	2	1	0	0	7	
TOTAL PRE-PLANT COSTS	0.23	8	8	3	122	45	185	
Cultural:								
Irrigate: Water & Labor	0.00	44	0	0	150	0	194	
Seed: Soak & Deliver	0.00	0	0	0	57	5	62	
Planting: Seed - 175 lbs./Acre	0.00	0	0	0	0	21	21	
Weeds: Grasses (Butte)	0.00	0	0	0	128	12	140	
Insects: Midge/Shrimp/Weevil 25% Ac (Lambda cy)	0.00	0	0	0	3	3	6	
Weeds: Algae 30% Ac (Copper Sulfate)	0.00	0	0	0	6	4	10	
Weeds: Broadleaf (Grandstand/Super Wham)	0.00	0	0	0	71	20	91	
Weeds: Cleanup 80% Ac (Regiment)	0.00	0	0	0	24	16	40	
Fertilize: Top-Dress 75% Ac (NH_4SO_4)	0.00	0	0	0	36	11	47	
Insects: Armyworms 25% Ac (Dimilin 2L)	0.00	0	0	0	3	3	6	
Disease: Fungus 80% Ac (Quadris)	0.00	0	0	0	11	10	21	
Truck: ½-Ton	0.47	16	5	2	0	0	22	
Truck: ¾-Ton	0.50	17	5	4	0	0	25	
TOTAL CULTURAL COSTS	0.97	76	9	5	490	105	686	
Harvest:								
Combine/Header 30'	0.33	11	26	47	0	0	84	
Bankout Grain	0.30	10	16	7	0	0	33	
Haul to Dryer & Storage	0.00	0	0	0	0	51	51	
Dry & Store Rice	0.00	0	0	0	0	167	167	
TOTAL HARVEST COSTS	0.63	21	42	54	0	218	335	
Assessments:								
Rice Research Board Assessment	0.00	0	0	0	6	0	6	
California Rice Commission	0.00	0	0	0	6	0	6	
TOTAL ASSESSMENTS COSTS	0.00	0	0	0	13	0	13	
Post-Harvest:								
Straw: Chop 100% Ac	0.25	8	4	3	0	0	14	
Straw: Disc 100% Ac	0.17	6	9	4	0	0	18	
Straw: Roll/Stomp 100% Ac	0.17	6	9	3	0	0	18	
TOTAL POST-HARVEST COSTS	0.58	20	21	10	0	0	51	
Interest on Operating Capital at 4.0 %							21	
TOTAL OPERATING COSTS/ACRE	3.33	156	126	89	625	450	1,466	

UC COOPERATIVE EXTENSION
AGRICULTURAL AND RESOURCE ECONOMICS, UC DAVIS
Table 1. Continued
Sacramento Valley- 2021

CASH OVERHEAD:			
Land Rent			475
Liability Insurance			2
Office Expense			50
Compliance & Administration			25
Crop Insurance			18
GPS System/Activation fee			2
Property Taxes			8
Property Insurance			1
Investment Repairs			14
TOTAL CASH OVERHEAD COSTS/ACRE			595
TOTAL CASH COSTS/ACRE			2,061
NON-CASH OVERHEAD:	Per Producing Acre	Annual Cost Capital Recovery	
Fuel Tanks (1-1,000/1-500 Gal)	22	2	2
Service Trailer	22	2	2
Shop Building/Pole Barn	183	14	14
Shop Tools	31	2	2
Implement Carrier	19	1	1
Backhoe	28	3	3
Road Grader	94	6	6
GPS Stationary Receiver/Sender	5	1	1
GPS Receiver/Tractor (2)	5	1	1
Truck: Bobtail 5th-Wheel	90	8	8
Equipment	910	118	118
TOTAL NON-CASH OVERHEAD COSTS	1,407	158	158
TOTAL COSTS/ACRE			2,219

UC COOPERATIVE EXTENSION
AGRICULTURAL AND RESOURCE ECONOMICS, UC DAVIS

Table 2. COSTS AND RETURNS PER ACRE TO PRODUCE RICE

Sacramento Valley- 2021

	Quantity/ Acre	Unit	Price or Cost/Unit	Value or Cost/Acre	Your Cost
GROSS RETURNS					
Rice	90	Cwt	21.50	1,935	
TOTAL GROSS RETURNS				1,935	
OPERATING COSTS					
Fertilizer:				**158**	
Aqua Ammonia NH_4OH	130.00	Lb. N	0.55	72	
Starter 12-23-20	200.00	Lb.	0.23	45	
Zinc Sulfate 36%	10.00	Lb.	0.52	3	
Ammonia Sulfate 21-0-0	112.50	Lb.	0.32	36	
Herbicide:				**205**	
Butte	9.00	Lb.	13.05	117	
Grandstand	4.80	FlOz	1.40	7	
Super Wham	4.80	Qt	11.75	56	
Regiment	0.33	Oz	74.00	24	
Insecticide:				**10**	
Lambda Cyhalothrin	0.77	FlOz	0.85	1	
Copper Sulfate-Fine	3.00	Lb.	2.26	6	
Dimilin 2L	2.00	FlOz	1.42	3	
Fungicide:				**11**	
Quadris	8.80	FlOz	1.30	11	
Adjuvant:				**21**	
Crop Oil	2.05	Gal	10.00	20	
Adjuvant	3.50	FlOz	0.22	1	
Seed:				**57**	
Seed – Rice (Medium grain)	1.75	Cwt	32.50	57	
Custom:				**200**	
GPS Laser Leveling	0.50	Acre	100.00	50	
Fertilizer Rig - Aqua Ammonium	1.00	Acre	25.00	25	
Ground Application – Fertilizer	1.00	Acre	20.00	20	
Air Application - Dry Fertilizer	0.75	Acre	15.00	11	
Seed Soaking (Chlorine)	1.75	Cwt	2.25	4	
Seed Delivery	1.75	Cwt	0.70	1	
Air Application – Seed	1.75	Cwt	12.00	21	
Air Application - Butte	1.00	Acre	12.00	12	
Air Application – Lambda Cyhalothrin	0.25	Acre	12.00	3	
Air Application - Copper Sulfate	0.30	Acre	12.00	4	
Ground Application – Grandstand/Super Wham	1.00	Acre	20.00	20	
Ground Application - Regiment	0.75	Acre	20.00	16	
Air Application – Dimilin 2L	0.25	Acre	12.00	3	
Air Application – Quadris	0.80	Acre	12.00	10	
Irrigation:				**150**	
Water - Irrigation	1.00	Acre	150.00	150	
Contract:				**218**	
Hauling	102.00	Cwt	0.50	51	
Drying Charge	102.00	Cwt	0.95	97	
Storage Charge	90.00	Cwt	0.78	70	
Assessment:				**13**	
California Rice Research Board	90.00	Cwt	0.07	6	
California Rice Commission	90.00	Cwt	0.07	6	
Rent:				**32**	
Tractor 325 HP 4WD	0.40	Hour	80.00	32	
Labor:				**156**	
Equipment Operator Labor	4.00	Hour	27.93	122	
Irrigation Labor	1.00	Hour	44.09	44	
Machinery:				**214**	
Fuel-Gas	2.42	Gal	3.90	9	
Fuel-Diesel	41.50	Gal	2.80	116	
Lube				19	
Machinery Repair				70	
Interest on Operating Capital @ 4.00%				21	
TOTAL OPERATING COSTS/ACRE				1,466	
TOTAL OPERATING COSTS/CWT				16.29	
NET RETURNS ABOVE OPERATING COSTS				469	

UC COOPERATIVE EXTENSION
AGRICULTURAL AND RESOURCE ECONOMICS, UC DAVIS
Table 2. Continued
Sacramento Valley- 2021

	Value or Cost/Acre	Your Cost
CASH OVERHEAD COSTS		
Land Rent	475	
Liability Insurance	2	
Office Expense	50	
Compliance & Administration	25	
Crop Insurance	18	
GPS System/Activation fee	2	
Property Taxes	8	
Property Insurance	1	
Investment Repairs	14	
TOTAL CASH OVERHEAD COSTS/ACRE	595	
TOTAL CASH OVERHEAD COSTS/CWT	6.61	
TOTAL CASH COSTS/ACRE	2,061	
TOTAL CASH COSTS/CWT	22.90	
NET RETURNS ABOVE CASH COSTS	-126	
NON-CASH OVERHEAD COSTS (Capital Recovery)		
Fuel Tanks (1-1,000/1-500 Gal)	2	
Service Trailer	2	
Shop Building/Pole Barn	14	
Shop Tools	2	
Implement Carrier	1	
Backhoe	3	
Road Grader	6	
GPS Stationary Receiver/Sender	1	
GPS Receiver/Tractor (2)	1	
Truck: Bobtail 5th-Wheel	8	
Equipment	118	
TOTAL NON-CASH OVERHEAD COSTS/ACRE	158	
TOTAL NON-CASH OVERHEAD COSTS/CWT	1.76	
TOTAL COST/ACRE	2,219	
TOTAL COST/CWT	24.66	
NET RETURNS ABOVE TOTAL COST	-284	

UC COOPERATIVE EXTENSION
AGRICULTURAL AND RESOURCE ECONOMICS, UC DAVIS

Table 3. MONTHLY CASH COSTS PER ACRE TO PRODUCE RICE

Sacramento Valley- 2021

	APR	MAY	JUN	JUL	AUG	SEP	OCT	Total
Ground Preparation:								
Irrigation: Maintain laterals/Boxes/Drains	7							7
Irrigation: Maintain Interior Levees	13							13
Chisel 2x	46							46
Stubble Disc	29							29
Finish Disc	15							15
Land Level: Tri-plane 50% Ac	15							15
Land Level: GPS Laser 50% Ac	50							50
TOTAL GROUND PREP COSTS	175							175
Pre-Plant:								
Fertilize: NH_4OH @ 130lbs. N/Ac	109							109
Fertilize: 12-23-20/Zinc Sulfate	70							70
Finish Roll	7							7
TOTAL PRE-PLANT COSTS	185							185
Cultural:								
Irrigate: Water & Labor		39	39	39	39	39		194
Seed: Soak & Deliver		62						62
Planting: 175 lbs./Acre		21						21
Weeds: Grasses (Butte)		140						140
Insects: Midge/Shrimp/Weevil 25% Ac (Lambda)		6						6
Weeds: Algae 30% Ac (Copper Sulfate)		10						10
Weeds: Broadleaf (Grandstand/Super Wham)			91					91
Weeds: Cleanup 80% Ac (Regiment)			40					40
Fertilize: Top-Dress 75% A c (NH_4SO_4)				47				47
Insects: Armyworms 25% Ac (Dimilin 2L)				6				6
Disease: Fungus 80% Ac (Quadris)				21				21
Truck: ½-Ton	3	3	3	3	3	3	3	22
Truck: ¾-Ton	4	4	4	4	4	4	4	25
TOTAL CULTURAL COSTS	7	285	177	120	46	46	7	686
Harvest:								
Combine/Header 30'						84		84
Bankout Grain						33		33
Haul to Dryer & Storage						51		51
Dry & Store Rice							167	167
TOTAL HARVEST COSTS	0	0	0	0	0	168	167	335
Assessments:								
Rice Research Board Assessment							6	6
California Rice Commission							6	6
TOTAL ASSESSMENTS COSTS	0	0	0	0	0	0	13	13

UC COOPERATIVE EXTENSION
AGRICULTURAL AND RESOURCE ECONOMICS, UC DAVIS
Table 3. Continued
Sacramento Valley- 2021

	APR	MAY	JUN	JUL	AUG	SEP	OCT	Total
Post-Harvest:								
Straw: Chop 100% Ac							14	14
Straw: Disc 100% Ac							19	19
Straw: Roll/Stomp 100% Ac							18	18
TOTAL POST-HARVEST COSTS	0	0	0	0	0	0	51	51
Interest on Operating Capital @4.0 %	1.22	2.17	2.76	3.16	3.31	4.02	4.82	21.47
TOTAL OPERATING COSTS/ACRE	368	287	180	123	49	217	242	1,466
CASH OVERHEAD								
Land Rent							475	475
Liability Insurance							2	2
Office Expense	7	7	7	7	7	7	7	50
Compliance & Administration	4	4	4	4	4	4	4	25
Crop Insurance							18	18
GPS System/Activation fee							2	2
Property Taxes								8
Property Insurance								1
Investment Repairs	2	2	2	2	2	2	2	14
TOTAL CASH OVERHEAD COSTS	13	13	13	13	13	13	510	595
TOTAL CASH COSTS/ACRE	381	300	193	136	62	230	752	2,061

UC COOPERATIVE EXTENSION
AGRICULTURAL AND RESOURCE ECONOMICS, UC DAVIS

Table 4. RANGING ANALYSIS

Sacramento Valley- 2021

COSTS PER ACRE AT VARYING YIELDS TO PRODUCE RICE

	YIELD (CWT)						
	75.00	80.00	85.00	90.00	95.00	100.00	105.00
OPERATING COSTS/ACRE:							
Ground Prep	175	175	175	175	175	175	175
Pre-Plant	185	185	185	185	185	185	185
Cultural	686	686	686	686	686	686	686
Harvest	299	311	323	335	347	359	371
Assessments	11	11	12	13	13	14	15
Post-Harvest	51	51	51	51	51	51	51
Interest on Operating Capital @ 4.00%	21	21	21	21	22	22	22
TOTAL OPERATING COSTS/ACRE	1,428	1,440	1,453	1,466	1,479	1,492	1,505
TOTAL OPERATING COSTS/CWT	19.04	18.01	17.10	16.29	15.57	14.92	14.33
CASH OVERHEAD COSTS/ACRE	595	595	595	595	595	595	595
TOTAL CASH COSTS/ACRE	2,022	2,035	2,048	2,061	2,074	2,087	2,100
TOTAL CASH COSTS/CWT	26.97	25.44	24.10	22.90	21.83	20.87	20.00
NON-CASH OVERHEAD COSTS/ACRE	158	158	158	158	158	158	158
TOTAL COSTS/ACRE	2,181	2,194	2,207	2,219	2,232	2,245	2,258
TOTAL COSTS/CWT	29.08	27.42	25.96	24.66	23.50	22.45	21.50

Net Return per Acre above Operating Costs

PRICE ($/cwt)	YIELD (Cwt/acre)						
Rice	75.00	80.00	85.00	90.00	95.00	100.00	105.00
15.50	-265	-200	-136	-71	-7	58	123
17.50	-115	-40	34	109	183	258	333
19.50	35	120	204	289	373	458	543
21.50	185	280	374	469	563	658	753
23.50	335	440	544	649	753	858	963
25.50	485	600	714	829	943	1,058	1,173
27.50	635	760	884	1,009	1,133	1,258	1,383

Net Return per Acre above Cash Costs

PRICE ($/cwt)	YIELD (Cwt/acre)						
Rice	75.00	80.00	85.00	90.00	95.00	100.00	105.00
15.50	-860	-795	-731	-666	-601	-537	-472
17.50	-710	-635	-561	-486	-411	-337	-262
19.50	-560	-475	-391	-306	-221	-137	-52
21.50	-410	-315	-221	-126	-31	63	158
23.50	-260	-155	-51	54	159	263	368
25.50	-110	5	119	234	349	463	578
27.50	40	165	289	414	539	663	788

Net Return per Acre above Total Costs

PRICE ($/cwt)	YIELD (Cwt/acre)						
Rice	75.00	80.00	85.00	90.00	95.00	100.00	105.00
15.50	-1,018	-953	-889	-824	-759	-695	-630
17.50	-868	-793	-719	-644	-569	-495	-420
19.50	-718	-633	-549	-464	-379	-295	-210
21.50	-568	-473	-379	-284	-189	-95	0
23.50	-418	-313	-209	-104	1	105	210
25.50	-268	-153	-39	76	191	305	420
27.50	-118	7	131	256	381	505	630

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Table 5. WHOLE FARM ANNUAL EQUIPMENT, INVESTMENT, AND OVERHEAD COSTS

Sacramento Valley- 2021

ANNUAL EQUIPMENT COSTS

Description	Price	Years Life	Salvage Value	Capital Recovery	Cash Overhead: Insurance	Cash Overhead: Taxes	Total
Combine/Harvester	600,000	7	153,075	83,810	334	3,765	87,909
300 HP 4WD Tractor	300,000	10	88,615	31,253	172	1,943	33,368
95 HP 4WD Tractor	95,000	15	18,495	8,125	50	567	8,743
Combine Header 30'	80,000	7	21,771	11,006	45	509	11,560
Pickup: ¾-Ton	75,000	4	36,536	12,520	49	558	13,127
Disc - Offset 26'	48,000	8	10,838	6,207	26	294	6,527
Disc-Stubble 17'	45,000	8	10,160	5,819	24	276	6,119
Triplane 24' x 40'	38,000	10	6,720	4,321	20	224	4,564
Bankout Wagon	41,000	8	9,257	5,302	22	251	5,575
Rice Roller	34,000	10	6,013	3,866	18	200	4,084
Pickup: ½-Ton	32,000	4	15,589	5,342	21	238	5,601
Chisel 26'	24,000	7	6,123	3,352	13	151	3,516
Roller/Stomper Heavy 18'	28,000	10	4,952	3,184	15	165	3,363
Disc Ridger 12'	36,000	10	6,366	4,094	19	212	4,324
Mower - Flail 15'	14,000	10	2,476	1,592	7	82	1,682
V-Ditcher	6,700	15	643	604	3	37	644
TOTAL	1,496,700	-	397,629	190,397	839	9,472	200,708
60% of New Cost*	898,020	-	238,577	114,238	504	5,683	120,425

*Used to reflect a mix of new and used equipment

ANNUAL INVESTMENT COSTS

Description	Price	Years Life	Salvage Value	Capital Recovery	Insurance	Taxes	Repairs	Total
INVESTMENT								
Fuel Tanks (1-1,000/1-500 Gal)	17,275	20	0	1,357	14	86	3,455	4,912
Service Trailer	17,500	20	1,225	1,337	8	94	350	1,789
Shop Building/Pole Barn	146,400	20	0	11,500	162	732	2,928	15,322
Shop Tools	25,000	20	1,750	1,909	51	134	500	2,595
Implement Carrier (straddle bug)	15,500	20	1,085	1,184	7	83	310	1,584
Backhoe	22,000	15	1,540	2,011	10	118	440	2,579
Road Grader	75,000	25	5,250	5,075	36	401	1,500	7,012
GPS Stationary Receiver/Sender	3,675	10	0	470	2	18	74	564
GPS Receiver/Tractor (2)	3,770	10	0	482	2	19	75	578
Truck: Bobtail 5th-Wheel	72,000	15	5,040	6,582	34	385	1,440	8,441
TOTAL INVESTMENT	398,120	-	15,890	31,907	326	2,070	11,072	45,375

ANNUAL BUSINESS OVERHEAD COSTS

Description	Units/ Farm	Unit	Price/ Unit	Total Cost
Land Rent	800	Acre	475	380,000
Liability Insurance	800	Acre	1.83	1,464
Office Expense	800	Acre	50	40,000
Compliance & Administration	800	Acre	25	20,000
Crop Insurance	800	Acre	18	14,400
GPS System/Activation fee	800	Acre	2.00	1,600

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Table 6. HOURLY EQUIPMENT COSTS

Sacramento Valley- 2021

			Cash Overhead		Operating			
Description	Rice Hours Used	Capital Recovery	Insurance	Taxes	Lube & Repairs	Fuel	Total Oper.	Total Costs/Hr.
300 HP 4WD Tractor	1,101	11.72	0.06	0.73	15.29	48.75	64.04	76.56
95 HP 4WD Tractor	440	6.09	0.04	0.43	3.78	13.06	16.84	23.40
Bankout Wagon	200	12.72	0.05	0.60	5.71	0.00	5.71	19.09
Chisel 26'	227	7.06	0.03	0.32	5.17	0.00	5.17	12.58
Combine/Harvester	293	167.62	0.67	7.53	115.53	70.00	185.53	361.35
Combine Header 30'	267	22.01	0.09	1.02	14.00	0.00	14.00	37.13
Disc - Offset 26'	107	14.90	0.06	0.71	8.02	0.00	8.02	23.69
Disc Ridger 12'	93	12.28	0.06	0.64	5.94	0.00	5.94	18.91
Disc-Stubble 17'	227	250	13.97	0.06	0.66	7.52	0.00	7.52
Mower - Flail 15'	200	4.78	0.02	0.25	5.90	0.00	5.90	10.95
Pickup: ½-Ton	373	6.41	0.03	0.29	3.86	9.75	13.61	20.33
Pickup: ¾-Ton	400	15.02	0.06	0.67	7.08	9.75	16.83	32.58
Rented 325 HP 4WD Tractor	249	0.00	0.00	0.00	7.92	52.81	60.73	60.73
Rice Roller	93	11.60	0.05	0.60	3.90	0.00	3.90	16.15
Roller/Stomper Heavy 18'	133	9.55	0.04	0.49	3.21	0.00	3.21	13.30
Triplane 24'x40'	108	8.64	0.04	0.45	5.84	0.00	5.84	14.97
V-Ditcher	107	2.73	0.01	0.17	1.83	0.00	1.83	4.73

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Table 7. OPERATIONS WITH EQUIPMENT & MATERIALS
Sacramento Valley- 2021

Operation	Operation Month	Tractor	Implement	Labor Type/ Material	Rate/ acre	Unit
Irrigation: Maintenance	Apr	95 HP 4WD Tractor	V Ditcher	Equipment Operator Labor	0.16	Hour
Irrigation: Maintenance	Apr	300 HP 4WD Tractor	Disc Ridger - 12'	Equipment Operator Labor	0.14	Hour
Chisel 2x	Apr	Rented 325 HP 4WD	Chisel - 26'	Equipment Operator Labor	0.14	Hour
				Tractor 325 HP 4WD	0.20	Hour
	Apr	300 HP 4WD Tractor	Chisel - 26'	Equipment Operator Labor	0.20	Hour
Stubble Disc	Apr	Rented 325 HP 4WD	Stubble Disc 17'	Equipment Operator Labor	0.14	Hour
				Tractor 325 HP 4WD	0.20	Hour
Finish Disc	Apr	300 HP 4WD Tractor	Disc - Offset 26'	Equipment Operator Labor	0.16	Hour
Land Level: Tri-plane	Apr	300 HP 4WD Tractor	Triplane 24' x 40'	Equipment Operator Labor	0.16	Hour
Land Level: GPS Laser	Apr			GPS Laser Leveling	0.50	Acre
Fertilize: Pre-plant	Apr	300 HP 4WD Tractor		Equipment Operator Labor	0.14	Hour
				Aqua Ammonia NH_4OH	130.00	Lb. N
				Fertilizer Rig - Aqua	1.00	Acre
Fertilize: Starter	Apr			12-23-20	200.00	Lb.
				Zinc Sulfate 36%	10.00	Lb.
				Ground Application-Fertilizer	1.00	Acre
Finish Roll	Apr	95 HP 4WD Tractor	Rice Roller	Equipment Operator Labor	0.14	Hour
Irrigate: Water & Labor	May			Irrigation Labor	0.20	Hour
				Water - Irrigation	0.20	Acre
	June			Irrigation Labor	0.20	Hour
				Water - Irrigation	0.20	Acre
	July			Irrigation Labor	0.20	Hour
				Water - Irrigation	0.20	Acre
	Aug			Irrigation Labor	0.20	Hour
				Water - Irrigation	0.20	Acre
	Sept			Irrigation Labor	0.20	Hour
				Water - Irrigation	0.20	Acre
Seed: Soak & Deliver	May			Seed - Rice	1.75	Cwt
				Soaking (Chlorine) Seed	1.75	Cwt
				Delivery - Seed	1.75	Cwt
Planting: 175 lbs./Ac	May			Air Application - Seed	1.75	Cwt
Weeds: Grasses	May			Butte	9.00	Lb.
				Crop Oil	1.00	Gal
				Adjuvant	3.50	FlOz
				Air Application - Butte	1.00	Acre
Insects: Midge/Shrimp	May			Lambda Cyhalothrin	0.77	FlOz
				Air Application – Lambda Cy	0.25	Acre
				Crop Oil	0.25	Gal
Weeds: Algae 30% Ac	May			Copper Sulfate Fine	3.00	Lb.
				Air Application -Copper	0.30	Acre
Weeds: Broadleaf	June			Grandstand	4.80	FlOz
				Crop Oil	0.80	Gal
				Super Wham	4.80	Qt
				Ground Application - S/G	1.00	Acre
Weeds: Cleanup 80% Ac	June			Regiment	0.33	Oz
				Ground Application-Regiment	0.80	Acre
Fertilize: Top-Dress	July			21-0-0 Ammonia Sulfate	112.50	Lb.
				Air Application-Dry Fertilizer	0.75	Acre
Insects: Armyworms	July			Dimilin 2L	2.00	FlOz
				Air Application – Dimilin 2L	0.25	Acre
Disease: Fungus 80% Ac	July			Quadris	8.80	FlOz
				Air Application - Quadris	0.80	Acre
Truck 1/2 Ton	July		Pickup - 1/2 Ton	Equipment Operator Labor	0.56	Hour
Truck 3/4 Ton	July		Pickup - 3/4 Ton	Equipment Operator Labor	0.60	Hour
Combine/Header	Sept	Combine/Header 30’		Equipment Operator Labor	0.40	Hour
Bankout Grain	Sept	300 HP 4WD Tractor	Bankout Wagon	Equipment Operator Labor	0.36	Hour
Haul to Dryer & Storage	Sept			Hauling	102.00	Cwt
Dry & Store Rice	Oct			Drying Charge	102.00	Cwt
				Storage Charge	90.00	Cwt
Straw: Chop 100% Ac	Oct	95 HP 4WD Tractor	Mower - Flail 15'	Equipment Operator Labor	0.30	Hour
Straw: Disc 100% Ac	Oct	300 HP 4WD Tractor	Disc - Stubble 17'	Equipment Operator Labor	0.20	Hour
Straw: Roll/Stomp 100%	Oct	300 HP 4WD Tractor	Roller/Stomper Heavy 18'	Equipment Operator Labor	0.20	Hour

Managing Potassium in Rice Fields

Why Is It Important?

Potassium (K) is an essential nutrient for rice. It is important to have good K fertility not only for optimizing yields, but also K helps reduce the severity of some common plant diseases that we see (e.g. aggregate sheath spot and stem rot).

Deficiency Symptoms

K deficiency symptoms include (1) yellow/brown leaf margins, (2) dark brown spots on leaf surface, and (3) leaf bronzing (Figure 1).

Figure 1. Potassium deficiency symptoms. Yellow leaf margins and bronzing (top); brown spots (bottom). Source: top - IRRI (Rice Knowledge Bank), bottom - AgFax.

Potassium Fertilizers

In this Fact Sheet, we will be referring to elemental K, unless otherwise specified. To convert to K_2O, multiply elemental K value by 1.2.

The most common K fertilizer sources for rice are potassium chloride (muriate of potash; 60% K_2O) and potassium sulfate (sulfate of potash; 44% K_2O). Potassium nitrate is a common K fertilizer, however, it is generally advisable to avoid applying nitrate to rice fields, as it is highly susceptible to losses under flooded conditions.

How Much Potassium Is in a Rice Crop?

Rice takes up about the same amount of K as N during the growing season (about 150 lb K/ac in a 90 cwt yielding field). However, less K is usually applied as fertilizer because the soil supplies much of the K needs. At harvest, about 20% of the K is in the grain and 80% in the straw (grain is 0.29% K and straw 1.4% K). For example, in a field where the yield is 90 cwt, there is about 26 lb K/ac in the grain and 126 lb K/ac in the straw.

Maintaining Soil K Balances

If only grain is removed, roughly 26 lb K/ac (31 lb K_2O/ac) is removed in a 90 cwt yielding crop. This amount would need to be replaced to be applied to maintain soil K balances.

Straw removal has a large impact on K fertility. For modern, high yielding varieties, the amount of straw in a field is roughly equal to the amount of grain harvested from the field. Therefore, in a field that yielded 90 cwt, there is 4.5 tons of rice straw. For every ton of straw removed, about 28 lb K/ac (34 lb K_2O/ac) is removed with it (most bailing operations remove about 40-80% of the straw). If this K is not replaced, depending on soil, the soil K reserves will become depleted and K deficiency symptoms will begin to appear with time.

Determining K Deficiencies

In the Sacramento Valley, K deficiencies are most common in soils with a low clay content and those on the eastern side of the Sacramento Valley (including the red soils). Plant sampling is a good way to determine a deficiency; however, by the time a deficiency is determined, it may be too late to correct. A Y-leaf sample taken between tillering and panicle initiation should have a K concentration of 1.5% or more. A flag-leaf sample taken around heading should have a K concentration of 1.2% or more.

Soil testing is another good option. The most common soil test is the ammonium acetate (NH_4OAc) extractable K test. With this method, when soil extractable K is less than 60 ppm, K fertilizer is definitely needed. If extractable K is between 60 and 120 ppm, K fertility is on the lower end and it is likely that deficiency symptoms may appear. In a study conducted on 55 California rice fields, if the extractable K levels were below 120 ppm, 27% of the fields showed K deficiency symptoms (low flag-leaf K values). Another soil test is the percent base saturation of K. If the K saturation is 1.6% or less then you should consider adding K fertilizer.

Soil Sampling Considerations

When testing the soil for K, be mindful of how you sample. In a study we did of 55 rice fields, we found that in 70% of the fields, the bottom check had higher K levels than the top check. This may be for a couple of reasons. First, it may be a legacy of field leveling. When leveling a field, it is likely that top soil (higher in K) is moved from the upper part (top check) of the field to the lower part (bottom check). A second reason is that K is relatively mobile in water and irrigation water can push K from the top checks to the lower checks in the field.

Other Considerations

Irrigation water is a source of K. In California well water had the highest and most variable K concentration (1.8 ppm), followed by the Sacramento river (1.2 ppm) and rivers coming from the Sierra Nevada mountain range (0.9 ppm).

Burning rice straw does not remove K, however the ash which contains the K can blow around the field resulting in non-uniform distribution.

For more on this topic:

- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu
- ✓ Dobermann, A and T. Fairhurst. 2000. Rice: Nutrient Disorders & Nutrient Management. International Rice Research Institute.
- ✓ Linquist, B.A., M. Ruark, R. Mutters, C. Greer, and J. Hill. (2014). Nutrients and sediments in surface runoff water from rice fields: Implications for nutrient budgets and water quality. *Journal of Environmental Quality* 43:1725-1735.

Agronomy Research and Information Center

http://agric.ucdavis.edu/

UC CE University of California Cooperative Extension

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2020

Managing Phosphorus in California Rice Fields

Why is it Important?

Phosphorus (P) is the second most commonly applied fertilizer to rice (nitrogen is the first). Plants use P for membrane integrity, energy storage and phloem transport. Phosphorus deficiencies are not common in California as many farmers apply P fertilizer (on average, 40-45 lb P_2O_5/ac). However, in a recent study, we found 10% of fields tested to be deficient. With farmers achieving higher yields, deficiencies may become more common unless P fertilizer rates are increased.

Deficiency Symptoms & Critical Levels

Deficiency symptoms often diminish with time but include: Stunted dark green plants, narrow leaves, reduced tillering, and delayed flowering.

Figure 1. Phosphorus deficiency symptoms showing narrow dark green leaves.

The Olsen-P soil test (sodium-bicarbonate) is the best test for identifying P-deficient rice soils in California. The Bray test does not work as well. An Olsen P value above 6-9 ppm is indicative of a soil that is not P deficient.

For plant tissue, if the Y-leaf P concentration at 35 days after seeding (DAS) is below 0.2% P, then a deficiency is possible.

Soil Phosphorus Budgets

A P budget accounting for all of the P fertilizer added and removed in grain or straw over the past five years also provides a good indicator of soil P status. If more P has been removed from the soil than has been applied, it is likely the soil P status is low (Table 1). Importantly, at harvest, about 70% of the P in the plant is in the grain; therefore, P removal in grain is the major pathway that P is removed from the system. Very little P is lost via leaching or in the tailwater drain. Given that these losses are low, it is possible to build up P in the soil.

The Four Rs of P Fertilizer Management

Right rate: First ask, should you apply? If your soil test levels are high (>15 ppm Olsen P), you probably do not need to apply any P fertilizer. If soil P levels are between 6 and 15 ppm Olsen P, apply the maintenance application rate. If Olsen P levels are below 6 ppm consider build-up application rates (rates higher than maintenance). To calculate the maintenance application rate you can go to "rice.ucanr.edu/P_Budget_calculator/". However, Table 1 provides general guidelines that will give you a rough estimate based on your expected yields and straw management.

Right time: Phosphorus fertilizer can be applied anytime from before flooding to about 30 DAS for optimal yield response. Applying P before planting can lead to algae (scum) build up in the water and lead to poor stand establishment (Fig. 2). This is especially the case when the P fertilizer is not incorporated or the water temperatures are warm. If scum is an issue, P can be applied into the water up to 30 DAS.

Right place: If applied before flooding, it should be incorporated into the soil to help reduce scum.

Table 1. The amount of P removed (hence the amount required to maintain soil P levels) from the field based on rice grain yields and straw management. Removing straw (i.e. bailing) assumes 50% of straw is removed. Retained straw includes any operation (including burning) where straw remains in the field after harvest.

Grain yield (cwt/ac)	Straw management	Maintenance P fertilizer requirement lb P_2O_5/ac
70	Retained	36
70	Removed	44
80	Retained	42
80	Removed	50
90	Retained	47
90	Removed	56
100	Retained	52
100	Removed	63

Right source: The most common P sources are various forms of calcium phosphates or ammonium phosphates (e.g. 16-20-0; 11-52-0). In California, ammonium phosphates are most commonly available, thus the application of P also includes nitrogen. In general, we recommend using a P source with the lowest amount of N because the more N applied as aqua-ammonia, the more efficient the N uptake.

Manure is also a source of P and can contain a relatively high amount of P (especially poultry). Thus, organic rice field soils often have high soil P values. The nutrient content of manure is highly variable and depends on a number of factors including the source, how it has been stored, and its moisture content.

Figure 2. Rice field early in the season with algae (scum) on the water surface, which prevents good stand establishment.

For more on this topic:

- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu
- ✓ Dobermann, A and T. Fairhurst. 2000. Rice: Nutrient Disorders & Nutrient Management. International Rice Research Institute.
- ✓ Linquist, B.A. and M.D. Ruark. 2011. Re-evaluating diagnostic phosphorus tests for rice systems based on soil phosphorus fractions and field level budgets. *Agronomy Journal* 103:501-508.
- ✓ Lundy, M.E., D.F. Spencer, C. van Kessel, J.E. Hill and B.A. Linquist. 2012. Managing phosphorus fertilizer to reduce algae, maintain water quality, and sustain yields in water-seeded rice. *Field Crops Research* 131:81-87.
- ✓ Spencer, D. and B.A. Linquist. (2014) Reducing rice field algae and cyanobacteria by altering phosphorus fertilizer applications. Paddy and Water Environment 12:147-154.

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Managing Rice with Limited Water

Background

During drought years water deliveries are often restricted. In these situations, how can you use the least amount of water to grow rice without reducing yields? Based on past studies, the amount of water delivered to rice fields varies widely (i.e. 4 to 7.7 ft). This water is lost as evapotranspiration, percolation and seepage, and tailwater drainage (Figure 1).

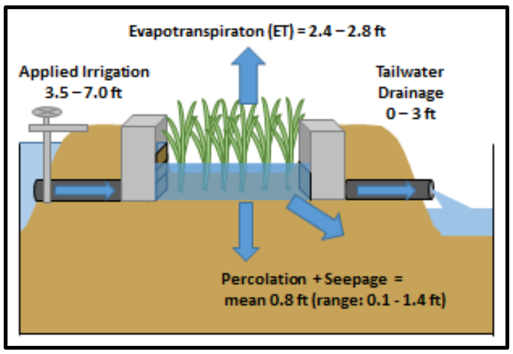

Figure 1. Ranges in water inputs and potential losses from California rice fields.

Best Practices to Conserve Water while not Reducing Yields

Avoid fields that have high percolation. In most California rice soils, water percolation rates are low due to the high clay soils that rice is typically grown on. However, some soils may have high percolation rates due to a highly permeable layer or old creek bed that runs through the field. When water is in short supply, consider fallowing these fields.

Avoid early planting. Planting early increases water use because planting occurs during a cooler time of the year. Since crop duration is dependent on temperature (growing degree days), early planting extends the duration of the crop, thus needing to be irrigated for longer and increasing ET and percolation/seepage losses.

Short duration varieties. Choose shorter duration varieties which reduce the time the field has to be flooded. Rice typically needs to be flooded from planting to reproductive stage R7 (R7, when one kernel on the main panicle is yellow; about 3 weeks after heading). Table 2 gives an indication of the differences flooding period by variety.

Table 1. Days to from planting to R7 for different varieties grown in California

Variety	Days to reach R7*
M-105, S-102, CM-101	99-102
M-206, M-210	105
M205, M-209, M-211	108-112
M-410, M-402	124-128

** Days from planting to R7 (typically when it is time to safely drain) for different California rice varieties at the Rice Experiment Station. These days are to be used for comparison among varieties. Actual days to R7 will vary depending on year and location in the Sacramento Valley.*

Don't spill. Rice can be grown using 3.5 to 4 ft of water (depends on the percolation and seepage characteristics of the field) if there is no tailwater drainage (Figure 1). Tailwater drainage results from lowering the water for herbicide applications, maintenance flow, and draining the field at the end of the season for harvest. No-spill (no tailwater) practices require closer management of irrigation water and planning for upcoming events where water may need to be lowered. With no-spill management, yields can be maintained as long as the irrigation water has relatively low salinity (<0.6 dS/m) and soils are not saline. Most California rice fields receive irrigation water that has low salinity.

Fix leaks. Leaks around outlet boxes or in levees can result in significant water loss. These leaks can be caused by water erosion, crayfish, or rodents. Fields should be routinely monitored for such leaks and leaks repaired.

Figure 2. Leak near outlet caused by crayfish.

Don't drain at the end of the season. It is common to pull outlet boards at the end of the season to drain the field in preparation for harvest, resulting in significant tailwater drainage losses. Instead, growers should turn off irrigation before needing to drain and allow the water to naturally subside rather than drain the field. Determining when the irrigation water can be turned off depends on how much water is in the field, climate, and soil properties. Fields with heavy clay soils can safely have no standing water 21 to 24 days after 50% heading without risking yield loss and grain quality.

Dry- versus water-seeding. While it may seem counter intuitive, dry/drill seeding does not necessarily require less water than water-seeding. In California, dry seeding usually requires two or three flushes of irrigation water to establish the crop before a permanent flood is established. These flushes require a lot of water. Once the field is flooded the water has to be drained resulting in high tailwater losses. Dry seeding can use less water if rice seed is planted to moisture which reduces the need to flush the field (or number of times field is flushed) in order to germinate the seed and establish the crop.

Figure 4. Drill seeded rice field before permanent flood.

For more on this topic:

- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu
- ✓ View video at http://ucanr.edu/insights.

- ✓ Linquist, B.A. et al. (2015) Water balances and evapotranspiration in water- and dry-seeded rice systems. Irrigation Science 33:375-385.
- ✓ Montazar, A. et al. (2017) A crop coefficient curve for paddy rice from residual of the energy balance calculations. Journal of Irrigation and Drainage Engineering. 143(2) doi: 10.1061/(ASCE)IR.1943-4774.0001117.
- ✓ Marcos, M, et al. (2018) Spatio-temporal salinity dynamics and yield response of rice in water-seeded rice fields. Agricultural Water Management 195:37-46.

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2020

Managing Water Salinity in Rice Fields

Background

Rice yields are sensitive to salinity, so it is important to monitor and manage fields to prevent high salt concentrations from developing. High water salinity can reduce rice yield by decreasing stand density, reducing plant growth, and increasing pollen sterility. In most CA rice fields, salinity is not a problem. However, if using recycled water or well water for irrigation, or if soils have high salinity, then salinity may be a problem.

Figure 1. Most of the water delivered to rice fields in California is good quality and has low salinity. However, recycled water and water from wells can have high salinity which may affect rice growth and yields.

When Can High Water Salinity Lead to Yield Loss?

In rice fields, when average flood water salinity is greater than 0.88 dS/m, yields begin to decline (Figure 2). This yield threshold is lower than the previous report of 1.9 dS/m.

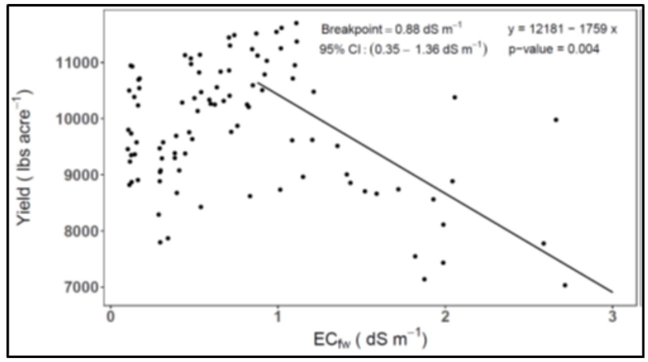

Figure 2. The relationship between yield and season average field water salinity (EC_{fw}).

Where is Salinity a Problem in Fields?

Salinity in a field increases as the distance from the irrigation inlet increases (Figures 3 &4) due to evapo-concentration (evaporation causing salts to concentrate in the remaining water). As water moves down a field, it experiences more evapo-concentration and thus higher water salinity in bottom checks. For a 100 ac field, water salinity at the bottom of the field is roughly 50% higher than the irrigation water entering the field. Water salinity is also higher in stagnant areas of the check with no water flow (Figure 4, left).

When in the Growing Season is Flood Water Salinity the Highest?

Flood water salinity is highest early in the season (Figure 3) due to:

- Low canopy cover early in the season resulting in high rates of evapo-concentration (from temperature and wind).
- Holding water or allowing water to subside early in the season, primarily for herbicide applications, concentrates salts in the field water.

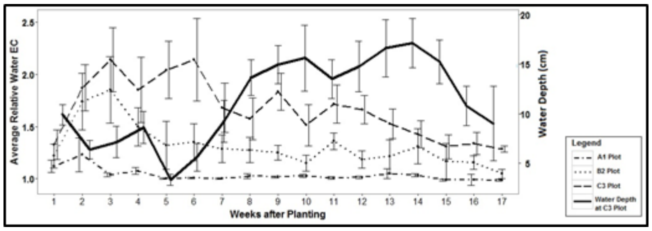

Figure 3. Water salinity varies over time and location within a rice field. Average relative water EC (field water salinity relative to irrigation water salinity) during the growing season in the top (plot A1), middle (plot B2), and bottom checks (plot C3). Average water depth in the bottom check (dark solid line) is shown on the right axis. Error bars represent standard error.

Managing Salinity

- **Irrigation water should have an EC below 0.6 dS/m** – For an averaged sized field this will help ensure that the field water salinity does not increase beyond the 0.88 dS/m yield threshold at the bottom of a field.
- **Change water flow path** – Salinity builds-up in stagnant parts of the field. Changing the water flow path will reduce salinity hot spots from developing (Figure 4).
- **Early in the season when salinity is highest, allow for spillage and maintain higher water levels** – This may not be possible in drought years or with certain herbicide programs.
- **Smaller fields and multiple side inlets** – The distance water travels in a field determines the build-up of water salinity. Larger fields will have greater water salinity build-up in the bottom of the field. Smaller fields and multiple inlets should be considered in areas that have saline soils or that receive irrigation water high in salinity.

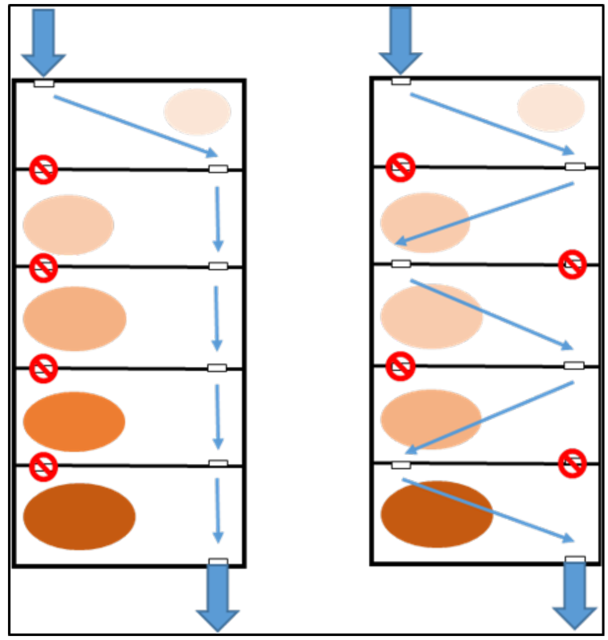

Figure 4. The diagram on left shows a field with water running down one side of the field and how flood water salinity (increasing darkness of the circle) is concentrated on one side of the field. Changing the water flow path (shown on right) the water flow path is forced through the high salinity areas and helps flush out the high salinity water.

For more on this topic:

- Marcos et al. (2018) Spatio-temporal salinity dynamics and yield response of rice in water-seeded rice fields. Agric. Water Mgmt. 195:37-46.
- Scardaci et al. (2002) Water management practices can affect salinity in rice fields. California Agriculture 56:184-188.
- Grattan et al. (2002) Rice is more sensitive to salinity than previously thought. California Agriculture 56:189-195.

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(2023)

Optimal and Critical Nutrient Concentrations in Rice Tissue

Background

Nutrient deficiencies or toxicities can be hard to determine visually. Knowing the nutrient concentration in the plant can greatly facilitate understanding problems in the field. Table 1 provides some overall guidelines as to what is optimal, low or excessive (and therefore possibly toxic) for rice plant tissues.

*Table 1. Optimal, critical and excessive or toxic nutrient concentration for rice at differ crop stages (panicle initiation - PI). Data source (Dobermann and Fairhurst, 2000; Williams 2010 in "()"). *see note on nitrogen in text.*

Element	Growth stage	Plant part	Optimum Range	Critical level for deficiency	Critical level for excess or toxicity
Nitrogen*	Tillering-PI	Y-leaf	2.9-4.2% (3.2-3.6%)	<2.5% (<3.2%)	>4.5%
	Flowering	Flag-leaf	2.2-2.5% (2.8-3.2%)	<2.0% (<2.8%)	
	Maturity	Straw	0.6-0.8%		
Phosphorus	Tillering-PI	Y-leaf	0.2-0.4%	<0.10%	>0.50%
	Flowering	Flag-leaf	0.2-0.3%	<0.18%	
	Maturity	Straw	0.1-0.15%	<0.06%	
Potassium	Tillering-PI	Y-leaf	1.8-2.6%	<1.5%	>3.0%
	Flowering	Flag-leaf	1.4-2.0%	<1.2%	
	Maturity	Straw	1.5-2.0%	<1.2%	
Zinc	Tillering-PI	Y-leaf	25-50 ppm	<20 ppm	>500 ppm
	Tillering	Shoot	25-50 ppm	<10 ppm	>500 ppm
Sulfur	Tillering	Y-leaf		<0.16%	
	Tillering	Shoot	0.15-0.30%	<0.11%	
	Flowering	Flag-leaf	0.10-0.15%	<0.10%	
	Flowering	Shoot		<0.07%	
	Maturity	Straw		<0.06%	
Silica	Tillering	Y-leaf		<5%	
	Maturity	Straw	8-10%	<5%	
Magnesium	Tillering-PI	Y-leaf	0.15-0.30%	<0.12%	>0.5%
	Tillering-PI	Shoot	0.15-0.30%	<0.13%	
	Maturity	Straw	0.20-0.30%	<0.10%	
Calcium	Tillering	Y-leaf	0.2-0.6%	<0.15%	>0.7%
	Tillering-PI	Shoot	0.3-0.6%	<0.15%	
	Maturity	Straw	0.3-0.5%	<0.15%	
Iron	Tillering	Y-leaf	75-150 ppm	<70 ppm	>300 ppm
	Tillering	Shoot	60-100 ppm	<50 ppm	
Manganese	Tillering	Y-leaf	40-700 ppm	<40 ppm	>800 ppm
	Tillering	Shoot	50-150 ppm	<20 ppm	
Copper	Tillering	Y-leaf	7-15 ppm	<5 ppm	>25 ppm
	Maturity	Straw		<6 ppm	>30 ppm
Boron	Tillering	Y-leaf	6-15 ppm	<5 ppm	>100 ppm
	Maturity	Straw		<3 ppm	>100 ppm
Aluminum	Tillering	Shoot	15-18 ppm	<5 ppm	>100 ppm

Some Considerations

Table 1 is based on data largely from Asia. That said, most values presented align very close to what would be expected in California. The main difference is in the leaf nitrogen levels, where the optimal N concentration or the critical level may be a bit higher for California. This may be due to the higher yield potential for California.

Nutrient concentrations in the plant vary among tissues (leaves, stems, etc.) and over time. Therefore, it is important to sample the correct plant tissue at the correct time.

Importantly, when trying to determine a problem, a nutrient's optimal and critical concentration assumes that all other nutrients are at optimal levels. Therefore, if more than one nutrient is deficient and/or toxic, it may not be possible to accurately determine the problem.

One disadvantage with determining a problem using plant tissue is that many times it cannot be corrected in the current season. Often the problem is noticed late in the season and it can take further time to get lab results. Nevertheless, the information is valuable for the next season.

Sampling Plant Tissue

- The Y-leaf is the uppermost fully extended leaf with a visible collar (Fig. 1). The flag-leaf is the top-most leaf below the panicle (Fig. 1). That said the flag-leaf can be taken in the later stages of booting before the panicle has emerged.
- When taking a sample, do not take the sample from just one small area, but get a representative sample from across the area in question. Take at least 20-30 leaf samples.
- When there are areas of your field with a problem and other areas that look good, take separate plant samples from both the problem and the good areas for analysis. This will further help determine what the problem may be.
- There needs to be enough tissue material for analysis and this may depend on the lab to which the samples are being sent. Be sure to follow the instructions provided by the laboratory for sampling, handling, and packaging the material before sending to the laboratory.

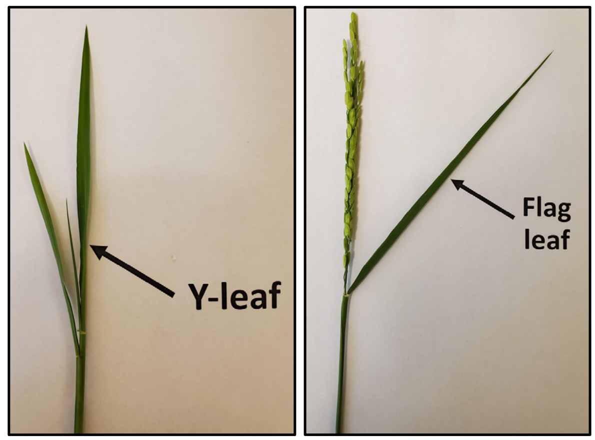

Figure 1. Rice Y-leaf and flag-leaf. Flag leaf is taken at flowering.

For more on this topic:

- ✓ Dobermann, A. and T.H. Fairhurst. 2000. Rice: Nutrient Disorders and Management. International Rice Research Institute
- ✓ Williams, J.F. 2010. Rice Nutrient Management in California. University of California, Agriculture and Natural Resources. Publication 3516
- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu

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2020

Nutrients in Rice Grain and Straw at Harvest

Background

Knowing the amount of nutrients in a rice crop at harvest time is important for several reasons.

1. It provides an idea of the crop's nutritional needs. Some of these nutrients are applied routinely in fertilizer applications, while others are readily available from the soil or irrigation water.

2. It helps us understand how to better manage soil nutrient balances. Grain (and the nutrients in it) are removed from the field at harvest while straw may or may not be removed.

3. The nutrient composition of straw has implications for how it can be used.

Nutrient Concentration of Grain and Straw

Table 1 provides the nutrient concentration of grain and straw at harvest, the amount of nutrients in a crop that yields 10,000 lb/ac (100 cwt/ac), and the amount of nutrient in a ton of grain and straw at harvest. The concentration data are from Dobberman and Fairhurst (2000) and are based on numbers from Asia; however, based on our research in California, we have found the values to be similar.

Key Takeaways

1. At harvest, most of the crop N and P is in the grain. This is why N and P fertilizer are typically applied in the largest amounts.

2. How much straw is in a rice field and how much is removed if it is bailed? For most modern high yielding varieties, the amount of straw is roughly equal to the grain yield. That is, if the grain yield is 10,000 lb/ac then there is about 10,000 lb/ac of straw. The amount of straw removed during a bailing operation depends on how low the straw

Table 1. Nutrient concentration, the amount of nutrient in a crop that yields 10,000 lb/ac (100 cwt/ac), and the amount of nutrient in a ton of either straw or grain at harvest. Source of concentration data (Dobermann and Fairhurst, 2000).

Nutrient	Concentration	Amount in 100 cwt/ac yield	Amount per ton	Concentration	Amount in 100 cwt/ac yield	Amount per ton
	%	lb/ac	lb/ton	%	lb/ac	lb/ton
	Grain			Straw		
Nitrogen	1.1	110	22	0.65	65	13
Phosphorus*	0.2	20	4	0.1	10	2
Potassium*	0.29	29	5.8	1.4	140	28
Calcium	0.05	5	1	0.3	30	6
Magnesium	0.15	15	3	0.2	20	4
Sulfur	0.1	10	2	0.075	7.5	1.5
Silicon	2	200	40	5.5	550	110
Zinc	0.002	0.2	0.04	0.003	0.3	0.06
Iron	0.025	2.5	0.5	0.035	3.5	0.7
Manganese	0.005	0.5	0.1	0.045	4.5	0.9
Copper	0.001	0.1	0.02	0.0003	0.03	0.006
Boron	0.005	0.5	0.1	0.001	0.1	0.02

* To convert P to P_2O_5 multiply P by 2.29. To convert K to K_2O multiply K by 1.2.

is cut before bailing. It is unlikely that all the straw is removed; typically, 40 to 80% of the total amount of straw may be. In a field that yields 100 cwt/ac that would amount to 2 to 4 ton of straw being removed per acre.

3. The straw contains a lot of K and Si. Given these high concentrations, when rice straw is burned there is a lot of ash which can be an issue for some applications. Potassium is a big concern as continual removal of straw will result in soil K deficiencies.

4. Retaining straw in the field during the fallow. It is common practice to leave the straw in the field during the winter fallow period. Growers need to make sure that the rice straw decomposes during the winter. This is facilitated by incorporating the rice straw and flooding the field. Doing this ensures nutrients from the straw are retained in the field and available for the next crop. Good decomposition is important so that the straw does not bind (immobilize) N fertilizer the following growing season.

5. What if straw is removed? When the straw is removed (Fig. 1), nutrients are also removed that need to be replaced (Table 1). Potassium is removed in the largest quantities, but N is also removed. While not all of the N in rice straw is available in the next season, research has found that fertilizer N inputs can be reduced by about 25 lb N/ac if straw is retained in the field. Silica is also removed in large quantities, but it is not normally deficient as adequate amounts are usually provided from soil and irrigation water.

6. What happens if rice straw is burned? Many of the nutrients remain in the field when the straw is burned; however, most N and S are lost in the burning process. Furthermore, since ash can be blown around the field, the nutrients contained in the ash may not be uniformly distributed in the field.

Figure 1. Rice straw bailing in the Sacramento Valley.

For more on this topic:

- ✓ Dobermann, A. and T.H. Fairhurst. 2000. Rice: Nutrient Disorders and Management. International Rice Research Institute
- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu
- ✓ Phosphorus Budget Calculator for rice: rice.ucanr.edu/P_Budget_calculator
- ✓ Nader, G.A. and P.H. Robinson. A. 2010. Rice Producers' Guide to Marketing Rice Straw. https://anrcatalog.ucanr.edu/pdf/8425.pdf

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2020

Growing Season Water Use in California Rice Systems

Overview

In California, there is very little to no rainfall during the rice growing season, so this is not usually considered in water budgets. On average, about 5 acre feet/acre (AF/ac) of irrigation water is applied to a rice field during the growing season. Evapotranspiration is not highly variable but ranges from 2.4 to 2.8 ft (29-34 in). On most rice soils percolation (the downward flow of water below the root zone), is about X ft during the season but this can be highly variable depending on soil type. Seepage (lateral movement of water out of field) is also highly variable, but on average is about X ft. Tailwater drainage is also highly variable and can range from 0 to 3 AF/ac.

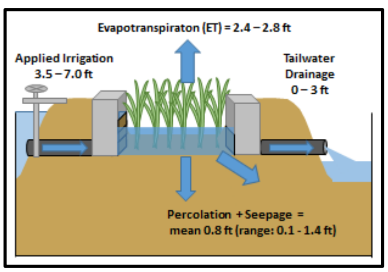

Figure 1. Ranges in water inputs and losses from California rice fields. Seepage and percolation ranges are based on indirect measurements.

Importantly, water lost as evapotranspiration cannot be reused. However, water lost in tailwater drainage and seepage can be reused down stream to irrigate other fields. Water lost via percolation recharges aquafers or streams.

At a minimum, enough water needs to be applied to meet the seasonal ET demand and make up for losses due to percolation and seepage. This is roughly 3.5 AF/ac. However, fields and how they are managed are highly variable, and this may require additional applied water. Some of these factors are discussed next.

Factors Resulting in Water Use Variability

Percolation and seepage losses: On average, these losses are very low in most California rice fields due to the heavy clay soils or the presence of a hard pan. However, on coarse textured soils or where the field may be located over an old stream bed (have a gravel or sand bed underneath) percolation and seepage rates may be higher.

Soil water storage: Depending on how dry the soil below the tilled layer is at the start of the season affects how much water is required to initially flood a field. If the winter and spring have been dry, it may take more water to initially flood a field than in wet years when the soil below the plow layer is still relatively wet.

Early season drains: Water may need to be drained from the field during the first few weeks of a season for a number of reasons. First, some growers practice the Leather's method which is draining the field for a few days shortly after planting. This prevents damage to the stand from winds churning up the water, which dislodges seedlings. Draining early may also reduce tadpole shrimp damage. The field is flooded after the young seedlings have anchored their roots in the soil (usually 2-5 days after draining). Second, fields are drained for certain herbicide applications (pinpoint drain), usually around 3-4 weeks after planting. Some herbicides require that the weeds be exposed; thus the field needs to be drained.

Increasing water height during booting: Pollen formation occurs during booting (between panicle initiation and heading) which usually occurs during the last half of July. Developing pollen is very susceptible to cold temperatures, which cause blanking and lower yields. Farmers are encouraged to raise the water level in their fields up to 8 to 10 inches deep to protect the developing panicle from cold nighttime temperatures. Cool nighttime temperatures are most commonly a problem in the southern part of the Sacramento Valley but can be a problem in some years throughout the valley.

Managing salinity: High salinity can reduce rice yields. Salinity is a problem when rice is grown on saline soils or receives high salinity irrigation water. Irrigation water with a high amount of recycled water or well water can be high in salinity. As the applied water flows from the field inlet down the field to the drain, the salinity in the water increases due to evaporation of water. One way farmers can reduce salinity build up in the flood water is to keep the water flowing through the field. This practice is referred to as maintenance flow. This practice also helps farmers maintain a uniform water height in the field throughout the season.

End of season drain: At the end of the season farmers drain their fields about six weeks before harvest in preparation for the harvest. The timing of the drain is important and varies depending on soils and weather. The goal is to dry the soil enough to allow a combine to go over it without causing large ruts, while not drying out too early which can lower yields and grain quality. This drying can be either accomplished by allowing the water to subside naturally or releasing the water through the tailwater drain. The later practice results in higher tailwater drain losses.

Varieties and crop development: The time from planting to harvest (and thus the period of irrigation) varies depending on the rice variety being grown, the region of the valley and the time of planting. Rice varieties grown side-by-side can vary in duration by as much as a couple weeks. Moving from south to north in the valley, average temperatures increase and thus the time from planting to harvest is shorter in the north than in the south. Finally, planting later, usually means planting during a warmer time of the season; thus later plantings tend to have shorter crop duration.

For more on this topic:

- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu
- ✓ Linquist, B.A. et al. (2015) Water balances and evapotranspiration in water- and dry-seeded rice systems. Irrigation Science 33:375-385.
- ✓ Montazar, A. et al. (2017) A crop coefficient curve for paddy rice from residual of the energy balance calculations. Journal of Irrigation and Drainage Engineering. 143(2) doi: 10.1061/(ASCE)IR.1943-4774.0001117.
- ✓ Marcos, M. et al. (2018) Spatio-temporal salinity dynamics and yield response of rice in water-seeded rice fields. Agricultural Water Management 195:37-46.
- ✓ LaHue, G.T. and B.A. Linquist (2019) The magnitude and variability of lateral seepage in California rice fields. Journal of Hydrology 574:202-210

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2020

Tadpole Shrimp Damage to Rice

Background

Tadpole shrimp (*Triops longicaudatus*) is a crustacean adapted to live in vernal pools. Rice fields provide excellent habitat for this arthropod, which has been recognized as a pest of rice in California since the 1940s.

Life Cycle

When rice fields are flooded, eggs in the soil rehydrate and hatch, as quickly as two days after the water is started. The first tadpole shrimp instars are very small and translucent, and very difficult to see in the water. As they grow, they become easier to spot; however, the coloration of their shell (carapace) allows them to blend with the soil. Young tadpole shrimp look just like adults.

Figure 1. Tadpole shrimp with a shell size of 4 mm, or about half the size of a rice seed, can injure germinating rice seeds.

Tadpole shrimp molt throughout their life. Their initial growth is quick, reaching When they reach the adult stage, they develop egg sacs under the shell. Eggs are laid in the soil, plants, and other substrate available in the water. Eggs require a dehydration period before hatching. Newly laid eggs therefore will not hatch unless the field is drained, let to dry, and reflooded. After fields are drained for harvest, tadpole shrimp eggs remain dormant in the soil. Next spring, when rice fields are flooded, eggs will float, rehydrate and hatch. Eggs hatch in installments, meaning that some of the eggs laid the previous year will hatch, but others will remain dormant in the soil and hatch only if they go through another dehydration-hydration cycle. Eggs can remain dormant in the soil for several years.

Injury to Rice

Tadpole shrimp will feed on germinating seeds once they reach a shell size of about 4 mm (about half the size of a rice seed) (Fig. 1). They can reach this size as quick as five days after the water is started when temperatures are warm. Smaller shrimp are not able to injure the germinating seed. Larger shrimp will feed on the emerging coleoptile and radicle, cutting them completely and killing the germinating seed (Fig. 2). Once seedlings have a green spike (the prophyll), tadpole shrimp won't feed on them. However, they will feed on exposed roots. If seedlings are not well anchored, or if they are uprooted by wind, tadpole shrimp will feed on the roots, consuming them to the point where those seedlings won't be able to get established (Fig. 3).

Management

The longer a field takes to flood, the more time tadpole shrimp will have to develop and reach a size that can injury rice as it germinates. Small fields that can be flooded quickly (in two to three days) can avoid tadpole shrimp injury by seeding soon after flooding. Monitor the seedling stage of development and tadpole shrimp size. Once seedlings have a spike and the root is well established, tadpole shrimp will not affect them.

Figure 2. Germinating rice seed with coleoptile and radicle consumed by tadpole shrimp, and tadpole shrimp egg on seed.

If tadpole shrimp shell is smaller than 4 mm, they won't injure rice; however, they can grow quickly, especially in warm weather. Monitor frequently and take action if tadpole shrimp shell is larger than 4 mm and seedlings do not have a spike yet. Fields that are drained soon after seedling (Leather's method) are at low risk of tadpole shrimp injury. When draining the water, any young tadpole shrimp will be carried out the field by the water or will be killed once the field dries. Draining a field to kill tadpole shrimp works if the field is dried to the point that no standing water or puddles remain.

Insecticides can be used to control tadpole shrimp. Pyrethroid insecticides are highly effective. However, in recent years, control failures have been reported when using them. In those cases, other insecticides can be used, such as clothianidin, carbaryl, or copper sulfate. Always follow the label and use full label rates to avoid the development of resistance.

Figure 3. Tadpole shrimp will consume the roots of dislodged seedlings, preventing them from establishing.

For more on this topic:

- ✓ Integrated Pest Management for Rice, Third Edition. UC Agriculture and Natural Resources.
- ✓ UC IPM for Rice: ipm.ucanr.edu
- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu

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2020

Armyworms in Rice

Background

The armyworm (*Mythimna unipuncta*) (Fig. 1) is an insect commonly found in rice fields; it can become a pest when populations reach high densities. A serious armyworm outbreak occurred in 2015, resulting in yield reductions of up to 20% in some fields. The western yellowstriped armyworm (*Spodoptera praefica*) can sometimes be also found in rice fields, mostly feeding on broadleaf weeds such as ducksalad and redstem.

Figure 1. Armyworm larvae feed on rice foliage and panicles. Severe injury can lead to yield reductions.

Life Cycle

Armyworm adults are thick straw-colored moths that fly at night. Pheromone trapping in the Sacramento Valley has shown that moths start flying in early June and increase in numbers quickly, peaking in late June or early July. Another peak occurs in mid-August (Fig. 2)

Mated females lay egg masses in the vegetation around rice fields and rice field borders. Each egg mass can have over 100 eggs, and a single moth is capable of laying up to 2000 eggs in her lifespan. Egg masses are very difficult to find in the field.

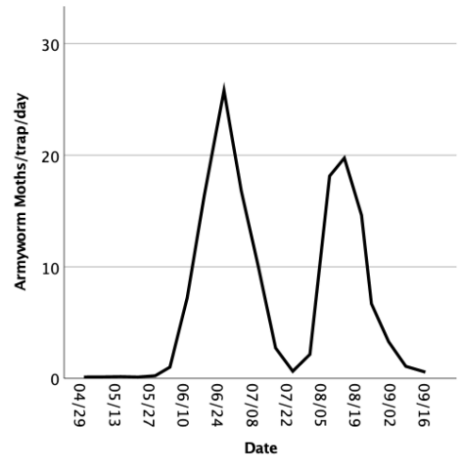

Figure 2. Average number of moths caught with pheromone traps at 15 locations in the Sacramento Valley in 2018, a year with average worm pressure.

Eggs hatch after four or five days. Young larvae are small and do little feeding, making their detection difficult. Larvae feed at night, spending the day hidden in the foliage near the water level. Larvae go through six instars, with instars five and six being the most conspicuous because of their size and the large amount of foliage they consume. Large larvae can take a week or longer to complete their development and turn into a pupa. Armyworm larvae pupate in rice fields by lodging themselves between tillers and making a protecting case with pieces of foliage. Adults emerge in about 10 days.

Injury to Rice

Larvae can be found in rice fields in early July and mid-August. During early July, infestations start near field borders and progress into the field. When larval density is high, defoliation can be severe. During the mid-August infestation, armyworms also feed on panicle branches, resulting in partially blanked panicles (Fig. 3).

Figure 3. Armyworms can feed on panicle branches, causing partial panicle blanking.

Management

Rice plants are very tolerant of defoliation during vegetative growth. Research has shown that when more than 25% of rice foliage is consumed, a yield reduction can be expected. When defoliation is severe (to the water level), the yield reduction can be as high as 26%. Significant yield reductions because of panicle feeding can occur when more than 10% of panicles are injured.

Managers should scout fields frequently during late June and early July and monitor the level of defoliation and the presence of larvae in the field. Experience shows that weedy fields can harbor more armyworms than clean fields. If defoliation approaches 25% and larvae are present, an insecticide treatment may be needed. Similarly, during mid-August, growers should monitor for panicle injury and the presence of larvae.

The insecticides methoxyfenozide (Intrepid) and diflubenzuron (Dimilin) are effective insecticides. Methoxyfenozide is currently (2021) available through a Section 18 label. Dimilin has an 80-day pre harvest interval, so it cannot be used during the heading infestation.

Pheromone traps can aid in monitoring by providing a relative measure of moth populations. However, moth catches do not predict larval injury – high moth captures do not necessarily produce high larval populations. Armyworms have many natural enemies in rice fields, including predators and parasitoids that can significantly reduce larval populations (Fig. 4). Avoiding unnecessary insecticide applications can allow these natural enemies maintain armyworm populations below damaging levels.

Figure 4. Armyworm parasitoid cocoons are commonly found in rice fields.

For more on this topic:

- ✓ Integrated Pest Management for Rice, Third Edition. UC Agriculture and Natural Resources.
- ✓ UC IPM for Rice: ipm.ucanr.edu
- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu

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2022

Stem Rot and Aggregate Sheath Spot of Rice

Background

Stem rot and aggregate sheath spot are two common diseases of rice in California. Both are present in almost every field. At low levels, the diseases do not affect yield. However, when disease levels are high, early leaf senescence, lodging, and blanking can result in yield reductions.

Stem Rot

Stem rot is caused by the fungus *Sclerotium oryzae*. During the winter, the pathogen survives in straw residue in the form of resting structures called sclerotia. During warm weather, the sclerotia can geminate, grow, and produce more sclerotia. Research has shown that as the number of viable sclerotia in the soil increases, disease severity increases.

After fields are flooded, sclerotia float to the surface and, when conditions are appropriate, germinate and infect rice plants at the water level. Initially, the infection produces small black lesions on the leaf sheath (Fig. 1A). As the disease progresses, lesions get bigger and penetrate into the culm, and in severe cases the whole culm is rotted through. After fields are drained, sclerotia begin forming inside the lesions (Fig. 1B).

Aggregate Sheath Spot

This disease is caused by the fungus *Rhizoctonia oryzae-sativae*. Its cycle is similar to that of stem rot; sclerotia in crop residue constitute the inoculum that will cause infections the following season. In contrast to stem rot, aggregate sheath spot lesions are gray or green with well-defined borders (Fig. 2). As the disease progresses, lesions start developing on higher leaf sheaths (Fig. 3). Leaves of affected sheaths turn yellow and die. When the disease is severe, panicles can be affected; however, this is rare.

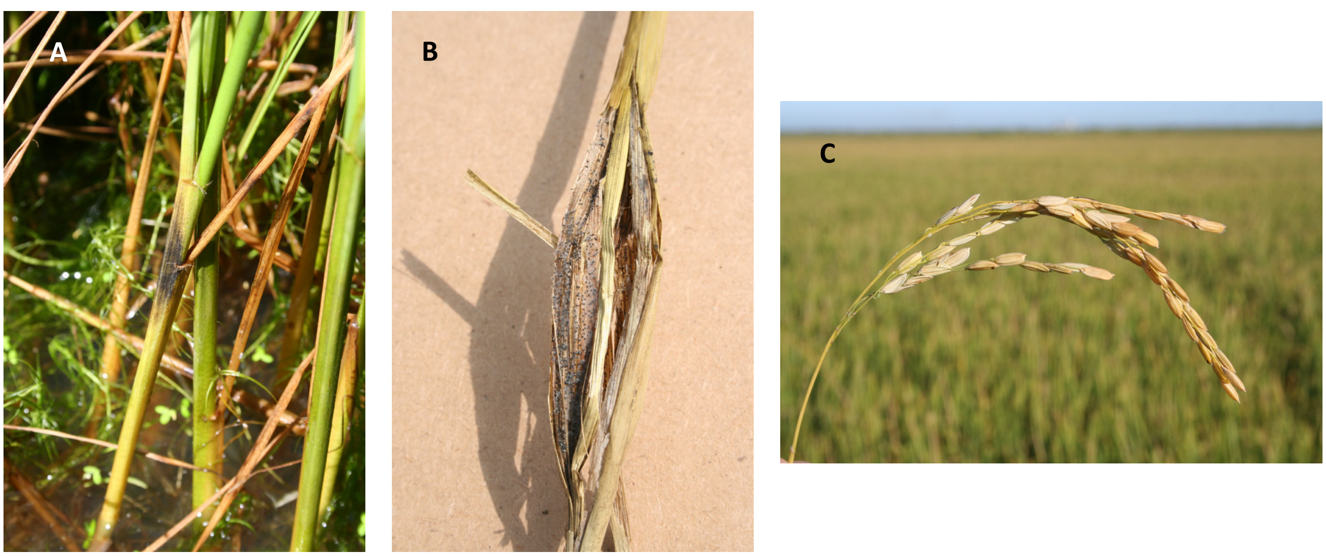

Figure 1. A. Initial stem rot lesion developing near the water level. B. At the end of the season, sclerotia can be found inside rotted culms. C. Panicle blanking caused by stem rot infection.

Management

Straw management

Because both pathogens can survive in straw during the winter, management of straw residue is critical to reduce disease severity. Any actions that improve straw decomposition during the winter will reduce viability of the sclerotia. Chopping and disking straw, followed by winter flooding for several years will reduce disease severity in the field.

Bailing can reduce the amount of inoculum in the field by removing sclerotia with the straw. Cut the straw as close to the ground level as possible to maximize the amount of sclerotia removed.

Burning eliminates the sclerotia, therefore it is recommended when possible.

Fertility

Stem rot development is favored by high nitrogen rates. Apply nitrogen to maximize yield and asses the need of a mid-season nitrogen application.

Aggregate sheath spot can be more severe when potassium is deficient. Asses the level of potassium in the soil and apply if needed.

Varieties

Currently, all pubic varieties in California are susceptible to both diseases.

Fungicides

Fungicides can reduce the incidence and severity of both diseases. The fungicide azoxystrobin (active ingredient in Quadris) applied at the early heading stage has resulted in good levels of disease reduction. Applications made early in the season (35-45 days after seeding) are not as beneficial as applications during early heading.

When disease levels are high, fungicides may not be enough to reduce disease severity. Several years of improved straw management and fertility, combined with fungicides, will help reduce disease levels.

Figure. 2. Early lesions of aggregate sheath spot at the water level

Figure. 3. *Aggregate sheath spot lesions affecting leaf sheath.*

For more on this topic:

- ✓ Integrated Pest Management for Rice, Third Edition. UC Agriculture and Natural Resources.
- ✓ UC IPM for Rice: ipm.ucanr.edu
- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu

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2020

Kernel Smut of Rice

Background

Kernel smut was fist found in California in the mid 1980s. Since then, the disease has been present in rice fields across the Sacramento Valley without causing problems. However, starting in the mid 2010s, growers and pest control advisers started noticing an increase in the incidence of the disease. In 2018, many fields were severely affected, especially in the northern part of the Valley.

Kernel smut can affect rice production in several ways. Anecdotal evidence suggests severely affected fields can suffer yield reductions. Because the fungus affects the kernels directly, milling and head rice yield are affected, with reductions of up to 15% observed in California. Additionally, during the milling process smutted kernels contaminate other kernels, resulting in off-colored milled rice. When grain is severely affected, spores may be visible when the milled rice is cooked. While *T. horrida* is not toxic if ingested, this may cause health risks concerns among consumers.

The Pathogen

Kernel smut is caused by the fungus *Tilletia horrida*. This pathogen has a rather complicated cycle that is poorly understood. During grain maturity, infected rice kernels are partially or completely replaced by a black mass of spores called teliospores (Fig. 1).

During harvest, teliospores disperse and can cover equipment, grain, and soil. In the spring, spores present in the field float to the surface and germinate, forming primary sporidia, a type of dispersing spore. These sporidia germinate, grow and later form secondary sporidia. Secondary sporidia are discharged into the air and infect ovaries of open rice flowers. The pathogen then develops inside the flower and forms the black mass of spores evident as the grain matures (Fig. 2). Smutted kernels are more noticeable early in the morning because they swell with the morning dew.

Figure. 1. Panicle showing smutted kernels. Smutted kernels are more noticeable early in the morning.

Management

Seed

Infected seed can be a source of the disease. A 2019 survey showed that most seed sources in the Sacramento Valley have various levels of kernel smut. At this time, it is not known if the sodium hypochlorite seed treatment commonly used for bakanae disease reduces the viability of spores in seed. Make sure to use certified seed and continue to treat with sodium hypochlorite when possible.

Varieties

Long grains are more susceptible than medium and short grains, with some differences among varieties (Fig. 3). Of the medium grains, M-209 seems to be the most susceptible.

Fertility

Excess nitrogen increases the susceptibility of plants to the disease. Apply nitrogen to maximize yield and asses the need of a mid-season nitrogen application.

Figure. 2. Smutted kernels break during the milling process, resulting in lower milling and head rice yield. Also, spores contaminate other kernels, producing off-colored milled rice.

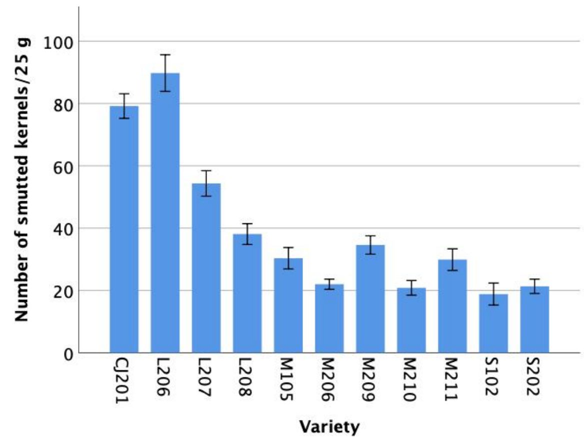

Figure. 3. Number of smutted kernels in 25 g of seed in a variety trail conducted in 2018 in Butte County.

Fungicides

It is challenging to monitor for this disease because smutted kernels are not noticed until harvest. The decision to use a fungicide should be based on the history of the field. Trials have shown that the fungicide propiconazole (the active ingredient in Tilt) can reduce the severity of the disease. Applications should be made at the mid boot stage, before panicles emerge from the boot.

For more on this topic:

- ✓ Integrated Pest Management for Rice, Third Edition. UC Agriculture and Natural Resources.
- ✓ UC IPM for Rice: ipm.ucanr.edu
- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu

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Rice Blast in California

Introduction

Rice blast is the most destructive disease of rice worldwide. In California, blast was first found in the late 1990s, and since then it has become endemic in the northwestern part of the Sacramento Valley. However, in years with favorable weather conditions, the disease has been observed in all rice production areas of the state.

The Pathogen

Blast is caused by the fungus *Magnaporthe oryzae*. The fungus can infect any part of the plant, except the roots. In California, noticeable infections usually occur after full tillering, causing leaf lesions. Lesions are diamond shaped and have a yellow halo around them (Fig. 1).

Figure 1. Diamond shaped blast lesion. Notice the yellow halo and gray sporulation in the center of lesion.

In severe cases, blast lesions coalesce and burn foliage to the water level (Fig. 2). This usually occurs in field headlands, where nitrogen application overlaps. Blast infections on leaf tissue are commonly referred to as “leaf blast”.

Blast infections can also occur later, during heading, with blast lesions developing in the node below the panicle, causing “neck blast”, which can produce blanked panicles (Fig. 3).

Figure 2. Leaf blast in nitrogen overlap.

Blast spores can be moved by air currents. They need free moisture on the plant surface (leaf wetness) to germinate and penetrate the tissue. After infection, lesions develop in four to five days, and spores are formed on lesions two to three days later. These spores can then be moved by wind and cause new infections. As tissues mature, they become more resistant to blast infection. During the off-season, the fungus survives on infested rice residue and seeds on the soil.

Blast is favored by long periods of leaf wetness, high relative humidity (>90%), and warm temperatures (>68F). Leaf wetness that starts early in the evening or lasts into the late morning hours, coupled with warm temperatures, can lead to spore germination and infection.

Figure 3. Neck blast. Notice lesion in the node below the panicle.

Management

Seed

Blast spores can be found infecting rice seed. The sodium hypochlorite treatment used during the seed soak does not eliminate blast spores from the seed. Using certified seed reduces the risk of introducing inoculum to a field.

Water Management

Infection from seed to seedling under flooded conditions is very unlikely. Draining early for stand establishment or herbicide application may allow seedling infection.

Fertility

Excess nitrogen increases the susceptibility of plants to the disease. Leaf blast is usually observed first in nitrogen overlap areas. Midseason nitrogen applications should only be made when the crop is nitrogen deficient.

Fungicides

Azoxystrobin and trifloxystrobin (the active ingredients in Quadris and Stratego, respectively) are registered for control of blast disease in California. In general, applications to control leaf blast are not recommended unless plant stand is severely affected. Presence of leaf blast should be an indication that a treatment for neck blast will be needed. To protect the panicles from neck blast, applications should be made at the early heading stage (20-50% heading). If economics allow for two applications, target the boot split and 50% heading stages.

For more on this topic:

- ✓ Integrated Pest Management for Rice, Third Edition. UC Agriculture and Natural Resources.
- ✓ UC IPM for Rice: ipm.ucanr.edu
- ✓ Agronomy Research and Information Center-Rice: rice.ucanr.edu
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95 .	1978	BOCKUS, WW (BOCKUS, WW); WEBSTER, RK (WEBSTER, RK); KOSUGE, T (KOSUGE, T)	PHYTOPATHOLOGY	68:417-421	COMPETITIVE SAPROPHYTIC ABILITY OF SCLEROTIUM ORYZAE DERIVED FROM SCLEROTIA
96 .	1978	Scott, S. R., and A. A. Grigarick	The Wasmann Journal of Biology	36: 116-126	Observations on the biology and rearing of the tadpole shrimp Triops longicaudatus (Leconte) (Notostraca: Triopsidae).
97 .	1978	MIKKELSEN, DS (MIKKELSEN, DS); DEDATTA, SK (DEDATTA, SK); OBCEMEA, WN (OBCEMEA, WN)	Soil Science Society of America Journal	42:725-730	AMMONIA VOLATILIZATION LOSSES FROM FLOODED RICE SOILS
98 .	1979	Zalom, F. G., A. A. Grigarick, and M. O. Way	Environ. Entomol	8: 938-943	Seasonal and diel flight periodicities of rice field Hydrophilidae.
99 .	1979	BOCKUS, WW (BOCKUS, WW); WEBSTER, RK (WEBSTER, RK)	PHYTOPATHOLOGY	69:389-392	DECLINE IN NUMBERS AND INOCULUM POTENTIAL OF SCLEROTIUM-ORYZAE IN FIELD SOIL
100 .	1979	BOCKUS, WW (BOCKUS, WW); WEBSTER, RK (WEBSTER, RK); WICK, CM (WICK, CM); JACKSON, LF (JACKSON, LF)	PHYTOPATHOLOGY	69:862-865	RICE RESIDUE DISPOSAL INFLUENCES OVERWINTERING INOCULUM LEVEL OF SCLEROTIUM-ORYZAE AND STEM ROT SEVERITY
101 .	1979	Scott, S. R., and A. A. Grigarick	Hydrobiologia	63: 145-152	Laboratory studies of factors affecting egg hatch of Triops longicaudatus (Leconte) (Notostraca: Triopsidae).
102 .	1979	Brandon, D.M. and D.S. Mikkelsen	Soil Science Society of America Journal	43:989-994	Phosphorus transformations in alternately flooded California soils: I. Cause of plant phosphorus deficiency in rice rotation crops and correctional methods
103 .	1979	MIKKELSEN, DS (MIKKELSEN, DS); DEDATTA, SK (DEDATTA, SK)	Soil Science Society of America Journal	43:630-631	AMMONIA VOLATILIZATION FROM FLOODED RICE SOIL
104 .	1979	KUO, S; MIKKELSEN, DS	Soil Science	128:274-279	ZINC ADSORPTION BY 2 ALKALINE SOILS
105 .	1979	KUO, S; MIKKELSEN, DS	Soil Science	127:18-25	DISTRIBUTION OF IRON AND PHOSPHORUS IN FLOODED AND UNFLOODED SOIL PROFILES AND THEIR RELATION TO PHOSPHORUS ADSORPTION
106 .	1979	BOARD, JE, ML PETERSON, JN RUTGER	California Agriculture	33:10-11	RESPONSE OF CALIFORNIA RICE VARIETIES TO COOL TEMPERATURES
107 .	1980	Zalom, F. G., A. A. Grigarick, and M. O. Way	Hydrobiologia	75: 195-200	Habits and relative population densities of some hydrophilids in California rice fields.

108 .	1980	Zalom, F. G., and A. A. Grigarick	Ann. Entomol. Soc. Am.	73: 167-171	Predation by Hydrophilus triangularis and Tropisternus lateralis in Calfornia rice fields.
109 .	1980	Barret, S.C.H. and D.E. Seaman	Aquatic Botany	9:351-376	The weed flora of Californian rice fields
110 .	1980	BOARD, JE AND ML PETERSON	California Agriculture	34 (ISSUE 11):5-7	MANAGEMENT DECISIONS CAN REDUCE BLANKING IN RICE
111 .	1980	BOARD, JE, ML PETERSON, E NG	Agronomy Journal	72:483-487	FLORET STERILITY IN RICE IN A COOL ENVIRONMENT
112 .	1980	WILLIAMS, WA (WILLIAMS, WA); DAWSON, JH (DAWSON, JH)	California Agriculture	34:(issue 8-9):15-16	VETCH IS AN ECONOMICAL SOURCE OF NITROGEN IN RICE
113 .	1981	WEBSTER, RK (WEBSTER, RK); WICK, CM (WICK, CM); BRANDON, DM (BRANDON, DM); HALL, DH (HALL, DH); BOLSTAD, J (BOLSTAD, J)	HILGARDIA	49:1-12	EPIDEMIOLOGY OF STEM ROT DISEASE OF RICE - EFFECTS OF BURNING VS SOIL INCORPORATION OF RICE RESIDUE
114 .	1981	KUO, S; MIKKELSEN, DS	Soil Science	132:353-357	THE EFFECTS OF STRAW AND SULFATE AMENDMENTS AND TEMPERATURE ON SULFIDE PRODUCTION IN 2 FLOODED SOILS
115 .	1982	Rice, S. E., A. A. Grigarick, and M. O. Way	Environ. Entomol.	11: 648-651.	Relationship of larval density and instars of Pseudaletia unipuncta to rice leaf feeding.
116 .	1982	Rice, S. E., A. A. Grigarick, and M. O. Way	J. Econ. Entomol.	75: 593-595	Effect of leaf and panicle feeding by armyworm (Lepidoptera: Noctuidae) larvae on rice grain yield.
117 .	1982	Grigarick, A. A., and M. O. Way	J. Econ. Entomol.	75: 633-636	Role of crayfish (Decapoda: Astacidae) as pests of rice in California and their control.
118 .	1983	Way, M. O., A. A. Grigarick, and S. E. Mahr	Environ. Entomol.	12: 949-952	Effects of rice plant density, rice water weevil (Coleoptera: Curculionidae) damage to rice, and aquatic weeds on aster leafhopper (Homoptera: Cicadellidae) density.
119 .	1983	Manandhar, D. N., and A. A. Grigarick	J. Econ. Entomol	76: 1022-1027.	Effect of rice leafminer (Diptera: ephydridae) feeding on early growth of the rice plant
120 .	1983	GUNNELL, PS (GUNNELL, PS); WEBSTER, RK (WEBSTER, RK)	PHYTOPATHOLOGY	73:796-796	SHEATH BLIGHT OF RICE IN CALIFORNIA
121 .	1983	MAHROUS, FN (MAHROUS, FN); MIKKELSEN, DS (MIKKELSEN, DS); HAFEZ, AA (HAFEZ, AA)	Plant and Soil	75:455-472	EFFECT OF SOIL-SALINITY ON THE ELECTRO-CHEMICAL AND CHEMICAL-KINETICS OF SOME PLANT NUTRIENTS IN SUBMERGED SOILS
122 .	1983	WESTCOTT, MP; MIKKELSEN, DS	Plant and Soil	74:31-39	THE RESPONSE OF RICE SEEDLINGS TO O2 RELEASED FROM CAO2 IN FLOODED SOILS
123 .	1983	Sah, R.N. and D.S. Mikkelsen	Plant and Soil	75:221-226	AVAILABILITY AND UTILIZATION OF FERTILIZER NITROGEN BY RICE UNDER ALTERNATE FLOODING .1. KINETICS OF AVAILABLE NITROGEN UNDER RICE CULTURE
124 .	1983	Sah, R.N. and D.S. Mikkelsen	Plant and Soil	75:227-234	AVAILABILITY AND UTILIZATION OF FERTILIZER NITROGEN BY RICE UNDER ALTERNATE FLOODING .2. EFFECTS ON GROWTH AND NITROGEN USE EFFICIENCY
125 .	1984	Way, M. O., A. A. Grigarick, and S. E. Mahr	J. Econ. Entomol	77: 936-942	The aster leafhopper (Homoptera: Cicadellidae) in California rice: herbicide treatment affects population density and induced infestations reduce grain yield.
126 .	1984	GUNNELL, PS (GUNNELL, PS); WEBSTER, RK (WEBSTER, RK)	PHYTOPATHOLOGY	74:857-857	THE TELEOMORPH OF RHIZOCTONIA-ORYZAE
127 .	1984	GUNNELL, PS (GUNNELL, PS); WEBSTER, RK (WEBSTER, RK)	Plant Disease	68:529-531	AGGREGATE SHEATH SPOT OF RICE IN CALIFORNIA

128 .	1984	Grigarick, A. A.	Prot. Ecol.	7: 105-114	General problems with rice invertebrate pests and their control in the United States.
129 .	1985	GUNNELL, PS (GUNNELL, PS); WEBSTER, RK (WEBSTER, RK)	PHYTOPATHOLOGY	75:1340-1340	THE EFFECT OF CULTURAL-PRACTICES ON AGGREGATE SHEATH SPOT OF RICE IN CALIFORNIA
130 .	1985	Smith, K. A., A. A. Grigarick, J. H. Lynch, and M. J. Oraze	J. Econ. Entomol.	78: 185-189	Effect of alsystin and diflubenzuron on the rice water weevil (Coleoptera: Curculionidae).
131 .	1985	Grigarick, A. A., J. H. Lynch, and M. O. Way	California Agriculture	39: 12-13	Controlling tadpole shrimp
132 .	1985	JENKINS, BM,DA TOENJES, JB DOBIE, JF ARTHUR	TRANSACTIONS OF THE ASAE	28:360-363	PERFORMANCE OF LARGE BALERS FOR COLLECTING RICE STRAW
133 .	1986	Way, M. O., A. A. Grigarick, S. E. Mahr, M. J. Oraze, and K. A. Smith	J. Econ. Entomol	79: 1711-1713	Evaluation of three drop traps for sampling aster leafhoppers (Homoptera: Cicadellidae) in rice.
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135 .	1986	Sah, R.N. and D.S. Mikkelsen	Soil Science	142:267-274	EFFECTS OF ANAEROBIC DECOMPOSITION OF ORGANIC-MATTER ON SORPTION AND TRANSFORMATIONS OF PHOSPHATE IN DRAINED SOILS .1. EFFECTS ON PHOSPHATE SORPTION
136 .	1986	Sah, R.N. and D.S. Mikkelsen	Soil Science	142:346-351	EFFECTS OF ANAEROBIC DECOMPOSITION OF ORGANIC-MATTER ON SORPTION AND TRANSFORMATIONS OF PHOSPHATE IN DRAINED SOILS .2. EFFECTS ON AMORPHOUS IRON CONTENT AND PHOSPHATE TRANSFORMATION
137 .	1986	Sah, R.N. and D.S. Mikkelsen	Plant and Soil	92:265-278	SORPTION AND BIOAVAILABILITY OF PHOSPHORUS DURING THE DRAINAGE PERIOD OF FLOODED-DRAINED SOILS
138 .	1986	Sah, R.N. and D.S. Mikkelsen	Plant and Soil	95:163-171	EFFECTS OF TEMPERATURE AND PRIOR FLOODING ON INTENSITY AND SORPTION OF PHOSPHORUS IN SOIL .1. EFFECTS ON THE KINETICS OF SOLUBLE-P IN SOIL
139 .	1986	Sah, R.N. and D.S. Mikkelsen	Plant and Soil	95:173-181	EFFECTS OF TEMPERATURE AND PRIOR FLOODING ON INTENSITY AND SORPTION OF PHOSPHORUS IN SOIL .2. EFFECTS ON P-SORPTION
140 .	1986	Sah, R.N. and D.S. Mikkelsen	Soil Science Society of America Journal	50:62-67	Transformations of inorganic phosphorus during the flooding and draining cycles of soil
141 .	1986	JAYAWEERA, GR (JAYAWEERA, GR); MIKKELSEN, DS (MIKKELSEN, DS)	ABSTRACTS OF PAPERS OF THE AMERICAN CHEMICAL SOCIETY	192:9-FERT	MODELING THE RATE OF AMMONIA VOLATILIZATION FROM FLOODED RICE
142 .	1987	RUTGER, JN (RUTGER, JN); FIGONI, RA (FIGONI, RA); WEBSTER, RK (WEBSTER, RK); OSTER, JJ (OSTER, JJ); MCKENZIE, KS (MCKENZIE, KS)	Crop Science	1319-1320	REGISTRATION OF EARLY MATURING, MARKER GENE, AND STEM ROT RESISTANT GERMPLASM LINES OF RICE
143 .	1987	WESTCOTT, MP (WESTCOTT, MP); MIKKELSEN, DS (MIKKELSEN, DS)	Agronomy Journal	79:937-943	COMPARISON OF ORGANIC AND INORGANIC NITROGEN-SOURCES FOR RICE
144 .	1987	MIKKELSEN, DS	Plant and Soil		NITROGEN BUDGETS IN FLOODED SOILS USED FOR RICE PRODUCTION

145 .	1988	Oraze, M. J., A. A. Grigarick, J. H. Lynch, and K. A. Smith	J. Arachnol	16: 331-337	Spider fauna of flooded rice fields in northern California.
146 .	1988	Smith, K. A., A. A. Grigarick, and M. J. Oraze	J. Agric. Entomol.	5: 121-126	Field evaluations of diflubenzuron and triflumuron for control of the rice water weevil in California rice fields.
147 .	1988	BM JENKINS	California Agriculture	43:25-27	FIELD-DRYING RICE USING MODIFIED SWATH HARVESTING
148 .	1989	Oraze, M. J., A. A. Grigarick, and K. A. Smith	J. Arachnol.	17: 163-170	Population ecology of Pardosa ramulosa (Araneae, Lycosidae) in flooded rice fields of northern California
149 .	1989	Oraze, M. J., and A. A. Grigarick	J. Econ. Entomol	82: 745-749.	Biological control of aster leafhopper (Homoptera: Cicadellidae) and midges (Diptera: Chironomidae) by Pardosa ramulosa (Araneae: Lycosidae) in California rice fields.
150 .	1989	Smith, K. A., and A. A. Grigarick	J. Econ. Entomol.	82: 645-648	Triflumuron: residual activity and ovicidal longevity in the rice water weevil (Coleoptera: Curculionidae)
151 .	1989	Sah, R.N. and D.S. Mikkelsen	Soil Science Society of America Journal	53:1718-1722	Phosphorus behavior in flooded-drained soils. I. Effects on phosphorus sorption
152 .	1989	Sah, R.N., D.S. Mikkelsen and A.A. Hafez	Soil Science Society of America Journal	53:1723-1729	Phosphorus behavior in flooded-drained soils. II. Iron transformation and phosphorus sorption
153 .	1989	Sah, R.N., D.S. Mikkelsen and A.A. Hafez	Soil Science Society of America Journal	53:1729-1732	Phosphorus behavior in flooded-drained soils. III. Phosphorus desorption and availability
154 .	1989	MIKKELSEN, RL (MIKKELSEN, RL); MIKKELSEN, DS (MIKKELSEN, DS); ABSHAHI, A (ABSHAHI, A)	Soil Science Society of America Journal	53:122-127	EFFECTS OF SOIL FLOODING ON SELENIUM TRANSFORMATIONS AND ACCUMULATION BY RICE
155 .	1989	WELLS, BR, PK BOLLICH,W EBELHAR, DS MIKKELSEN, RJ NORMAN,DM BRANDON, RS HELMS, FT TURNER, MP WESTCOTT	COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS	20:2023-2047	DICYANDIAMIDE (DCD) AS A NITRIFICATION INHIBITOR FOR RICE CULTURE IN THE UNITED-STATES
156 .	1989	CARNAHAN, HL, CW JOHNSON, ST TSENG, JJ OSTER, JE HILL, DM BRANDON	Crop Science	29:1089-1090	REGISTRATION OF M-203 RICE
157 .	1989	JOHNSON, CW, HL CARNAHAN, ST TSENG, JJ OSTER, JE HILL, JN RUTGER, DM BRANDON	Crop Science	29:1090-1091	REGISTRATION OF S-101 RICE
158 .	1989	BM JENKINS	TRANSACTIONS OF THE ASAE	32:1399-1408	A MODIFIED SWATH HARVESTING TECHNIQUE FOR RICE .1. INFLUENCE ON MOISTURE, QUALITY, AND HARVESTER PERFORMANCE
159 .	1989	BM JENKINS	TRANSACTIONS OF THE ASAE	32:1409-1418	A MODIFIED SWATH HARVESTING TECHNIQUE FOR RICE .2. PRELIMINARY ECONOMIC-ANALYSIS
160 .	1990	Grigarick, A. A., R. K. Webster, R. P. Meyer, F. G. Zalom, and K. A. Smith	Hilgardia	58: 1-36	Effect of pesticide treatments on nontarget organisms in California rice paddies.
161 .	1990	GRIGARICK, AA (GRIGARICK, AA); WEBSTER, RK (WEBSTER, RK); MEYER, RP (MEYER, RP); ZALOM, FG (ZALOM, FG); SMITH, KA (SMITH, KA); SMITH, KA (SMITH, KA); GRIGARICK, AA (GRIGARICK, AA)	HILGARDIA	58:1-36	EFFECT OF PESTICIDE TREATMENTS ON NONTARGET ORGANISMS IN CALIFORNIA RICE PADDIES .1. IMPACT OF TRIPHENYLTIN HYDROXIDE .2. IMPACT OF DIFLUBENZURON AND TRIFLUMURON
162 .	1990	Grigarick, A. A., R. K. Webster, R. P. Meyer, F. G. Zalom, and K. A. Smith	Hilgardia	58	Effect of pesticide treatments on nontarget organisms in California rice paddies. I. Impact of triphenyltin hydroxide. II. Impact of diflubenzuron and triflumuron
163 .	1990	WILLIAMS JF; SR ROBERTS, JE HILL, SC SCARDACI, G TIBBITS	California Agriculture	44:7-10	MANAGING WATER FOR WEED CONTROL IN RICE

164 .	1990	HILL, JE, SR ROBERTS, DE BAYER, JF WILLIAMS	Weed Technology	4:838-842	CROP RESPONSE AND WEED-CONTROL FROM NEW HERBICIDE COMBINATIONS IN WATER-SEEDED RICE (ORYZA-SATIVA)
165 .	1990	JOHNSON, CW, HL CARNAHAN, ST TSENG, JJ OSTER, KS MCKENZIE, JE HILL, JN RUTGER, DM BRANDON	Crop Science	30:960-961	REGISTRATION OF M-103 RICE
166 .	1991	JAYAWEERA, GR (JAYAWEERA, GR); MIKKELSEN, DS (MIKKELSEN, DS)	Advances in Agronomy	45:303-356	ASSESSMENT OF AMMONIA VOLATILIZATION FROM FLOODED SOIL SYSTEMS
167 .	1991	LAGUE, C and BM JENKINS	TRANSACTIONS OF THE ASAE	34:1797-1811	MODELING PREHARVEST STRESS-CRACKING OF RICE KERNELS .1. DEVELOPMENT OF A FINITE-ELEMENT MODEL
168 .	1991	LAGUE, C and BM JENKINS	TRANSACTIONS OF THE ASAE	34:1812-1823	MODELING PREHARVEST STRESS-CRACKING OF RICE KERNELS .2. IMPLEMENTATION AND USE OF THE MODEL
169 .	1991	MILLER, BC, JE HILL, SR ROBERTS	Agronomy Journal	83:291-297	PLANT POPULATION EFFECTS ON GROWTH AND YIELD IN WATER-SEEDED RICE
170 .	1991	JOHNSON, CW, KS MCKENZIE, ST TSENG, JJ OSTER, JE HILL, DM BRANDON, HL CARNAHAN	Crop Science	31:1090-1091	REGISTRATION OF S-301 RICE
171 .	1992	Hesler, L. S., A. A. Grigarick, M. J. Oraze, and A. T. Palrang	J. Econ. Entomol.	85: 950-956	Effects of temporary drainage on selected life history stages of the rice water weevil (Coleoptera: Curculionidae) in California.
172 .	1992	Hesler, L. S., and A. A. Grigarick	Environ. Entomol.	21: 731-736	Aquatic arthropods in California rice paddies: effects of water-drainage versus continuous-flood regimes on abundance and species composition.
173 .	1992	TSENG, ST, CW JOHNSON, KS MCKENZIE, JJ OSTER, JE HILL, DM BRANDON	Crop Science	32:496	REGISTRATION OF L-203 RICE
174 .	1992	JENKINS, BM, SQ TURN, RB WILLIAMS	AGRICULTURE ECOSYSTEMS & ENVIRONMENT	38:313-330	ATMOSPHERIC EMISSIONS FROM AGRICULTURAL BURNING IN CALIFORNIA - DETERMINATION OF BURN FRACTIONS, DISTRIBUTION FACTORS, AND CROP-SPECIFIC CONTRIBUTIONS
175 .	1992	CASSMAN, KG and RE PLANT	Fertilizer Research	31:151-163	A MODEL TO PREDICT CROP RESPONSE TO APPLIED FERTILIZER NUTRIENTS IN HETEROGENEOUS FIELDS
176 .	1993	Palrang, A. T., and A. A. Grigarick	J. Econ. Entomol.	86: 1376-1380	Flight response of the rice water weevil (Coleoptera: Curculionidae) to simulated habitat conditions.
177 .	1993	Hesler, L. S., A. A. Grigarick, M. J. Oraze, and A. T. Palrang	J. Econ. Entomol.	86: 149-158	Arthropod fauna of conventional and organic rice fields in California.
178 .	1993	MILLER, BC, TC FOIN, JE HILL	Agronomy Journal	85:938-947	CARICE - A RICE MODEL FOR SCHEDULING AND EVALUATING MANAGEMENT ACTIONS
179 .	1993	ROBERTS, SR, JE HILL, DM BRANDON, BC MILLER, SC SCARDACI, CM WICK, JF WILLIAMS	Journal of Prodcution Agriculture	6:585-588	BIOLOGICAL YIELD AND HARVEST INDEX IN RICE - NITROGEN RESPONSE OF TALL AND SEMIDWARF CULTIVARS
180 .	1993	BOUHACHE, M and DE BAYER	Weed Science	41:611-614	PHOTOSYNTHETIC RESPONSE OF FLOODED RICE (ORYZA-SATIVA) AND 3 ECHINOCHLOA SPECIES TO CHANGES IN ENVIRONMENTAL-FACTORS

181 .	1993	JONGKAEWWATTANA, S, S GENG, JE HILL, BC MILLER	JOURNAL OF AGRONOMY AND CROP SCIENCE	171:236-242	WITHIN-PANICLE VARIABILITY OF GRAIN FILLING IN RICE CULTIVARS WITH DIFFERENT MATURITIES
182 .	1993	JONGKAEWWATTANA, S, S GENG, DM BRANDON, JE HILL	Agronomy Journal	85:1143-1146	EFFECT OF NITROGEN AND HARVEST GRAIN MOISTURE ON HEAD RICE YIELD
183 .	1994	Palrang, A. T., A. A. Grigarick, M. J. Oraze, and L. S. Hesler	J. Econ. Entomol	87: 1701-1706	Association of levee vegetation to rice water weevil (Coleoptera: Cuculionidae) infestation in California rice.
184 .	1994	Hill, J.E., S.M. Brouder, S.R. Roberts, J.F. Williams, S.C. Scardaci, and C.M. Wick	Journal of Natural Resources and Life Science Education	23:119-124	A survey of water management practices of California rice growers
185 .	1994	LAUREN, JG, GS PETTYGROVE, JM DUXBURY	Biogeochemistry Journal	24:53-65	METHANE EMISSIONS ASSOCIATED WITH A GREEN MANURE AMENDMENT TO FLOODED RICE IN CALIFORNIA
186 .	1994	Hill, J. E., Brouder, S. M.; Scardaci, S. C.; Williams, J. F.	Abstracts of Papers American Chemical Society	207:AGRO 113	Effective rice irrigation management strategies to reduce pesticide pollution of downstream surface waters
187 .	1994	MCKENZIE, KS, CW JOHNSON, ST TSENG, JJ OSTER, DM BRANDON	AUSTRALIAN JOURNAL OF EXPERIMENTAL AGRICULTURE	34:897-905	BREEDING IMPROVED RICE CULTIVARS FOR TEMPERATE REGIONS - A CASE-STUDY
188 .	1994	HILL, JE, RJ SMITH,DE BAYER	AUSTRALIAN JOURNAL OF EXPERIMENTAL AGRICULTURE	34:1021-1029	RICE WEED-CONTROL - CURRENT TECHNOLOGY AND EMERGING ISSUES IN TEMPERATE RICE
189 .	1995	JOHNSON, CW, ST TSENG, KS MCKENZIE, JJ OSTER, JE HILL, DM BRANDON	Crop Science	35:281-283	REGISTRATION OF M-204 RICE
190 .	1996	Yim, KO, and DE Bayer	Weed Research	36:49-54	Root growth inhibition of rice by bensulfuron
191 .	1996	Jenkins, BM, RR Bakker, JB Wei	BIOMASS & BIOENERGY	10:177-200	On the properties of washed straw
192 .	1997	Cartwright, RD (Cartwright, RD); Webster, RK (Webster, RK); Wick, CM (Wick, CM)	MYCOLOGIA	89:163-172	Ascochyta mycoparasitica sp nov, a novel mycoparasite of Sclerotium oryzae in California rice fields
193 .	1997	Greer, CA (Greer, CA); Scardaci, SC (Scardaci, SC); Webster, RK (Webster, RK)	Plant Disease	81:1094-1094	First report of rice blast caused by Pyricularia grisea in California.
194 .	1997	Caton, BP, TC Foin, JE Hill	Weed Science	45:269-275	Mechanisms of competition for light between rice (Oryza sativa) and redstem (Ammannia spp.)
195 .	1997	Yim, KO, YW Kwon, DE Bayer	JOURNAL OF PLANT GROWTH REGULATION	16:35-41	Growth responses and allocation of assimilates of rice seedlings by paclobutrazol and gibberellin treatment
196 .	1997	McKenzie, KS, CW Johnson, ST Tseng, JJ Oster, JE Hill, DM Brandon	Crop Science	37:1018-1019	Registration of 'S-102' rice
197 .	1997	Tseng, ST, KS McKenzie, CW Johnson, JJ Oster, JE Hill, DM Brandon	Crop Science	37:1390-1391	Registration of 'A-201' rice
198 .	1998	Caton, BP, TC Foin, KD Gibson, JE Hill	AGRICULTURAL AND FOREST METEOROLOGY	90:91-102	A temperature-based model of direct-, water-seeded rice (Oryza sativa) stand establishment in California
199 .	1999	Bossio, DA, WR Horwath, RG Mutters, C van Kessel	Soil Biology & Biochemistry	31:1313-1322	Methane pool and flux dynamics in a rice field following straw incorporation

200 .	1999	Bernheim, LG, BM Jenkins, RE Plant, L Yan	BIOMASS: A GROWTH OPPORTUNITY IN GREEN ENERGY AND VALUE-ADDED PRODUCTS	1&2:69-74	Geographic information system modeling of rice straw harvesting and utilization in California
201 .	1999	Bakker-Dhaliwal, R, BM Jenkins, H Lee	BIOMASS: A GROWTH OPPORTUNITY IN GREEN ENERGY AND VALUE-ADDED PRODUCTS	1&2:335-341	Equipment performance and economic assessments of harvesting and handling rice straw
202 .	1999	Jenkins, BM, RB Williams, RR Bakker, S Blunk, DE Yomogida, W Carlson, J Duffy, R Bates, K Stucki, V Tiangco	BIOMASS: A GROWTH OPPORTUNITY IN GREEN ENERGY AND VALUE-ADDED PRODUCTS	1&2:1357-1363	Combustion of leached rice straw for power generation
203 .	2000	Hesler, L. S., M. J. Oraze, A. A. Grigarick, and A. T. Palrang	J. Agric. Urban Entomol.	17: 99-108	Numbers of rice water weevil larvae (Coleoptera: Curculionidae) and rice plant growth in relation to adult infestation levels and broadleaf herbicide applications.
204 .	2000	Zeng, L.H. and M.C. Shannon	Crop Science	40:996-1003	Salinity effects on seedling growth and yield components of rice
205 .	2000	Redeker, K.R., N.-Y. Wang, J.C. Low, A. McMillan, S.C. Tyler, R.J. Cicerone	Science	290:966-969	Emissions of methyl halides and methane from rice paddies
206 .	2000	Fitzgerald, G.J., K.M. Scow and J.E. Hill	Global Biogeochemical Cycles	14: 767-776	Fallow season straw and water management effects on methane emissions in California rice
207 .	2000	Eagle, A.J., J.A. Bird, W.R. Horwath, B.A. Linquist, S.M. Brouder, J.E. Hill and C. van Kessel	Agronomy Journal	92:1096-1103	Rice yield and nitrogen utilization efficiency under alternative straw management practices
208 .	2000	Devevre, OC, WR Horwath	Soil Biology & Biochemistry	32:1773-1785	Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures
209 .	2000	Bird, J.A., G.S. Pettygrove, and J.M. Eadie	Journal of applied Ecology	37:728-741	The impact of waterfowl foraging on the decomposition of rice straw: mutual benefits for rice growers and waterfowl
210 .	2000	Fischer, AJ, CM Ateh, DE Bayer,JE Hill	Weed Science	48:225-230	Herbicide-resistant Echinochloa oryzoides and E-phyllopogon in California Oryza sativa fields
211 .	2000	Fischer, AJ, DE Bayer, MD Carriere ,CM Ateh, KO Yim	PESTICIDE BIOCHEMISTRY AND PHYSIOLOGY	68:156-165	Mechanisms of resistance to bispyribac-sodium in an Echinochloa phyllopogon accession
212 .	2001	Williams, J. and S. Goldman Smith	Better Crops	85:7-9	Correcting potassium deficiency can reduce rice stem diseases
213 .	2001	Miller, TC and RK Webster	Plant Disease	85:967-972	Soil sampling techniques for determining the effect of cultural practices on Rhizoctonia oryzae-sativae inoculum in rice field soils

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215 .	2001	Cintas, NA (Cintas, NA); Webster, RK (Webster, RK)	Plant Disease	85:1140-1144	Effects of rice straw management on Sclerotium oryzae Inoculum, stem rot severity, and yield of rice in California
216 .	2001	Devevre, OC, WR Horwath	Soil Science Society of America Journal	65:499-510	Stabilization of fertilizer nitrogen-15 into humic substances in aerobic vs. waterlogged soil following straw incorporation
217 .	2001	Eagle, AJ, JA Bird, JE Hill, WR Horwath, C van Kessel	Agronomy Journal	93:1346-1354	Nitrogen dynamics and fertilizer use efficiency in rice following straw incorporation and winter flooding
218 .	2001	Bird, JA, WR Horwath, AJ Eagle, C van Kessel	Soil Science Society of America Journal	65:1143-1152	Immobilization of fertilizer nitrogen in rice: Effects of straw management practice
219 .	2001	Gibson, KD, AJ Fischer, TC Foin	Weed Research	41:59-67	Shading and the growth and photosynthetic responses of Ammannia coccinnea
220 .	2001	Gibson, KD, JE Hill, TC Foin, BP Caton, AJ Fischer	Agronomy Journal	93:326-332	Water-seeded rice cultivars differ in ability to interfere with watergrass
221 .	2001	Caton, BP, AM Mortimer, TC Foin, JE Hill, KD Gibson, AJ Fischer	Weed Research	41:155-163	Weed shoot morphology effects on competitiveness for light in direct-seeded rice
222 .	2001	Fischer, AJ, HV Ramirez, KD Gibson, BD Pinheiro	Agronomy Journal	93:967-973	Competitiveness of semidwarf upland rice cultivars against palisadegrass (Brachiaria brizantha) and signalgrass (B-decumbens)
223 .	2001	Gibson, KD and AJ Fischer	INTERNATIONAL JOURNAL OF PEST MANAGEMENT	47:305-309	Relative growth and photosynthetic response of water-seeded rice and Echinochloa oryzoides (Ard.) Fritsch to shade
224 .	2001	Gibson, KD, JL Breen, JE Hill, BPCaton, TC Foin	Weed Science	49:381-384	California arrowhead is a weak competitor in water-seeded rice
225 .	2001	Tseng, ST, KS Mckenzie, CW Johnson, JI Oster, JE Hill, DM Brandon	Crop Science	41:2005	Registration of 'Calmati-201' rice
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227 .	2002	Bird, JA, AJ Eagle, WR Horwath, MW Hair, EE Zilbert and C van Kessel	California Agriculture	56:69-75	Long-term studies find benefits, challenges in alternative rice straw management
228 .	2002	Steven C. Scardaci, Michael C. Shannon, Stephen R. Grattan, Austine U. Eke, Stacey R. Roberts, S. Goldman-Smith, James E. Hill	California Agriculture	56:184-188	Water management practices can affect salinity in rice fields
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234 .	2003	Lawler, SP, DA Dritz, LD Godfrey	JOURNAL OF THE AMERICAN MOSQUITO CONTROL ASSOCIATION	19:430-432	Effects of the agricultural insecticide lambda-cyhalothrin (Warrior (TM)) on mosquitofish (Gambusia affinis)
235 .	2003	van Groenigen, JW, EG Burns, JM Eadie, WR Horwath, C van Kessel	Agriculture, Ecosystems and Environment	95:289-296	Effects of foraging waterfowl in winter flooded rice fields on weed stress and residue decomposition
236 .	2003	van Groenigen, JW, CS Mutters, WR Horwath, C van Kessel	Plant and Soil	250:155-165	NIR and DRIFT-MIR spectrometry of soils for predicting soil and crop parameters in a flooded field
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239 .	2003	Tsuji, R,AJ Fischer, M Yoshino, A Roel, JE Hill, Y Yamasue	Weed Science	51:740-747	Herbicide-resistant late watergrass (Echinochloa phyllopogon): similarity in morphological and amplified fragment length polymorphism traits
240 .	2003	Bakker, RR and BM Jenkins	BIOMASS & BIOENERGY	25:597-614	Feasibility of collecting naturally leached rice straw for thermal conversion
241 .	2003	Summers, MD BM Jenkins, PR Hyde, JF Williams, RG Mutters, SC Scardacci, MW Hair	BIOMASS & BIOENERGY	24:163-173	Biomass production and allocation in rice with implications for straw harvesting and utilization
242 .	2004	van Diepen, L.T.A., van Groenigen, J.W. and C. van Kessel	Agriculture, Ecosystems and Environment	102:41-47	Isotopic evidence for changes in residue decomposition and N-cycling in winter flooded rice fields by foraging waterfowl
243 .	2004	Fischer, AJ, DP Cheetham, F Vidotto, R De Prado	Weed Biology and Management	4:206-212	Enhanced effect of thiobencarb on bispyribac-sodium control of Echinochloa phyllopogon (Stapf) Koss. in California rice (Oryza sativa L.)
244 .	2004	Gibson, KD, AJ Fischer, TC Foin	Weed Science	52:271-280	Compensatory responses of late watergrass (Echinochloa phyllopogon) and rice to resource limitations
245 .	2004	Roel, A and R Plant	Agronomy Journal	96:1481-1494	Factors underlying yield variability in two California rice fields
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249 .	2005	Champagne, ET (Champagne, ET); Bett-Garber, KL (Bett-Garber, KL); Thompson, J (Thompson, J); Mutters, R (Mutters, R); Grimm, CC (Grimm, CC); McClung, AM (McClung, AM)	Cereal Chemistry	82:369-374	Effects of drain and harvest dates on rice sensory and physicochemical properties

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251 .	2005	Pan, Z (Pan, Z); Thompson, JF (Thompson, JF); Amaratunga, KSP (Amaratunga, KSP); Anderson, T (Anderson, T); Zheng, X (Zheng, X)	TRANSACTIONS OF THE ASABE	48:1865-1871	Effect of cooling methods and milling procedures on the appraisal of rice milling quality
252 .	2006	Thompson, JF (Thompson, JF); Mutters, RG (Mutters, RG)	TRANSACTIONS OF THE ASABE	49:435-440	Effect of weather and rice moisture at harvest on milling quality of California medium-grain rice
253 .	2006	Hill, J.E., J.F. Williams, R.G. Mutters, and C.A. Greer	Paddy and Water Environment	4:13-19	The California rice cropping system: agronomic and natural resource issues for long-term sustainability
254 .	2006	Linquist, B.A., S. M. Brouder and J.E. Hill	Agronomy Journal	98: 1050-1059	Winter straw and water management effects on soil nitrogen dynamics in California rice system
255 .	2006	Spencer, D., C. Lembi, and R. Blank	Journal of Freshwater Ecology	21:649-656	Spatial and temporal variation in the composition and biomass of algae present in selected California rice fields
256 .	2006	Ruiz-Santaella, JP, R De Prado, J Wagner, AJFischer, R Gerhards	Journal of Plant Diseases and Protection	20:95-100	Resistance mechanisms to cyhalofop-butyl in a biotype of Echinochloa phyllopogon (Stapf) Koss. from California
257 .	2006	Busi, R, F Vidotto, AJ Fischer, MD Osuna, R de Prado, A Ferrero	Weed Technology	20:1004-1014	Patterns of resistance to ALS herbicides in smallflower umbrella sedge (Cyperus difformis) and ricefield bulrush (Schoenoplectus mucronatus)
258 .	2006	McKenzie, KS, CW Johnson, F Jodari, JJ Oster, JE Hill, RG Mutters, CA Greer, WM Canevari, K Takami	Crop Science	46:2321-2322	Registration of 'Calamylow-201' rice
259 .	2007	Pan, Z (Pan, Z.); Amaratunga, KSP (Amaratunga, K. S. P.); Thompson, JE (Thompson, J. E.)	TRANSACTIONS OF THE ASABE	50:1307-1313	Relationship between rice sample milling conditions and milling quality
260 .	2007	McMillan, A.M.S., M.L. Goulden, S.C. Tyler	Journal of Geophysical Research	112: Issue G1	Stoichiometry of CH4 and CO2 flux in a California rice paddy
261 .	2008	Linquist, B.A., E. Byous, G. Jones, J.F. Williams, J. Six, W. Horwath and C. van Kessel	Journal of Plant Production Science	11:260-267	Nitrogen and potassium fertility and straw management effects on aggregate sheath spot disease and yields of rice
262 .	2008	Carter, LLA (Carter, L. L. A.)[1,2] ; Leslie, JF (Leslie, J. F.)[1] ; Webster, RK (Webster, R. K.)[2]	PHYTOPATHOLOGY	98:992-998	Population structure of Fusarium fujikuroi from California rice and water grass
263 .	2008	Linquist, B. A., A. Fischer, L. Godfrey, C. Greer, J. Hill, K. Koffler, M. Moeching, R. Mutters and C. van Kessel	California Agriculture	62:24-29	Minimum-till could benefit California rice farmers
264 .	2008	Pan, ZL, R Khir, LD Godfrey, R Lewis, JF Thompson, A Salim	Journal of Food Engineering	84:469-479	Feasibility of simultaneous rough rice drying and disinfestations by infrared radiation heating and rice milling quality
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266 .	2008	Yasuor, H, PL TenBrook,RS Tjeerdema, AJ Fischer	Pest Management Science	64:1031-1039	Responses to clomazone and 5-ketoclomazone by Echinochloa phyllopogon resistant to multiple herbicides in Californian rice fields
267 .	2009	Linquist B.A., J.E. Hill, R.G. Mutters, C.A. Greer, C. Hartley, M.D. Ruark and C. van Kessel	Agronomy Journal	101:906-915	Assessing the necessity of surface applied pre-plant nitrogen fertilizer in rice systems

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270 .	2009	Reddy, AP BM Jenkins, JS VanderGheynst	TRANSACTIONS OF THE ASABE	52:673-676	THE CRITICAL MOISTURE RANGE FOR RAPID MICROBIAL DECOMPOSITION OF RICE STRAW DURING STORAGE
271 .	2010	Chaijuckam, P (Chaijuckam, Patcharavipa)[1] ; Baek, JM (Baek, Jong-Min)[2,3] ; Greer, CA (Greer, Christopher A.)[4] ; Webster, RK (Webster, Robert K.)[1] ; Davis, RM (Davis, R. Michael)[1]	PHYTOPATHOLOGY	100:502-510	Population Structure of Rhizoctonia oryzae-sativae in California Rice Fields
272 .	2010	Ruark, M.D., B.A. Linquist, J. Six, C. van Kessel, C.A. Greer, R.G. Mutters and J.E. Hill	Journal of Environmental Quality	39:304-313	Seasonal losses of dissolved organic carbon and total dissolved solids from rice production systems in northern California
273 .	2010	Lundy, M., A. Fisher, C. van Kessel, J.E. Hill, M. Ruark and B.A. Linquist	Weed Technology	24:295-302	Surface-applied calcium phosphate stimulates weed emergence in flooded rice
274 .	2010	Merotto, A, M Jasieniuk, AJ Fischer	Weed Science	58:22-29	Distribution and Cross-Resistance Patterns of ALS-Inhibiting Herbicide Resistance in Smallflower Umbrella Sedge (Cyperus difformis)
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276 .	2010	Fischer, AJ, GL Strong, K Shackel, RG Mutters	Aquatic Botany	92:257-264	Temporary drought can selectively suppress Schoenoplectus mucronatus in rice
277 .	2010	Thy, P and BM Jenkins	WATER AIR AND SOIL POLLUTION	209:429-437	Mercury in Biomass Feedstock and Combustion Residuals
278 .	2010	Cheng, YS, Y Zheng, CW Yu, TM Dooley, BM Jenkins, JS VanderGheynst	APPLIED BIOCHEMISTRY AND BIOTECHNOLOGY	162:1768-1784	Evaluation of High Solids Alkaline Pretreatment of Rice Straw
279 .	2010	Hauselt, P and R Plant	PROFESSIONAL GEOGRAPHER	62:462-477	Spatial Modeling of Water Use in California Rice Production
280 .	2010	Cui, L (Cui, Lu)[1,2] ; Pan, ZL (Pan, Zhongli)[1,3] ; Yue, TL (Yue, Tanli)[1] ; Atungulu, GG (Atungulu, Griffiths G.)[1] ; Berrios, J (Berrios, Jose)[3]	Cereal Chemistry	87:403-408	Effect of Ultrasonic Treatment of Brown Rice at Different Temperatures on Cooking Properties and Quality
281 .	2011	Prakash, B (Prakash, Bhagwati)[2] ; Bingol, G (Bingol, Gokhan)[1] ; Pan, ZL (Pan, Zhongli)[1,2]	DRYING TECHNOLOGY	29:939-945	Moisture Diffusivity in Rice Components During Absorption and Desorption
282 .	2011	Khir, R (Khir, Ragab)[1,3] ; Pan, ZL (Pan, Zhongli)[1,2] ; Salim, A (Salim, Adel)[3] ; Hartsough, BR (Hartsough, Bruce R.)[1] ; Mohamed, S (Mohamed, Sherief)[3]	LWT-FOOD SCIENCE AND TECHNOLOGY	44:1126-1132	Moisture diffusivity of rough rice under infrared radiation drying
283 .	2011	Pan, Z (Pan, Z.)[1,2] ; Khir, R (Khir, R.)[2,3] ; Bett-Garber, KL (Bett-Garber, K. L.)[4] ; Champagne, ET (Champagne, E. T.)[4] ; Thompson, JF (Thompson, J. F.)[2] ; Salim, A (Salim, A.)[3] ; Hartsough, BR (Hartsough, B. R.)[2] ; Mohamed, S (Mohamed, S.)[3]	TRANSACTIONS OF THE ASABE	54:203-210	DRYING CHARACTERISTICS AND QUALITY OF ROUGH RICE UNDER INFRARED RADIATION HEATING

284 .	2011	Linquist, B.A., K. Koffler, J.E. Hill and C.van Kessel	California Agriculture	65:80-84	Rice field drainage affects nitrogen dynamics and management
285 .	2011	Linquist, B.A., M.D. Ruark and J.E. Hill	Nutrient Cycling in Agroecosystems	90:51-62	Soil order and management practices control soil phosphorus fractions in managed wetland ecosystems
286 .	2011	Linquist, B.A. and M.D. Ruark	Agronomy Journal	103:501-508	Re-evaluating diagnostic phosphorus tests for rice systems based on soil phosphorus fractions and field level budgets
287 .	2011	Wild, P., C. van Kessel, J. Lundberg and B.A. Linquist	Agronomy Journal	103:1284-1291	Nitrogen availability from poultry litter and pelletized organic amendments for organic rice production
288 .	2011	Krupa, M., R.G.M. Spencer, K.W. Tate, J. Six, C. van Kessel and B.A. Linquist	Biogeochemistry Journal	108:447-466	Controls on dissolved organic carbon composition and export from rice dominated systems
289 .	2011	Krupa, M., K.W. Tate, C. Kessel, N. Sarwar and B.A .Linquist	Agriculture, Ecosystems and Environment	144:290-301	Water quality in rice-growing watersheds in a Mediterranean climate
290 .	2011	Osuna, MD,M Okada, R Ahmad, AJ Fischer, M Jasieniuk	Weed Science	59:195-201	Genetic Diversity and Spread of Thiobencarb Resistant Early Watergrass (Echinochloa oryzoides) in California
291 .	2012	Espino, L.	Florida Entomologist	95: 445-453	Occurrence and abundance of Lissorhoptrus oryzophilus (Coleoptera: Curculionidae) relative to field borders in California rice
292 .	2012	Prakash, B (Prakash, Bhagwati)[1] ; Pan, ZL (Pan, Zhongli)[1,2]	DRYING TECHNOLOGY	30:801-807	Effect of Geometry of Rice Kernels on Drying Modeling Results
293 .	2012	Bingol, G (Bingol, Gokhan)[1] ; Prakash, B (Prakash, Bhagwati)[2] ; Pan, Z (Pan, Zhongli)[1,2]	LWT-FOOD SCIENCE AND TECHNOLOGY	48:156-163	Dynamic vapor sorption isotherms of medium grain rice varieties
294 .	2012	Pittelkow, C.M., A.J. Fischer, M.J. Moechnig, J.E. Hill, K.B. Koffler, R.G. Mutters, C.A. Greer, Y.S. Cho, C. van Kessel, C. and B.A. Linquist	Field Crops Research	130:128-137	Agronomic productivity and nitrogen requirements of alternative tillage and crop establishment systems for improved weed control in direct-seeded rice
295 .	2012	Lundy, M.E., D.F. Spencer, C. van Kessel, J.E. Hill and B.A. Linquist	Field Crops Research	131:81-87	Managing phosphorus fertilizer to reduce algae, maintain water quality, and sustain yields in water-seeded rice
296 .	2012	Yasuor, H, M Milan, JW Eckert, AJ Fischer	Pest Management Science	68:108-115	Quinclorac resistance: a concerted hormonal and enzymatic effort in Echinochloa phyllopogon
297 .	2012	Boddy, LG, JC Streibig, Y Yamasue,AJ Fischer	Weed Science	60:401-410	Biomass, Fecundity, and Interference Ability of Multiple Herbicide-Resistant and -Susceptible Late Watergrass (Echinochloa phyllopogon)
298 .	2012	Boddy, LG, KJ Bradford, AJ Fischer	Journal of applied Ecology	49:1225-1236	Population-based threshold models describe weed germination and emergence patterns across varying temperature, moisture and oxygen conditions
299 .	2013	Atungulu, GG (Atungulu, G. G.)[1] ; Prakash, B (Prakash, B.)[1] ; Wang, X (Wang, X.); Wang, T (Wang, T.); Fu, R (Fu, R.); Khir, R (Khir, R.)[1,2] ; Pan, Z (Pan, Z.)[1,3]	APPLIED ENGINEERING IN AGRICULTURE	29:253-261	DETERMINATION OF DOCKAGE FOR ACCURATE ROUGH RICE QUALITY ASSESSMENT
300 .	2013	Pan, ZL (Pan, Zhongli)[1,2] ; Khir, R (Khir, Ragab)[1,3] ; Thompson, JF (Thompson, James F.)[1]	Cereal Chemistry	90:107-113	Effect of Milling Temperature and Postmilling Cooling Procedures on Rice Milling Quality Appraisals

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302 .	2013	Simmonds, M.B., R.E. Plant, J.M. Peña-Barragán, C. van Kessel, J. Hill and B.A. Linquist	Precision Agriculture	14:512-540	Underlying causes of yield spatial variability and potential for precision management in rice systems
303 .	2013	Pittelkow, C.M., M.A. Adviento-Borbe, J.E. Hill, J. Six, C. van Kessel, B.A. Linquist	Agriculture, Ecosystems and Environment	177:10-20	Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input
304 .	2013	Adviento-Borbe, M.A., C.M. Pittelkow, M. Anders, C. van Kessel, J.E. Hill, A.M. McClung, J. Six, and B.A. Linquist	Journal of Environmental Quality	42:1623-1634	Optimal fertilizer N rates and yield-scaled global warming potential in drill seeded rice
305 .	2013	Boddy, LG, KJ Bradford, AJ Fischer	PlosOne	10.1371/journal.pone.0071457	Stratification Requirements for Seed Dormancy Alleviation in a Wetland Weed
306 .	2013	Thy, P, CW Yu, BM Jenkins, CE Lesher	ENERGY & FUELS	27:3969-3987	Inorganic Composition and Environmental Impact of Biomass Feedstock
307 .	2014	Espino, LA (Espino, Luis A.); Greer, CA (Greer, Chris A.); Mutters, RG (Mutters, Randall G.); Thompson, JF (Thompson, James F.)[1]	California Agriculture	68:38-46	Survey of rice storage facilities identifies research and education needs
308 .	2014	Lundy ,M. E., J.E. Hill, C. van Kessel, D. A. Owen, R. M. Pedroso, L. G. Boddy, A. J. Fischer, and B. A. Linquist	Agricultural Systems	123:12-21	Site-specific, real-time temperatures improve the accuracy of weed emergence predictions in a direct-seeded rice system
309 .	2014	Liang, X.Q., T. Harter, L. Porta, C. van Kessel, and B.A. Linquist	Journal of Environmental Quality	43:881-894	Nitrate leaching in Californian rice fields: a field and regional scale assessment
310 .	2014	Linquist, B.A., M. Ruark, R. Mutters, C. Greer, and J. Hill	Journal of Environmental Quality	43:1725-1735	Nutrients and sediments in surface runoff water from rice fields: Implications for nutrient budgets and water quality
311 .	2014	Spencer, D. and B.A. Linquist	Paddy and Water Environment	12:147-154	Reducing rice field algae and cyanobacteria by altering phosphorus fertilizer applications
312 .	2014	Pittelkow, C.M., Y. Assa, M. Burger, W.R. Horwath, R.G. Mutters, C.A. Greer, L.A. Espino, J.E. Hill, C. van Kessel, B.A. Linquist	Agronomy Journal	106:968-980	Nitrogen management and methane emissions in direct-seeded rice systems
313 .	2014	Brodt, S., A. Kendall, Y. Mohammadi, A. Arslan, J.Yuan, I. Lee, B. Linquist	Field Crops Research	169:89-98	Life cycle greenhouse gas emissions in California rice production
314 .	2014	Hanson, BD, S Wright, LM Sosnoskie, AJ Fischer, M Jasieniuk, JA Roncoroni, KJ Hembree, S Orloff, A Shrestha, K Al-Khatib	California Agriculture	68:142-152	Herbicide-resistant weeds challenge some signature cropping systems
315 .	2014	Valverde, BE, LG Boddy, RM Pedroso, JW Eckert, AJ Fischer	Crop Protection	62:16-22	Cyperus difformis evolves resistance to propanil
316 .	2014	Yu, C, P Thy, L Wang, SN Anderson, JS VanderGheynst, SK Upadhyaya, BM Jenkins	FUEL PROCESSING TECHNOLOGY	128:43-53	Influence of leaching pretreatment on fuel properties of biomass
317 .	2014	Khir, R (Khir, Ragab)[1,3] ; Pan, ZL (Pan, Zhongli)[1,2] ; Thompson, JF (Thompson, James F.)[1] ; El-Sayed, AS (El-Sayed, Adel S.)[3] ; Hartsough, BR (Hartsough, Bruce R.)[1] ; El-Amir, MS (El-Amir, Mohamed S.)[3]	JOURNAL OF FOOD PROCESSING AND PRESERVATION	38:430-440	MOISTURE REMOVAL CHARACTERISTICS OF THIN LAYER ROUGH RICE UNDER SEQUENCED INFRARED RADIATION HEATING AND COOLING
318 .	2014	Wang, B (Wang, Bei)[1,2] ; Khir, R (Khir, Ragab)[2,3] ; Pan, ZL (Pan, Zhongli)[2,4] ; El-Mashad, H (El-Mashad, Hamed)[2] ; Atungulu, GG (Atungulu, Griffiths G.)[2] ; Ma, HL (Ma, Haile)[1] ; McHugh, TH (McHugh, Tara H.)[4] ; Qu, WJ (Qu, Wenjuan)[1] ; Wu, BG (Wu, Bengang)[1]	JOURNAL OF FOOD PROTECTION	77:1538-1545	Effective Disinfection of Rough Rice Using Infrared Radiation Heating

319 .	2014	Windham-Myers, L (Windham-Myers, Lisamarie)[1] ; Fleck, JA (Fleck, Jacob A.)[2] ; Ackerman, JT (Ackerman, Joshua T.)[3] ; Marvin-DiPasquale, M (Marvin-DiPasquale, Mark)[1] ; Stricker, CA (Stricker, Craig A.)[4] ; Heim, WA (Heim, Wesley A.)[5] ; Bachand, PAM (Bachand, Philip A. M.)[6] ; Eagles-Smith, CA (Eagles-Smith, Collin A.)[7] ; Gill, G (Gill, Gary)[8] ; Stephenson, M (Stephenson, Mark)[5] ; Alpers, CN (Alpers, Charles N.)	Science of the Total Environment	484:221-231	Mercury cycling in agricultural and managed wetlands: A synthesis of methylmercury production, hydrologic export, and bioaccumulation from an integrated field study
320 .	2014	Marvin-DiPasquale, M (Marvin-DiPasquale, Mark)[1] ; Windham-Myers, L (Windham-Myers, Lisamarie)[1] ; Agee, JL (Agee, Jennifer L.)[1] ; Kakouros, E (Kakouros, Evangelos)[1] ; Kieu, LH (Kieu, Le H.)[1] ; Fleck, JA (Fleck, Jacob A.)[2] ; Alpers, CN (Alpers, Charles N.)[2] ; Stricker, CA (Stricker, Craig A.)[3]	Science of the Total Environment	484:289-299	Methylmercury production in sediment from agricultural and non-agricultural wetlands in the Yolo Bypass, California, USA
321 .	2014	Windham-Myers, L (Windham-Myers, Lisamarie)[1] ; Marvin-DiPasquale, M (Marvin-DiPasquale, Mark)[1] ; Stricker, CA (Stricker, Craig A.)[2] ; Agee, JL (Agee, Jennifer L.)[1] ; Kieu, LH (Kieu, Le H.)[1] ; Kakouros, E (Kakouros, Evangelos)[1	Science of the Total Environment	484:300-307	Mercury cycling in agricultural and managed wetlands of California, USA: Experimental evidence of vegetation-driven changes in sediment biogeochemistry and methylmercury production
322 .	2014	Windham-Myers, L (Windham-Myers, Lisamarie)[1] ; Marvin-DiPasquale, M (Marvin-DiPasquale, Mark)[1] ; Kakouros, E (Kakouros, Evangelos)[1] ; Agee, JL (Agee, Jennifer L.)[1] ; Kieu, LH (Kieu, Le H.)[1] ; Stricker, CA (Stricker, Craig A.)[2] ; Fleck, JA (Fleck, Jacob A.)[3] ; Ackerman, JT (Ackerman, Josh T.)[4	Science of the Total Environment	484:308-318	Mercury cycling in agricultural and managed wetlands of California, USA: Seasonal influences of vegetation on mercury methylation, storage, and transport
323 .	2014	Bachand, PAM (Bachand, P. A. M.)[1] ; Bachand, SM (Bachand, S. M.)[1] ; Fleck, JA (Fleck, J. A.)[2] ; Alpers, CN (Alpers, C. N.)[2] ; Stephenson, M (Stephenson, M.)[3] ; Windham-Myers, L (Windham-Myers, L.)[4	Science of the Total Environment	472:957-970	Methylmercury production in and export from agricultural wetlands in California, USA: The need to account for physical transport processes into and out of the root zone
324 .	2015	Aghaee, MA and LD Godfrey	JOURNAL OF ECONOMIC ENTOMOLOGY	108:45-52	The Efficacy of Bacillus thuringiensis spp. galleriae Against Rice Water Weevil (Coleoptera: Curculionidae) for Integrated Pest Management in California Rice
325 .	2015	Simmonds, M.B., M. Anders, M.A. Adviento-Borbe, C. van Kessel, A. McClung, and B.A. Linquist	Journal of Environmental Quality	44:103-114	Seasonal methane and nitrous oxide emissions of several rice cultivars in direct seeded rice systems
326 .	2015	Espe, M.B., E. Kirk, C. van Kessel, W.H. Horwath, and B.A. Linquist	Soil Science Society of America Journal	79:569-576	Indigenous nitrogen supply of rice is predicted by soil organic carbon
327 .	2015	Kirk, E.R., C. van Kessel, W.R. Horwath, B.A. Linquist	PLoS One	10(3): e0121432. doi:10.1371/journal.pone.0121432	Estimating annual soil carbon loss in agricultural peatland soils using a nitrogen budget approach
328 .	2015	Adviento Borbe, M.A., G.N. Padilla, C. Pittelkow, M. Simmonds, C. van Kessel, and B. Linquist	Journal of Environmental Quality		Methane and nitrous oxide emissions from flooded rice systems following the final drain
329 .	2015	Ding, C (Ding, Chao)[2,1] ; Khir, R (Khir, Ragab)[3,2] ; Pan, ZL (Pan, Zhongli)[4,2] ; Zhao, LM (Zhao, Liming)[5] ; Tu, K (Tu, Kang)[1] ; El-Mashad, H (El-Mashad, Hamed)[6,2] ; McHugh, TH (McHugh, Tara H.)[4]	FOOD AND BIOPROCESS TECHNOLOGY	8:1149-1159	Improvement in Shelf Life of Rough and Brown Rice Using Infrared Radiation Heating
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331 .	2003	Yang, W., C. C. Jia, T. J. Siebenmorgen, Z. Pan, and A. G. Conossen	Biosystems Engineering	85(4): 467-476	Relationship of kernel moisture content gradients and glass transition temperatures to head rice yield
332 .	2005	Pan, Z., J. F. Thompson, K. S. P. Amaratunga, T. Anderson, and X. Zheng.	TRANSACTIONS OF THE ASABE	48:1865-1871	Effect of cooling methods and milling procedures on the appraisal of rice milling quality
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334 .	2005	Zheng, X., Z. Pan, and K. S. P. Amaratunga	Journal of Northeast Agricultural University	12(2):130-136	Effect of drying methods on moisture distribution of paddy rice
335 .	2006	Pan, Z., A. Cathcart, and D. Wang	Industrial Crops and Products	23(1):40-45	Properties of particleboard bond with rice bran and polymeric methylene diphenyl diisocyanate adhesives
336 .	2007	Lagunas-Solar, M. C., Z. Pan, N. X. Zeng, T. D. Truong, R. Khir, and K. S. P. Amaratunga	Applied Engineering in Agriculture	23(5):747-654	Application of radiofrequency power for non-chemical disinfestation of rough rice with full retention of quality attributes
337 .	2007	Pan, Z. K. S. P. Amaratunga, and J. F. Thompson.	TRANSACTIONS OF THE ASABE	50:1307-1313	Relationship between rice sample milling conditions and milling quality
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339 .	2010	Cui, L., Z. Pan, T. Yue, G. G. Atungulu, and J. Berrios	Cereal Chemistry	87:403-408	Effect of Ultrasonic Treatment of Brown Rice at Different Temperatures on Cooking Properties and Quality
340 .	2011	Prakash, B., G. Bingol, and Z. Pan	DRYING TECHNOLOGY	29:939-945	Moisture Diffusivity in Rice Components During Absorption and Desorption
341 .	2011	Khir, R., Z. Pan, A. Salim, B.R. Hartsough, and S. Mohamed	LWT-FOOD SCIENCE AND TECHNOLOGY	44:1126-1132	Moisture diffusivity of rough rice under infrared radiation drying
342 .	2011	Pan, Z., R. Khir, K.L. Bett-Garber, E.T. Champagne, J.F. Thompson, A. Salim, B.R. Hartsough, and S. Mohamed	TRANSACTIONS OF THE ASABE	54:203-210	DRYING CHARACTERISTICS AND QUALITY OF ROUGH RICE UNDER INFRARED RADIATION HEATING
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344 .	2011	Avaro, M.R.A, Z. Pan, Y. Wada, and T. Yoshida	Plant Production Science	14(2):164-168	Two alternative methods to predict amylose content in rice grain by using tristimulus CIELAB values and developing a specific color board of starch iodine complex solution
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351 .	2013	Khir, R., Z. Pan, and J.F. Thompson	TRANSACTIONS OF THE ASABE	56:1051-1060	INFLUENCE OF RICE SAMPLE PREPARATION AND MILLING PROCEDURES ON MILLING QUALITY APPRAISALS
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354 .	2014	Wang, B., R. Khir, Z. Pan, H. El-Mashad, G.G. Atungulu, H. Ma, T.H. McHugh, W. Qu, and B. Wu	JOURNAL OF FOOD PROTECTION	77:1538-1545	Effective Disinfection of Rough Rice Using Infrared Radiation Heating
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361 .	2016	Adviento-Borbe, M.A. and B.A. Linquist	Geoderma	266:40-45	Assessing fertilizer N placement strategies for lower CH4 and N2O emissions in irrigated rice systems.
362 .	2016	Espe, M. H. Yang, K.G. Cassman, N. Guilpart, H. Sharifi, and B.A. Linquist	Field Crops Research	193:123-132	Estimating yield potential in temperate high-yielding, direct-seeded rice US rice production systems.

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365 .	2016	Wang, B., N.E. Mahoney, Z. Pan, R. Khir, B. Wu, and H. Ma. 2016	Food Control	59:461-467	Effectiveness of pulsed light treatment for degradation and detoxification of aflatoxin B1 and B2 in rough rice and rice bran
366 .	2016	Ding, C., R. Khir, Z. Pan, D.F. Wood, K. Tu, H. El-Mashad and J. Berrios.	Food and Bioprocess Technology: An International Journal	9:1010-1020	Improvement in storage stability of infrared dried rough rice
367 .	2016	Wang, B., R. Khir, Z. Pan, H. El-Mashad, D. Wood, N.E. Mahoney, B. Wu, and H. Ma	Journal of the Science of Food and Agriculture	96:2874-2881	Simultaneous drying and decontamination of rough rice using combined pulsed light and holding treatment
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372 .	2017	Brim-Deforest, W.B., K. Al-Khatib, B.A. Linquist, and A.J. Fisher	Weed Science	65:177-188	Weed community dynamics and system productivity in alternative irrigation systems in California rice.
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375 .	2017	Khir, R., G. G. Atungulu, C. Ding, and Z. Pan	Applied Engineering in Agriculture. International Journal of Agricultural Biological Engineering	4:216-223	Influence of harvester and weather conditions on filed loss and milling quality of rough rice.
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379 .	2018	Espe, M.B., D. MacKill, J.E. Hill, M. Lienfelder-Miles, L. Espino, R. Mutters, C. van Kessel, B.A. Linquist	Field Crops Research	222:59-65	Rice yield improvements through plant breeding are offset by inherent yield declines over time.
380 .	2018	Carrijo, D., P. Green, A. Gaudin, N. Akbar, A. Borja Reis, C. Li, S. Parikh, B. Linquist	Field Crops Research	222:101-110	Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics.
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384 .	2018	Sharifi, H., R.J. Hijmans, J.E. Hill, B. Linquist	Paddy, Water and Environment	16:467-476	Water and air temperature impacts on rice (Oryza sativa) phenology
385 .	2019	Carrijo, D.R., C. Li, S.J. Parikh, and B.A. Linquist	Science of the Total Environment	649:300-307	Irrigation management for arsenic mitigation in rice grain: Timing and severity of soil drying
386 .	2019	Li, Chongyang, D. Carrijo, Y. Nakayama, B.A. Linquist, P.G. Green, and S.J. Parikh.	Agriculture, Ecosystems and Environment	272:188-198	Impact of alternate wetting and drying irrigation on arsenic uptake and speciation in flooded rice systems
387 .	2019	LaHue, G.T. and B.A. Linquist	Journal of Hydrology	574:202-210	The magnitude and variability of lateral seepage in California rice fields
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390 .	2020	Pedroso, R.M., C. van Kessel, D.D. Neto, B.A. Linquist, L.G. Boddy, R.V. Filho, and A.J. Fisher	Weed Science	68:51-62	ALS Inhibitor-Resistant Cyperus difformis seed germination requires fewer growing degree-days and lower soil moisture
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396 .	2022	Perry, H., D. Carrijo, and B.A. Linquist	Field Crops Research	doi.org/10.1016/j.fcr.2021.108312.	Single midseason drainage events decrease global warming potential without sacrificing grain yield in flooded rice systems.
397 .	2022	Linquist, B.A., J. Campbell, and R.J. Southard	Nutrient Cycling in Agroecosystems	122:255-271. doi.org/10.1007/s10705-022-10200-w	Assessment of potassium availability and soil balances in high yielding rice systems.
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