REPORT RM-4

# ANNUAL REPORT
# COMPREHENSIVE RESEARCH ON RICE
January 1, 2002 - December 31, 2002

PROJECT TITLE: Does long-term rice straw incorporation impair maximum yield potential through non-nitrogen limiting factors compared to burning?

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LEVEL OF 2002 FUNDING: $ 45,144

## SUMMARY OF 2002 RESEARCH RESULTS BY OBJECTIVE

**Specific Objectives:**

1. **To determine changes in rice fertility after 8 years of alternative residue management.**

2. **To determine extent of root pathogens in non-burned rice fields.**

3. **Produce a comprehensive fertility management document based on field observations after 8 years of alternative residue management.**

Summary of 2002 research results:

### Introduction

Over the past 8 years, the impact of various straw management practices on nutrient cycling, in particular N and K, has been followed under controlled experimental conditions. We continued to examine the impact of rice straw management on soil fertility and the expression of soil pathogens. Finally we began work on a comprehensive soil fertility guide for rice based on the results of long-term field plots and individual grower fields funded in part by the Rice Research Board. As part of the 2002 RM-4 objectives, a shorten version of the rice fertility guide was published in California Agriculture. The publication is entitled:

Jeffrey A. Bird, Alison J. Eagle, William R. Horwath, Mike W. Hair, Eric E. Zilbert and Chris van Kessel. 2002. **Long-term studies find benefits, challenges in alternative rice straw management**. California Agriculture 56:69-75.

The publication can be downloaded from:

http://danr.ucop.edu/calag/0202MA/toc.html

and can be found in Appendix A.

Over the six years of RM-4 project, over one million dollars in research money was obtained from various sources including the California Energy Commission, Ducks Unlimited, Sustainable Agricultural Research and Education Program, Rice Foundation and California Department of Food and Agriculture Fertilizer Research and Education Program. The Rice Research Board contributed about 20% to the effort of straw impacts on soil fertility. Numerous publications have resulted from this research. This research has also been recognized nationally and internationally. The Soil Science Society of America 2002 Emil Truog Award for the best soil science Ph.D. dissertation was awarded to Jeff Bird for his work on RM-4.

In 2002, the validity of the results obtained under experimental conditions was verified in farmer's fields. Though the general trend of increased N availability under straw incorporation and winter flooding was generally observed, grower management practices for rice straw compared to the controlled studies done on the Dennis's Ranch, Mathews Ranch and the Rice Experimentation Station are considerably different. The difference lies not in the management itself, rather in the implementation of the management approaches. In our cursory survey of practices, growers generally change straw management practices reflecting the impact of weather and other factors. The consequence of this flexible management approach is that a direct comparison to the long-term rice straw management plots is not clear-cut, however the long-term studies provided us on information on the direction of alternative straw management techniques. This is invaluable information required to evaluate mixed management approaches practiced by growers. As mentioned last year, we feel the N story is complete, however the interaction of N fertilization with other fertilizer sources, such as phosphorus and other macro and micronutrients have not been studied. These interactions may help explain some of the non-N limiting response seen in rice yields from our previous reports.

We continued work on the soil pathogen that was shown to slow the growth of rice through impacting root growth negatively. Some pathogens killed rice seedlings outright. These pathogens are common in monoculture systems, such as rice in the northern Sacramento Valley. These hidden pathogens will most likely only be controlled through changes in management that change the monoculture aspects of rice production in the valley.

**OBJECTIVE 1. To determine changes in rice fertility after 8 years of alternative residue management.**

**Changes in soil carbon and nitrogen under alternative straw management**

Soil carbon was highest in the straw incorporated plots, followed by the rolled, non-flooded plots, but none of the numbers was significantly different (Fig. 1). A similar trend was seen in soil nitrogen, with the rolled, non-flooded plots having the highest amount, followed by the incorporated plots. Again, however, none of the differences in total nitrogen were statically significant.

The results indicate that rice system respond slowly to changes in soil carbon and nitrogen. However, these results are from Maxwell a site with a heavy clay soil. Other sites and soils may respond differently. The small increase in soil carbon has positively affected rice yield as discussed in the Soil Fertility section.

The data does indicate that alternative straw management practices have the potential to increase soil carbon. It is not unusual to take more than 5 and up to 10 years to see differences in soil carbon as a result in changes in crop residue management. These data will be useful to demonstrate that rice systems in California have the potential to sequester soil carbon. The data are a first step in establishing a system of carbon offset payments to growers who demonstrate sustainable

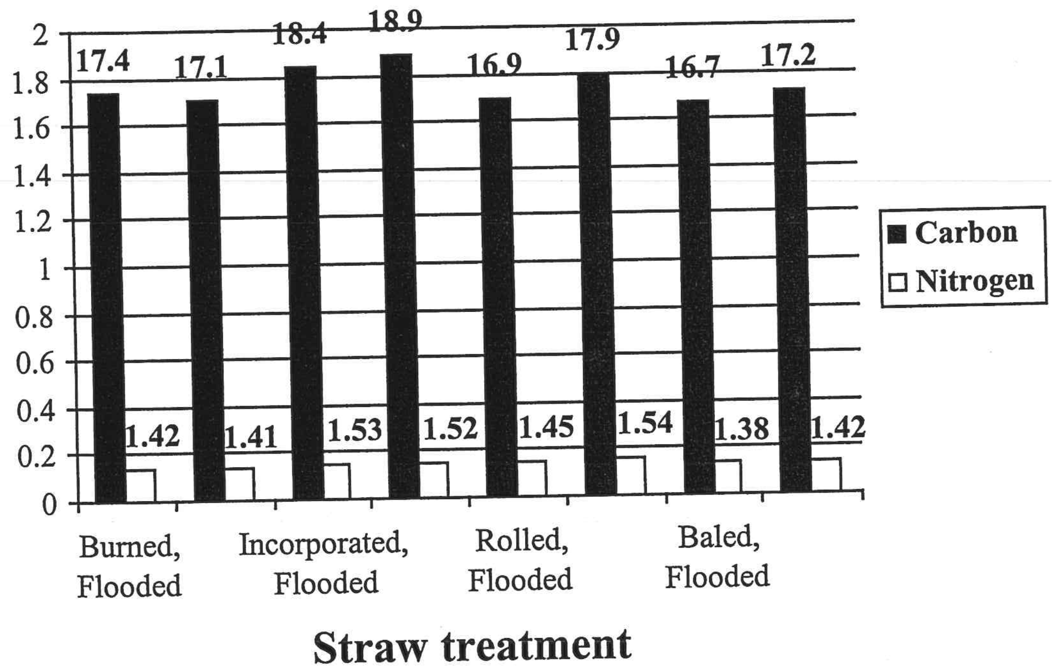


Figure 1. Soil C and N at the Maxwell site following 8 years of open field burning and alternative straw management including the comparison of winter flooding and no winter flooding.

**Soil Fertility**

Over the past 10 years, in-field residue incorporation has transitioned from a burning "alternative" to the primary means of residue management. As a result, the amount of organic matter in the soil has increased and nutrient availability has been altered. From long-term experiments, it is clear that available soil N is increased after 3 years of residue incorporation and winter flooding; however, the impact on soil fertility in growers' fields, where management options are frequently rotated to reduce pest and weed pressure, is uncertain. Likewise, the impact of straw management on the availability of P, K and other nutrients under grower managed conditions needs to be more thoroughly evaluated.

**Summary of Maxwell yield data**

In 2001, the last year of the project, the results of 3 previous N rate trials was validated (Fig. 2). The main conclusion from these data is that after 5 years of straw incorporation and winter flooding, fertilizer N application rates could be reduced to 90 lbs. per acre. This value is for heavy clay soils and would need to be adjusted for different soil types. The reduction in fertilizer N application is necessary to avoid problems with pests such as weeds and disease.

In addition to the N rate trial, a 0 lb N trial was continued to determine changes in soil fertility following straw management. In the 0 N plots, the incorporated, flooded treatment had significantly higher yields than any of the other treatments (Fig. 3). Non-winter flooded plots, regardless of management had the lowest yield. The baled, non-flooded treatment had significantly lower yields than the rolled, flooded and burned, non-flooded treatments. This was after eight years of continuous treatments. The 0 N plot treatments exemplify the value of increased soil carbon. Yields in the straw incorporated/winter flooded plots approach 75% of yields in fully fertilized plots. Growers considering organic rice production should consider yearly adoption of straw incorporation and winter flooding management to maintain rice yield.

The whole plots were fertilized in 2001 at the rate of 127 lb N/acre, less than in previous years to account for increased N availability in the straw incorporated plots. The yields were significantly higher than in the winter-flooded plots except for the burn plot (Fig. 4). Winter flooding burned plots reduced yield compared to burning and not winter flooding. Straw incorporation in combination with winter flooding appears to increase available nitrogen and was significantly the best treatment. The straw incorporated/winter flooded plots consistently produced the highest yield of all treatments following the third year of the implementation of the alternative straw management treatments. Depending on soil type, growers practicing yearly straw incorporation and winter flooding should reduce fertilizer N input to reduce problems with weeds and disease.

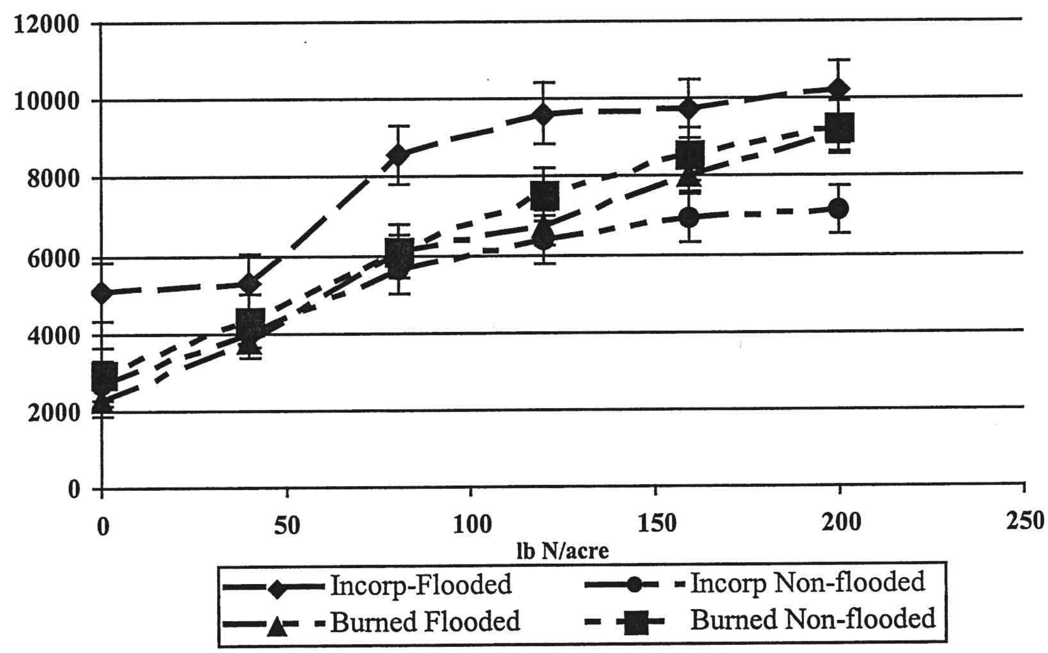


Figure 2. Results of the 2001 N rate trial (lb/ac N) confirming the positive benefits of greater than five years of straw incorporation and winter flooding.

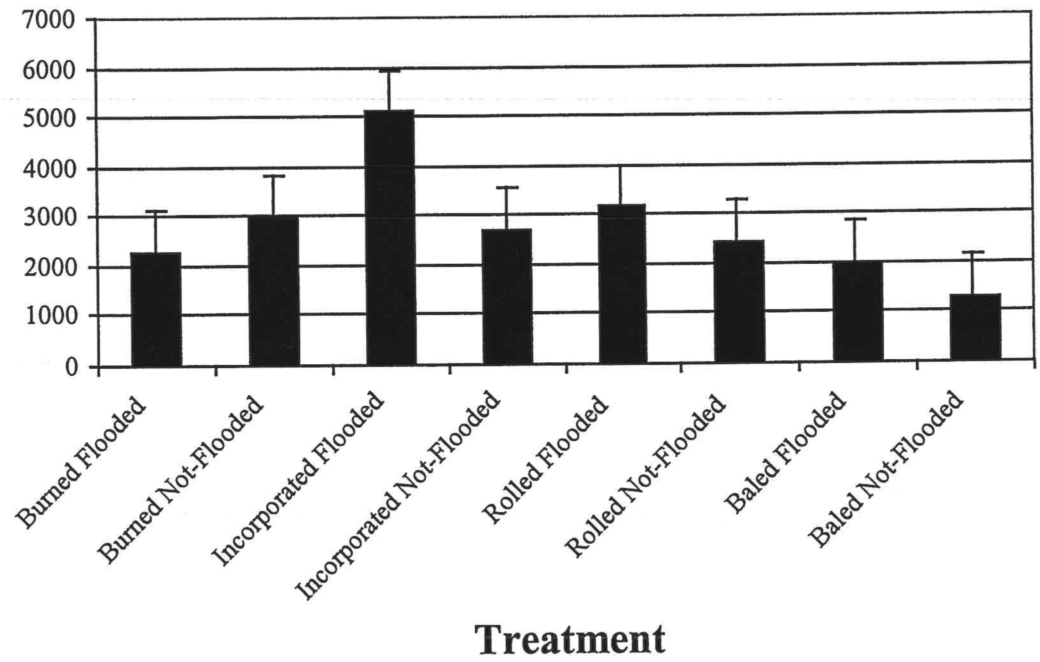


Figure 3. Yields in various straw management and winter flooding treatments with no N fertilizer addition.

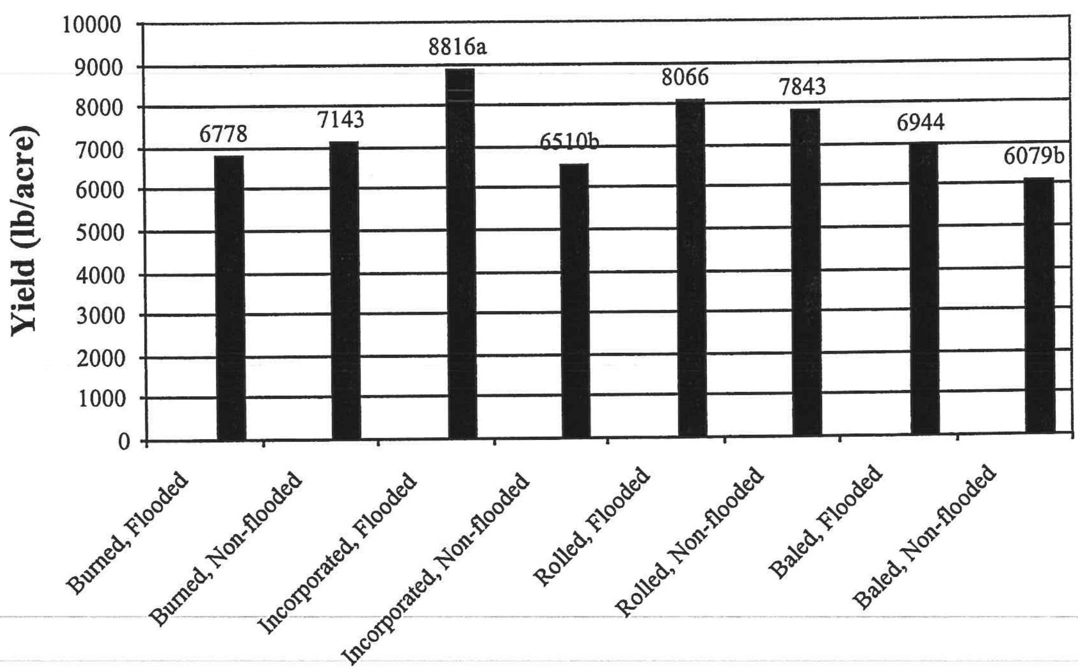


Figure 4. Whole plot yields of all straw treatments from final year of the Maxwell experiment.

## Impact of Straw Management on Fertility in Growers' Fields

In 2002, we followed soil nutrient status, plant nutrient uptake, and yield in 10 fields under grower management in Butte and Colusa counties. The sites include a range of soil types and management practices, and have been examined for macronutrients N, P, K, Ca, and Mg, and micronutrients Na, Fe, B, Zn and Mo (Table 1). The results from the soil micronutrients and plant analysis have not come back from the DANR Analytical Lab and will be reported on later. The yield data were supplied by growers and are recorded relative to other fields in the area, allowing us to normalize yields across years and environmental constraints.

Although the data set is relatively small, there are some interesting observations. First, yield is positively correlated with winter flooding (P=0.02) as was predicted by the long-term results collected at the Dennis ranch and the Rice Experimental Farm at Biggs, it also provides a partial explanation for the dramatic increase in winter flooding that has been observed in recent years. Second, Na availability is negatively correlated with winter flooding (P=0.03), and may offer a partial explanation for some of the yield differences between flooded and non-flooded fields. Third, though not significant, cation exchange capacity (CEC) is increased with straw incorporation (P=0.08), suggesting that residue incorporation increases the soils ability to retain nutrients. The CEC of soil is the ability of soil to retain nutrients. The higher the CEC the more nutrients a sold can hold and make available for plant uptake. The soil CEC is related to soil carbon and will increase as soil carbon increases.

Table 1. Macronutrient and yield data from ten grower fields.

| Straw Treatment | Winter Flooding | County | Ca | K | Mg | Na | P | CEC | Ca/Mg | N | C | Relative Yield |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Available (ppm in soil) | | | | | meq/100g | | g/kg soil | | |
| Incorp | Flood | Butte | 4609 | 165 | 484 | 36 | 44 | 13.8 | 9.5 | 1.7 | 17.6 | 1.04 |
| Incorp | NonFlood | Butte | 3530 | 146 | 391 | 26 | 36 | 10.7 | 9.0 | 1.4 | 19.3 | 1.04 |
| Fallow | NonFlood | Butte | 4893 | 179 | 817 | 33 | 34 | 15.9 | 6.0 | 1.9 | 21.4 | 1.06 |
| Burned | Flood | Butte | 4146 | 130 | 637 | 28 | 39 | 13.2 | 6.5 | 1.5 | 17.3 | 1.04 |
| Incorp | Flood | Butte | 3847 | 152 | 1306 | 81 | 8 | 15.3 | 2.9 | 1.3 | 16.6 | 0.98 |
| Incorp | Flood | Butte | 5427 | 237 | 948 | 63 | 36 | 17.9 | 5.7 | 1.9 | 22.7 | 1.01 |
| Incorp | Flood | Butte | 4296 | 206 | 1484 | 114 | 27 | 17.3 | 2.9 | 1.6 | 20.1 | - |
| Baled | NonFlood | Colusa | 2939 | 147 | 898 | 232 | 17 | 11.7 | 3.3 | 2.0 | 24.2 | 0.96 |
| Baled | Flood | Colusa | 2730 | 145 | 790 | 116 | 18 | 10.5 | 3.5 | 1.7 | 20.0 | 1.07 |
| Baled | NonFlood | Colusa | 2807 | 94 | 1409 | 231 | 3 | 13.4 | 2.0 | 1.6 | 19.7 | 0.91 |

In the 2003 and 2004 seasons, we hope to expand the research to include 50 sites located throughout the Sacramento Valley.

## Liming Trials

Grower interest in liming and its potential to improve the rice production environment has increased with the wide spread adoption of in-field straw management. When rice straw is incorporated, Ca is retained in organic forms that are less readily available than CaO contained in the ash of burned fields, suggesting that changes in straw management decreased the amount of Ca available to subsequent rice crops and altered the timing of calcium availability. There have been numerous anecdotal reports that liming fields may increase yields, improve soil tilth and bring about changes in weed pressure. However, there is little scientific evidence to support the claims, and a great deal of skepticism whether it is economically viable.

In 2002, we initiated liming trials at two grower-managed sites in the Sacramento Valley. The trials were designed to run for 3 years, and incorporated extensive pre-application sampling and multiple liming rates applied at different points in time to reflect current grower practices. Parameters to be evaluated include:

- Mid-season growth (plant height, color, vigor and 20 leaf weight)
- Grain and Straw Yield
- Fertilizer Use Efficiency
- Weed and Disease incidence
- Grain Quality (head rice yield, grain size)
- Soil Nutrient Status
- Tilth
- Straw Decomposition
- Production Cost

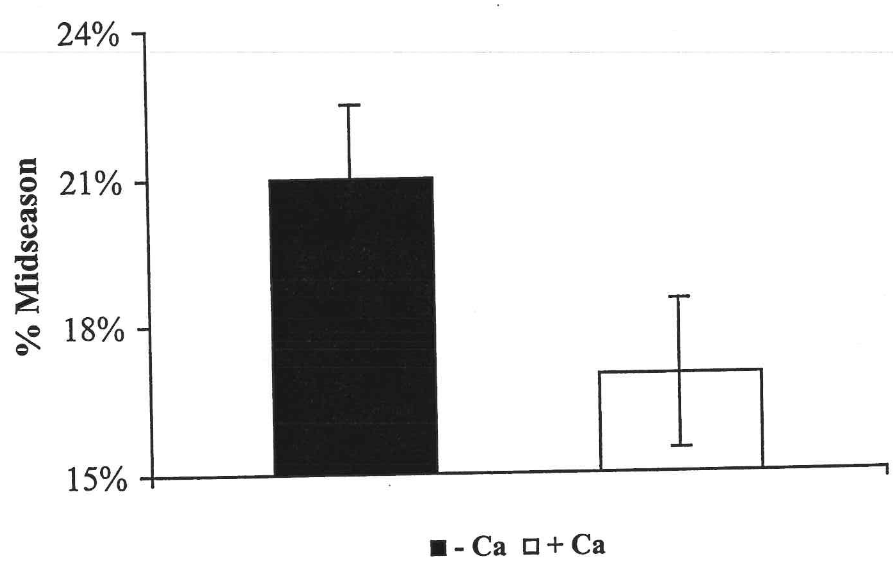


Figure 5. Incidence of rice field bullrush with and without calcium fertilization.

Preliminary results indicate that liming reduces N fertilizer use efficiency and can have a significant impact on weeds (Fig. 5); however, under standard fertilizer and weed management there was no appreciable effect on either straw or grain yield. We are currently evaluating head rice yields, and preparing to measure soil tilth in the spring. The trials will continue through 2004, at which time we will be able to provide a complete evaluation of the impact of liming on production and the cost efficiency of lime use.

**Objective 2.** To determine extent of root pathogens in non-burned rice fields.

Agronomic systems that rely on long-term monoculture practices often exhibit yield decline. Nutrient availability can rarely be attributed to these yield declines. No clear mechanisms of yield decline have been elucidated, but the incidence of weeds and pests are often implicated. The incorporation of residue acts as a means or habitat for disease vectors. For example, wheat declines in the eastern Washington have been attributed to deleterious bacteria that impair root growth. Declines in ryegrass yield in the Willamette Valley of Oregon have also been attributed to these bacteria. The incidence of these pathogens is often related to mono-cropping, a characteristic of rice cropping systems in the northern Sacramento Valley. As a class of organisms these root pathogens are called deleterious rhizobacteria.

In 2001, several rice and weed plants were taken from the Maxwell site and the root bacteria from them were isolated using *Pseudomonas* isolation agar. We reported last year that the isolated bacteria showed strong pathogenicity to rice in laboratory assays. A greenhouse experiment was performed this summer, looking at the effect of certain pathogens in soil on the growth of rice and watergrass, a weed. The soil used was a mix of sand and silty clay loam from an incorporated plot in the Maxwell research site. The plants were inoculated with one of pathogenic and nonpathogenic isolates. A group of soils were left un-inoculated as a control group. The plants were harvested, cleaned of soil, dried, and the above- and below-ground parts of the plant were weighed separately. Though the pathogenicity of these organisms was clearly demonstrated in the laboratory, their efficacy in the greenhouse trails was not evident (Fig.6, 7).

There is no significant difference between any of the treatments for root or shoot weight, for rice or watergrass plants with the bacterial isolates. The negative results of these experiments are not conclusive. There are many reasons for these results including not understanding the conditions where these organisms express pathogenicity. A much larger effort to identify soil and climate conditions would be needed to assess the pathogenetic ability of these organisms. These factors include considering the years in monoculture crop production, years of straw incorporation, years of winter-flooding etc. A study accounting for these variables and differences in soils is beyond the scope of this objective.

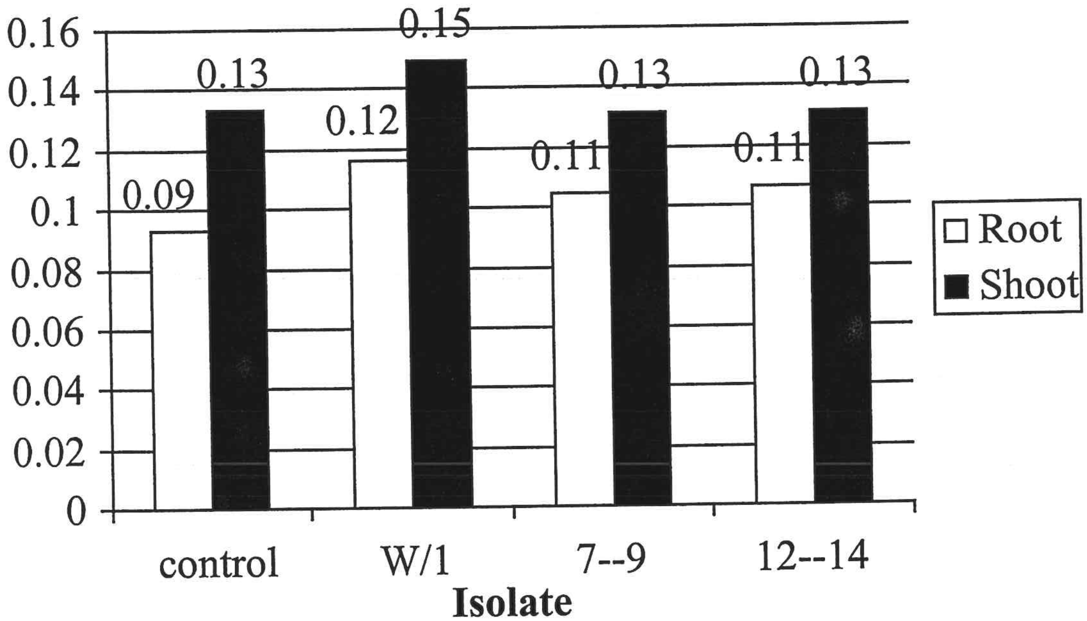


Figure 6. Root and shoot weight of the control and inoculated rice plants.

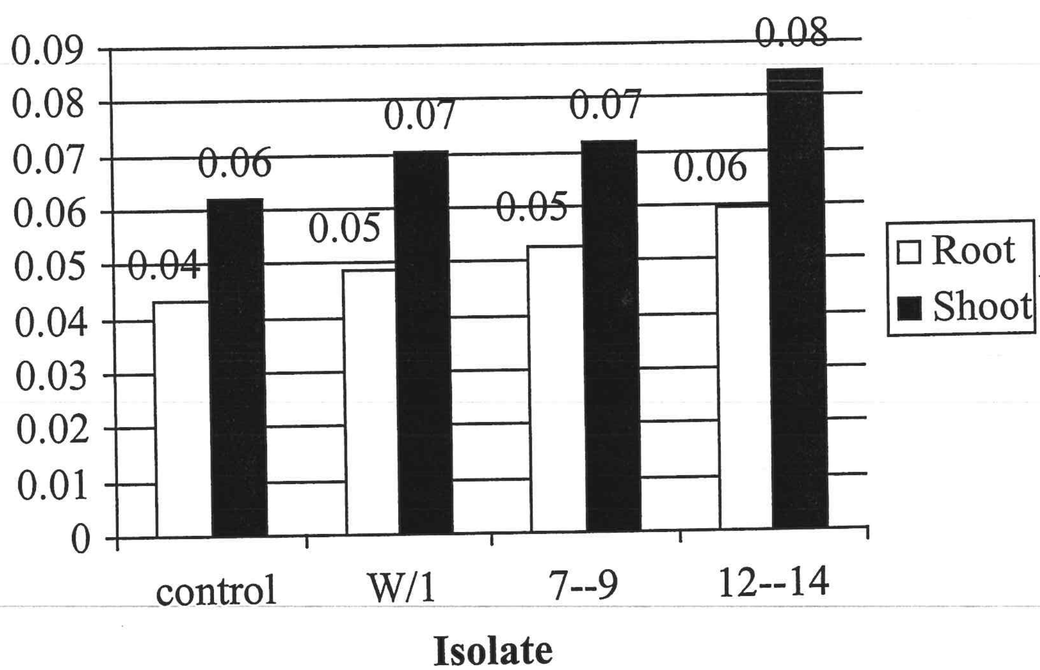


Figure 7. Root and shoot weight of the control and inoculated watergrass plants.

We did demonstrate that in sterile soil, rice grew about twice as fast as in non-sterile soil. This was not a soil nutrient effect. The literature on this subject indicates that the only viable solution to reducing the effect of these pathogens in monoculture systems such as rice in California is to change monoculture practices. Changes in monoculture practices include introducing rotation crops or winter cover crops. Rotating rice varieties may also break these pest cycles. Unfortunately not all farmers have soils suitable to incorporate these management approaches. As mentioned above, the pathogenicity of these bacteria is easily demonstrated in the laboratory. These organisms no doubt exert chronic pathogenicity to rice, especially in fields under extended monoculture. We do not know what impact they have in the field, but in the absence of any management alternative (other than soil sterilization) or evidence of substantial yield effect we will no longer pursue this line of research.

## CONCISE GENERAL SUMMARY OF CURRENT YEARS RESULTS:

### To determine changes in rice fertility after 8 years of alternative residue management.

After 10 years of implementing alternative rice straw management practices, grain yield did not decline compared to burning rice straw under standard fertilizer practices. Under continuous straw incorporation and winter flooding, fertilizer N application could be reduced to 90 lbs per acre without sacrificing. However, these results are derived from three sites and are not a universal prescription. Additional data (see 2003 RM-4 proposal) are needed to validate this prescription for general use. When practicing any treatment without winter flooding, no soil fertility benefit was seen and normal fertilizer practices must be maintained.

Continuous straw incorporation increased soil C and N only marginally compared to burning or baling. However, increases in cation exchange capacity were seen showing that small increases in soil organic matter affect soil fertility greatly. Winter flooding also seemed to reduce soil sodium levels possibly explaining some of the yield increases in winter-flooded systems. Reduced sodium levels may also imply a reduction in salinity related effects. Liming increased the yield of rice in 0 N plots and reduced fertilizer N use efficiency at full fertilizer application rates. This indicates that calcium additions affect N fertility in rice. In addition, calcium additions reduced the incidence of some weeds.

### To determine extent of root pathogens in non-burned rice fields.

We have isolated numerous isolates of deleterious rhizobacteria (DRB) from both rice roots and weed roots. The DRB normally stop the growth of roots, but we also identified isolates which inhibit shoot and root growth completely. The burned plots sampled showed the lowest number of pathogenic isolates, while the incorporated, non-winter-flooded plots showed the highest number. Incorporating seemed to exacerbate the monoculture effect. These organisms no doubt exert chronic pathogenicity to rice, especially in fields under monoculture. We do not know what impact they have in the field, but in the absence of any management alternative (other than soil sterilization) or evidence of substantial yield effect we will no longer pursue this line of research. The most viable solution to reducing the effect of these root pathogens is to change monoculture management. Suggestions to change monoculture management include introducing new and different crops into a rotation or growing a winter covercrop.

**Produce a comprehensive fertility management document based on field observations after 8 years of alternative residue management.**

We began work on a comprehensive soil fertility guide for rice based on the results of long-term field plots and individual grower fields funded in part by the Rice Research Board. As part of the 2002 RM-4 objectives, a shorten version of the rice fertility guide was published in California Agriculture. The publication is entitled:

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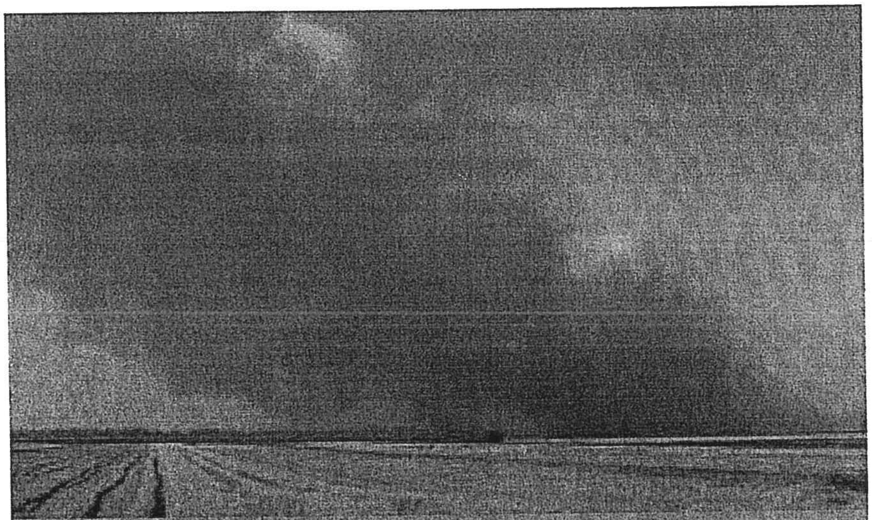
and can be found in Appendix A.

Work on the comprehensive soil fertility guide is an ongoing effort, which is not possible to complete in one year. Additional data for macronutrients and micronutrients must be obtained from grower fields. This data is critical to interpret the variance in straw management currently practiced by rice growers. We are satisfied with the results for N and K but require additional data for the remaining macro and micro-nutrients. A shorten draft field version of the fertility guide for N and K is currently being finished and will be sent to farm advisors for review. The draft guide for N and K will be available in March of 2003 as a two to four page document.

## APPENDIX A

# Long-term studies find benefits, challenges in alternative rice straw management



*California state legislation passed in 1991 mandated a phased reduction of rice straw burning in the Central Valley, to reduce air pollution. In 1993, UC Davis scientists launched an 8-year research project on the long-term effects of various alternative means of managing rice straw. Burning, incorporation into the soil, rolling, and baling and removing the straw were compared, with and without winter flooding. None of the various practices reduced grain yields on our experimental plots, but there was an increase in weeds when straw was incorporated, and in particular when the fields were not winter flooded. However, when straw is incorporated, nutrients are returned to the soil and less nitrogen fertilizer can be applied, resulting in lower production costs and less potential for water pollution. In addition, waterfowl on the Pacific Flyway benefit significantly from the wetlands created when fields are flooded during the winter.*

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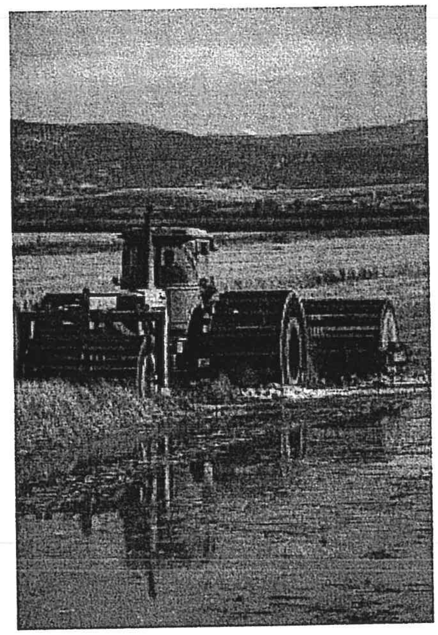


**The burning of rice straw, *top left,* was the norm until 1991, when a state law was passed to phase out the practice in order to prevent air pollution. Growers have turned to alternative practices such as winter flooding of fields, *above,* to reduce weed and disease pressure. Winter flooding has also been a boon for birds on the Pacific Flyway.**

Rice straw management in California's Central Valley has undergone profound changes over the past decade. Historically, rice growers routinely burned their field to dispose of rice straw for sanitation and seedbed preparation purposes. In 1989, when 400,000 acres of rice were grown in California, 95% of the resulting debris was burned in the field, creating air pollution in the Central Valley and statewide.

California state legislation passed in 1991 (Connelly-Areias-Chandler Rice Straw Burning Reduction Act) mandated a phased reduction of rice straw burning. The final step of the phase-down started in September 2001, when the law allowed burning only for disease control. Under the current scenario, disease-control burning will be limited to 25% of the approximately 500,000 planted acres or 125,000 acres, whichever is less. In the future, further reduction in burning is likely. The intent of the phase-down was to allow growers to make a gradual transition and allow some burning while alternative uses for straw were developed. Unfortunately, the market for rice straw has failed to grow as anticipated. Less than 3% of straw that is not burned is used off site (CRARB/CDFA 2000), resulting in a dramatic increase in the incorporation of rice straw.

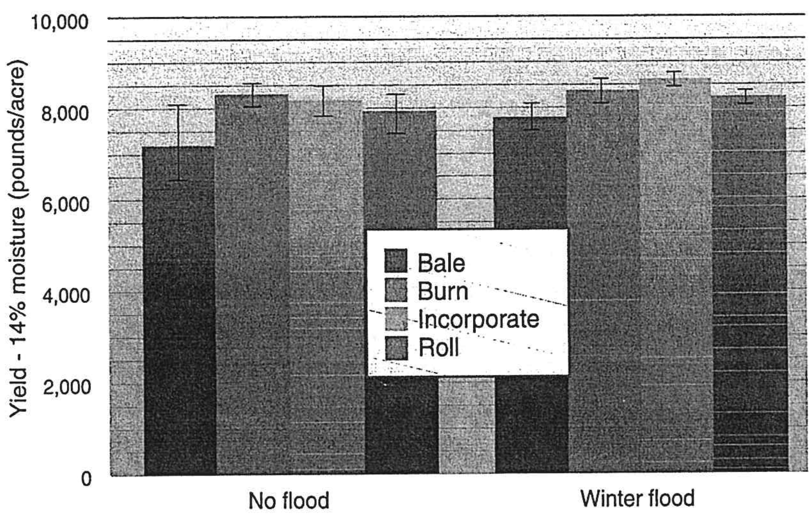



**Fig. 1. Yield of rice grain in Maxwell (Colusa County) in 2000, after seven seasons of alternative straw management practices. Lines in bars represent standard error.**

In 1993, UC Davis scientists launched an 8-year research project on the long-term effects of various alternative rice straw management practices. With funding from the California Energy Commission, Ducks Unlimited and the California Rice Research Board, several alternatives to burning were examined for their effects on rice yield, soil fertility, insect pests, diseases and weeds. Four straw management practices were examined: burning, incorporation, rolling, and baling and removing the straw. Each of these straw treatments was compared with and without winter flooding, resulting in the evaluation of eight different straw management practices. In this review, we summarize the key findings of several related studies.

## The research effort

The primary purpose of the project was to examine the impact of long-term straw incorporation and winter flooding on nutrient cycling and rice production. An experimental site was established in fall 1993, at Maxwell in Colusa County. The experiment was laid out in a randomized split-plot design with four replications. The main plot treatments for the experiment were winter flooding and no winter flooding. The subplot treatments were the four straw management practices mentioned above.

Cultural practices typical for California rice production were used for flood water, tillage, pest and fertilizer management. Field plots were large (2 acres per subplot treatment) to allow the use of commercial field-scale equipment. Fields were flooded during the growing season and then drained before harvest. Each fall following harvest the straw was either (1) burned, (2) chopped and then incorporated using a chisel plow or disc, (3) rolled with a heavy roller to crush the straw into the soil surface, or (4) windrowed, baled and removed from the field.

Fields were winter flooded 4 to 6 inches deep following the completion of the straw management practices and drained in early spring to allow sufficient time for soils to dry before spring tillage. Fields were tilled in the spring and nitrogen (N) fertilizer was applied at an average rate of 150 pounds per acre as aqua ammonia, and phosphorous (P) at an average rate of 20 pounds per acre as ammonium phosphate prior to seeding. Rice variety M202 (medium-size grain, early variety, approximately 140 days to maturity) was aerially seeded.

## Straw management and yield

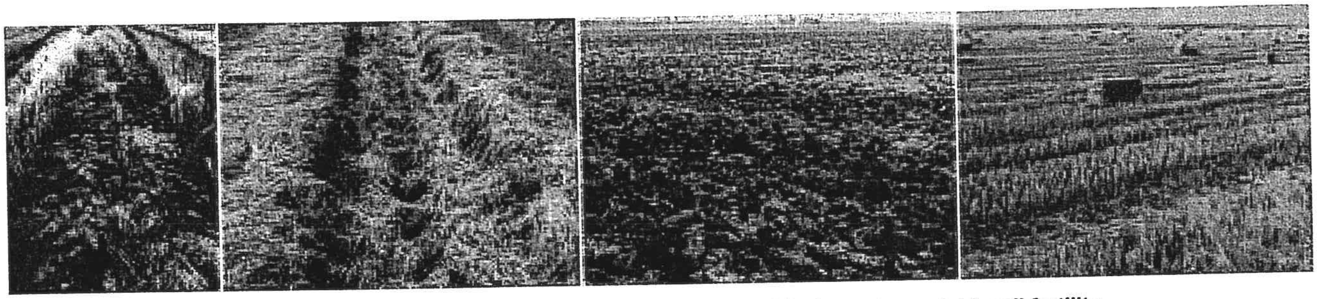
Rice growers in California have expressed concern that the conversion from burning to incorporating straw will increase weed and plant disease problems and possibly immobilize available soil nitrogen, thereby increasing the need for pesticide and additional fertilizer inputs. Grain yield was determined for each straw treatment from yield plots that ranged in size from 10 to 1,000 square feet (fig. 1). When averaged across years, grain yield was not significantly different among all straw treatments. Winter flooding had no significant effect on grain yield.

When straw is baled and removed, nutrients are exported from the field. Rice straw was collected when the straw treatments had been in place for 6 years. Straw was analyzed for elemental composition in the UC Division of Agriculture and Natural Resources (ANR) Analytical Laboratory at UC Davis using standard procedures (table 1). The nitrogen in rice

**TABLE 1. Nutrient content of rice straw (pounds/acre) after 6 years of treatment (assumes 10,000 pounds straw/acre)**

| | N* | P | K | S | Ca | Mg | Na | Cl | B | Zn | Cu | Mo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Burn | 61 | 14 | 72 | 10 | 29 | 18 | 79 | 8 | 0.15 | 0.41 | 0.31 | 0.02 |
| Incorporate | 67 | 13 | 80 | 10 | 28 | 18 | 77 | 8 | 0.14 | 0.41 | 0.31 | 0.02 |
| Roll | 69 | 13 | 75 | 10 | 28 | 18 | 79 | 8 | 0.16 | 0.42 | 0.37 | 0.03 |
| Bale | 70 | 14 | 79 | 10 | 27 | 19 | 74 | 8 | 0.15 | 0.41 | 0.23 | 0.02 |
| Mean | 68 | 14 | 77 | 10 | 28 | 18 | 78 | 8 | 0.15 | 0.41 | 0.31 | 0.02 |

* N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mg = magnesium; Na = sodium; Cl = chlorine; B = boron; Zn = zinc; Cu = copper; Mo = molybdenum.



**In an 8-year study, a variety of alternatives to rice straw burning were evaluated for impacts on yield, soil fertility, insect pests, disease and weeds.** ***From left to right:*** **burned, cut, stubble-disked and baled rice straw.**

straw ranges between 61 and 70 pounds per acre, and the amount of potassium (K) can be as much as 80 pounds per acre. Phosphorus levels in the straw ranged from 13 to 14 pounds per acre. It should be pointed out that approximately 50% to 60% of the straw will actually be baled and removed, and therefore the absolute amounts of nutrients removed will be less than reported in table 1.

Although nitrogen and phosphorus fertilizers were applied, potassium was not. Since most of the potassium taken up by the rice plant is in the straw and roots, the bale and remove treatment would result in substantial potassium losses from the system.

## Soil fertility

Several studies were conducted to determine the effects of straw management practices on soil fertility. Zero-nitrogen microplots were established within each main plot treatment. The microplots received no nitrogen fertilizer. Phosphorus was added to the zero-nitrogen plots at rates equivalent to those applied to the main plots.

After 3 years, rice grain yield in the zero-nitrogen microplots was significantly affected by straw treatment (Eagle et al. 2000, 2001). From 1996 through 1999, treatments where straw was rolled or incorporated showed higher grain yields for every year than where the straw was burned or baled. Overall, winter flooding had no impact on grain yields with or without nitrogen fertilizer. This data suggests that rolling or incorporation of rice straw had increased the soil nitrogen supply of the fields after 3 years of straw retention. This appears to contradict the finding of no improvement in yields with standard rates of nitrogen fertilizer with straw incorporation. This is due to the fact that the amount of nitrogen fertilizer applied exceeds the amount needed for optimum yields.

To determine the amount of nitrogen fertilizer that can be reduced with annual straw incorporation, a nitrogen fertilizer response study was initiated in 1998 and carried out for three growing seasons. Progressively increasing levels of nitrogen fertilizer were applied on subplots located within the subplot treatments where rice straw was either burned or incorporated, with and without winter flooding (fig. 2). Similar nitrogen-fertilizer response curves were observed in all three years. As the level of nitrogen fertilizer applied increased, grain yields increased when straw was burned or incorporated. However, grain yields when straw was incorporated were higher than when straw was burned and received nitrogen fertilizer up to a rate of 120 pounds nitrogen per acre. These rate trials indicate that nitrogen fertilizer application can be decreased when straw is incorporated, because no yield response was further observed when more than 100 pounds nitrogen per acre was applied.

Based on all the results of the nitrogen application-rate study, we recommend that nitrogen rates can be decreased by at least 25 pounds per acre after 5 years of straw incorporation (Eagle et al. 2000, 2001).

## Cycling of nitrogen and carbon

To further investigate the increased soil-nitrogen availability due to straw incorporation, new experiments were started in 1997 using labeled (heavy) nitrogen ($^{15}N$). These experiments sought to answer three primary questions:

1. How much of the nitrogen taken up by the crop is from fertilizer and how much is from the soil?
2. Does the efficiency of added nitrogen fertilizer differ with straw incorporation or burning?
3. Does annual straw incorporation build up soil nitrogen and carbon (C)?

The $^{15}N$ experiment confirmed the finding of increased soil nitrogen up-

TABLE 2. Total soil nitrogen (N) pool size (pounds/acre) as affected by 5 years of incorporating or burning straw, winter flooding and no winter flooding fields, May 1998*

| | Soil N pools | | | | |
|---|---|---|---|---|---|
| Treatment | Inorganic N | Microbial biomass | Light fraction | Mobile humic | Total soil N |
| Burn/flood | 16.2 | 62.2 | 40.2 | 493 | 1930 |
| Burn/no flood | 11.5 | 66.3 | 43.8 | 455 | 1974 |
| Incorporate/flood | 16.0 | 79.8 | 47.3 | 536 | 1927 |
| Incorporate/no flood | 13.7 | 86.6 | 52.7 | 522 | 1940 |
| P values | | | | | |
| Straw | 0.039 | 0.003 | 0.095 | 0.109 | NS† |
| Flood | 0.055 | NS | NS | NS | NS |
| S × F | NS | NS | NS | NS | NS |

* Least-squares means (N = 12).
† NS = not significant.

take through incorporation. The cumulative effects of straw incorporation over the years led to greater net nitrogen mineralization, an increase in microbial biomass nitrogen and greater recovery of $^{15}N$ in the soil 1 year after application (Bird et al. 2001, in press)(table 2).

Carbon and nitrogen are retained in soil organic matter when straw is incorporated (fig. 3). The carbon is fixed by the plant via photosynthesis; the nitrogen is taken up by the crop from soil mineral nitrogen. This pool of available soil nitrogen consists of native soil nitrogen that has been mineralized by microbes or introduced to the system through the application of nitrogen fertilizer. When the crop residue is incorporated into the soil, some of the carbon and nitrogen move into what is known as the labile soil organic matter pool, which consists of partially broken-down residues and soil microbes. Some of the carbon and nitrogen is sequestered in the more stabilized fractions.

The study showed that a consistently larger soil microbial biomass nitrogen pool was observed when straw was incorporated than when burned

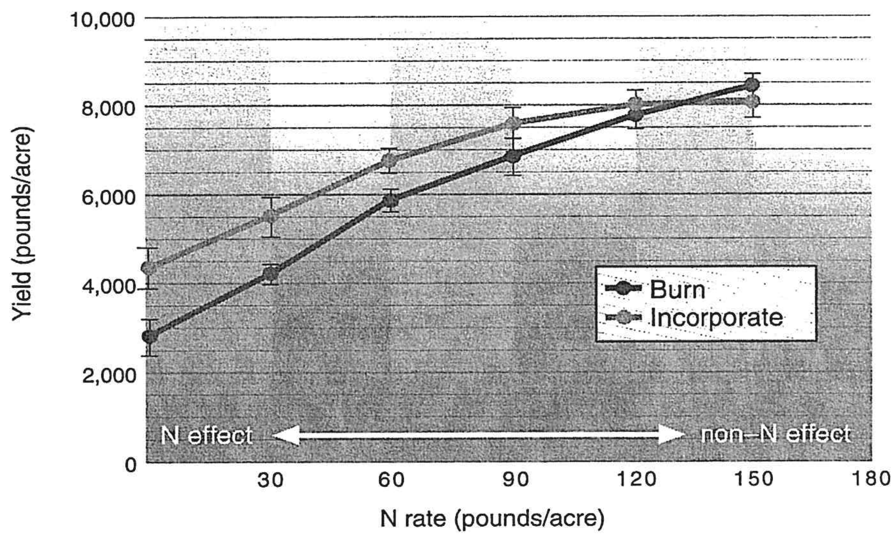


**Fig. 2. Impact of burning and straw incorporation on grain yield as affected by nitrogen (N) fertilizer application in 1999. Lines in bars represent standard error.**

(Bird et al. 2001)(table 2). The soil microbial biomass carbon was always significantly greater when straw was incorporated than when burned. Because soil microbial biomass is a prime source of available nitrogen for the crop, the incorporation of straw led to an increase in the crop-available soil nitrogen. Although the total soil nitrogen content had not changed after 5 years of straw incorporation or burning, a significant increase had taken place in the more labile soil nitrogen pools (that is, humic substances)(Bird et al. in press)(table 2). Those more labile soil nitrogen pools remain key sources of readily available nitrogen for crop utilization.

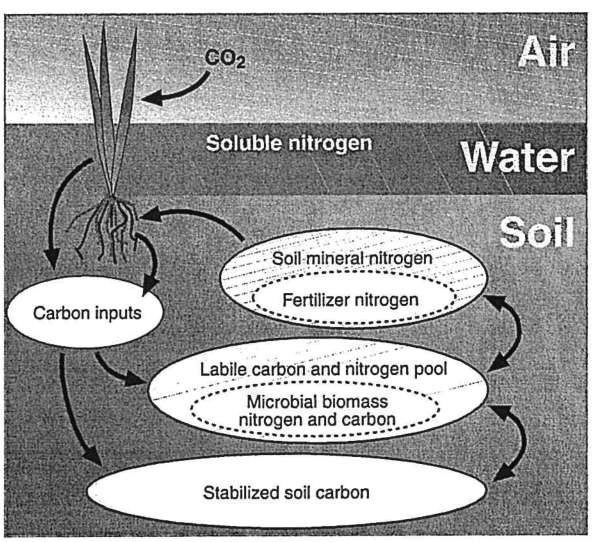


**Fig. 3. Carbon-nitrogen interactions in rice.**

## N fertilizer use efficiency

Determining the amount of nitrogen recovered by crops is reported as the nitrogen fertilizer use efficiency (FUE). Two methods of calculating FUE were compared as part of the study (Eagle et al. 2001). The first is the commonly used nitrogen-difference method. The amount of nitrogen in the crop that received nitrogen fertilizer is compared with the crop that received no nitrogen fertilizer. The difference between these two values in total nitrogen is assumed to be the amount of nitrogen from the fertilizer taken up by the crop, expressed as a percentage of the total nitrogen fertilizer applied.

A second method of determining FUE is the isotope dilution method. The total amount of nitrogen taken up by the plants is calculated using labeled nitrogen fertilizer ($^{15}N$). The proportion of $^{15}N$ in the crop is expressed as a percentage of the total $^{15}N$ applied. A significant difference was found between the estimation of FUE using the two methods for each of the treatments (Eagle et al. 2001)(fig. 4). Although there was no significant treatment difference in FUE when calculated using either method, the large discrepancy between the two methods of estimating FUE suggests the presence of an added nitrogen interaction (ANI)(Eagle et al. 2001).

An ANI effect occurs when applied $^{15}N$ is made unavailable for crop uptake by soil microorganisms. Soil microorganisms immobilize the $^{15}N$-labeled nitrogen that would have been accumulated by the crop. On the other hand, through mineralization, unlabeled nitrogen becomes available, replaces fertilizer $^{15}N$ in the soil solution and is accumulated by the crop. Therefore the unlabeled

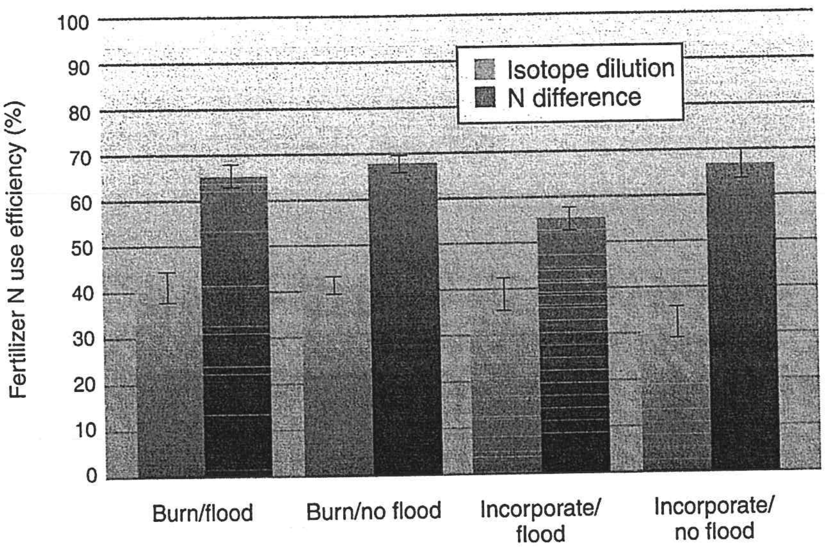
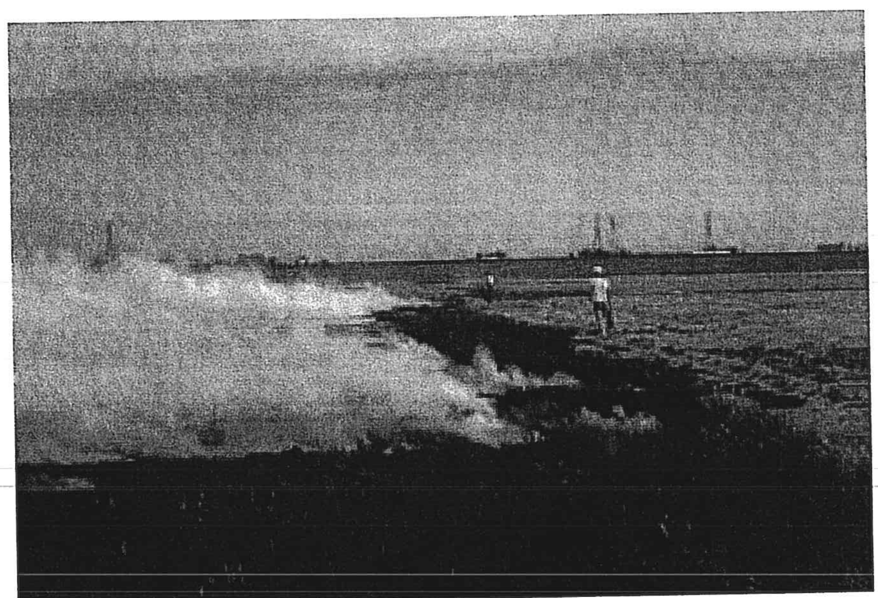



**Fig. 4. Comparison of nitrogen (N) fertilizer recovery by plants using labeled fertilizer (FUE-$^{15}N$) and N balance (FUE-ND) techniques. Lines in bars represent standard error.**

nitrogen previously immobilized by the soil microorganisms now becomes available for crop uptake. In other words, $^{15}N$-labeled fertilizer is replaced by unlabeled nitrogen that is accumulated by the crop. This explanation is supported by the finding that the gross mineralization of nitrogen in the soil was increased significantly in the treatments where straw was incorporated (Eagle 2000). The nitrogen fertilizer recovery by the $^{15}N$-isotope dilution method would have underestimated nitrogen fertilizer recovery when an ANI occurred. The actual nitrogen fertilizer recovery would then have been higher than observed by using $^{15}N$ isotopes and be closer to the value for the recovery of nitrogen that was observed for the nitrogen-difference method. However, it accurately describes the fate of fertilizer and shows the importance of soil nitrogen in supplying crop need.



**There were no major differences among various alternative practices (including burning) in terms of yield, but there was an increase in weed pressure when straw was incorporated into the soil, especially when not winter flooded.**

Subsequently, we determined how much of the labeled fertilizer nitrogen was available for the following year's crop (Eagle et al. 2001). The percentage of labeled nitrogen present that was recovered in the grain of the next year's crop reached 2.9% when straw was incorporated followed by winter flooding. The recovery declined to 1.7% when the straw was burned and the field was winter flooded (Eagle et al. 2001).

Two years after the application, the total loss of nitrogen fertilizer, based on the $^{15}N$ isotope balance, was approximately 50% and was largely independent of straw management practice (Bird et al. 2001). Incorporating straw did not lead to lower fertilizer nitrogen losses compared to when straw was burned. Although there were no significant differences in total soil nitrogen under the various straw management practices, there was an increase in soil microbial biomass (Bird et al. 2001) and the more available soil organic matter nitrogen pool — that is, humic nitrogen (Bird et al. in press)(table 2). An increase in total soil microbial biomass in combination with a large amount of added straw could have led to a temporary strong sink for nitrogen fertilizer. The ensuing immobilization process could have led to lower nitrogen fertilizer losses.

## Mixed findings on weeds

Examining the effects of the various practices on weeds showed that straw incorporation tended to increase the prevalence of grassy weeds, particularly water grass. This effect of straw incorporation became less strong when the field was winter flooded (fig. 5). When rice fields are flooded during the winter months, they attract larger numbers of foraging waterfowl. The higher incidence of weeds in the incorporated, non-winter-flooded fields may be due to a lower incidence of waterfowl for-

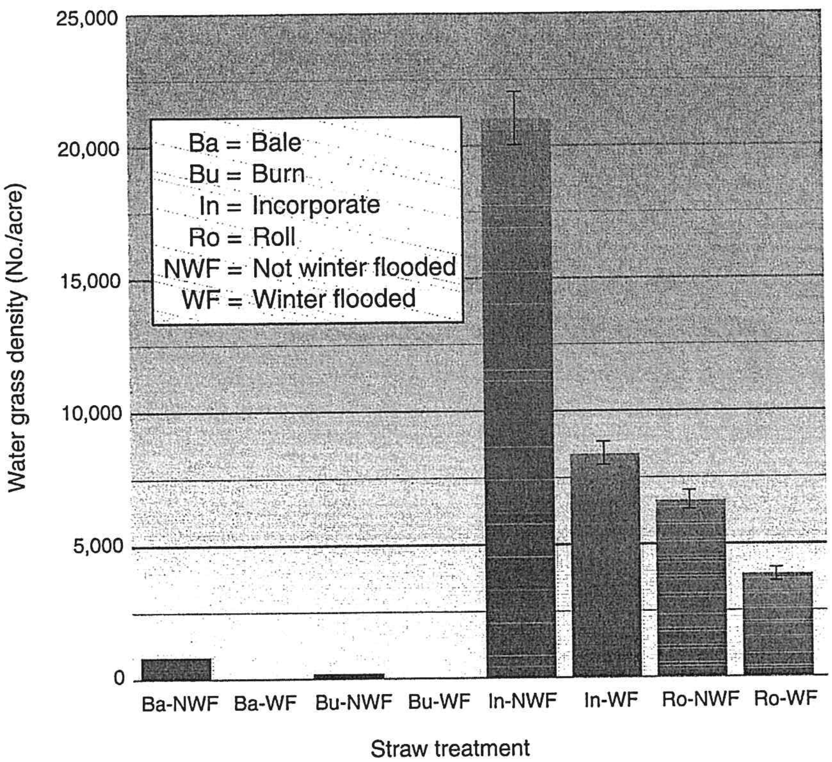



**Fig. 5. Average density of mature water grass plants (*Echinochloa* spp.) in rice grown under different straw management practices for 7 years at Maxwell (Colusa County). Means and standard error bars are shown.**

aging in these plots. Researchers found lower waterbird densities in nonflooded fallow rice fields compared with flooded in California (Elphick and Oring 1998). Winter flooding demonstrated significant benefits for weed control, whether the field was burned or not. In this study, burning and baling/removal with winter flooding produced the least water grass. Incorporation without flooding resulted in the highest amount of water grass seeds, followed by rolling without flooding. In addition, winter-flooded fields provide habitat for waterfowl, providing an example of a wildlife-friendly agronomic practice.

It is important to note that the rice fields in this study were treated with herbicides for weed control, following standard management practices. An herbicide program was used each year during this study, primarily to address the development of thiocarbamate herbicide resistance in the water grass population. For both incorporate/winter flood and roll/winter flood, the number of water grass seeds was significantly reduced as compared to rolling or incorporating without winter flooding. The mechanism for this decrease in the density of water grass seed may be in part due to the foraging of waterfowl in winter-flooded fields (unpublished data). If rice growers cannot burn, and decide not to bale due to the cost and negative effects on fertility, then a combination of incorporation and winter flooding would be an attractive alternative in terms of weed control.

## Environmental benefits and costs

One question raised by researchers in this long-term study was the possibility that anaerobic decomposition in the winter-flooded fields might lead to the formation of methane, an important greenhouse gas. A research project examining methane production showed that methane was produced in all of the winter-flooded treatments, with significantly more methane produced when the residue is incorporated or rolled compared to burned or baled (Bossio et al. 1999).

Over the long term, however, incorporation or rolling may also provide benefits through the accumulation of carbon as soil organic matter. To help reduce the amount of greenhouse gasses in the atmosphere, it has been suggested that producers be paid for the amount of carbon they return to the soil. Farmers would be compensated for soil carbon storage in the form of carbon credits. This policy, if implemented, could enhance farm income and offset the effects of methane production under straw incorporation.

## Less N fertilizer needed

The various alternative rice straw management practices we tested did not lead to a decline in grain yield on our experimental plots. However, there was an increase in the weed population when straw was incorporated, in particular when the fields were not winter flooded. Increased weed pressure when straw is incorporated for a prolonged period of time remains a concern.

When straw is incorporated, nutrients are returned to the soil. Clearly, the incorporation of straw led to an increase in the soil fertility, in particular nitrogen and potassium. Less nitrogen can be applied to fields where the straw has been incorporated, resulting in reduced production costs and decreasing the potential for water pollution. When straw has been incorporated for 5 years, we recommend a reduction of 25 pounds nitrogen per acre in the rate of nitrogen fertilizer applied.

Winter flooding slightly increased rice straw decomposition in combination with straw incorporation, but decreased straw decomposition of rice crowns and stubble remaining after burning (Bird 2001). In addition, winter flooding along with waterfowl foraging at regionally observed densities

**Incorporation of rice straw returned nutrients to the soil, allowing for reductions in the application of nitrogen and potassium fertilizer, without any impacts on yield.**

has been shown to increase straw decomposition rates in both tilled and untilled rice fields (Bird et al. 2001; unpublished data). As compared to burning, winter flooding also reduces the production of pollutants known to cause smog. Finally, ducks, geese and other birds on the Pacific Flyway benefit significantly from the wetlands that are created when fields are flooded during the winter months (Bird et al. 2000). Other studies show some benefits of winter flooding for controlling rice water weevil and the important rice disease stem rot (Hill et al. 1999).

As stated earlier, the major disadvantage to incorporation of rice straw as compared to burning is the increase in weed and possible pest pressure (Hill et al. 1999), an effect that is minimized by winter flooding. The long-term effects (more than 10 years) of straw incorporation on the occurrence and build up of weeds and pests, and how the buildup may affect the maximum yield potential for rice in California, remain to be determined. The study, which has been completed, exemplifies the need for continued long-term research because agronomic systems can take up to 10 to 20 years to respond to or equilibrate as a result of changes in residue management.

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