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Kinetics of Rice Straw Decomposition in Soils[1]

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ABSTRACT

Mature rice straw was decomposed in Sacramento clay and Stockton adobe clay at loading rates up to 8% of soil weight for 120 days. Carbon loss was linearly related to loading rate, and carbon loss at given loading rates was described by equations of the form $C = kt^m$. Rice straw labeled with ^{13}C and ^{15}N added to the same two soils permitted distinction between straw and soil carbon and nitrogen during decomposition. A pronounced effect of straw on loss of soil carbon was observed, but the effects on soil nitrogen were small. Turnover times for the immature labeled straw were calculated to be between 0.8 and 3.4 years, depending on loading rate and soil. Priming ratios, defined as (soil C-loss with straw) ÷ (soil C-loss without straw) were greater than unity throughout the 120-day period of incubation.

Additional Index Words: N mineralization, carbon loss, turnover time.

The traditional practice of burning rice straw residues and stubble has resulted in considerable air pollution and reduction in visibility which are becoming unacceptable in an urban society. Already, burning restrictions have been imposed, and more strict regulations may be forthcoming in the future. The disposal of bulky rice straw residues has therefore become a matter of urgent concern of rice growers as well as to agricultural scientists. Alternative ways of disposing of residues, as for example, by soil incorporation, must take into consideration effects on the physical, chemical, and biological properties of soils. Actively decomposing organic materials influence crop production as shown by Plice (8), Williams et al. (9), and Gotoh and Onikura (6). Since not all of added plant material in soils is fully oxidized to simple end products such as carbon dioxide, water, and inorganic nitrogen, the residual material which undergoes a series of complex transformations involving its incorporation into the re-

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sistant soil humus is of considerable concern to the soil scientist.

By means of the stable tracers, ^{13}C and ^{15}N, it has been possible to follow the fate of added plant materials in a more detailed way than in nontracer experiments. In some of the experiments reported here, rice straw labeled with these two stable tracers was utilized as a means of obtaining specific information on added materials as distinguished from the native soil organic matter.

MATERIALS AND METHODS

Soils

Two fine-textured rice soils, Sacramento clay and Stockton adobe clay, were sampled from the 0- to 20-cm horizon in the field, air-dried, and passed through a 2-mm sieve. Some of the properties of these soils are given in Table 1.

Plant Materials

Plant materials consisted of (i) unlabeled mature rice straw containing 37.1% C and 0.46% N, and (ii) immature, doubly labeled rice tissue which was obtained by growing rice plants in a closed chamber in the greenhouse. The bottom of the chamber contained Yolo fine sandy loam which was fertilized with ^{15}N-enriched ammonium sulfate. Rice seedlings (*Oryza sativa*) about 10-days old were planted in the chamber, and labeled carbon dioxide was produced inside the closed system by decomposition of ^{13}C-enriched $BaCO_3$ with lactic acid. The CO_2 concentration in the chamber varied between 0.02 and 0.62% by volume. Rice was grown in two seasons, once in summer and once in winter, but in neither case was it possible to grow the plants to full maturity. Composition of the plant tissue obtained is shown in Table 2. Straw I was less mature than straw II and had a rather low carbon content. The straw was dried at 70C and ground to pass a 20 mesh (1.2-mm) screen.

Incubation Experiment with Unlabeled Straw

Rice straw was added to Sacramento clay soil at rates of 0.25, 0.5, 1.0, 2.0, 4.0, and 8.0% of soil weight in a 120-day laboratory incubation experiment. After the required amounts of straw were mixed with duplicate 25 g soil samples, contained in 237-ml (8-oz) bottles, 20 mg N was added as $(NH_4)_2SO_4$ solution. The moisture content was brought to 60% of water holding capacity. The incubation was carried out at 22C. Carbon/nitrogen ratios on the straw basis ranged from 1.1 at 0.25% added straw to 25.4 at 8% added straw. Nitrogen should not be limiting for decomposition at C/N ratios below about 30. Soon after, the bottles were closed with stoppers to which 5-ml beakers had been attached to hold standard NaOH for absorption of CO_2. The absorbed CO_2 was determined frequently by a titrimetric procedure after precipitation of carbonate as $BaCO_3$ (4). The frequent opening of the bottles to replace the NaOH replenished the oxygen in them.

Decomposition of Labeled Rice Straw

Doubly labeled rice straw I was added to Sacramento clay and Stockton adobe clay at rates of 0, 0.25, 0.5, and 1.0% of soil weight. Straw II was added only at the 2.0% level. The soils were incubated at 60% WHC and 22C for periods ranging up to 4 months. The $BaCO_3$ precipitate was saved after titration of excess NaOH and analyzed in the mass spectrometer for ^{13}C (5).

To estimate N release and tie-up as a result of added plant material, eight 10-g samples of soil were weighed into beakers for each application rate of straw I. After mixing of the soil and straw the samples were wetted to 60% WHC, covered with parafilm perforated with a few small holes, and incubated at 22C. Moisture loss was made up after periodic weighing. NH_4 and NO_3-N were determined after 10, 30, 60, and 120 days by extraction of the soil with 1*N* KCl and steam distillation of the extract as described by Bremner. This inorganic nitrogen was converted to N_2 and analyzed for ^{15}N by mass spectrometry (2).

Table 1—Some properties of Sacramento and Stockton adobe clay

Soil	pH*	C	N	C/N ratio	Sand	Silt	Clay	WHC
		%				%		
Sacramento clay	5.7	1.74	0.157	11.1	1.8	47.6	50.6	67.0
Stockton adobe clay	6.3	1.69	0.143	11.8	20.0	41.8	38.2	54.0

* On the basis of 1:2, soil/water suspension.

Table 2—Carbon and nitrogen in labeled rice tissue

Straw	C	^{13}C excess	N	^{15}N excess	C/N ratio
		%			
I	29.8	5.76	2.80	24.34	10.7
II	39.2	1.85	2.65	7.33	14.8

RESULTS

Incubation Experiment with Unlabeled Straw

Log-log plots of cumulative C loss at various loading rates are shown in Fig. 1. The relatively uniform spacing between curves indicate that a constant proportion of the added carbon was decomposed at each level of straw addition. Plots of total CO_2 loss vs. loading rate for periods up to 120 days (Fig. 2) confirm a linear relationship, with correlation coefficients very close to 1.00 for incubation periods 30 days and longer. In these plots the intercept of the regression line on the y-axis is a measure of soil carbon loss in straw amended samples without the use of

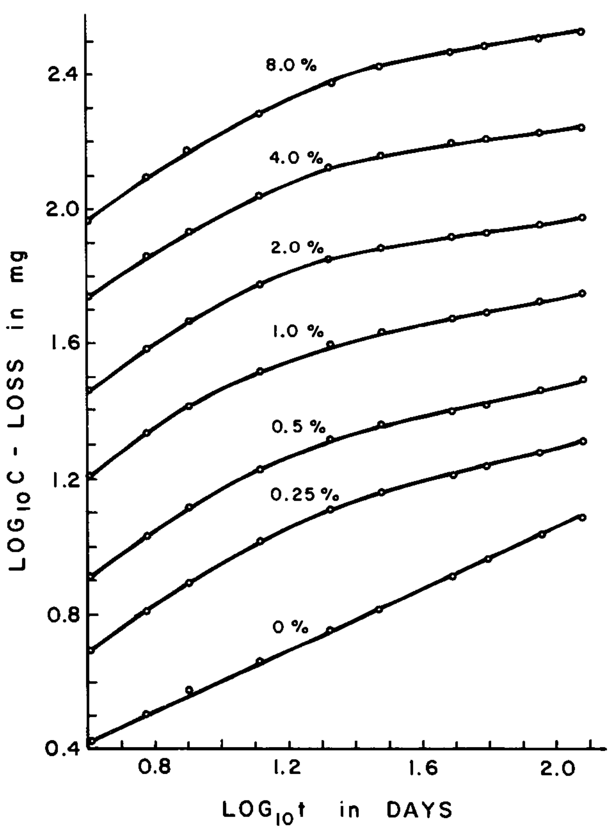

Fig. 1—Log-log plot of the cumulative C loss as a function of time at various loading rates of untagged mature straw incorporated in Sacramento clay soil.

isotopically labeled straw. The intercept for the 120-day line is 12.2, compared to an identical value obtained for soil alone. The slopes of the regression lines indicate the fraction of added carbon lost during a given period of incubation. For example, 43.5% of the straw was decomposed in 120 days.

Attempts at fitting equations to the cumulative C-loss vs. time data by statistical means showed that quadratic functions of the form $C = a + bt + ct^2$ where C = carbon loss, t = time, and a, b, and c are constants, fit reasonably well for the first 2 or 3 weeks. Subsequently the data conformed best to power functions of the form $C = kt^m$ where k and m are constants. Equations applicable at various times and loading rates are given in Table 3. Also shown are values of the coefficient of determination, R^2. The quadratic functions are of limited value since they are applicable only for short time periods, but some extrapolation of the power functions may be feasible in predicting decomposition over longer periods then those actually measured (5).

Decomposition of Labeled Rice Straw

Use of the ^{13}C-labeled rice straw permitted identification of that part of the CO_2 evolved which was derived from straw. Plots of log C-loss (C) vs. log time (t) showed that after a short initial period of rapid decomposition, usually about a week, the data conformed reasonably well to equations of the form $\log C = m \log t + \log b$ where m and b are constants. Correlation coefficients for the regression lines ranged bewteen 0.965 and 0.996. In

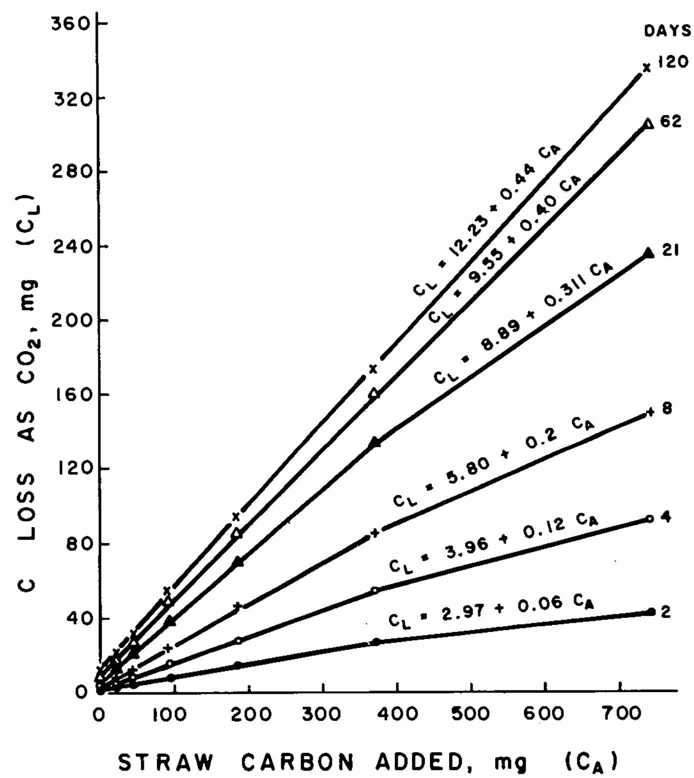

Fig. 2—Total cumulative C loss as a function of straw C added at varying lengths of incubation period.

Table 3—Equations describing cumulative C loss as a function of time at different straw loading rates

Straw added	Time interval, days	Equation	R^2
%			
0.00	0–120	$C = 1.03t^{0.542}$	0.984
0.25	0–14	$C = 0.653 + 1.18t - 0.034t^2$	0.999
	14–120	$C = 5.75t^{0.265}$	0.999
0.50	0–14	$C = 0.935 + 2.01t - 0.062t^2$	0.999
	14–120	$C = 10.4t^{0.227}$	0.999
1.00	0–14	$C = 1.49 + 4.08t = 0.128t^2$	0.999
	14–120	$C = 22.4t^{0.190}$	0.997
2.00	0–21	$C = 3.30 + 6.56t - 0.160t^2$	0.998
	21–120	$C = 46.7t^{0.145}$	0.999
4.00	0–21	$C = 4.30 + 12.6t - 0.314t^2$	0.994
	21–120	$C = 92.0t^{0.133}$	0.996
8.00	0–21	$C = 1.50 + 22.8t - 0.563t^2$	0.995
	21–120	$C = 154t^{0.164}$	0.990

linear coordinates this equation takes the form, $C = kt^m$, as previously noted to describe loss of carbon by soil and straw combined. Curves and equations are shown in Fig. 3. It should be noted that the curves for the 2% loading rate are not strictly comparable to the others since a different straw was used at this rate.

Carbon losses expressed as percentages of that added in straw are given in Table 4. As with the more mature straw of Fig. 2 the percentage loss of straw carbon was relatively independent of loading rate.

Differentiating the function for cumulative carbon loss of the form $C = kt^m$ yields the rate function $dC/dt = kmt^{(m-1)}$.

Equations of this form were used to calculate the data of Table 5, expressed as percentage of added carbon lost per day. Loss rates were relatively independent of loading, and decomposition in Stockton adobe clay was consistently higher than in Sacramento clay.

Carbon balance data shown in Table 6 indicate that,

Table 4—Percentage loss of C added in a straw at various incubation times

Soil	Straw added, % of soil weight	Percentage loss of straw carbon at incubation time (days) specified				
		10	30	61	91	121
Sacramento	0.25 (I)	30.8	41.3	49.2	53.1	55.1
	0.50 (I)	34.8	44.5	52.6	56.1	57.8
	1.00 (I)	40.1	52.0	59.7	64.5	67.1
	2.00 (II)	27.2	26.6	40.3	42.3	43.1
Stockton adobe clay	0.25 (I)	36.4	57.4	65.0	68.7	70.6
	0.50 (I)	42.4	59.9	68.4	72.2	74.2
	1.00 (I)	46.8	58.6	66.2	71.7	74.5
	2.00 (II)	30.2	42.9	49.7	51.2	52.4

Table 5—Rates of C loss from straw-amended soils expressed as percentage of straw C day^{-1}

Days incubation	Percentage of straw carbon lost day^{-1} at loading rates of		
	0.25	0.50	1.0
	Sacramento Clay		
10	0.78	0.72	0.77
30	0.34	0.32	0.37
60	0.20	0.19	0.22
90	0.15	0.14	0.16
120	0.12	0.11	0.13
	Stockton Adobe Clay		
10	1.10	1.01	0.96
30	0.51	0.48	0.39
60	0.31	0.29	0.22
90	0.23	0.21	0.16
120	0.19	0.17	0.13

Table 6—Carbon balance data and changes in soil C as affected by addition of rice straw

C added	C lost in 4 months		Net gain or loss of C	Percent of added C retained	Turnover time
	Straw	Soil			
mg					years
		Sacramento Clay			
0.0	-	14.5	-14.5	-	-
18.6	10.3	18.0	-9.7	44.9	2.88
37.3	21.5	19.6	-3.8	42.2	2.38
74.6	50.0	20.9	+3.7	32.9	1.76
		Stockton Adobe Clay			
0.0	-	17.0	-17.0	-	-
18.6	13.2	20.7	-15.3	29.4	0.77
37.3	27.7	22.0	-12.4	25.8	0.79
74.6	55.5	21.3	-2.2	25.5	1.24

Table 7—Priming ratios as affected by straw level and time of incubation

Soil	Straw added	Days of incubation				
		10	30	61	91	121
	%	priming ratios				
Sacramento clay	0.25	1.57	1.44	1.32	1.27	1.25
	0.50	1.80	1.60	1.47	1.38	1.35
	1.00	2.06	1.80	1.59	1.49	1.45
Stockton adobe clay	0.25	1.45	1.39	1.29	1.24	1.22
	1.50	1.64	1.53	1.40	1.33	1.30
	1.00	1.51	1.47	1.35	1.27	1.25

with one exception, net losses of carbon occurred at loading rates up to 1%.

Turnover times, that is, time required for complete loss of added straw, were calculated from the equations of Fig. 3 by substituting values for C equal to the quantity added and then solving for t. These range from 1.8 to 3.4 years in Sacramento clay and from 0.77 to 1.2 years in Stockton adobe clay (Table 6). It should be pointed out, however, that losses of soil carbon were such that the time required for the soil samples receiving straw to reach the same carbon level as before straw addition was in general $<$ 4 months. Losses of soil carbon were affected by the quantity of straw added. The magnitude of the influence of decomposing straw on soil organic matter breakdown can be described in terms of priming ratio, which is defined as (soil carbon loss with straw added) ÷ (soil carbon loss without added straw). Values for this ratio are given in Table 7. These were greater than unity throughout the experimental period and increased with loading rate in Sacramento clay, although this trend was not consistent in Stockton adobe clay. The ratios decreased with time in both soils, as expected.

Nitrogen Mineralization

Net levels of inorganic nitrogen derived from added straw are shown in Fig. 4. In Sacramento clay the mineralization rate of N from the immature rice straw was initially very high. Possibly some loss of N through denitrification occurred after 30 days, but the abrupt decrease in inorganic N may also have resulted from interchange with soil N. The Stockton soil had a pattern of gradual release of inorganic N throughout the decomposition period. Mineralization of soil N (Fig. 5) was essentially unaffected by straw addition except in Stockton adobe clay at the 1% level. Values for nitrogen mineralized in 120 days calculated as percentage of the total N present are given in Table 8. These values contrast the

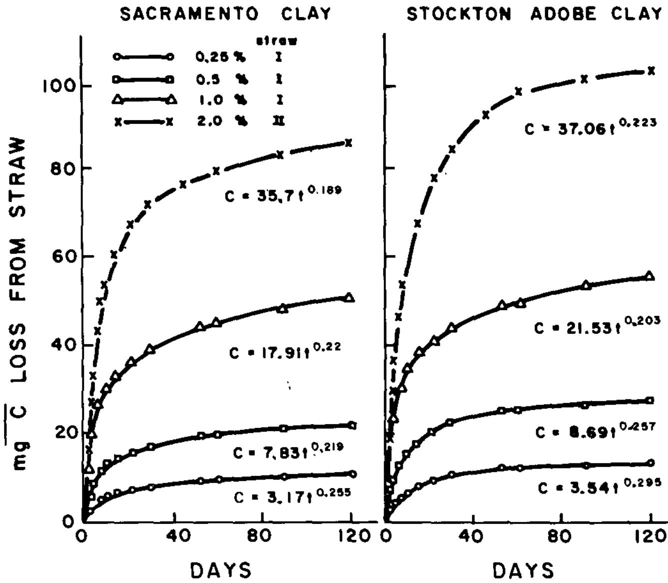

Fig. 3—Cumulative C loss from straw incorporated into soils at varying rates of loading. Equations corresponding to each curve fit data for incubation period; $7 < t < 121$ days.

high availability of straw N as compared to soil N. It should be noted, however, that if some denitrification occurred, the values of Table 8 may be low. Soil N mineralization although quite low, is comparable in magnitude with other experiments where crop uptake of N has been used as a measure of N mineralization (1, 3, 7).

DISCUSSION

The mature straw (Fig. 1) is doubtless more representative of rice residues incorporated into soil in field practice than the immature, labeled tissue (Table 2), but it seems

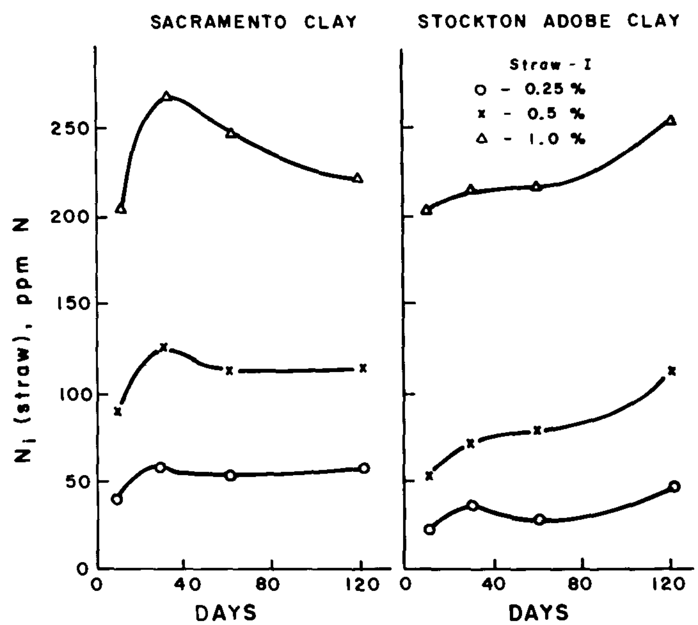

Fig. 4—Net release and loss of inorganic nitrogen from straw, N_i (straw) as a function of time during decomposition in soils at various loading rates.

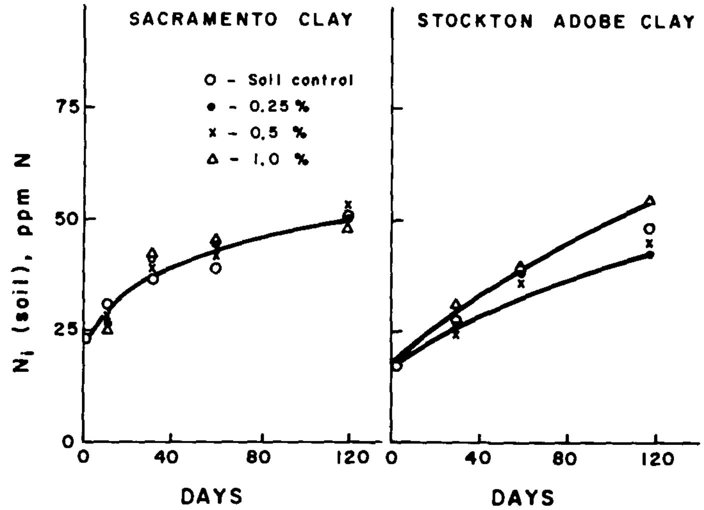

Fig. 5—Dynamic changes in soil inorganic N as a function of time at varying rates of straw loading.

likely that the linear relationship noted in Fig. 2 would not have been maintained at the higher levels of addition without supplemental nitrogen. An inverse relationship was reported between relative decomposition rate and level of addition of mature straw in other experiments (4) where nitrogen may have been limiting decomposition at higher rates of straw addition.

Estimates of the time required for the loss of total C equal to added C in the form of mature straw were made by setting the equations of Table 3 equal to the quantity of carbon added and solving for t. This gave values between 0.53 and 97.4 years for different loading rates. The time required for complete decomposition of added straw was estimated in another way by plotting the slopes (m) of the regression lines for Fig. 2 against time (t), which yielded the function, $m = 0.216 \log t + 0.0093$. By setting this equation equal to 1.0 and solving for t, a turnover time of 104 years is obtained.

Extrapolation of the regression lines given in Fig. 2 to the y-axis provides an estimate of soil carbon loss in the presence of straw during various incubation periods, whereby the "priming ratio" can be calculated without the use of isotopically labeled plant material. This ratio was 1.92 at 2 days, 1.57 at 21 days, 1.05 at 60 days, and 1.0 after 120 days. These values are comparable in magnitude to those of Table 7 obtained with labeled straw, but

Table 8—Mineralized N from straw and soil after 120 days expressed as % of total N present

Straw loading rate	Sacramento clay		Stockton adobe clay	
	Straw N	Soil N	Straw N	Soil N
	%			
0.00	-	1.70	-	1.92
0.25	81.1	1.71	66.1	1.75
0.50	83.4	1.85	80.6	1.91
1.00	79.1	1.56	90.2	2.56

approach closer to unity at the end of the decomposition period.

The carbon loss data could not be described by first order kinetics even during the initial period of rapid decomposition. Neither did they conform well to Michaelis-Menten kinetics which frequently can be applied to individual enzyme systems. The quadratic functions which provided a good fit to the experimental data during the early period of rapid decomposition represent mixed order kinetics between 0 and first order. Soil carbon loss was of the order of 3.3 to 4.8% in Sacramento clay and 4 to 5.2% in Stockton adobe clay. Soil carbon mineralization values exceed soil nitrogen mineralization values, partly because nitrogen losses by denitrification, clay fixation, etc. were not accounted for in the present experiment.

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