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Feasibility of collecting naturally leached rice straw for thermal conversion

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Abstract

The practical application of field or natural leaching to rice straw was evaluated with the goal of improving biomass fuel value. Observations on three rice farms in the Sacramento Valley, California indicated that potassium, chlorine and total ash are leached from rice straw by rainfall regardless of rice variety, grain harvest method, straw arrangement, or stubble length. Leaching of sulfur by natural precipitation was not clearly established. In selected field plots leached straw was successfully collected in spring, even though biomass yields were variable (2.2–3.4 Mg ha^{-1}) and equipment had to operate in difficult conditions. Total costs for collecting leached straw on an area basis (\$77.07 ha^{-1}) are 31% higher compared to collecting crude straw in the fall (\$58.67 ha^{-1}), due to reduced performance of machinery and addition of field curing operations. Analysis of historical rainfall data for the Sacramento Valley revealed that there is an 85% probability of receiving sufficient rainfall (250 mm or more) for substantial natural leaching of straw during the winter period. The available period for mechanized collection of rice straw after the winter period ranges from 0 to 45 days, depending on drying time needed to accomplish favorable field conditions, and planting date of the next crop. The feasibility of spring collection of rice straw could be improved if straw collection equipment were better equipped to operate under wet field conditions. The commercial implementation of natural leaching of rice straw as a strategy to improve fuel quality depends on a combination of factors that include grain harvest and straw collection practices, rainfall intensity and distribution, and field-specific factors.

Keywords: Biomass; Straw; Combustion; Inorganic elements; Slagging; Fouling; Leaching; Delayed harvesting; Feasibility

1. Introduction

Cereal straws and many other types of biomass have proved to be difficult to burn in most existing combustion systems. A major reason for this is the rapid formation of fouling deposits, slag formation in furnaces, and accelerated corrosion due to sometimes high concentrations of chloride. In California, boiler operators have excluded rice, wheat, and other straw as fuel in existing wood-fueled power plants in order to avoid high operating costs, even though many of the plants hold air permits allowing them to burn straw. In Denmark, experience with combustion of straw has

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been more successful, however, straw creates maintenance problems there as well.

Ash fouling and slagging are related to the presence of certain elements in the fuel and other materials in the boiler (e.g., sand media used in fluidized beds). Of primary importance for biomass are the alkali and alkaline earth metals, chloride, silica, and sulfur. Of the alkali elements, potassium is the principal constituent in biomass due to its role as a macronutrient in plant nutrition. In recent years, leaching of these constituents from biomass prior to combustion has been shown to improve combustion properties and reduce fireside fouling. Leaching rice straw, wheat straw, switchgrass (*Panicum virgatum*), and wood fuels with water extracts large amounts of alkali and chloride and leads to substantial improvements in combustion behavior [1–3]. Pilot-scale combustion experiments reveal a remarkable change in fouling tendency of leached rice straw [4]. Full-scale boiler experiments indicate that leached rice straw is technically suitable as boiler fuel under normal operating conditions [5,6]. The beneficial impact of leaching biomass fuels for thermal conversion purposes has also been demonstrated for banagrass (*Pennisetum purpureum*), a dedicated high-yielding energy crop [7,8], and leaching during sugar extraction is largely responsible for the generally low fouling rates associated with sugar cane bagasse combustion.

Leaching occurs by rain washing in the field or can be accomplished by washing at a central site (e.g. power plant) under more controlled conditions. Leaching by natural precipitation in the field (here referred to as natural leaching) is of substantial interest because of its perceived greater economic feasibility compared to industrial leaching due to the reduced need for material handling and the direct nutrient recycling without need for waste water disposal or treatment. Natural leaching is an option for crops or residues that have been left standing in the field (e.g. switchgrass and stripper-harvested cereal straw), as well as residues that have been cut as a result of previous field operations (e.g., conventional combine harvest of grains). Natural leaching however needs a certain period where no other field operations are required, and in which sufficient rainfall can be anticipated. Natural leaching of K, Cl, and total ash from biomass has been reported for rice straw, reed canary grass (*Phalaris arundinacea*), barley straw, and *Miscanthus* (*Miscanthus* spp.) in a variety of locations. Landstrom et al. [9] observed a significant decline of K and Cl in reed canary grass that was collected in spring (compared to summer harvest) and attributed this decline to leaching. Jenkins et al. [2], observed leaching rates of potassium and total ash from windrowed rice straw in the field, finding K extractions above 80% under typical winter conditions. Burvall [10] showed that both potassium and chlorine in reed canary grass grown in Sweden decreased by a factor 5–6 when the grass had over-wintered in the field, and that the average value of initial ash deformation temperature increased by more than 300°C. Sander [11] measured the effect of rainfall on inorganic composition of windrowed barley straw in Denmark and concluded that significant amounts of Cl and K are removed by natural precipitation, while Ca content in straw was not affected. Joergensen [12] investigated K and Cl content of Miscanthus and determined that a substantial decline in K and Cl occurred as a result of over-wintering.

As part of a larger study investigating fuel leaching in biomass combustion, we conducted an analysis of the technical and economic feasibilities of leaching rice straw in the Sacramento Valley, California. In this region, approximately 1.2 million metric tons (dry basis) of rice straw are produced every year. Only a fraction of the total straw ($< 5\%$) is collected for commercial off-field utilization in the weeks immediately following grain harvest in September through October. The remaining straw is disposed of or managed by a variety of methods including field burning and soil incorporation. The valley regions of California are semi-annual deserts, with nearly all rainfall occurring during the period November–February. Conditions during this period are generally unfavorable for straw collection by mechanized equipment due to high soil and straw moistures. However, double-cropping with winter crops is not a common practice for much of the rice in California, therefore leaving straw in the field during this interval does not interfere with other field operations. If rice straw is left after grain harvest for leaching purposes, straw collection is not likely to take place until several months later, when straw and field conditions permit mechanized field collection. To investigate the practical application of field or natural leaching to rice straw for the purposes of improving fuel value, we conducted field experiments to:

1. identify changes in rice straw composition at various locations throughout the Sacramento Valley rice growing region during the winter season and assess whether straw could be mechanically collected in the following spring,
2. compare straw collection methods and costs for naturally leached rice straw with collection of unleached (crude) straw in the fall using actual field data from time and motion studies of equipment operations, and
3. evaluate the probability using historical rainfall data of successfully collecting leached straw in the Sacramento Valley.

2. Materials and methods

2.1. Field observations, straw sampling and analysis

Natural leaching of rice straw was investigated by observing straw in three commercial fields in the Sacramento Valley during a 7-month period following rice grain harvest in September 1997. The observation period included the months of November through February, in which the majority of annual rainfall occurs. An overview of the fields that were part of this investigation is presented in Table 1. The three fields, identified A through C, were selected from rice growers willing to cooperate with the study. The fields differed in location (all fields are within a 25 km radius, however), variety of rice (all medium-grain varieties), and field size. In all three fields rice was harvested by combine harvesters employing conventional cutterbar headers. As a result, the straw that remained in the field after grain harvest consisted of two fractions: (1) uncut straw stubble that had not passed through the combine harvester (i.e. still connected to the roots), and (2) loose straw that was discharged behind the combine harvester onto the uncut stubble or the field surface. The combine harvester used in field C employed an axial flow thresher that macerated the straw to a greater extent than the other harvesters that employed conventional spike-tooth threshing cylinders. As noted later, this had some effect on the rate of organic matter loss during the winter leaching period.

As indicated in Table 1, the length of the uncut straw stubble varied, with taller rice varieties having longer stubble length. This is a direct result of operators attempting to optimize grain-to-straw ratio in threshing. Due to traffic of harvesting equipment in the three fields, a significant amount of straw stubble was overrun by the wheels or tracks and pushed onto or into the soil. Field surveys in the days following grain harvest indicated that approximately 41% of stubble was overrun in Fields A and B, and 26% was overrun in Field C (Table 1). The fraction was lower in Field C because only one harvester was used, and grain was off-loaded at the side of the field rather than into self-propelled bankout wagons normally used to shuttle grain from harvesters to trucks. There were also differences in the manner in which loose straw was discharged after passing through the combine. In Field A, straw was discharged from the combine straw separators (straw-walkers) directly into 1 m wide windrows. In Field C, straw was spread behind the combine through the use of straw spreaders, rotating flexible beaters used to distribute straw over the harvester swath to enhance drying. In Field B, straw spreaders were used as well, however cut straw was primarily discharged in windrows as spreaders were either not effective or not turned on by the operator. Field surveys indicated that the fraction of the Fields A and B covered by windrows was approximately 20%. In Field C, all loose straw appeared to be well distributed over the field.

In September, prior to any rainfall, multiple 1 m^2 samples of stubble and loose straw were collected and weighed to determine the yield (kg m^{-2}) of biomass in the windrows or spread over the field. For this purpose, stubble was cut by hand at approximately 8 cm above ground level (i.e. typical of what might be achieved under machine swathing of stubble for straw collection), and loose straw was collected by hand. The sample biomass yields were used to calculate potential field yields prior to the winter leaching period. Potential yield was corrected for the fraction overrun by the harvesting equipment.

Hourly precipitation data were obtained from a nearby weather station operated by the state Department of Water Resources California Irrigation Management Information System (CIMIS). Samples of stubble and loose straw were collected after 0, 97, 250 and 626 mm of cumulative rainfall. In Fields A

Table 1
Summary of field and grain harvest conditions for leaching trials

Field	Location	Rice variety	Height of plant at grain harvest[a]	Field area	Average stubble length after grain harvest	Straw treatment	Fraction of field overrun by harvest operation	Fraction of field covered by uncut stubble[b]	Fraction of field covered by windrowed straw[c]
	Municipality[d], county		cm	ha	cm		%	%	%
A	Maxwell, Glenn	M 401	98	44	41	Windrowed	40.6	59.4	19.4
B	Williams, Colusa	Kokuho Rose	115	24	55	Windrowed/ spread	41.0	59.0	21.0
C	Williams, Colusa	M 202	93	16	28	spread	26.3	73.7	—

[a] Source: UCCE, 1998.
[b] Fraction covered by uncut stubble only—i.e. not covered by loose straw.
[c] Fraction covered by windrowed straw on top of stubble, or the field surface.
[d] Nearest town to field.

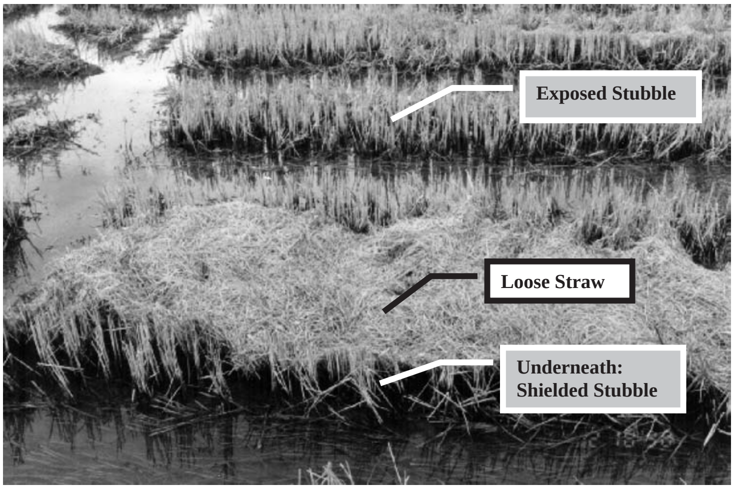

Fig. 1. Straw fractions sampled in Field A, February 1998.

and B, two different types of stubble were sampled: stubble that was not covered by other straw (hereafter referred to as "exposed" stubble), and stubble that was covered by loose straw, whether windrowed or spread ("shielded" stubble). This was done to investigate to what extent the loose straw inhibited the leaching of the stubble underneath. The different straw fractions that were sampled are indicated in Fig. 1. Samples were analyzed for moisture content (air oven method), elemental K, Cl, and S (single measurement per sample), and total ash (in triplicate by igniting in an air muffle furnace at 575°C for 2 h).

2.2. Straw collection operations and costs

Rice straw was mechanically collected in the fields at the end of the winter period. In total, 15.8 ha were collected in Field A and 24.1 ha in Field B. Straw collection practices consisted of swathing the remaining stubble, raking straw and stubble into windrows, baling into 3.6 m^3 ($1.2 \times 1.2 \times 2.4$ m^3) bales, and stacking the bales at the edge of the field adjacent to a road (roadsiding). Machinery used for these operations included a MacDon 9000 swather (MacDon Inc., Kansas City, MO), a Sperry New Holland Rotabar 460 rake (CNH Corporation, New Holland, PA), a Hesston 4900 baler plus accumulator (Hesston Corporation, Hesston, KS), and a John Deere 2020 tractor (Deere and Company, Moline, IL) with forklift for roadsiding.[1] During the straw collection operations, time and motion studies were conducted to estimate field capacities (ha h^{-1}) for swathing, raking, baling and roadsiding. Moisture and ash content of baled straw were determined from core samples obtained with a Penn State Forage sampler. Based on cost data provided by local farm machinery supplier, costs per hour of operation ($ h^{-1}) were determined for each operation. Straw collection costs per area ($ ha^{-1}) were then computed by dividing the costs per hour of operation by the observed field capacities. Straw collection costs per material collected ($ Mg^{-1}) were also computed by dividing collection costs per field area by the observed straw yield (Mg ha^{-1}). Straw collection costs were compared to data from commercial fall straw collection operations observed in October–November 1997 that included swathing, baling in the same sized bales, and roadsiding with similar equipment as noted above.

2.3. Probability of rainfall

To assess rainfall distribution and probability in the Sacramento Valley, historical precipitation data were obtained from the National Climatic Data Center (National Oceanic and Atmospheric Administration, Asheville, NC). For the analysis, the longest daily precipitation record in the area (Sacramento, 1878–1993) was selected to determine frequency distributions of cumulative rainfall for 4, 5, and 6 month time intervals starting on October 1 of each year. The historical data were also used to assess the feasibility of straw collection in the February–April period by determining probability of dry weather for time intervals ending on April 30 and advancing in 1 week increments from February 1 (i.e. February 1–April 30, February 8–April 30, February 15–April 30, etc.). Probability was defined by dividing the number of years with no precipitation (defined as less than 10 mm precipitation) in the interval by the total number of years in the record (115 for Sacramento). Finally, historical rainfall data were used to determine the distribution of rainfall in February–April by determining the probability of 0, 1 or 2 rainy days for the time intervals ending April 30. Again, probability was defined by dividing the number of years having a specified number of rainy days in the time interval by the total number of years. A rainy day was defined as any day with measurable precipitation (greater than 2.54 mm or 0.10 in in the historical records, the resolution of most rain gages).

3. Results and discussion

3.1. Field observations

Table 2 presents the sample yields and potential field yields for straw determined from the measurements made immediately after grain harvest. Among the three fields, Field A exhibits a much larger yield in loose straw than in stubble, which is consistent with the lower cut of straw (refer to stubble length in Table 1) and the fact that straw was discharged in windrows. For both Fields B and C, yields of stubble and loose straw are similar, although sample yields in Field B are higher compared to Field C. The taller plant variety and higher stubble length in Field B may have caused this difference. As shown in Table 2, total potential straw yield for the three fields ranged from 4.5 Mg ha^{-1} for Field B to 5.3 Mg ha^{-1} for Field C. The majority of the straw in Field A would come from the loose straw fraction (63% of total straw), whereas in Field B the majority of straw would come from the uncut stubble fraction (78%). In Field B, only 21% of the field was covered by windrows, which explains the low fraction of loose straw in total straw yield. In Field C, uncut stubble and loose straw contribute approximately equal amounts to the total potential straw yield. The potential straw yields shown in Table 2 are

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[1] Mention of brand names does not constitute endorsement by the University of California.

Table 2
Sample and potential field yields of straw[a]

Field	Handcollected loose straw[b] (kg m^{-2}) (range)	Handcollected Uncut stubble[b] (kg m^{-2}) (range)	Potential yield from loose straw[c] (Mg ha^{-1}) (% of total)	Potential yield from uncut stubble[c] (Mg ha^{-1}) (% of total)	Total potential straw yield (Mg ha^{-1}) (% of total)
A	1.68 (1.62–1.79)	0.33 (0.26–0.40)	3.3 (63%)	1.9 (37%)	5.2 (100%)
B	0.53 (0.52–0.54)	0.58 (0.42–0.72)	1.1 (24%)	3.4 (76%)	4.5 (100%)
C	0.37 (0.19–0.54)	0.36 (0.27–0.44)	2.8 (52%)	2.6 (48%)	5.3 (100%)

[a] All straw quantities on dry weight basis.
[b] Average of nine measurements.
[c] On total field area basis.

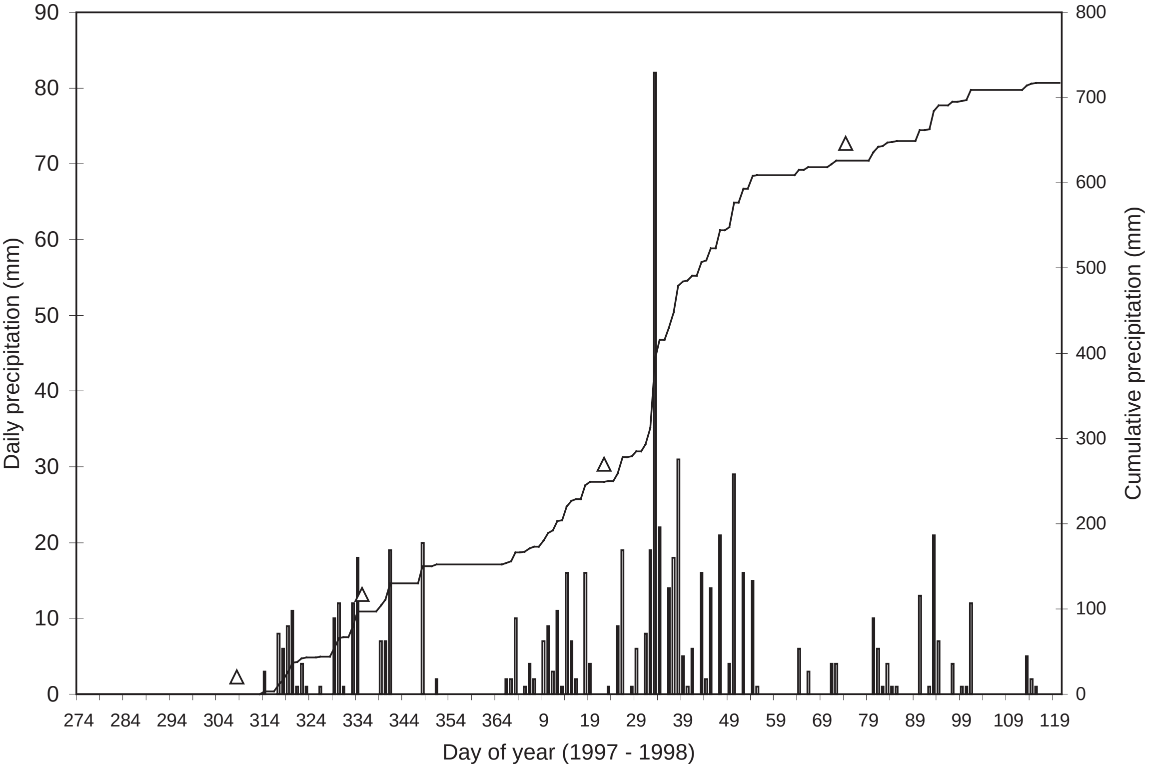

Fig. 2. Daily and cumulative precipitation on rice straw fields, Winter 1997–1998. Dates straw samples were collected are indicated by triangular symbols.

in good agreement with actual rice straw yields observed in commercially baled fields during the fall of 1997 that averaged 4.9 Mg ha^{-1} [13].

Fig. 2 presents daily and cumulative precipitation recorded by the weather station in the vicinity of the three fields. A total of 717 mm cumulative precipitation was received, with the majority of rainfall in the months of January and February, 1997. Monitoring of the fields during the rainy months revealed impacts of prolonged rainy weather on rice straw left in the field. Generally, water flooded the fields to several cm deep and remained for extended periods due to inadequate drainage, in addition to low air temperatures and cloudy weather (leading to low evaporation). Straw overrun during grain harvesting operations was completely submerged (Fig. 1). Flooding did not exceed 4 cm depth, except for a small (5%) section of Field A where the water depth exceeded the stubble height (45 cm) for more than 1 week. In Fields A and B, loose straw that was initially located on top of the stubble settled over time through the supporting stubble.

3.2. *Straw composition*

As indicated by the triangular markers in Fig. 2, samples of stubble and loose straw were collected on November 5, 1997, December 2, 1997, January 23, 1998, and March 16, 1998. Table 3 lists K, Cl, S and total ash concentrations of all samples taken from Fields A–C. There is considerable variability among straw compositions from the three fields, even between samples taken on the same date. The variability may be due to the rice variety (each field represents a different variety, as noted in Table 1), cultural practices (each field also represents a different grower), and other location-specific characteristics such as soil type, nutrient availability, and impact of birds and other animals during the winter season. The data in Table 3 suggest a few general trends that are important in assessing the feasibility of natural leaching. The average compositions for each sampling date show a gradual decline of K and Cl as the rainy season progresses, with highest concentrations on the first sample date (1.4% K and 0.5% Cl), and lowest concentrations on the fourth and last sample date (0.2% K and 0.1% Cl). This confirms earlier findings by Jenkins et al. [1,2] that close to 90% of K and Cl originally present in rice straw is removed by rain washing, at least for the majority of samples (the shielded stubble in Fields A and B being the exceptions). Using the K and Cl concentrations in Table 3, the remaining K and Cl fractions were calculated for the second, third, and fourth sampling dates. Results are shown in Fig. 3. The data clearly show the decline of K and Cl as the season progresses, even though differences between the second (97 mm cumulative precipitation) and third (249 mm cumulative precipitation) sampling dates are not always significant. For sulfur, average concentrations in Table 3 indicate a gradual increase with time, although differences are not significant due to the high variance. The reason for the S increase is unknown but is likely the result of organic matter loss leading to a higher S concentration in residual straw. Data for total ash by date are widely scattered with no apparent trend. The sample of straw from Field C with extremely high ash content (62.8%) was picked up from the field surface, and its ash content reflects the extensive decomposition of organic matter and soil contamination of straw that is submerged by flooding for extensive periods of time. Averages of total ash for individual fields (Fig. 4) show the overall higher concentration for rice straw in field A (variety M401; average ash 21.1%) compared to straw from Fields B (Kokuho Rose; 14.2% ash) and Field C (M202; 16.4% ash). As noted earlier, the differences may be due to rice variety as well as cultural practices, in particular irrigation and grain harvest practices leading to a larger amount of soil contamination. Data for total ash for Field B (Fig. 4) show a decline at 97 and 249 mm precipitation, followed by an increase at 626 mm. Straw from field C experiences a decline in ash through 97 mm rainfall, but then begins to increase. Total ash in Field A shows an opposite trend with an initial increase in ash and final decline. Differences may not be significant. Nevertheless, there are several processes that contribute to a change in ash concentration of straw over time in the field including extraction of inorganic constituents by leaching, decomposition of the organic fraction, and contamination from soil. Soil contamination can generally be detected from aluminum concentrations, as this element is mostly toxic to plants and not inherent in ash, but Al concentrations were not determined for these samples. Moisture content of straw on the second, third, and fourth sample dates (after rain had started) averaged 65% wet basis, with stubble samples generally exhibiting higher moisture content (69%) than windrowed samples (60%). These moisture contents are similar to those of rice plants just prior to harvest.

The possible leaching-inhibiting effect of stubble covered by loose straw was evaluated by analysis

Table 3
Compositions of rice straw field samples[a]

Sample date	Field	Straw configuration	K (%)	Cl (%)	S (ppmm)[b]	Ash (%)
11/5/97	A	Loose straw	1.55	0.28	590	22.5
11/5/97	A	Exposed stubble	1.85	0.37	930	16.6
11/5/97	B	Loose straw	1.27	0.35	500	15.8
11/5/97	B	Exposed stubble	1.03	0.78	900	14.2
11/5/97	C	Loose straw	1.78	0.52	620	15.3
11/5/97	C	Stubble	1.15	0.66	1050	16.6
		Average	1.40	0.50	765	16.8
		Std.dev.	0.34	0.20	223	2.9
12/2/97	A	Loose straw	0.90	0.13	840	22.8
12/2/97	A	Exposed stubble	0.75	0.11	650	16.6
12/2/97	A	Shielded stubble	1.59	0.24	810	24.5
12/2/97	B	Loose straw	0.51	0.11	640	14.4
12/2/97	B	Exposed stubble	0.13	0.13	990	12.5
12/2/97	B	Shielded stubble	0.81	0.50	1380	15.7
12/2/97	C	Loose straw	0.69	0.16	500	14.6
12/2/97	C	Stubble	0.55	0.15	1310	15.9
		Average	0.70	0.20	890	17.1
		Std.dev.	0.42	0.13	318	4.2
1/23/98	A	Loose straw	0.71	0.08	460	24.2
1/23/98	A	Exposed stubble	0.27	< 0.01	810	17.6
1/23/98	A	Shielded stubble	1.44	0.23	860	24.3
1/23/98	B	Loose straw	0.26	0.04	630	13.4
1/23/98	B	Exposed stubble	0.34	0.35	1310	11.9
1/23/98	B	Shielded stubble	0.32	0.28	1020	14.3
1/23/98	C	Loose straw	0.76	0.15	560	15.9
1/23/98	C	Stubble	0.20	0.05	980	15.5
		Average	0.50	0.20	829	17.1
		std.dev.	0.42	0.13	278	4.7
3/16/98	A	Loose straw	0.21	0.01	820	20.6
3/16/98	A	Exposed stubble	0.09	0.01	560	20.3
3/16/98	A	Shielded stubble	0.67	0.05	760	21.8
3/16/98	B	Loose straw	0.10	0.01	630	15.5
3/16/98	B	Exposed stubble	0.11	0.22	1990	13.0
3/16/98	B	Shielded stubble	0.33	0.40	2690	15.8
3/16/98	C	Loose straw	0.13	< 0.01	480	62.8
3/16/98	C	Stubble	0.13	0.03	950	21.3
		Average	0.20	0.09	1110	23.9
		Std.dev.	0.20	0.14	796	16.1

[a] All compositions on dry weight basis.
[b] Parts per million mass.

of variance (ANOVA) with the compositional data from Fields A and B. To facilitate this, compositions were normalized and grouped in a split-plot design with Fields A and B as blocks, sampling date as main treatment, and straw configuration (loose straw, exposed stubble, shielded stubble) as subtreatments. As expected from the results described above, mean compositions for the main treatment (sampling date) were significantly different at the 5% level for K and Cl, whereas for

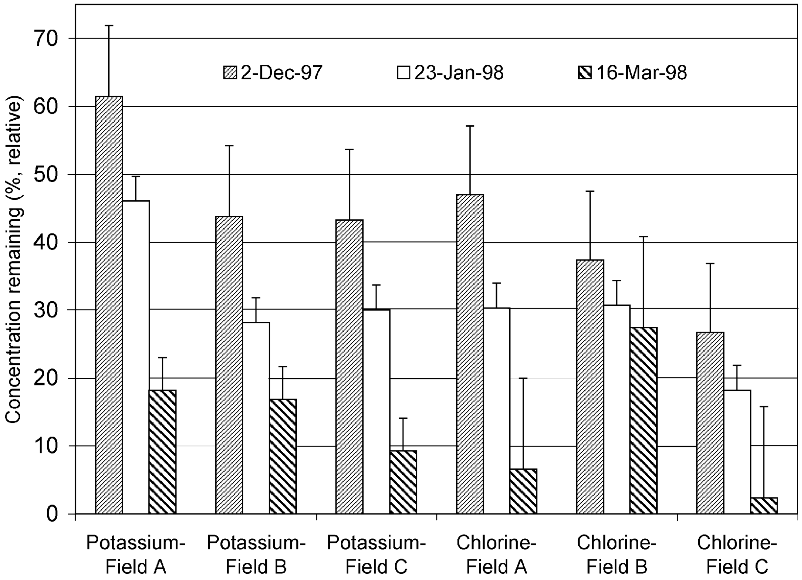

Fig. 3. K and Cl fractions in composite straw samples by field and sampling date relative to original concentrations (composite from all sampled straw fractions; error bars represent one standard deviation).

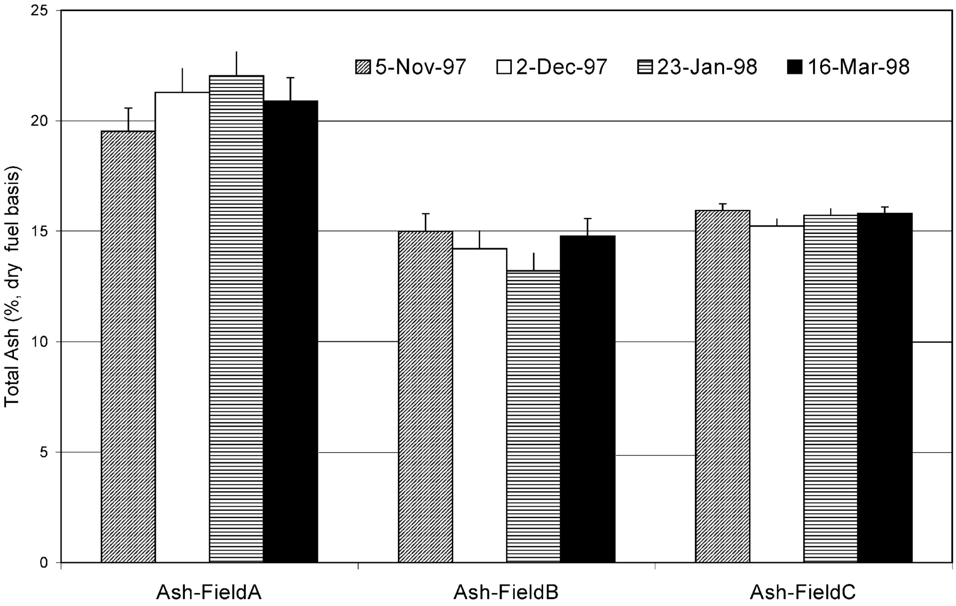

Fig. 4. Ash concentration (% dry matter) of composite rice straw samples by sampling location and date (composite from all sampled straw fractions; error bars represent one standard deviation).

Table 4
Average compositions for loose straw and exposed and shielded stubble in Fields A and B

	K (% DM)	Cl (% DM)	S (ppmm)	Total ash (% DM)
Loose straw	0.7a	0.13a	639a	18.6a
Exposed stubble	0.6a	0.25a	1018b	15.3a
Shielded stubble	1.0b	0.36b	1169b	18.4a

Means with same letter are not statistically different at 5% (Duncan's Multiple Range Test).

S and total ash, means were not significantly different. Results for the subtreatments (Table 4) show that shielded stubble has significantly higher concentrations of K and Cl than exposed stubble and loose straw, suggesting that the thatching effect of straw does reduce leaching rate. For S and total ash however, concentrations in shielded stubble were not significantly different.

3.3. Straw collection operations

By the end of the rainy period in April 1998 straw and stubble in many locations of Fields A and B had settled to the soil surface making collection by conventional straw collection equipment difficult. Even so, a considerable amount of straw was left in Fields A and B that justified mechanized collection. Fig. 5 shows a section of Field A where straw could be collected. Straw in Field C was not collected due to more extensive decomposition and settling. Straw decomposition in this field may have been enhanced by the lower stubble height, spreading rather than windrowing, and the macerating effect of the thresher used at grain harvest. Equipment mobility in Field A was quite poor, and stubble in only one-third of the field could be swathed. Plugging of the swather header by windrowed straw was a frequent problem, leading to slower speeds and greater unproductive time. Swathing was also difficult in Field B due to high soil moisture, low soil strength, poor equipment mobility, and plugging of the header by windrowed straw.

Following swathing, straw was baled during the last week of April. The extended rainy season, the longer drying times, and the equipment mobility problems delayed the field preparation activities for the next growing season in field A, but a new rice crop for the 1998 growing season was planted. While the majority of remaining stubble in Field B was swathed in early May, straw was not baled until mid-June due to additional rainfall in May. The field was taken out of production for the 1998 season to allow time for straw collection. Straw yields for Fields A and B are shown in Table 5 along with moisture and ash contents of samples taken from selected bales. Straw yield in Field A averaged 3.35 Mg ha^{-1}, or 65% of the 5.2 Mg ha^{-1} potential straw yield shown in Table 2. Straw collected from Field B amounted to 2.22 Mg ha^{-1} or 49% of original potential yield (4.5 Mg ha^{-1}). The yield data reflect an extensive loss of straw associated with the rainfall received during this particular season, the long residence time of straw in the field, the high straw moisture, and the organic matter decomposition over time. Furthermore, straw yields were reduced because not all stubble could be swathed, leaving some of the uncut stubble behind in the field. The yield of straw in Field B may have further declined due to the additional time necessary to take the straw out of the field after swathing, with the warmer temperatures enhancing the rate of organic matter decomposition. The difference in ash content of baled straw between Fields A and B reflects a difference in rice variety (ash content of straw prior to rainfall was 21.2% in Field A, and 15.2% in Field B) and increased contamination of straw with soil in Field A due to added operations in straw collection.

3.4. Straw collection costs

Table 6 presents operating costs for equipment for collection crude rice straw during the fall of 1997 (using machinery performance data from Bakker-Dhaliwal et al., 1998). Table 6 also shows

Fig. 5. View of remaining straw in Field A at the end of the rainy season, April 1998.

Table 5
Yields of rice straw collected in April/May 1998

Field	Harvested area (ha)	Quantity of straw baled (Mg)	Yield[a] (Mg ha^{-1})	Straw moisture (% wet basis)	Ash[b] (%)
A	15.8	53.0	3.35	10.8	32.2
B	24.1	53.5	2.22	8.2	17.9

[a] Yield on dry basis.
[b] Dry weight basis.

Table 6
Equipment performance and costs for field collection of rice straw[a]

Operation	Equipment costs per hour[c] (\$ h^{-1})	Field capacity[b] (ha h^{-1})		Costs per field area (\$ ha^{-1})	
		Fall 1997 (crude straw)	Spring 1998 (leached straw)	Fall 1997 (crude straw)	Spring 1998 (leached straw)
Swathing	43.41	2.1	1.2	20.67	36.18
Raking	27.48	—[d]	4.6	—[d]	5.97
Baling	101.52	3.1	3.2	32.75	31.73
Roadsiding	30.96	5.9	9.7	5.25	3.19
		Total cost per field area (\$ ha^{-1})		58.67	77.07
		Straw yield (Mg ha^{-1})		4.2	2.9
		Costs per material collected (\$ Mg^{-1})		13.97	26.58

[a] Observed area: Fall 1997: 46.5 ha; Spring 1998: 15.8 ha.
[b] Field capacity includes turning time and machine-related idle time.
[c] Based on equipment costs provided by machinery supplier.
[d] No raking performed during Fall 1997 operations.

harvesting costs for leached straw during the spring 1998 derived from time and motion studies of the equipment operations. Fall operations did not include a raking operation. Raking in spring 1998 was necessary to enhance drying of soil located underneath the straw to improve mobility for the heavier baling equipment. Also, in field sections that had suffered extensive loss of straw during the winter, raking was done to combine windrows prior to baling and improve field efficiency. Equipment costs per hour are highest for the baling operation ($101.52 h^{-1}) due mostly to the higher capital costs for baling equipment. Comparison of field capacities of Fall 1997 and Spring 1998 operations reveal that swathing capacity was 43% lower for collection of leached straw due to the difficulties encountered with the swather, as noted earlier. Roadsiding capacity (ha h^{-1}) was 64% higher for leached straw, reflecting the smaller number of bales retrieved due to the lower straw yield in Spring 1998. Total costs for collecting rice straw on an area basis are 31% higher for leached straw ($77.07 ha^{-1}) compared to unleached straw in the fall ($58.67 ha^{-1}). This increase is primarily due to higher costs for swathing and an additional raking operation in Spring 1998. Costs for collection on a material basis are 90% higher in Spring 1998 ($26.58 Mg^{-1}) than in Fall 1997 ($13.97 Mg^{-1}) due to the much lower dry matter yield in the spring (2.7 Mg ha^{-1}) compared to the fall (4.1 Mg ha^{-1}). In summary, the extensive loss of straw incurred over the winter period resulted in a significant increase in costs for collecting the leached straw. The sensitivity of collection costs at the observed straw yields (as indicated by the slope on the appropriate curve in Fig. 6) is −9.04$ ha Mg^{-2} for Spring 1998, and −3.36 for Fall 1997. These results indicate that there are potentially much larger risks associated with spring collection operations at lower straw yields.

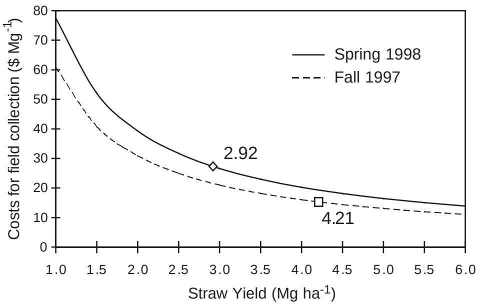

Fig. 6. Costs for field collection of rice straw as a function of straw yield (markers indicate observed straw yields in Mg ha^{-1}).

Table 7
Frequency[a] (%) of cumulative precipitation received in Sacramento for time intervals starting on October 1

Cumulative rainfall (mm)	Time interval		
	October 1–January 31	October 1–February 28	October 1–March 30
< 100	5.2	1.7	0.0
< 150	25.2	7.0	2.6
< 200	39.1	15.7	7.0
< 250	60.9	30.4	13.9
< 300	67.0	47.0	27.8
< 350	81.7	64.3	42.6
< 400	90.4	75.7	60.9
< 450	93.9	82.6	71.3
< 500	96.5	87.0	79.1
< 550	97.4	91.3	83.5
< 600	98.3	94.8	85.7
< 650	100.0	99.1	94.8

[a] Frequency that the precipitation is less than shown for the indicated time interval.

3.5. *Probability of leached straw collection*

Table 7 presents the cumulative frequency of total precipitation received in Sacramento for three time intervals starting on October 1, based on the historical rainfall data from 1878–1993. As an example, if 250 mm of rainfall is arbitrarily used as benchmark for extensive leaching of straw (data in Table 3 suggest that 250 mm of cumulative rainfall results in removal of two-thirds of K and three-quarters of Cl), the probability of having received less than sufficient rain on January 31 is 61%. In other words, having well-leached rice straw in the field by the end of January can only be expected in approximately four out of every 10 years. If the field leaching period however is extended through February (5 months), or through March (6 months), the probability of having less than sufficient rain for leaching declines to 30.4% and 13.4%, respectively. Therefore, these data show that cumulative rainfall is not likely a constraint in the feasibility of leaching rice straw in California. The greater limitation lies in field accessibility for straw collection equipment. Data in Table 7 further show that the probability of receiving 100 mm or more of cumulative rainfall is very high (i.e. 94.8%, 98.3%, and > 99% for the three time intervals, respectively). Therefore, even in relatively dry years, significant leaching of K and Cl from straw can be anticipated since data in Table 3 indicate that even 100 mm of rain can lead to 47% reduction in K and 58% reduction in Cl.

Historical rainfall data are also helpful in assessing how much straw can be collected at the end of the leaching period, and whether there is a time interval or "window of opportunity" available to collect the leached biomass. To formulate a general benchmark that would indicate the amount of rainfall above which extensive losses of straw in the field can be anticipated is difficult, as there are many other factors besides rainfall quantity that may contribute to straw yield decline including intensity of rainfall, flooding tendency of the field, geographical location, straw configuration in the field, and straw collection practices. If, however, an arbitrary benchmark of 500 mm of cumulative precipitation is defined above which severe flooding of fields and extensive decomposition of straw can be expected, Table 7 indicates a probability of 10–20% within the October 1–March 30 period. The feasibility of collecting leached straw at the end of the winter period will further depend on the occurrence of sufficient dry weather in the February through April period allowing for drying of soil and straw. Fig. 7, shows probabilities of receiving no precipitation and less than 10 mm of precipitation during the months of February through April, in Sacramento. The figure shows that prior to March 22, there is a zero probability of receiving no precipitation, but in the interval April 22–April 30, the chance rises to 50% for receiving no rain (alternatively, this suggests there is a 50% chance of receiving some rainfall). Fig. 7 also indicates that the probability of receiving less than 10 mm of rain sharply increases starting after March 22. Although the feasibility of collecting rice straw in March or April depends on a number of factors, it is likely that the probability curve for straw collection shows a similar trend as the curves in Fig. 7. In other words, collecting rice straw prior to March 22 is not likely due to continued rainfall, while there is at least a good probability of collecting straw between March 22 and the end of April. The actual probability for spring collection will shift to later times due to the need for drying of straw and soil after the last rain is received on the field. The length of the drying time depends on a large number of factors (e.g. air temperature, wind speed and direction, field conditions at the start of drying, straw configuration in the field) but a larger amount of cumulative rainfall received during the winter months will likely result in a longer drying time.

Besides the total quantity of rain received in February, March, or April, feasibility of spring collection will depend on how the rain is distributed, in other words how many rain events there are in the time interval that straw collection is attempted. Although one rain event may not significantly affect spring collection (depending on rain quantity and intensity), several rainy days within this period will likely impede, if not preclude, straw collection. Fig. 8 gives the probability of a specified number of rainy days for times through the end of April. Probability curves in the figure indicate a similar trend as for rainfall shown in Fig. 7: the probability of having one rainy day or no rain increases from 10% for the March 22–April 30 interval to 82% for the April 22–April 30 interval.

The timing of straw collection in spring is dictated by the planning of field preparation activities for the next crop, assuming that rice or other crops are grown every year. The suggested planting dates for rice varieties grown in the Sacramento Valley range from April 25th to May 25th depending on variety and location [14]. Assuming that a 15-day period prior to planting is necessary for soil preparation and related activities, the latest dates for field collection of leached rice straw in the spring range from April 10th to May 10th. Fig. 9 indicates the number of days that are available for spring collection as a function of the required planting date for the next crop and the time interval necessary for field drying of straw and soil. Assumptions in determining the curves are that spring collection is not feasible prior to March 22, and that a 15 day period is needed for soil preparation prior to actual planting. Fig. 9 shows that in relatively wet years (assuming 20 days are needed for drying straw and field), the window of opportunity for straw collection is approximately 30 days for the later planting date (May 25) and 15 days for the intermediate planting date (May 10), but that there is no opportunity for straw collection for the early planting date (April 25).

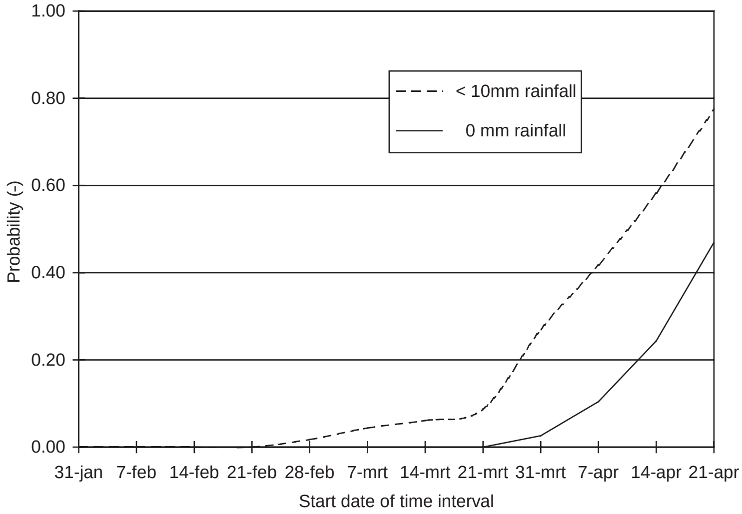

Fig. 7. Probability of rainfall for time intervals ending on April 30 (Sacramento, 1878–1993).

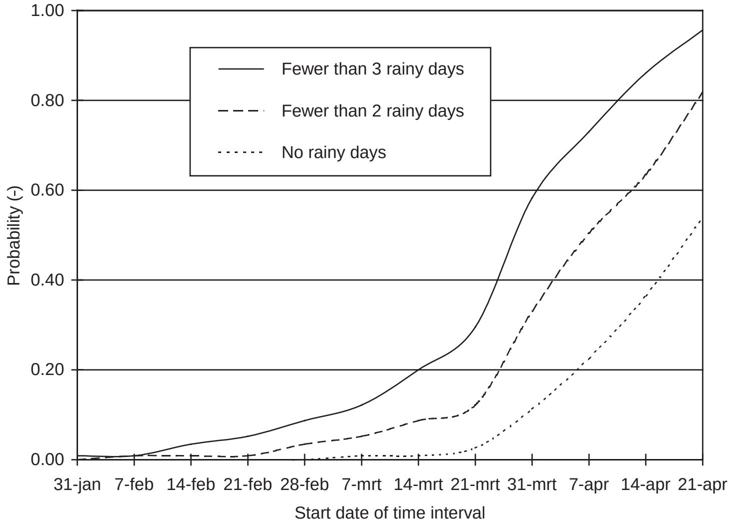

Fig. 8. Probability of number of rainy days for time intervals ending on April 30 (Sacramento, 1878–1993).

In relatively dry years (assuming only 5 days of drying time are needed), the window of opportunity ranges from approximately 45 days for the late planting date to 15 days for early planting date.

3.6. Costs of natural and industrial leaching

Given the recent interest of leaching biomass crops at an industrial site, it is relevant to compare the cost of collecting naturally leached straw with straw that is collected in the fall and leached by means of an industrial process. Table 8 presents a comparison of incremental fuel costs of naturally leached straw and industrially leached straw (e.g. fall-harvested straw that is leached at a power plant site). Cost data are based on the data presented here, in addition to earlier cost projections for industrial leaching [3], costs estimates for transportation and straw conversion [15], and nutrient replacement cost estimates [16]. Collection costs for naturally leached straw are higher

Table 8
Comparison of incremental fuel costs for naturally leached rice straw and centrally leached straw

	Natural leaching (\$ Mg^{-1})	Industrial leaching (\$ Mg^{-1})	Difference natural leaching-industrial leaching (\$ Mg^{-1})
Collection costs	26.58	13.97	12.61
Transportation	7.32	7.32	0
Straw leaching			
Leaching + dewatering	0	10.22	−10.22
Leachate treatment	0	5.88	−5.88
Increased fuel input	0	1.78	−1.78
Conversion costs			
NO_x management	0.26	0.26	0
Ash handling	1.62	0.84	0.78
Total	35.78	40.27	−4.49
Fertilization costs	4.33	17.18	−12.85
Total (incl. nutrient replacement costs)	41.73	58.29	−16.56

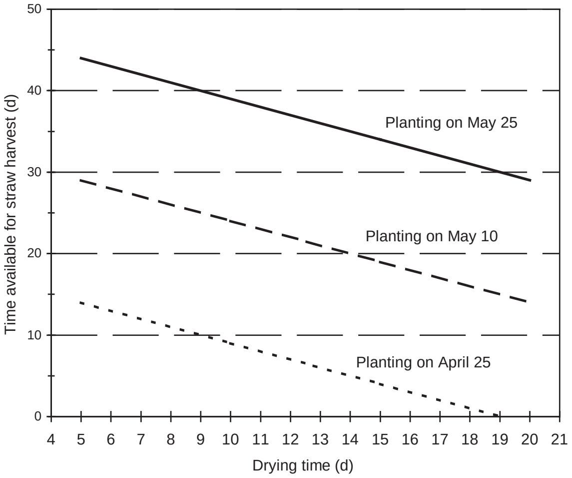

Fig. 9. Days available for spring collection of rice straw as a function of the straw drying time and required planting date for the next crop.

on a material basis due to the lower yield, as reported above. Transportation costs include average costs for a short-haul transport of 32 km, and are assumed to be equal for both straw fuels, although higher package densities with leached straw may lead to lower transport costs as will be noted later. Fuel processing costs for leaching at the industrial location include costs for leaching, dewatering, leachate treatment, and costs for increased fuel input. The data are based on a 135 Mg d^{-1} sized facility that would provide 20% of total fuel input of a 25 MW_e power plant. The additional fuel input serves to offset the decline of 1.78 MJ kg^{-1} in heating value that occurs due to higher as-fired moisture content of industrially leached straw compared to naturally leached straw. Conversion costs related to firing straw in a facility that is normally using more beneficial fuels such as wood include costs related to increased NO_x emissions from higher fuel nitrogen in straw (assumed to be equal for both naturally and industrially leached straw), and ash handling costs (assumed to be higher for naturally leached straw with an ash content of 33% compared to 17% for industrially leached straw). The lower costs of collecting straw for industrial leaching are entirely offset by the costs of the leaching process. Total incremental costs of industrial leaching exceed those of naturally leaching by approximately 12.5%. However, if the costs related to nutrient replacement are taken into account, the incremental costs of industrial leaching are as much as 40% higher because much larger quantities of nutrients need replacement.

4. Conclusions and recommendations

Observations of three commercial rice fields during October 1997 through April 1998 indicate that potassium and chlorine are substantially leached from rice straw by rainfall regardless of rice variety, grain harvest method, straw arrangement (i.e. loose straw, stubble, windrowed, spread), or stubble height. Leaching of sulfur by natural precipitation was not clearly established, however, and total ash content of straw initially declined with increasing precipitation, but then increased due to decomposition of straw organic matter and contamination with soil. A controlled experiment that eliminates location-specific factors such as flooding, soil contamination, and straw yield could perhaps better assess differences in leaching behavior of S and ash than the method followed in this study (i.e. sampling on commercial farms with no direct control over specific factors). Leached straw was successfully collected by conventional equipment in spring, even though equipment had to operate under difficult conditions, but straw collection in one field was only possible after an untimely delay, and was not possible in another due to the effects of flooding. The observations and experiences obtained during the 1997–1998 season may signify a “worst case scenario” with regards to straw collection in spring because the cumulative precipitation received during this El Niño associated event was well above the historical average. The high rainfall might also have resulted in greater leaching than otherwise would occur, although indications are that in most years rainfall is adequate.

Due largely to the much lower straw yield in spring, collection costs for leached straw on a material basis were 90% higher than straw collected in the fall. It should be noted that the cost estimates did not include indirect costs or benefits related to collection of leached straw through improvements in fuel value, management of remaining (i.e. not collected) residues, and recycling of nutrients. In many fall operations, straw residues that are not recovered by baling are incorporated in the soil shortly after straw bales have been removed from the field. The advantage of this practice is that following incorporation, residual straw is subject to conditions that enhance straw decomposition for several months during the rainy period. After spring collection of leached straw, unrecovered straw residues are incorporated as well, but the time period available for straw to decompose before the new crop is planted is reduced from several months to several weeks. Although spring-collected straw has undergone some organic matter decomposition and warmer spring temperatures accelerate decomposition, the presence of poorly decomposed straw may have a negative effect on crop growth, or directly impede field preparation for planting. The cost estimates also do not include potential benefits of spring collection that are related to recycling of plant nutrients, in particular potassium. Spring collection of rice straw might lead to a reduced fertilization equivalent to \$54 ha^{-1} compared to fall [16]. Therefore, indirect costs (insufficient decomposition of unrecovered straw) and benefits (improved nutrient recycling) of spring collection should be evaluated. The transportation cost of straw (i.e. transport from roadside to storage or utilization plant site) was not incorporated because the assumption was made that the cost for transporting straw is independent of whether straw is leached or not. From observations made during Spring 1998 however, there is some indication that leached rice straw bales achieve higher density (185 kg m^{-3} compared to 170 kg m^{-3}) and therefore would improve truck payloads. These observations have so far not been confirmed.

Historical rainfall data for the Sacramento Valley reveal that the probability of receiving insufficient rainfall for substantial natural leaching of rice straw during the six months following grain harvest is less than about 15%. There is a time interval of 0–45 days available for mechanized collection of rice straw in spring, depending on drying time needed to accomplish favorable field conditions and on planting date for the succeeding crop. Probability curves for rainfall and rain events in February–April indicate that the most likely earliest date for leached straw collection would occur in or after the last week in March. The feasibility of collecting rice straw in spring would be improved if straw collection equipment were better equipped to operate under wet field conditions than currently is the case, as straw moistures will decline faster than soil moistures.

The feasibility of spring collection is dictated by the seasonality of crop production (start and end of growing season), the weather (distribution and intensity of rainfall), and agronomic practices (grain harvesting, land preparation, management of remaining straw, etc.). In relatively dry years, the total amount of rainfall received on the field may be insufficient to leach biomass for combustion purposes, while in relatively wet years (i.e. years with precipitation much higher than the historical average), natural leaching may be accompanied by extensive loss of organic matter and fuel value, in addition to difficulties with timely collection at the end of the rainy season as illustrated by the field observations described in this paper. Although a window of opportunity for spring collection of rice straw can be predicted on the basis of the seasonality of these factors, the economic potential of natural straw leaching is likely more affected by risks associated with the largely unpredictable straw yield. Leaving straw in the field for 5–7 months may lead to extensive loss of dry matter. Agronomic practices will need adaptation if collection of naturally leached straw is pursued on a large scale. Future evaluations of collection of rice straw in spring therefore should assess how current farm practices could be adjusted to optimize the feasibility of collection in spring. For instance, traffic patterns during grain harvest operations could be modified in order to increase the potential straw yield or harvesting methods that avoid trafficking over straw and stubble could be developed [17]. In case timely removal of leached straw in the spring is not feasible, allowing field burning of straw as a contingency in the spring, although undesirable from an environmental point of view, would reduce the economic risk that is associated with spring collection. Smoke dispersion in the Sacramento Valley is greater in the spring than in the fall, so that a shift towards leaching might on average improve air quality overall if it results in greater straw utilization and less fall burning. Finally, an important element in the feasibility of rice straw collection is the availability of sufficient labor and equipment for straw collection, especially when the time interval for collection is short. During fall collection operations, labor and equipment shortages often lead to baled straw remaining in the field for extended periods after baling, and this leads occasionally to interference with other field operations [13]. In the spring, earlier mobilization of farm operations might be possible with reduced likelihood of labor and equipment shortages, and possible economic benefits to the local communities. Any shortages, however, would make spring collection untenable due to the short time available prior to planting.

Even with lower dry matter yields and higher collection costs, natural in-field leaching appears to be lower cost than industrial leaching of crude straw. In-field leaching avoids the cost of capital equipment needed for washing straw at a facility site as well as costs associated with leachate treatment and disposal and costs of nutrient replacement due to higher nutrient export in crude straw compared with field leached straw. Both leaching techniques result in higher costs compared with crude straw collection alone, and economic benefits of leaching accrue only where crude straw cannot be used directly. Improved systems for in-field and industrial leaching should continue to be investigated in order that the fuel and agronomic benefits may be realized.

Acknowledgements

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References

[1] Jenkins BM, Bakker RR, Wei JB. On the properties of washed straw. Biomass and Bioenergy 1996;10(4):177–200.

[2] Jenkins BM, Bakker RR, Baxter LL, Gilmer JH, Wei JB. Combustion characteristics of leached biomass. In: Bridgewater AV, Boocock DGB, editors. Developments in thermochemical biomass conversion. London: Blackie Academic and Professional, 1996. p. 1316–30.

[3] Bakker RR. Biomass fuel leaching for the control of fouling, slagging, and agglomeration in biomass power generation. Unpublished PhD dissertation, University of California, Davis, USA, 2000.

[4] Bakker RR, Jenkins BM, Williams RB. Fluidized bed combustion of leached rice straw. Energy and Fuels 2002;16:356–65.

[5] Bakker RR, Jenkins BM, Williams RB, Carlson W, Duffy J, Baxter LL, Tiangco VM. Boiler performance and furnace deposition during a full-scale test with leached biomass. In: Overend RP, Chornet E, editors. Making a business from biomass in energy, environment, chemicals, fibers and materials. Oxford: Pergamon, 1997. p. 497–510.

[6] Jenkins BM, Williams RB, Bakker RR, Blunk S, Yomogida DE, Carlson W, Duffy J, Bates R, Stucki K, Tiangco VM. Combustion of leached rice straw for power generation. In: Overend RP, Chornet E, editors. Biomass: a growth opportunity in green energy and value-added products. Oxford: Pergamon, 1999. p. 1357–63.

[7] Turn SQ, Kinoshita CM, Ishimura DM. Removal of inorganic constituents of fresh herbaceous fuels. Biomass and Bioenergy 1997;12(4):241–52.

[8] Jenkins BM, Bakker RR, Williams RB, Baxter LL, Turn SQ, Thy P, Sime M, Lesher C, Sclippa G, Kinoshita C. Measurements of the fouling and slagging characteristics

of banagrass (*Pennisetum purpureum*) following aqueous extraction of inorganic constituents. In: Overend RP, Chornet E, editors. Making a business from biomass in energy, environment, chemicals, fibers and materials. Oxford: Pergamon, 1997. p. 705–18.

[9] Landstrom S, Lomakka L, Anderson S. Harvest in spring improves yield and quality of reed canary grass as a bioenergy crop. Biomass and Bioenergy 1997;11(4):333–41.

[10] Burvall J. Influence of harvest time and soil type on fuel quality in reed canary grass. Biomass and Bioenergy 1997;12(3):149–54.

[11] Sander B. Properties of Danish biofuels and the requirements for power production. Biomass and Bioenergy 1997;12(3):177–83.

[12] Joergensen U, Sander B. Biomass requirements for power production: how to optimise the quality by agricultural management. Biomass and Bioenergy 1997;12(3):145–7.

[13] Bakker-Dhaliwal R, Jenkins BM, Lee H, Bernheim L. Rice straw harvesting and handling for off-field utilization. Annual Report presented to US. Department of Agriculture, University of California, Davis, CA, USA, 1998.

[14] UCCE. Rice varieties. University of California Cooperative Extension, University of California, Davis, CA, USA, 1997. http://agronomy.ucdavis.edu/uccerice/index.htm, 1997.

[15] Jenkins BM, Bakker RR, Williams RB, Bakker-Dhaliwal R, Summers MD, Lee H, Bernheim LG, Huisman W, Yan LL, Andrade-Sanchez P, Yore M. Commercial feasibility of utilizing rice straw in power generation. Proceedings of the Bioenergy 2000: Moving Technology to the Marketplace (CD-ROM). Madison, WI: Omnipress International, 2000.

[16] Yomogida DE, Jenkins BM. Nutrient replacement for rice fields under straw removal, soil incorporation, and burning management. In: Overend RP, Chornet E, editors. Making a business from biomass in energy, environment, chemicals, fibers and materials. Oxford: Pergamon, 1997, p. 257–67.

[17] Yore MW, Summers MD, Jenkins BM. Development of a stubble cutting system for a combine harvester. Paper No. 011087, ASAE, St. Joseph, MI, 2001.