Nitrogen Availability from Poultry Litter and Pelletized Organic Amendments for Organic Rice Production

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ABSTRACT

Nitrogen is the most limiting nutrient in irrigated rice (*Oryza sativa* L.) production, and growers continue to be faced with the challenge of meeting crop N demand, particularly in organic production systems. The main objective of this study was to determine how rice yield was affected by seasonal availability of N from organic sources under continuously and noncontinuously flooded conditions. Laboratory and field experiments were conducted to determine the effectiveness of the commonly used poultry litter, pelletized organic fertilizers (blood, meat, and feather meal 13–0–0, feather meal 12–0–0, poultry litter plus feather meal 6–3–2), and $(NH_4)_2SO_4$, in synchronizing the supply of mineralized N with the demand of N by rice. The N mineralization of all organic fertilizers occurred primarily during the first 53 d after planting, results which were confirmed subsequently in a laboratory incubation study. In all fields, fertilizers increased grain yield and N uptake relative to a zero N control. Relative to poultry litter, the pelletized fertilizers resulted in higher yields (9980 vs. 9267 kg ha^{-1}), N uptake (140 vs. 114 kg ha^{-1}), and N recovery efficiency (35 vs. 20%) in all fields. It was concluded that pelletized fertilizers were significantly more effective than poultry litter in supplying N to the crop when fields were continuously flooded. In contrast all organic fertilizers were less effective in supplying N when fields were drained for weed control due to lower N recovery efficiency (26%) and N loss through denitrification, indicating that organic fertilizer application may not be economically viable under such circumstances.

Organic rice is produced on 20,000 ha in the United States, and California is the single largest producer with 9400 ha (USDA-Economic Research Service, 2008), most of which is grown in the Sacramento Valley. In this region N fertilizer has traditionally been applied as poultry litter, because cover crops do not grow well on the heavy textured, high clay soils of the Sacramento Valley. While poultry litter is relatively cheap, its low N concentration and bulk density can lead to high transport costs per unit N (Hadas et al., 1983). Furthermore, poultry litter is challenging to manage due to inconsistent nutrient content and release (Sims, 1986; Rees et al., 1993; Chadwick et al., 2000), Also, due to its relatively high P content, continued applications of poultry litter to meet an N requirement can lead to high soil P contents (Linquist et al., 2010) and the possibility of off-site contamination (Pote et al., 1996; Golden et al., 2006). Finally, key changes in the poultry industry including increased regulation of unprocessed organic wastes, a shift toward in-house pelletization by major producers, and an increase in the use of sterilants and absorbents in poultry houses necessitating less-frequent litter renewal, have recently led to decreased availability of poultry litter for the organic production market, even as demand for this N-source has grown (L. Benson, personal communication, 2008). Collectively, these factors have resulted in organic growers searching for alternative sources of organic N.

One strategy to combat the disadvantages of using poultry litter in field-scale production is to isolate the fine fraction and pelletize it (Ndegwa et al., 1991). Pelletizing poultry litter increases bulk density and particle size uniformity (McMullen et al., 2005) and concentrates nutrients, resulting in a more rapidly mineralizable form of N (Hadas et al., 1983). Lopez-Mosquera et al. (2008) found that pelletized poultry litter had more stable nutrient characteristics, no fecal bacteria, no odor, and was easier to transport, store and apply in the field than fresh poultry litter. Studies comparing fresh and pelletized poultry litter have found that similar amounts of N are mineralized (Hadas et al., 1983; Cabrera et al., 1993) and plant N uptake and yield are similar regardless of litter form (Golden et al., 2006). In addition to poultry litter, blood meal, meat meal, and feather meal have been commercially pelletized and are being used as fertilizer for horticultural crops (Gaskell and Smith, 2007); however they have not been evaluated in rice production systems.

In all crop production systems improved synchronicity between N supply and crop N demand can lead to increased N use efficiency; however synchronicity may be more difficult to achieve with organic fertilizer N sources due to variable N mineralization rates (Sims, 1986; Dahlin et al., 2005). Golden et al. (2006) reported that asynchronicity of N supply with plant N demand results in low nitrogen recovery efficiency (NRE) of poultry litter-N (14%) and concluded that maximum grain yields could only be achieved with prohibitively high rates (270 kg N ha^{-1}) of poultry litter. In contrast, poultry manure NRE in rice systems in India showed 33 to 37% of N applied as poultry manure being recovered each season, and was similar to the NRE of urea (28–43%) at that field site (Bijay-Singh et al., 1997). These discrepancies may be attributable to

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Published in Agron. J. 103:1284–1291 (2011)
Posted online 9 Jun 2011
doi:10.2134/agronj2011.0005

Table 1. Soil characteristics (0–15 cm) of the three field trial sites in 2008 and 2009.

Field	pH	Clay-silt-sand	Organic carbon	Total N	Exchangeable–K	Olsen-P
		%	g kg^{-1}		mg kg^{-1}	
Continuously flooded 2008	4.9	49–33–18	17	1.4	171	10.4
Continuously flooded 2009	6.1	48–42–10	13	1.2	74	5.8
Drained 2009	6.5	47–42–11	12	1.2	81	10

differences in the condition and composition of the poultry litter, environmental conditions, and management practices.

While the number of field trials have been limited, several laboratory studies have examined N mineralization from poultry litter (Castellanos and Pratt, 1981; Hadas et al., 1983; Sims, 1986; Bitzer and Sims, 1988; Cabrera et al., 1993), blood meal (Ciavatta et al., 1997; Agehara and Warnacke, 2005; Hartz and Johnstone, 2006; Cayuela et al., 2009), and feather meal (Hadas and Kautsky, 1994; Hartz and Johnstone, 2006). In all of these studies, laboratory incubations were performed over periods ranging from 35 to 120 d, resulting in 25 to 77% of the N being mineralized. However, these studies were performed under aerobic conditions, while organic rice in California is predominantly grown under flooded, anaerobic conditions, which affects the N mineralization rate (Tusneem and Patrick, 1971). Currently, there is a paucity of information available on the mineralization of N from organic amendments added to soil under anaerobic conditions.

Therefore the objectives of the present study were (i) to determine the effectiveness of organic fertilizer N mineralization in meeting rice crop N demand, as reflected by plant N uptake, NRE, and improved grain yield, (ii) to determine N mineralization rates of organic fertilizers, that is, poultry litter; blood, meat, and feather meal; feather meal; and poultry litter plus feather meal under anaerobic conditions, and (iii) to compare the returns on investment in the pelletized organic materials with those of poultry litter.

MATERIALS AND METHODS

Field Trials

Field experiments were conducted at three different field sites in 2008 and 2009 in the Sacramento Valley of California. All field trials were planted with an N-responsive rice variety (S-102), aerially seeded onto flooded fields. The 2008 field trial was performed in a conventional, continuously flooded rice field located in Richvale (39°30'6" N, 121°45'17" W), and will be referred to as Continuously Flooded 08. During the previous year this field was also managed as a conventional rice field. In 2009, two field trials were performed in adjacent organically certified fields in Pleasant Grove (38°53'21" N, 121°32'47" W), which were planted on the same day but were managed differently in terms of water, and had different field histories. One field was continuously flooded during the growing season, and will be referred to as Continuously Flooded 09. This field was planted to rice in 2002, dryland farmed with barley in 2004, had one vetch crop in 2006 and has been fallow otherwise (A. Scheidel personal communication, 2009). The second organic field, (Drained 09), was planted to rice in 2008 and produced 9.5 Mg ha^{-1} of rice, followed by a vetch crop during the winter of 2008/2009 (A. Scheidel, personal communication, 2009). Planting rice in consecutive years was likely the main cause of weed seed bank accumulation and the resulting weed problems in Drained 09. This field was drained 25 days after sowing (DAS) to control weeds, and was not reflooded until 55 DAS. This 30-d drainage event retarded rice growth and development resulting in harvest being delayed by 3 wk in Drained 09. In Continuously Flooded 08, weeds were controlled using standard conventional practices, and no weed control was needed for Continuously Flooded 09. Soils were analyzed for total N (Horneck and Miller, 1998) exchangeable-K (Thomas, 1982), Olsen P (Olsen and Sommers, 1982), pH (Richards, 1954), and organic carbon (Harris et al., 2001) (Table 1). All fields had similar clay contents, but the Continuously Flooded 08 field had a lower pH and higher available K than either of the 09 fields (Table 1).

In both 2008 and 2009, treatments were laid out in a randomized complete block design, replicated four times. Plot sizes were 60 m^2 in 2008, and 37 m^2 in 2009. Treatments compared commercially available organic pelletized fertilizers to poultry litter, a zero N control, and ammonium sulfate (ammonium sulfate only in Continuously Flooded 08). The pelletized products were 13–0–0 (blood, meat, and feather meal), 12–0–0 (feather meal), and 6–3–2 (poultry litter and feather meal). Pellet size and product density varies by manufacturer and fertilizer composition and some manufactures offer different pellet size options. In all treatments receiving N, the N was applied at a rate of 157 kg ha^{-1} in 2008 and 134 kg ha^{-1} in 2009. Nitrogen rates were based on the manufacturers' stated N concentration for each fertilizer and an estimated 3% N concentration in the poultry litter. Subsequently all fertilizers were analyzed for total N (Horneck and Miller, 1998), total P and K (Sah and Miller, 1992), and organic carbon (Harris et al., 2001) (Table 2). All fertilizers were broadcast before seeding and lightly incorporated into the soil using a roller. Phosphorus (62–78 kg ha^{-1}) and potassium (45–117 kg ha^{-1}) were applied to all plots in both organic and conventional trials to ensure these nutrients were not limiting crop growth.

Stand density was similar in both 2009 fields and averaged 390 plants m^{-2} at 24 to 25 DAS, which is well within the established range of 130 to 500 plants m^{-2} for California (Miller et al., 1991). Stand density was not determined in 2008. Aboveground biomass at 25 DAS (2009 only), midseason and at harvest was determined by harvesting 1 m^2 from the center portion of each plot. Samples taken at harvest were separated into grain and straw fractions. All samples were oven dried at 60°C to a constant weight then ground and analyzed for total N by combustion. Grain yield is reported on a 14% moisture basis. Nitrogen recovery efficiency (NRE) was calculated as follows:

$$\mathrm{NRE} = \left[\frac{\left(\mathrm{TotalPlantN}_{(\mathrm{fertilized})} - \mathrm{TotalPlantN}_{(\mathrm{unfertilized})}\right)}{\mathrm{N\ fertilizer\ applied}}\right] 100$$

Soil NH_4–N was measured at 24 to 25 DAS (2009 only) and at 52 to 53 DAS in all fields. Eight soil samples (0–15 cm) were taken from each experimental plot, pooled, kept on ice and extracted with 2 M KCl within 24 h of sampling (Keeney and Nelson, 1982). Extractable NH_4–N was determined following the procedure of Forster (1995) and Verdouw et al. (1978). In Drained 09, soil NO_3–N was determined just before reflooding

Table 2. Properties and nutrient concentrations of fertilizers used in field trials in 2008 and 2009. Nutrient concentrations are given on a dry weight basis for poultry litter, and on an air dry basis for the pelletized fertilizers.

Fertilizer	Total N	Total P	Total K	Organic carbon	C/N	P/N	K/N
	%						
2008							
Pelletized 13–0–0†	13.8	0.9	0.2	54	3.9	0.07	0.01
Pelletized 12–0–0	10.9	2.5	0.4	48	4.4	0.23	0.04
Pelletized 6–3–2	6.4	1.6	2.3	38	5.9	0.25	0.36
Poultry litter	2.6	1.6	3.3	41	15.7	0.62	1.27
2009							
Pelletized 13–0–0	12.9	1.0	0.2	54	4.1	0.08	0.02
Pelletized 12–0–0	13.0	0.4	0.4	55	4.2	0.03	0.03
Pelletized 6–3–2	6.7	1.4	1.7	40	5.9	0.21	0.25
Poultry litter	3.2	1.4	2.3	36	11.2	0.44	0.72

† Numbers refer to the N–P–K content of fertilizers as stated by manufacturers.

using a procedure adapted from Miranda et al. (2001) and Doane and Horwath (2003). The NO_3–N was unlikely to be present in fields that were continuously flooded (Linquist et al., 2006) so the NO_3–N was not determined in Continuously Flooded 08 and 09.

A simple economic analysis of returns to fertilizer investment was based on the increase in grain yield attributable to fertilizer addition. The 2008 price of organic rice to the grower was used to determine benefits (A. Scheidel, personal communication, 2009). Costs taken into consideration included fertilizer purchase, fertilizer transport and application, harvesting, hauling, drying and storing the rice. Returns on investment for each field were calculated on a partial basis, only including costs and returns associated with the application of a single rate of fertilizer. In determining the cost of fertilizer per hectare, differences in N content of the various fertilizers were accounted for. Pelletized fertilizer prices ($ Mg^{-1}) are the manufacturers' list price. Cost of pelletized fertilizer transport was estimated at $27 Mg^{-1} of material (L. Benson, personal communication, 2010) and cost of fertilizer application by spreading was $37.00 ha^{-1} for 13–0–0 and 12–0–0, which increased to $49.00 ha^{-1} for 6–3–2 because of the additional volume required to achieve the target N rate. A range of costs ($55–116 Mg^{-1}) is reported for poultry litter because the price of the material varies widely according to local seasonal availability. Cost of transportation and application of poultry litter is included in the cost of material as the supplier delivers and applies the material.

Anaerobic Nitrogen Mineralization Laboratory Study

To compare and quantify mineralization rates of the organic N fertilizers under flooded conditions, a 60-d anaerobic laboratory incubation was conducted. The study was designed as a 5 × 6 factorial experiment using the four N fertilizers used in 2009 field trials plus a control with no fertilizer added. Extractable NH_4–N was determined at 0, 9, 18, 27, 36, and 60 d after the start of incubation. All treatments were replicated four times. The soil used in the study was collected from the top 15 cm of Drained 09 (Table 1). The anaerobic incubation was conducted following the procedure of Saeed (1995). Ten grams of soil, 5 g of K^+ saturated ion-exchange resins, and ground fertilizer (equivalent to 90 mg N kg^{-1} soil) were added to 200 mL glass bottles. The soil, resin, and fertilizers were mixed uniformly, and the bottles were filled with 60 mL of deionized water. The airspace was flushed for 30 s with a gas mixture of 95% N_2 and 5% CO_2 and then capped. Bottles were placed in an incubator at 25°C and were removed at the designated times and extracted for NH_4–N. The NH_4–N in the extract was determined following the procedure of Forster (1995) and Verdouw et al. (1978). The % N mineralized at each sampling time was calculated as follows:

$$\%\ \text{N mineralized} = \left[\frac{\left(\text{NH}_4\text{N}_{(\text{fertilized},\ t=0)} - \text{NH}_4\text{N}_{(\text{unfertilized},\ t=0)}\right)}{\text{N fertilizer applied}}\right]100$$

The mineralization rates were based on a regression analysis, where the slope of the linear regression between N mineralized and time, equals the rate of N mineralized in mg N kg^{-1} soil d^{-1}.

Statistical Analyses

Effects of fertilizer treatments on grain yield, N uptake, NRE, and soil mineral N were evaluated across sites by standard ANOVA using SAS 9.1. The anaerobic incubation was analyzed as a 5 × 6 factorial using a standard ANOVA with SAS 9.1. All data were tested for normality (Shapiro and Wilk, 1965) and homogeneity of variance (Levene, 1960). Data that did not meet the assumptions for ANOVA were transformed for statistical analysis, and detransformed means are presented in lieu of original means. All mean separations were determined using a Protected Least Significant Difference test (LSD), and differences were considered significant at $P < 0.05$ (Fisher, 1935).

RESULTS AND DISCUSSION

Fertilizer Nutrient Concentrations and Implications for Management

A major concern with using poultry litter to meet crop N demand is that the N content of the material varies widely due to differences in animal feed, water intake, bedding, poultry variety, and age (Chadwick et al., 2000). In the present study the total N concentration of the poultry litter ranged from 2.6 to 3.2% between years. The nutrient concentrations reported here for poultry litter are on a dry weight basis, and we know that the moisture content of poultry litter also varies widely which further increases the nutrient content variability and exacerbates the challenge of predicting plant available N. In the present study the variability in N content of poultry litter between the 2 yr was 21%, as compared to 10% for the pelletized materials.

The N content of the pelletized organic fertilizers was generally similar to manufacturer claims; however the two fertilizers that reported having no P and K did contain both of these nutrients (Table 2). The P/N and K/N contents were lower in the pelletized fertilizers (average 0.14:1, and 0.12:1 respectively) than for poultry

Table 3. Grain yield of rice in three field sites in 2008 and 2009 following the application of organic and inorganic N fertilizers.

Fertilizer	Continuously flooded 2008	Continuously flooded 2009	Drained 2009	Mean
	Grain yield, kg ha^{-1} at 14% moisture			
Pelletized 13–0–0†	11,325abc‡	10,073a	8,510a	9,969
Pelletized 12–0–0	10,621bc	10,049a	8,723a	9,797
Pelletized 6–3–2	11,522ab	9,876a	9,121a	10,173
Poultry litter	10,384c	8,968a	8,448a	9,267
Control (no N)	8,023d	7,055b	7,277b	7,452
$(NH_4)_2SO_4$	12,042a			
Average of all treatments	10,653	9,204	8,416	
Poultry litter vs. other fertilizers	P = 0.05	P = 0.04	ns	

† Numbers refer to the N–P–K content of fertilizers as stated by manufacturers.

‡ Means with the same letter within a column are not considered significantly different at $P < 0.05$.

litter (average 0.53:1, and 0.99:1, respectively) in both years. Rice growers managing poultry litter for crop N demand will inadvertently apply P in excess of crop demand that can lead to high soil P levels. Linquist et al. (2010) found that California organic rice systems had higher amounts of labile and moderately labile inorganic P than conventional systems, which they attributed to the use of poultry litter. Others have also reported that the use of manures for N-fertility can lead to excessively high soil P levels (Sharpley et al., 2003). This may be cause for concern, as continuous high P inputs decrease the ability of a soil to retain P and increase the risk of offsite contamination either through leaching or erosion (Richardson, 1985; Pote et al., 1996; Golden et al., 2006). Thus the use of these pelletized products which contain a lower P/N ratio may help reduce high soil P levels associated with the use of poultry litter in California organic rice systems.

Grain Yield in Response to Fertilizer

Grain yields ranged from 7.1 to 12.0 Mg ha^{-1} across all fields. In the Sacramento Valley, average organic rice yields are 7 Mg ha^{-1} (L. Benson, personal communication, 2010) and are lower than conventional rice yields (9.6 Mg ha^{-1} USDA-Economic Research Service, 2009) (Table 3). The soil indigenous N supply from the fields in this study was high, averaging 91 kg ha^{-1}, and resulted in relatively high yields in zero-N control plots which averaged 7.5 Mg ha^{-1} (Tables 3 and 4). In a previous study of 12 conventional California rice fields indigenous N supply ranged from 45 to 90 kg N ha^{-1} and grain yield in the absence of N fertilizer ranged from 1.6 to 6.9 Mg ha^{-1} (Linquist et al., 2009). The high indigenous soil N supply in the present study may explain the limited yield response to applied fertilizer N.

Despite the high yields in the control treatments, yields were significantly higher where N fertilizer was applied. There were significant site by treatment interactions for yield (P = 0.02) and N uptake (P = 0.019), so the data from the different field experiments are reported and discussed individually. Average grain yields in Continuously Flooded 08 were the highest (10.7 Mg ha^{-1}), followed by Continuously Flooded 09 (9.2 Mg ha^{-1}), and Drained 09 (8.4 Mg ha^{-1}) (Table 3). There was a significant yield response to all fertilizers at all locations, where the response to pelletized fertilizers was generally similar between treatments, and was generally higher than the yield response to poultry litter, although differences were not always significant. When the variation was partitioned using contrasts, poultry litter had a significantly lower grain yield than pelletized fertilizers in both continuously flooded fields but not in Drained 09 (Table 3). On average, pelletized fertilizer increased yield over the zero-N control by 2.5 Mg ha^{-1} compared to poultry litter, which increased it by 1.8 Mg ha^{-1}. To provide insight into why the pelletized fertilizers exhibited superior performance, we examined plant N uptake, recovery of applied N, and the mineralization rates of the various fertilizers.

Plant Nitrogen Uptake and Recovery Efficiency

Plant N uptake at harvest ranged from 76 to 198 kg N ha^{-1} in the three fields across all treatments (Table 4). In Continuously Flooded 08, N uptake of $(NH_4)_2SO_4$–N was higher than all other fertilizers, with plants accumulating 198 kg of N ha^{-1} by harvest. In all fields N uptake at harvest in the zero N control was significantly lower (76–102 kg N ha^{-1}) than in the organic fertilizer treatments (101–152 kg ha^{-1}). Comparing the organic

Table 4. Aboveground plant N uptake (kg ha^{-1}) in three field sites in 2008 and 2009 following the application of organic and inorganic N fertilizers.

	Continuously flooded 2008			Continuously flooded 2009				Drained 2009				
Fertilizer	0 to 53 DAS†	53 DAS to harvest	Seasonal total	0 to 24 DAS	24 to 53 DAS	53 DAS to harvest	Seasonal total	0 to 24 DAS	24 to 53 DAS	53 DAS to harvest	Seasonal total	Mean seasonal total
	Plant N uptake, kg ha^{-1}											
Pelletized 13–0–0‡	102bc§	45a	148bc	20a	111a	12a	143a	15a	68a	53b	135a	142
Pelletized 12–0–0	91c	42a	134cd	19a	111a	4a	139a	14ab	63ab	63ab	140a	138
Pelletized 6–3–2	126ab	26a	152b	19a	98ab	7a	126a	13b	54bc	76a	143a	140
Poultry litter	82cd	42a	124d	15b	76bc	9a	101b	10c	45cd	75ab	129a	118
Control (no N)	61d	33a	94e	12b	59c	3a	76c	10c	37d	55ab	102b	91
$(NH_4)_2SO_4$	154a	44a	198a									

† DAS refers to days after sowing.

‡ Numbers refer to the N–P–K content of fertilizers as stated by manufacturers.

§ Means with the same letter within a column are not considered significantly different at $P < 0.05$.

Table 5. Nitrogen recovery efficiency (%) of pelletized fertilizers, poultry litter and $(NH_4)_2SO_4$ in three field experiments.

Fertilizer	Continuously flooded 2008	Continuously flooded 2009	Drained 2009	Mean
Pelletized 13–0–0†	34b‡	50a	25a	36
Pelletized 12–0–0	25c	47a	28a	33
Pelletized 6–3–2	37b	37a	31a	35
Poultry litter	19c	19b	21a	20
$(NH_4)_2SO_4$	66a			

† Numbers refer to the N–P–K content of fertilizers as stated by manufacturers.
‡ Means with the same letter within a column are not considered significantly different at $P < 0.05$.

fertilizers, poultry litter had lower total N uptake (101–129 kg ha^{-1}) than the pelletized fertilizers (126–152 kg ha^{-1}) at all sites although differences were not always significant. Pelletized fertilizers performed similarly to each other with no consistent differences in plant N uptake between them.

The timing of N uptake differed between the continuously flooded and drained fields (Table 4). In the continuously flooded fields most of the seasonal N uptake across all treatments occurred by 53 DAS (84%) with the most active period of plant N uptake occurring between 25 and 53 DAS. From 53 DAS to the end of the season, only 16% of total seasonal N was accumulated by the crop in continuously flooded fields. In Drained 09 the total N uptake was similar to continuously flooded fields; however the pattern of N uptake was different, as roughly half of seasonal N uptake occurred between 53 DAS and harvest. Low N uptake before 53 DAS as compared to continuously flooded fields may have been due to drought stress created by the extended drain.

The most active period of N uptake in rice plants is between tillering and panicle initiation, which occurs approximately 30 to 35 DAS and 50 to 55 DAS, respectively (Peng and Cassman, 1998). Thus, mineralization of organic N fertilizer needs to occur during or before this time to optimize synchrony between N supply and crop N demand. In the present study differences in N uptake among fertilizer treatments occurred before 53 DAS in all fields, with pelletized fertilizers generally supplying more plant available N during this period than poultry litter (Table 4). While N uptake in all plots continued to increase from 53 DAS to harvest, the amount of N uptake during this period for the fertilizer treatments was not significantly different from the zero N control across fields (Table 4). This implies

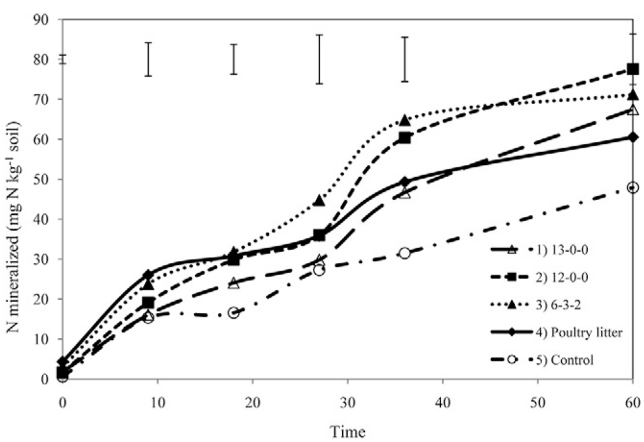

Fig. 1. NH_4–N (in mg N kg^{-1} soil) accumulation during a 60 d anaerobic laboratory incubation. Treatments were: Pelletized 13–0–0, Pelletized 12–0–0, Pelletized 6–3–2, Poultry litter, and Control (no N). Measurements were taken at six sampling times (Day 0, 9, 18, 27, 36, and 60). Least Significant Difference (*P* = 0.05) bars above each sample time.

that after 53 DAS the source of N for plant uptake is most likely from indigenous N sources—not from the fertilizer.

Many conventional rice growers provide supplementary N to the rice crop between tillering and panicle initiation if N deficiencies are apparent. Such a practice is effective when inorganic fertilizes are used, as N is immediately available for crop uptake. However, it may not be appropriate for organic fertilizers such as those used in this study due to the length of time required for the fertilizer N to mineralize, and become available to the plant. Nitrogen applied after panicle initiation, including inorganic fertilizer-N, is not efficiently used and results in lower grain yield responses (Linquist and Sengxua, 2003).

Across years and fields, the NRE of pelletized organic fertilizers ranged from 25 to 50% (averaging 35%), while poultry litter had the lowest NRE of all fertilizers averaging 20% (Table 5). The NRE of poultry litter is within the range of 14 to 35% reported for other rice systems (Bijay-Singh et al., 1997; Takahashi et al., 2004; Golden et al., 2006). While NRE is usually higher for inorganic vs. organic N sources (Brahmanand et al., 2009; Golden et al., 2006) we were not able to do this comparison in all fields. However, in Continuously Flooded 08, $(NH_4)_2SO_4$ had the highest NRE of 66%, followed by 32% for the pelletized fertilizers and 19% for the poultry litter. The NRE of pelletized fertilizers in Drained 09 (average of 28%) was lower overall than the NRE of pelletized fertilizers under a continuous flood (average of 38%), while poultry litter performed similarly in all fields despite differences in water management practices.

Laboratory Mineralization Study

In the anaerobic incubation study, NH_4–N concentration increased in all treatments, including the zero-N control, through Day 60 (Fig. 1). The mineralization of indigenous soil organic N occurred in two phases, an initial rapid phase followed by a slower phase (Table 6 and Fig. 1) as has been reported by others (Serna and Pomares, 1991; Hadas et al., 1983; Agehara and Warnacke, 2005). Pelletized fertilizer-N and poultry litter-N also exhibited a two phase mineralization pattern; an initial

Table 6. Nitrogen mineralization rates of organic N fertilizers and unamended soil over three time periods, and the percentage of fertilizer N mineralized after 60 d of incubation.

Fertilizer	0–9 d	9–36 d	36–60 d	N mineralized
	mg N kg^{-1} soil d^{-1}			%
Pelletized 13–0–0†	1.64ab‡	1.08ab	0.87a	22ab
Pelletized 12–0–0	1.88ab	1.45a	0.72a	33a
Pelletized 6–3–2	2.24ab	1.51a	0.46a	26ab
Poultry litter	2.35a	0.83b	0.47a	14b
Control (no N)	1.58b	0.66b	0.68a	

† Numbers refer to the N–P–K content of fertilizers as stated by manufacturers.
‡ Means with the same letter within a column are not considered significantly different at $P < 0.05$.

Table 7. Soil mineral N at three field sites at 24 to 25 days after sowing (DAS) and 52 to 53 DAS as affected by fertilizer treatment. All fertilizers were applied before sowing.

	Continuously flooded 2008	Continuously flooded 2009		Drained 2009		
	NH_4–N	NH_4–N	NH_4–N	NH_4–N	NH_4–N	NO_3–N
Fertilizer	52 DAS	24 DAS	53 DAS	25 DAS	53 DAS	53 DAS
	Mineral N, mg N kg^{-1} soil					
Pelletized 13–0–0†	1.1a‡	23.8ab	2.3a	17.5a	2.4a	16.4ab
Pelletized 12–0–0	0.9a	24.6a	2.4a	31.3b	2.9a	21.1a
Pelletized 6–3–2	0.8a	27.1a	2.2a	15.0b	2.3ab	18.0a
Poultry litter	1.0a	17.5bc	2.2a	12.5bc	2.3ab	7.4bc
Control (no N)	1.2a	14.9c	1.7a	8.0c	1.7b	4.3c
$(NH_4)_2SO_4$	1.3a					

†Numbers refer to the N–P–K content of fertilizers as stated by manufacturers.

‡ Means with the same letter within a column are not considered significantly different at $P < 0.05$.

rapid phase until Day 9, where net rates of N mineralization were highest ranging from 1.58 to 2.35 mg N kg^{-1} soil d^{-1}, followed by a slower phase to 36 d, where net rates of N mineralization ranged from 0.66 to 1.51 mg N kg^{-1} soil d^{-1} (Table 6). After 36 d there was little additional organic fertilizer N mineralized as the mineralization rates of all fertilizers treatments, which ranged from 0.46 to 0.87 mg N kg^{-1} soil d^{-1}, approximated that of the zero N treatment (0.68 mg N kg^{-1} soil d^{-1}) between 36 and 60 d. Poultry litter-N mineralized rapidly during the first 9 d and was the only fertilizer treatment with a significantly higher mineralization rate than the control during that period. However, in the secondary phase of mineralization between Days 9 and 36, poultry litter had a slower mineralization rate relative to other fertilizers (0.83 mg N kg^{-1} soil d^{-1}), which was not significantly different than the mineralization rate in the control (0.66 mg N kg^{-1} soil d^{-1}). In an aerobic laboratory study measuring N mineralization rates, Gordillo and Cabrera (1997) also observed an initial rapid, but short-lived increase of mineral N from poultry litter, where 50% of N mineralization occurred within the first 24 h of aerobic incubation. Rapid mineralization of poultry litter-N is likely due to the hydrolysis of urea, as a large portion of the organic N is in the form of uric acid, which is rapidly hydrolyzed to NH_3 and converted to NH_4–N (Schefferle, 1965).

After 60 d the amount of fertilizer N mineralized averaged 27% for pelletized fertilizers, as compared to 14% for poultry litter (Table 6). Previous incubation studies conducted under aerobic conditions have measured 25 to 77% of organic N from poultry litter being mineralized over periods ranging from 35 to 120 d (Castellanos and Pratt, 1981; Hadas et al., 1983; Cabrera et al., 1993). The lower mineralization value reported here may be due to the anaerobic conditions used to simulate the environment of an irrigated rice field. N mineralization and immobilization are different under waterlogged conditions (Tusneem and Patrick, 1971), where the decomposition of organic materials may be slower (Olk et al., 1998; Witt et al., 2000; Gambrell and Patrick, 1978).

The results from the field studies were consistent with the findings of the laboratory incubation study in a number of ways. First, in all field studies, N uptake between 53 DAS and harvest was similar to the zero N control treatment (Table 4), suggesting that after 53 DAS there was little to no fertilizer N mineralization and subsequent uptake by rice. These results are in accordance with the laboratory incubation study showing little to no mineralization of organic fertilizer N after 36 d of anaerobic incubation. Similarly, Agehara and Warnacke (2005) found that after 28 d of aerobic incubation, only an additional 5% of organic N from blood meal and poultry manure mineralized. Second, both field and the incubation studies showed that less N is mineralized from poultry litter than from the pelletized fertilizers. In the field studies, 35% of the pelletized fertilizer-N and 20% of the poultry litter-N was mineralized and accumulated by the plant (Table 5) as compared to 27 and 14% N mineralized, respectively, in the incubation study (Table 6).

Response to Nitrogen in Drained Fields

An extended drain of approximately 30 d early in the growing season is the most prevalent form of weed control in organic rice production in California (Sullivan, 2003). Draining the field for a 30 d period changed N dynamics (Table 7) reducing the yield response to added fertilizer, and the NRE (Tables 3 and 5) due to low N recovery by the crop during the drain period (Table 4). Low plant N-uptake coupled with aerobic soil conditions, allowed for the nitrification of accumulated NH_4–N, and resulted in the presence of NO_3–N which averaged 19 mg N kg^{-1} for treatments amended with pelletized fertilizers, and 7 mg N kg^{-1} for treatments amended with poultry litter at 53DAS (Table 7). The NO_3–N was susceptible to denitrification losses when the field was reflooded (Patrick and Wyatt, 1964) and this likely also contributed to the low NRE we found for all fertilizers in the drained field (Table 5).

Economic Analysis of Fertilizers

The returns on organic fertilizer investment were highest in continuously flooded fields and ranged from 30 to 72% (Table 8). There were no consistent differences between fertilizers, although the 6–3–2 performed relatively well in all fields. Returns on investment were much lower and sometimes negative in the drained field indicating that fertilizer applications may not be economically viable or sustainable under such conditions. However, we have only presented results from one field that underwent an extended drain, and the management of organic N fertilizers under such conditions merits further work.

CONCLUSIONS

Results from this study suggest that commercially pelletized organic fertilizers are a viable option for California organic rice growers and may be economically competitive with poultry litter in continuously flooded fields. The pelletized materials address grower concerns in that they are readily available, less bulky than poultry litter and, based on 2 yr of data, appear to have a more consistent nutrient content. Advantages of the

Table 8. Economic analysis of returns on investment in pelletized organic fertilizer and poultry litter based on three field experiments.

Fertilizer	Cost per Mg of material	Assumed N content	Cost per kg of N	Continuously flooded 2008 Returns on investment	Continuously flooded 2009 Returns on investment	Drained 2009 Returns on investment
	$ Mg^{-1}	%	$ kg^{-1}	%		
Pelletized 13–0–0†	798	13	6.13	63	72	–21
Pelletized 12–0–0	759	12	6.33	30	66	–12
Pelletized 6–3–2	358	6	5.96	68	59	11
Poultry litter‡	55 to 116	3	2.43 to 5.10	64 to 172	57 to 162	3 to 80

† Numbers refer to the N–P–K content of fertilizers as stated by manufacturers.

‡ The range in costs and returns associated with poultry litter is a reflection of the large variability in the price of the material due to local seasonal availability.

pelletized fertilizers over poultry litter were (i) higher and more predictable N concentration, (ii) higher amount of mineralizable N, (iii) higher NRE, and (iv) better grain yield response. We found no consistent differences between the pelletized products. Based on one field study, we found that fertilizer applications to fields that will experience a prolonged drain for weed control may not be economically advisable. Further investigation of N dynamics in noncontinuously flooded rice systems, coupled with the establishment of appropriate rates for these fertilizers would allow for the development of improved N management strategies for organic rice production systems.

ACKNOWLEDGMENTS

We would like to acknowledge the Organic Farming Research Foundation for providing funding for this research. We thank the University of California-Davis Department of Plant Sciences for the provision of a departmental Graduate Student Research fellowship for Paula Wild. We thank the Lundberg Family of Farms and Lance Benson for the provision of materials and information, and Aaron Scheidel for the use of his fields. We greatly appreciate the assistance of Cesar Abrenilla, Anne Noble, Michelle Mattson, and Emily Lundberg in the field and laboratory, and Maegen Simmonds in statistical analysis.

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