Determination of fertilizer effectiveness in meeting nitrogen demands in organic rice production.

By

PAULA LIDIA WILD
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Approved:

Chris van Kessel, Chair

James E. Hill

Bruce A. Linquist

Committee in Charge

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Abstract

Nitrogen (N) is the most limiting nutrient in irrigated rice production, and growers continue to be faced with the challenge of meeting crop N demand, particularly in organic production systems. Therefore the main objective of this study was to determine the availability of N from organic sources under continuous and non-continuously flooded conditions, and the returns on investment associated with organic fertility. Laboratory and field experiments were conducted to determine the effectiveness of the commonly used poultry litter, pelletized organic fertilizers (blood and bone meal 13-0-0, feather meal 12-0-0, poultry litter plus feather meal 6-3-2), and inorganic fertilizer applied as $(NH_4)_2SO_4$ in synchronizing the supply of mineralized N with the demand of N by rice, relative to an unfertilized control. Over two years the treatments were applied at a similar N rate and evaluated in two continuously flooded fields, and one field which was drained 24 days after sowing, with aerobic conditions maintained for one month as a form of weed control. In all fields, all fertilizers increased grain yield and N uptake relative to the 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%) although these effects were not always significant. $(NH_4)_2SO_4$ was only included as a treatment in 2008, and had the best yield response (12042 kg ha^{-1}), which was significantly higher than the yield of rice amended with poultry litter and one of the pelletized fertilizers (12-0-0), but similar to the other pelletized products (13-0-0 and 6-3-2). In the field studies, N mineralization of all organic fertilizers occurred primarily during the first 53 days after planting and before panicle initiation. An anaerobic incubation confirmed field study results showing that mineralization of organic fertilizers occurred primarily during the first 36 days of incubation and that the N mineralization of pelletized fertilizers, which averaged 27% of N mineralized, was greater than for poultry litter (14% of N mineralized). In the field study all organic fertilizers were less effective when the field was drained for weed control. An economic assessment of the products shows that pelletized

fertilizers are competitive with poultry litter when fields are continuously flooded, while any organic fertilizer applications to fields that will be drained for an extensive period may not be economically viable.

Chapter 1: Introduction

Availability of nitrogen (N) is essential to insure high yields in irrigated rice production because N is the most frequently deficient nutrient in these systems (Reddy 1982). Substantial efforts have been made to increase N use efficiency in rice production systems (Cassman et al. 2002); however growers continue to be faced with the challenge of meeting crop N demand, particularly in organically managed systems (Dahlin et al. 2005). Management practices that minimize losses, and maximize crop recovery of applied N increase the efficiency of production and decrease potentially negative impacts on the environment (Havlin et al. 2005). An understanding of rice nutrient requirements, and the N cycle in continuous and non-continuously flooded systems can aid us in determining the best management practices for N fertilization in organic rice systems.

1.1 Nutrient requirements of rice

Nitrogen is an essential element of DNA, amino acids and proteins, and it serves a key role in plant metabolism. Thus it is not surprising that plants contain 1 to 6% N by weight, and after carbon, hydrogen and oxygen, N is the mineral element that plants require in the largest amount (Taiz and Zeiger 2006). It has been reported that rice yield response to fertilization is greatest for N, and that additions of phosphorous and potassium alone do not significantly affect yield unless N is also applied (Cassman et al. 1998, Wade et al. 1999). The bulk of N is taken up by rice plants before the onset of the reproductive stage, therefore good N management is critical before panicle initiation (Peng and Cassman 1998). By mid-tillering the concentration of total N in leaf tissue should be ≥4.6% to avoid N deficiency (Mutters et al. 2003). California rice varieties in conventional systems exhibit maximum yields upon the addition of 157 to 173 kg N ha^{-1} (Mutters et al. 2003), and have N recovery efficiencies ranging from 40 to 62% (Linquist et al. 2009); however, N management for organic rice production systems in California has not been characterized in the literature.

1.2 Nitrogen Cycling in Rice Production Systems

In organic production systems N is added to the soil in an organic form; typically as residue or manure, and undergoes mineralization mediated by heterotrophic microorganisms resulting in the production of NH_4-N, which may be immobilized into microbial biomass, enter the soil mineral N pool, or become available to plants (Havlin et al. 2005) It is generally agreed upon that organic materials with a C:N ratio <25:1 contribute to N mineralization while those with a C:N ratio >25:1 contribute to N immobilization (Paul 2007). A highly diverse population of microorganisms is responsible for this transformation so N mineralization/immobilization occurs readily in both aerobic and anaerobic environments (Paul 2007).

Continuously flooded soils

Flooded soils are characterized by the absence of oxygen, and the formation of an aerobic, oxidized layer, atop an anaerobic reduced layer of soil (Broadbent 1979) (Figure 1a). In irrigated rice fields that remain continuously flooded for the duration of the growing season, NH_4 is the dominant form of plant available N (Broadbent 1979, Mikkelsen 1987). As NH_4 diffuses upwards into the oxidized soil layer some nitrification will occur, and subsequently NO_3 will diffuse downward into the reduced soil layer (Reddy 1982) (Figure 1a). The subsequent denitrification that occurs under anaerobic conditions constitutes a major N loss pathway in flooded rice fields (Buresh and De Datta 1991). N losses in this system may also be attributed to the volatilization of NH_3, particularly when fertilizers with high urea or ammonia content are surface applied (Reddy 1982). Losses of N through leaching and runoff are generally considered insignificant in continuously flooded rice fields (Reddy 1982).

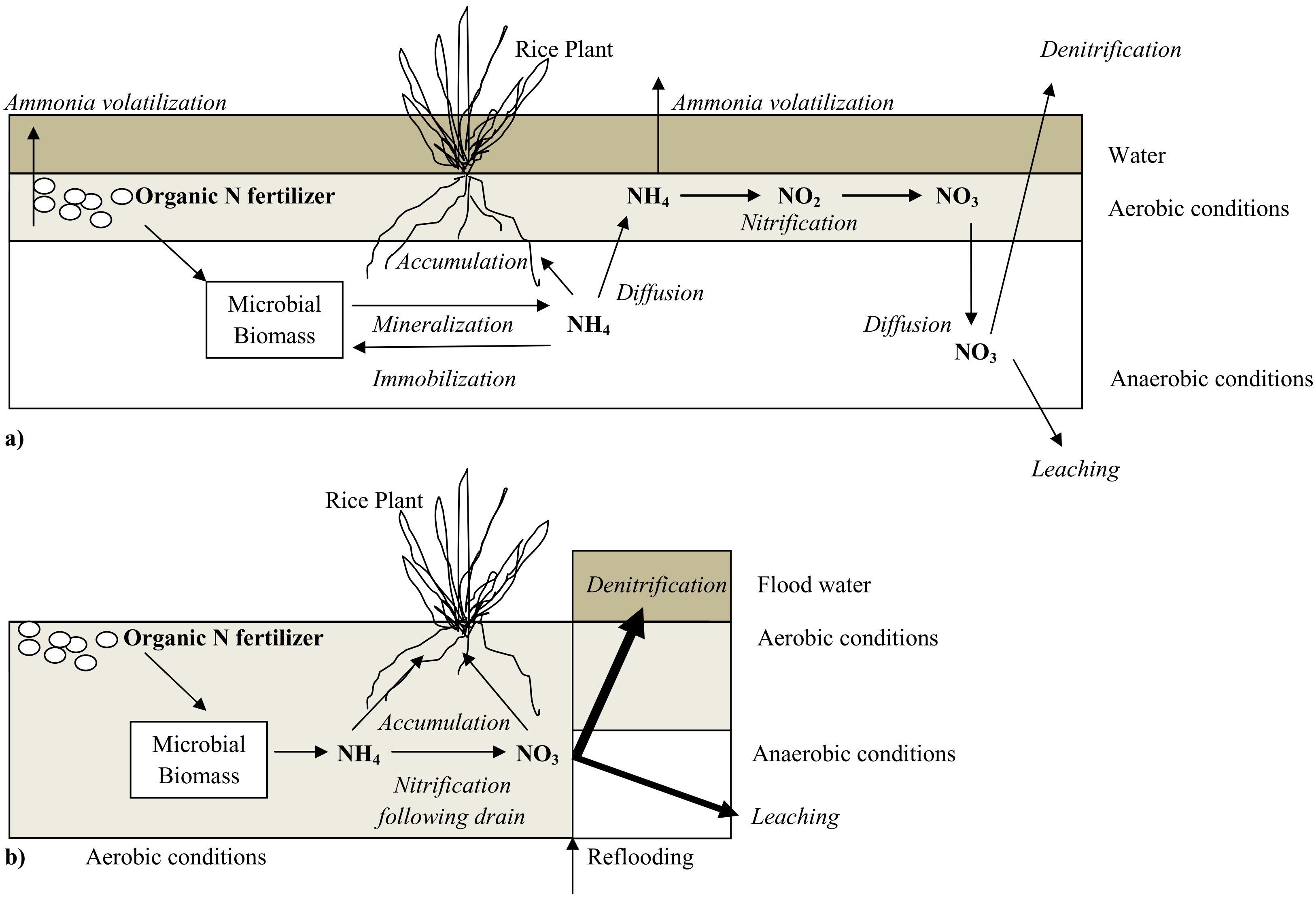


Figure 1. Adapted from Reddy (1982).
a) Nitrogen cycling in continuously flooded rice field. b) Nitrogen cycling in rice field subjected to alternate draining and flooding.

Non-continuously flooded soils

In fields that are subjected to alternate draining and reflooding, soil conditions become aerobic when the field is drained and NH_4 is readily converted to NO_2 and subsequently to NO_3 (Figure 1b). In this scenario the possibility for N loss through denitrification is greatly increased upon reflooding the field, with reported losses of up to 20% of total N following repeated cycles of flooding and drying (Patrick and Wyatt 1964). The possibility of N loss through leaching is also greater because of the large accumulation of NO_3 which is highly soluble in the flood water (Patrick and Wyatt 1964). This is of particular concern in organic rice production systems because water level management in the form of an extended drain of approximately 30 days is the most prevalent form of weed control (Sullivan 2003).

1.3 Organic Fertilizer N Sources

Organic fertilizer N is difficult to manage in part due to the low and variable N content of materials, coupled with low bulk density that necessitates the transportation and application of large volumes of material to satisfy crop N demand. This obstacle is now being addressed with the pelletization of organic manures and residues in order to increase their bulk density and particle size uniformity (McMullen 2005), and to concentrate nutrients resulting in a more rapidly mineralizable form of N (Hadas et al. 1983). Another challenge, common to the management of all organic N fertilizers, is the determination of appropriate fertilizer application rates due to the inability to accurately predict plant available N from these sources (Gordillo and Cabrera 1997). Overall soil N supply from organic amendments depends in part on the initial availability of mineral N from the fertilizers, as well as on the rate of mineralization which affects the long-term potential availability of N after mineralization (Flavel and Murphy 2006). The rate of mineralization affects how rapidly organic N is transformed into plant available forms, and whether this occurs in synchrony with critical periods of N demand during crop growth.

1.4 Drivers of N mineralization

Many researchers have fit N mineralization data to kinetic models and have generally found that N mineralization of organic N fertilizer sources occurs in two phases; an initial rapid release of labile N characterized by a high rate constant, followed by a slower release of less labile N, with a lower rate constant (Hadas et al. 1983, Serna and Pomares 1991, Gordillo and Cabrera 1997, Agehara and Warnacke 2005). A variety of mechanisms influence N mineralization in the rapid and slow phases including soil texture, temperature and moisture, which in turn affect the composition, size and activity of microbial communities. Moreover within a specific site, the chemical composition and form of the organic N source influences N mineralization rates.

Soil texture, temperature, and moisture

Differences in soil texture, temperature and moisture affect the composition of the microbial community at a given site, and therefore influence the rate of N mineralization of a specific organic N source (Hadas et al. 1983, Griffin et al. 2002). Maximum N mineralization occurs under aerobic conditions between 50 and 70% water filled pore space (Havlin et al. 2005) and it has been shown that decomposition of organic materials and mineralization of N is slower under anaerobic conditions (Gambrell and Patrick 1978, Olk et al. 1998, Witt et al. 2000). N mineralization proceeds most rapidly between temperatures of 25 and 35 °C (Havlin et al. 2005), and it has been reported that temperatures in the range of 14 to 35 °C had little effect on N mineralization rate (Hadas et al. 1983). It is widely recognized that coarse textured soils exhibit faster rates of N mineralization as compared with loam and clay soils, and that the fraction of small pores explains 50% of the variation in N mineralization rate between differently textured soils (Hassink 1992). Under anaerobic conditions, such as those present in continuously flooded rice fields, the type of clay mineral also influences the rate of N mineralization, where soils containing 2:1 clay minerals exhibit rapid rate constants of N mineralization that are 1.8 times larger than those in soils containing predominantly 1:1 clay minerals (Inubushi et al. 1985).

Chemical composition of N sources

Net mineralization of organic N within a specific site is also governed by the chemical composition of the fertilizer source and has been correlated to the total N content (Abbasi et al. 2007), C/N ratio (Aulakh et al. 2000) and lignin/N ratio (Kumar and Goh 2003). However, the heterogeneous composition of organic N sources causes high variability in N availability as shown by an incubation of dairy manure samples which exhibited both net N immobilization, and net N mineralization (Van Kessel and Reeves 2002). It has been suggested that simple correlations between manure composition parameters and mineralization potential are not sufficient for predicting available N (Van Kessel and Reeves 2002), even while it is well understood that chemical composition of the organic N affects mineralization rates (Gordillo and Cabrera 1997).

1.5 Methodology for quantifying N mineralization

A substantial amount of investigation has been dedicated to quantifying N mineralization of organic sources. Chemical methods attempt to extract a chemical fraction from the organic N source, measure it, and correlate it with mineralizable N (Castellanos and Pratt 1981, Serna and Pomares 1991). In contrast biological methods, which are the focus of the present study, are incubations of soil samples amended with organic N measuring mineral N accumulation over time (Chae and Tabatabai 1986, Bitzer and Sims 1988). Biological methods tend to be more accurate; however they are more laborious and time consuming (Quafoku 2001). While the results from many incubations measuring N mineralization have been published, there is a lack of a standard for this procedure and results are highly variable among working groups (Griffin et al. 2008). Much of the variability can be attributed to the mechanisms which drive N mineralization;

however it is also clear that there are variations in the methodology of measuring N mineralization that lead to substantially different results and conclusions. Many authors use the difference method where net N mineralized is equal to the difference between mineral N content of amended soil samples and mineral N content of unamended control samples at time *t* (Castellanos and Pratt 1981, Chae and Tabatabai 1986). Griffin, He and Honeycutt (2005) have elaborated on this by subtracting the initial mineral N in amended and unamended soils, in addition to the mineral N present in the control at time *t*. Other authors distinguish between the organic and mineral fractions such that when they report the percentage of applied N that underwent mineralization there are different values for N mineralized from the organic N fraction of the fertilizer and N mineralized from the fertilizer as a whole (Cabrera et al. 1993, Abbasi et al. 2007). Moreover some authors account for gaseous losses during incubations (Gale and Gilmour 1986, Cabrera et al. 1993), while others have not included this procedure (Hadas et al. 1983, Westermann 1987). Besides the difference method, it is possible to label organic fertilizer N sources with ^{15}N tracers to track N mineralization in laboratory incubations (Rees et al. 1993, Flavel and Murphy 2006) and in field trials (Thomsen 2004). However this was not pursued in the present study due to time and budget constraints, as well as to the difficulty of labeling poultry litter and commercially sourced pelletized organic fertilizers with ^{15}N.

1.6 Objectives

The objectives of the present study were: (1) to determine the effectiveness of organic fertilizer N mineralization in meeting crop N demand as reflected by plant N uptake, NRE and, improved grain yield, (2) to determine N mineralization patterns of organic fertilizers, i.e., poultry litter, pelletized blood and bone meal, pelletized feather meal, and pelletized poultry litter plus feather meal under anaerobic conditions, and (3) to compare the returns on investment in the pelletized organic materials with those of poultry litter.

Chapter 2: Nitrogen availability from poultry litter and pelletized organic amendments for organic rice production

2.1 Introduction

Organic rice is produced on 20,000 ha in the US, and California is the single largest producer with 9,400 ha (USDA 2008), most of which is grown in the Sacramento Valley. The predominant soils in the Sacramento Valley have high clay content so N fertilizer has traditionally been applied as poultry litter because cover crops do not grow well on these heavy textured soils. 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), Finally, poultry litter has a relatively high P content (Golden et al. 2006) and continued applications of poultry litter to meet an N requirement can lead to high soil P contents and the possibility for off-site contamination (Pote et al. 1996, Linquist et al. 2010). These factors, along with the uncertainty of poultry litter availability, have resulted in rice growers looking for alternative sources of organic N.

One strategy to combat the disadvantages of utilizing poultry litter in field-scale production is to isolate the fine fraction and pelletize it (Ndegwa 1991). Pelletizing poultry litter increases bulk density and particle size uniformity (McMullen 2005), and concentrates nutrients resulting in a more rapidly mineralizable form of N (Hadas et al. 1983). Lopez-Mosquera (2008) found that pelletized poultry litter had more stable nutrient characteristics, no fecal bacteria, nor 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, bone meal and feather meal have been commercially pelletized and are being utilized as fertilizer for horticultural crops (Gaskell and Smith 2007); however they have not previously 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 because of the variability in the rate at which N will be mineralized into plant available forms (Sims 1986; Dahlin 2005). It has been observed that rice fertilized with poultry litter exhibits symptoms of N deficiency due to low uptake of poultry litter N (11 to 39 kg N ha^{-1}) during the critical growth period approximately 4 weeks prior to panicle initiation (Golden et al. 2006). This asynchronicity of N supply with plant N demand results in a low N recovery efficiency (NRE) of poultry litter (14%), which led investigators to conclude that maximum grain yields could only be achieved with prohibitively high rates (270 kg N ha^{-1}) of poultry litter (Golden et al. 2006). In contrast, the NRE of poultry manure 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 to 43%) at that field site (Singh et al. 1997). These discrepancies may be attributable to differences in environmental conditions and management practices.

While the number of field trials have been limited, there have been more laboratory studies which 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 1997, Agehara and Warnacke 2005, Hartz and Johnstone 2006, Cayuela 2009), feather meal (Hadas and Kautsky 1994, Hartz and Johnstone 2006), and bone meal (Cayuela, 2009) in order to better formulate recommendations to growers regarding the agronomic use of these materials as fertilizer. In all of these studies an aerobic incubation was used over periods ranging from 35 to 120 days resulting in 25 to 77% of the N being mineralized. While such studies provide information on N availability under aerobic conditions, organic rice in California is predominantly grown under flooded, anaerobic conditions, which will affect the rate at which organic N is mineralized from fertilizer sources (Tusneem and Patrick, 1971). 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 to (1) to determine the effectiveness of organic fertilizer N mineralization in meeting crop N demand as reflected by plant N uptake, NRE and, improved grain yield, (2) to determine N mineralization patterns of organic fertilizers, i.e., poultry litter, blood and bone meal, feather meal, and poultry litter plus feather meal under anaerobic conditions, and (3) to compare the returns on investment in the pelletized organic materials with those of poultry litter.

2.2 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, CA and will be referred to as Continuously Flooded 08. The previous year this field was also managed conventionally and planted to rice. In 2009, two field trials were performed in adjacent organically certified fields in Pleasant Grove, CA 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. The other field, (Drained 09), was planted to rice in 2008 and produced 9.5 t ha^{-1} of organic long grain rice, followed by a vetch crop during the winter of 2009 (A. Scheidel pers. comm.). Planting rice Drained 09 during consecutive years was the main cause of weed seed bank accumulation and the resulting weed problems. This field was drained 25 DAS to control weeds, and was not reflooded until 55 DAS. This 30 day drainage event retarded rice growth and development resulting in harvest being delayed by three weeks in Drained 09. In Continuously Flooded 08, weeds were controlled using standard conventional practices, and no weed control was needed for Continuously Flooded 09. All fields had similar clay contents, but Continuously Flooded 08 had a lower pH and higher available K than either of the 09 fields (Table 1).

Table 1 Soil characteristics measured in the three field trail sites in 2008 and 2009.

Soil	pH	Clay-Silt-Sand (%)	Organic Carbon (g kg^{-1})	Total N (g kg^{-1})	Ex-K (ppm)	Olsen-P (ppm)
Continuously Flooded 08	4.9	49-33-18	17	1.4	171	10.4
Continuously Flooded 09	6.1	48-42-10	13	1.2	74	5.8
Drained 09	6.5	47-42-11	12	1.2	81	10.0

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 37m^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 and bone meal), 12-0-0 (feather meal), and 6-3-2 (poultry litter and feather meal). 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 (Table 2). All fertilizers were broadcast prior to seeding and lightly incorporated into the soil using a roller. Phosphorous and potassium were applied to all plots in both organic and conventional trials to ensure these nutrients were not limiting crop growth.

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

Fertilizer	Total N (%)	Total P (%)	Total K (%)	Organic C (%)	C:N	P:N	K:N
2008							
Pelletized 13-0-0	13.8	0.9	0.2	54	3.3	0.07	0.01
Pelletized 12-0-0	10.9	2.5	0.4	48	3.7	0.23	0.04
Pelletized 6-3-2	6.4	1.6	2.3	38	4.8	0.25	0.36
Poultry litter	2.6	1.6	3.3	41	11.5	0.62	1.27
2009							
Pelletized 13-0-0	12.9	1.0	0.2	54	3.6	0.08	0.02
Pelletized 12-0-0	13.0	0.4	0.4	55	3.6	0.03	0.03
Pelletized 6-3-2	6.7	1.4	1.7	40	5.0	0.21	0.25
Poultry litter	3.2	1.4	2.3	36	8.6	0.44	0.72

Stand density was similar in both 2009 fields and averaged 36 plants ft^{-2}, well within the established range of 12 to 46 plants ft^{-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 a one m^2 area 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^oC to a constant weight then ground and analyzed for total N by combustion. Grain yield is reported on a 14% moisture basis. N recovery efficiency (NRE) was calculated as follows:

NRE = ((total plant $N_{(fertilized)}$ – total plant $N_{(unfertilized)}$)/ N fertilizer applied)*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 plot, pooled, kept on ice and extracted with 2M KCl within 24 hours 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 prior to re-flooding using a procedure adapted from Miranda et al. (2001) and Doane and Horwath (2003). 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 rice to the grower was used to determine benefits (A. Scheidel pers. comm.). Costs taken into consideration included fertilizer purchase, fertilizer 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 ha ($ ha^{-1}), differences in N content of the various fertilizers were accounted for. 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. Cost of poultry litter application is included in the price of the fertilizer as it is common for the supplier to apply the purchased material.

Anaerobic N Mineralization Study

To compare and quantify mineralization rates of the organic N fertilizers under flooded conditions, a 60-day anaerobic laboratory incubation was conducted. The study was designed as a 5 by 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 days 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. The anaerobic incubation was conducted after the procedure of Saeed (1995). To each 200 ml glass bottle, 10 g of soil, 5g of K^+ saturated ion-exchange resins, and fertilizers (equivalent to 90 mg N kg^{-1} soil) were added. After the soil, resin and fertilizers were mixed uniformly the bottles were filled with 60mL of de-ionized water. The airspace was flushed for 30 sec. 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. NH_4-N in the extract was determined following the procedure of Forster (1995) and Verdouw et al. (1978). % N mineralized at each sampling time was calculated as follows:

% N mineralized from fertilizer = ((NH_4-N$_{(fertilized,\ t=0)}$ – NH_4-N$_{(unfertilized,\ t=0)}$)/ N fertilizer applied)*100.

The mineralization rates are 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 day^{-1}.

Statistical analyses

Effects of fertilizer treatments on grain yield, N uptake, NRE, and soil mineral N were evaluated across sites by standard analysis of variance (ANOVA) using SAS 9.1. The anaerobic incubation was analyzed as a 5x6 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 de-transformed means are presented in lieu of original means. All mean separations were determined using a protected LSD, and differences were considered significant at $p<0.05$.

2.3 Results

Nutrient concentrations of organic fertilizers

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 in fact contain both of these nutrients (Table 2). The total N concentration of the poultry litter varied from 2.6 to 3.2%, and poultry litter had the highest P:N and K:N ratios of all of the fertilizers (Table 2). The nutrient concentrations reported here for poultry litter are on a dry weight basis, however the moisture content of poultry litter also varies which increases the nutrient content variability. The variability in N content of poultry litter between the two years was 21%, as compared to 10% for the pelletized materials.

Grain yield in response to fertilizer

Grain yields ranged from 7.1 to 12.0 t ha^{-1} and are generally within the range expected for the Sacramento Valley (Table 3). There were significant interactions between field sites and treatments in regards to yield and N uptake responses, 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 t ha^{-1}), followed by Continuously Flooded 09 (9.2 t ha^{-1}), and Drained 09 (8.4 t 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.

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 08	Continuously Flooded 09	Drained 09	Mean
Grain yield (kg ha^{-1} at 14% moisture)				
Pelletized 13-0-0	11325 abc[1]	10073 a	8510 a	9969
Pelletized 12-0-0	10621 bc	10049 a	8723 a	9797
Pelletized 6-3-2	11522 ab	9876 a	9121 a	10173
Poultry litter	10384 c	8968 a	8448 a	9267
Control	8023 d	7055 b	7277 b	7452
$(NH_4)_2SO_4$	12042 a			
Average of all treatments	10653	9204	8416	
Poultry litter vs other fertilizers	*p=0.05	*p=0.04	ns	

[1] Means with the same letter within a column are not considered significantly different at $p<0.05$.

Nitrogen uptake and recovery efficiency

At harvest, seasonal plant N uptake ranged from 76 to 198 kg N ha^{-1} in the three fields across all treatments (Table 4). In Continuously Flooded 08 $(NH_4)_2SO_4$ performed significantly better than all other fertilizers with 198 kg of N ha^{-1} of plant N uptake at harvest. In all fields N uptake at harvest in the zero N control treatment was significantly lower (76 to 102 kg N ha^{-1}) than in the organic fertilizer treatments (101 to 152 kg ha^{-1}). Comparing the fertilizers, poultry litter had lower N uptake (101 to129 kg ha^{-1}) than the pelletized fertilizers (126 to152 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.

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

Fertilizer	Continuously Flooded 08			Continuously Flooded 09				Drained 09				Mean
	0 to 53 DAS[1]	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	Seasonal total
Plant N uptake (kg ha^{-1})												
Pelletized 13-0-0	102 bc[2]	45 a	148 bc	20 a	111 a	12 a	143 a	15 a	68 a	53 b	135 a	142
Pelletized 12-0-0	91 c	42 a	134 cd	19 a	111 a	4 a	139 a	14 ab	63 ab	63 ab	140 a	138
Pelletized 6-3-2	126 ab	26 a	152 b	19 a	98 ab	7 a	126 a	13 b	54 bc	76 a	143 a	140
Poultry litter	82 cd	42 a	124 d	15 b	76 bc	9 a	101 b	10 c	45 cd	75 ab	129 a	118
Control	61 d	33 a	94 e	12 b	59 c	3 a	76 c	10 c	37 d	55 ab	102 b	91
$(NH_4)_2SO_4$	154 a	44 a	198 a									

[1] DAS refers to days after sowing

[2] Means with the same letter within a column are not considered significantly different at $p<0.05$

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 (at least in Continuously Flooded 09). 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 much 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, and it coincided with an accumulation of NO_3-N in the soil while the field was under aerobic conditions (Table 5).

Table 5 Soil mineral N at three field sites at 24-25 DAS and 52-53 DAS[1] following the application of organic and inorganic N fertilizers.

Fertilizer	Continuously Flooded 08	Continuously Flooded 09		Drained 09		
	NH_4-N 52 DAS[1]	NH_4-N 24 DAS	NH_4-N 53 DAS	NH_4-N 25 DAS	NH_4-N 53 DAS	NO_3-N 53 DAS
Mineral N (mg N kg⁻¹ soil)						
Pelletized 13-0-0	1.1 a[2]	23.8 ab	2.3 a	17.5 a	2.4 a	16.4 ab
Pelletized 12-0-0	0.9 a	24.6 a	2.4 a	31.3 b	2.9 a	21.1 a
Pelletized 6-3-2	0.8 a	27.1 a	2.2 a	15.0 b	2.3 ab	18.0 a
Poultry litter	1.0 a	17.5 bc	2.2 a	12.5 bc	2.3 ab	7.4 bc
Control	1.2 a	14.9 c	1.7 a	8.0 c	1.7 b	4.3 c
$(NH_4)_2SO_4$	1.3 a					

[1] DAS refers to days after sowing

[2]Means with the same letter within a column are not considered significantly different at $p<0.05$

Differences in N uptake among fertilizer treatments occurred prior to 53 DAS in all fields. While N uptake continued to increase from 53 DAS to harvest, the amount of N uptake during this period was roughly the same for the fertilizer treatments (28 to 44 kg N ha^{-1}) as it was for the zero N control (30 kg N ha^{-1}) across fields. This implies that after 53 DAS the source of N for plant uptake is from native soil N pools – not from the fertilizer.

Across years and fields, the NRE of pelletized organic fertilizers ranged from 25 to 50%, while poultry litter had the lowest NRE of all fertilizers at an average of 20% (Table 6). 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.

Table 6 Nitrogen recovery efficiency (%) of fertilizer treatments in three field sites following the application of organic and inorganic N fertilizers.

Fertilizer	Continuously Flooded 08	Continuously Flooded 09	Drained 09	Mean
Pelletized 13-0-0	34 b[1]	50 a	25 a	36
Pelletized 12-0-0	25 c	47 a	28 a	33
Pelletized 6-3-2	37 b	37 a	31 a	35
Poultry litter	19 c	19 b	21 a	20
$(NH_4)_2SO_4$	66 a			

[1] Means with the same letter within a column are not considered significantly different at $p<0.05$

Anaerobic N mineralization study

In the anaerobic N mineralization study, NH_4-N concentration increased in all treatments, including the zero-N control, through day 60 (Fig. 1). After 60 days of incubation the amount of fertilizer N mineralized averaged 27% for pelletized fertilizers as compared to 14% for poultry litter (Table 7). N mineralization from the native soil N pool followed a two-phase increase, where initial N mineralization was rapid, followed by a period where N mineralization was slower between nine and 60 days. Organic fertilizers also had an initial phase of rapid N mineralization until day nine where net rates of N mineralization were highest ranging from 1.58 to 2.35 mg N kg^{-1} soil day^{-1}, followed by a slower phase of mineralization to 36 days where net rates of N mineralization ranged from 0.66 to 1.51 mg N kg^{-1} soil day^{-1} (Table 7). After 36 days 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 day^{-1}, approximated that of the zero N treatment (0.68 mg N kg^{-1} soil day^{-1}) between 36 and 60 days. Poultry litter had early rapid mineralization in the anaerobic incubation and was the only fertilizer treatment with a significantly higher mineralization rate than the control until day nine. In the secondary phase of mineralization between days nine and 36, poultry litter had a slower mineralization rate relative to other fertilizers (0.83 mg N kg^{-1} soil day^{-1}), which was not significantly different than the mineralization rate in the control (0.66 mg N kg^{-1} soil day^{-1}).

Table 7 The rates of N mineralization of organic N fertilizers and native soil over three time periods, and the percentage of fertilizer N mineralized after 60 days.

Fertilizer	0-9 days	9-36 days	36-60 days	N mineralized
	mg N kg^{-1} soil day^{-1}	mg N kg^{-1} soil day^{-1}	mg N kg^{-1} soil day^{-1}	(%)
Pelletized 13-0-0	1.64 ab[1]	1.08 ab	0.87 a	22 ab[1]
Pelletized 12-0-0	1.88 ab	1.45 a	0.72 a	33 a
Pelletized 6-3-2	2.24 ab	1.51 a	0.46 a	26 ab
Poultry litter	2.35 a	0.83 b	0.47 a	14 b
Control	1.58 b	0.66 b	0.68 a	

[1] Means with the same letter within a column are not considered significantly different at $p<0.05$

Economic analysis of fertilizers

The returns on organic fertilizer investment were highest in continuously flooded fields and ranged from 34 to 78% (Table 8). Returns on investment were much lower and sometimes negative in the drained field. There were no consistent differences between fertilizers, although the 6-3-2 (feather meal and poultry litter) performed relatively well in all fields.

Table 8 Economic analysis of returns on investment in fertilizer at three field sites following the application of organic N fertilizers.

Fertilizer				Continuously Flooded 08	Continuously Flooded 09	Drained 09
	Cost per tonne of material ($)	Assumed N content (%)	Cost per kg of N ($ kg^{-1})	Returns on investment (%)	Returns on investment (%)	Returns on investment (%)
Pelletized 13-0-0	798	13	6.13	67	76	-19
Pelletized 12-0-0	759	12	6.33	34	70	-9
Pelletized 6-3-2	358	6	5.96	78	68	17
Poultry litter	116	3	5.10	64	57	3
$(NH_4)_2SO_4$	391	21	1.86	162		

2.4 Discussion

Cause for limited response to N in the present study

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 t 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 t ha^{-1} (Linquist et al. 2009). The high indigenous soil N supply may explain the limited yield response to applied fertilizer N. Despite the low yield response, yields were significantly higher where N fertilizer was applied in all fields.

Challenges associated with poultry litter as a fertilizer

Organic sources of fertility present a management challenge for growers, as these materials tend to be unstable, bulky, and have low N analysis and high variability in nutrient content relative to mineral N fertilizers (Hadas et al. 1983, Gaskell and Smith 2007). A specific concern in 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 pelletized products tended to have less variability in N content (10%) as compared to 21% for poultry litter; however products were only evaluated over two years. Another concern is whether N applied as poultry litter will mineralize rapidly enough to supply an appropriate amount of N to insure high rice yields. In the present study the yield of rice fertilized with poultry litter ranged from 8.4 to 10.3 t ha^{-1}, which is high compared with yields measured in India under similar N rates (120 to 180 kg N ha^{-1}) of 4.8 to 6.1 t ha^{-1} (Singh et al. 1997). Under a relatively high N rate (270 kg N ha^{-1}) Golden et al. (2006) reported yield increases of 2.1 to 5.8 t ha^{-1} with poultry litter application, which is 15% higher than the yield increases reported here. However, poultry litter performance was only assessed under a single rate of N in the present study, and the determination of appropriate N rates for organic rice production in the Sacramento Valley would require further investigation.

Performance of pelletized fertilizers

Relative to poultry litter, pelletized fertilizers produced higher grain yield in all locations, although this effect was not significant in Drained 09 (Table 3). On average, pelletized fertilizer increased yield over the zero-N control by 2.5 t ha^{-1} compared to poultry litter which increased it by 1.8 t ha^{-1}. To provide insight into why the pelletized fertilizers exhibit superior performance, information on plant N uptake, recovery of applied N and the mineralization rates of the various fertilizers is needed.

Plant N uptake and recovery

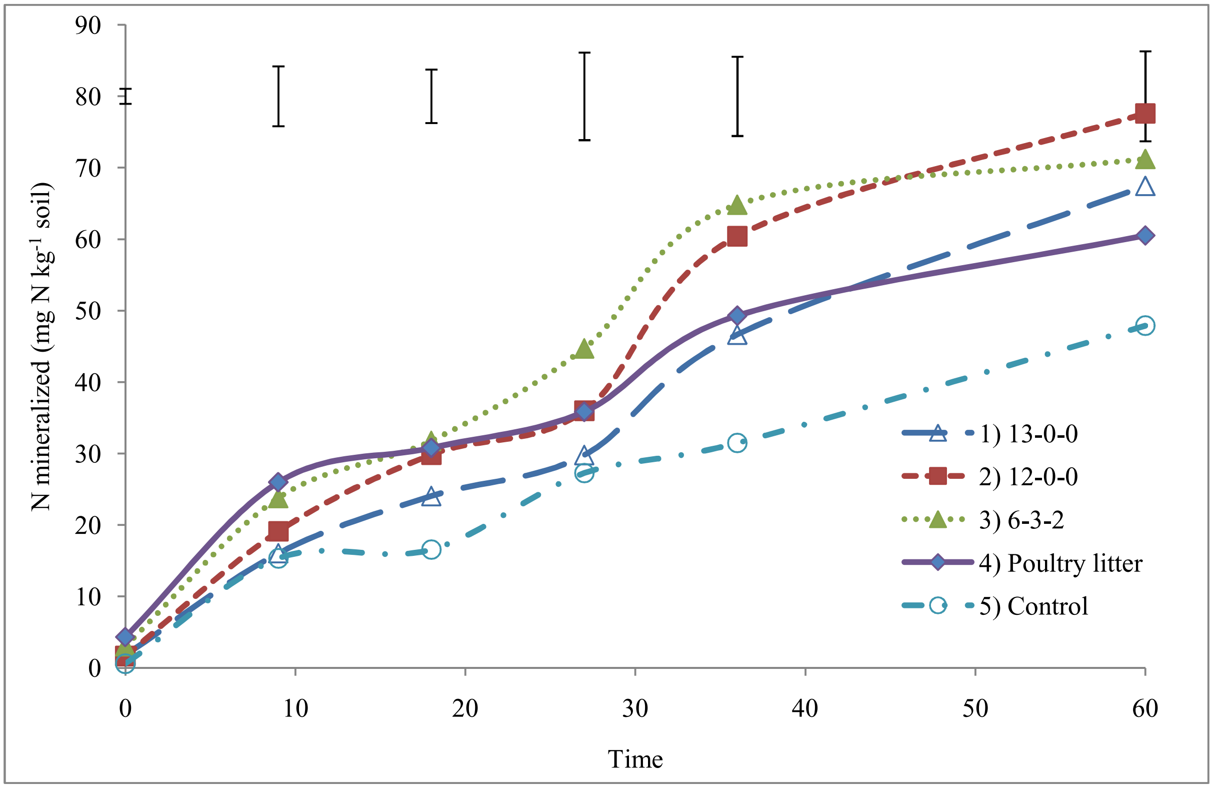
The most active period of N uptake in rice plants is between tillering and panicle initiation which occurs approximately 30 to 35 DAS, and 50 to 55 DAS, respectively (Peng and Cassman 1998) and results from our study support this conclusion (Table 4). Thus, mineralization of organic N fertilizer needs to occur during or before this time in order to optimize synchrony between N supply and crop demand. Results from the field studies indicate that mineralization of fertilizer N for all fertilizers occurred before 53 DAS, which is evidenced by plant N uptake from organic N fertilizers occurring before 53 DAS (Table 4). While N uptake continued in all fields after 53 DAS, mineralization of N during this period was most likely from indigenous N sources as the amount of N uptake during this period was similar for fertilizer treatments compared to the control.

On average 35% of the N in the pelletized fertilizer was mineralized and thus available for plant uptake as compared with only 20% of poultry litter N recovery (Table 6). The NRE of poultry litter is within the range reported of 14 to 35% in rice systems (Singh et al. 1997; Takahashi et al. 2004; Golden et al. 2006). While NRE is usually higher for inorganic versus organic N (Brahmanand et al. 2009, Golden et al. 2006) we were not able to compare the NRE of organic fertilizers with that of inorganic fertilizer in all fields. However the NRE of ammonium sulfate was highest among fertilizer treatments in Continuously Flooded 08 at 66% (Table 6).

Laboratory incubation study supports field findings

A mineralization study was conducted to compare fertilizers in terms of total N mineralized and the rate of N mineralization. The mineralization of indigenous soil organic N occurred in two phases, an initial rapid phase followed by a slower phase (Table 7 and Figure 2). Similar findings have been reported by others (Serna and Pomares 1981; Hadas et al. 1983; Agehara and Warnacke 2005). N mineralization of pelletized fertilizers and poultry litter behaved similarly to the mineralization of indigenous soil organic N and occurred in two phases. The initial phase of mineralization was most rapid in the poultry litter, which was the only fertilizer that had a significantly higher rate of N mineralization than the control between day zero and day nine (Table 7). However, the rate of poultry litter N mineralization slowed after day 9, and was similar to the rate of indigenous soil N mineralization, whereas pelletized fertilizers maintained higher mineralization rates until day 36. 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 hours of aerobic incubation. This pattern is likely due to the hydrolysis of urea, as a large portion of the organic N present in poultry litter is in the form of uric acid, which is rapidly hydrolyzed to NH_3 and may be lost through volatilization or converted to NH_4-N (Schefferle 1965). The N mineralization of all organic fertilizers proceeded until day 36, after which there was no further evidence of organic fertilizer mineralization and the rate of mineralization was similar for the control soil which received no N (Table 7). Following a 60 day anaerobic incubation, between 22 and 33% of the pelletized N fertilizer had been mineralized compared to 14% of the poultry litter N (Table 7). 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 days (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 utilized 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 (Gambrel and Patrick 1978, Olk et al. 1998, Witt et al. 2000). Our findings are more in line with Aulakh et al. (2000), who reported 29% of N added as poultry litter mineralized within 16 days of anaerobic incubation. While this rate of mineralization is higher than reported here (14%), it can be attributed to a higher incubation temperature of 35°C and because gaseous losses via denitrification were accounted for by Aulakh et al. (2000).

Figure 2 NH_4-N (in mg N kg^{-1} soil) measured over time in anaerobic incubation. Differences are denoted by LSD bars, and are significant at $p < 0.05$. Numbers represent the treatments; 1) Pelletized 13-0-0, 2) Pelletized 12-0-0, 3) Pelletized 6-3-2, 4) Poultry litter, 5) Control, at six sampling events (day 0, 9, 18, 27, 36, and 60)



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 days of anaerobic incubation. Similarly, Agehara and Warnacke (2005) found that after 28 days of aerobic incubation, only an additional 5% of organic N from blood meal and poultry manure mineralized. Secondly, both field and the incubation studies showed that less N is available to the crop from poultry litter (118 kg N ha^{-1}) as compared to the pelletized fertilizers (140 kg N ha^{-1}), particularly under anaerobic conditions. Golden et al. (2006) did not report any significant differences between N uptake from fresh and pelletized poultry litter, however their observations were made in a delayed flood system in which the soil was largely aerobic during the first seven weeks of the season.

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. Linquist and Sengxua (2003) reported that inorganic N applied after panicle initiation is not efficiently used and results in lower grain yield responses.

Response to N when field is drained

An extended drain of approximately 30 days 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 day period changed N dynamics (Table 5) reducing the yield response to added fertilizer and the NRE (Table 3 and 6) since little N was recovered by the crop during the drain period (Table 4). This, along with the aerobic soil conditions, allowed for nitrification and a build up of NO_3-N which averaged 19 mg N kg^{-1} for treatments amended with pelletized treatments, and 7 mg N kg^{-1} for treatments amended with poultry litter at 53DAS (Table 5). The NO_3-N was susceptible to denitrification losses when the field was reflooded (Patrick and Wyatt 1964) with the result being a lower NRE for all fertilizers in the drained field (Table 6). Based on these results and those from the economic analysis (Table 8), applications of fertilizer to fields that receive such extended drains may not be economically viable or sustainable. We have only presented results from one study and the management of organic N fertilizers under such conditions merits further work.

Fertilizer nutrient concentrations and management implications over time

All fertilizers contained some P and K despite manufacturer claims (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 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 (a calculated net gain of 8 kg P ha^{-1} yr^{-1}), which is found in labile and moderately labile inorganic P fractions (Linquist et al. 2010) Indeed Linquist et al. (2010) found that organic systems had high amounts of $NaHCO_3$ and NaOH extractable inorganic P, which led to these having higher total P soil levels than conventional systems. This may be cause for concern since it has been shown that continuous high P inputs will decrease the ability of a soil to retain P and the risk of loss is increased (Richardson 1985). P loss can lead to offsite contamination either through leaching or erosion (Pote et al. 1996) and have negative effects on water quality (Golden et al. 2006). In the present study all pelletized organic fertilizer contained some P, however the P:N ratio was roughly one-third that of poultry litter. Thus the use of these pelletized products may help reduce high soil P levels often associated with the use of poultry litter in California organic rice systems (Linquist et al. 2010).

2.5 Conclusion

Results from this study suggest that commercially pelletized organic fertilizers are a viable option for California organic rice growers and can be economically competitive with poultry litter. Advantages of the pelletized fertilizers over poultry litter were a higher and more predictable N concentration, a higher amount of mineralizable N, higher NRE, and 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 advisable. Further research is required to establish appropriate rates for these fertilizers which will also allow for a more rigorous economic analysis and the development of improved N management strategies for fields that will be drained.

Chapter 3: Overall Conclusions

The study of N mineralization, and the availability of N from organic fertilizer N sources to rice plants is essential to optimize their use for the appropriate supply of nutrients in irrigated rice fields, and to mitigate any potential adverse effects of these materials.

Economic analysis

A simple economic analysis suggests that that the returns on investment in the pelletized fertilizers are similar to poultry litter. This analysis is provided as a comparison between the various forms of organic fertilizers and highlights the potential for these pelletized fertilizers despite their relatively high cost. The use of any fertilizer in a field that is to be drained needs to be carefully considered as the yield response to N was 65% lower than in the continuously flooded fields and returns on investment were not favorable. While pelletized fertilizers have proven to be efficacious in providing a sufficient amount of mineral N to meet plant needs and achieve an NRE of 25 to 50%, at least in continuously flooded fields, their use is likely to be limited to organically certified rice production systems, where growers gain a price premium for their rice and can garner positive returns on investment in these materials.

Improvements on current work, and possibilities for further research

The present study was conducted in three fields that did not exhibit severe N deficiency, which resulted in a low grain yield response to N fertilizer. Further field trials seeking to evaluate the efficacy of organic fertilizers in rice fields should be conducted in locations where N deficiencies are more severe.

In the present study, fertilizers were surface applied and lightly incorporated with a roller immediately prior to aerial seeding utilizing a single rate of N application (157 kg N ha in 2008, and 134 kg N ha in 2009). It is unknown whether this N rate would be appropriate to insure maximal rice yields as N response curves were not pursued here. In order to formulate best management recommendations for organic fertilizers, a rate trial should be conducted, and an attempt made to calculate urea-N equivalents for the organic materials. Regarding application timing, the results showed that 84% of plant N uptake in continuously flooded fields occurred before 53 DAS, therefore the recommendation is to apply organic fertilizers in a single pre-planting application in order to insure that mineralization occurs in synchrony with plant N uptake. Regarding fertilizer application, it would be recommended to incorporate organic fertilizers into the soil during tillage as this will reduce losses due to run off (Pote 2009), and ammonia volatilization (Reddy 1982), and will increase NRE without causing N deficiency in young rice seedlings (Linquist et al. 2009).

While the present study showed no additional fertilizer mineralization after 53 DAS during a single growing season, many authors have described residual effects of organic N application on soil N pools (Singh et al. 1997, Thomsen 2004, Kong et al. 2007), therefore it would also be worthwhile to initiate a long term experiment utilizing high N-content organic fertilizers such as the pelletized products in this study to determine the possible long term benefits of their use.

The anaerobic incubation measuring N mineralization was performed by adapting the procedure of Saeed (1995) who utilized smaller samples (2 g of soil, and 1 g of K^+ ion exchange resins) with no fertilizer addition. The incubation generally confirmed results seen in the field; however it would be worthwhile to conduct the incubation utilizing the same N rate as that applied in field trials in order to be able to directly correlate N mineralization studied in the laboratory and plant N uptake in the field. Also in subsequent incubations it would be worthwhile to increase the frequency of sampling, particularly during the initial rapid period of N mineralization (to nine days) in order to insure that the initial flush of labile N from organic sources is adequately captured. Furthermore a second incubation could be designed to mimic the soil moisture conditions present in fields that receive an extended drain period for weed control, where samples would be under anaerobic conditions to 25 days, then aerobic to 55 days, followed by a reflooding of the microcosm, and anaerobic conditions to 65 days.

While microbial composition, size and activity was not determined in the present study, further work may seek to quantify this important driver of N transformations as it would provide a more complete understanding of N cycling in these systems.

The amount of land dedicated to organic rice production in the US has increased from 3,400 ha in 1995 to 20,000 ha in 2008, and now accounts for 1.8% of total US rice production (USDA, 2008). As the consumption of organically certified products rises, we may see more land dedicated to organic rice production, therefore it is certainly worthwhile to invest further work in this production system.

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