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Legume Decomposition and Nitrogen Release When Applied as Green Manures to Tropical Vegetable Production Systems

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ABSTRACT

For legume green manures (GM) to be effective, environmentally sound N sources for horticultural crops in the tropics, their N release must be in synchrony with crop N demand. Decomposition and N release of surface applied (mulch) or incorporated soybean [*Glycine max* (L.) Merr.] and indigofera (*Indigofera tinctoria* L.) GM were studied in six field studies conducted at three locations in Taiwan and the Philippines between 1993 and 1995. Litter bags and inorganic N soil samplings were used in order to understand tomato (*Lycopersicon esculentum* Mill.) crop responses to GM N. Resulting soil N contents were compared with a control (no GM, no fertilizer). The N content of 60 to 74 d soybean GM varied between 110 and 140 kg N ha^{-1} and that of indigofera between 5 and 40 kg N ha^{-1}. Nitrogen-15-labeled soybean GM was traced in the soil and in organic matter fractions (humic acids, calcium humates, humins) in one of the field studies. Soybean and indigofera decomposed rapidly, losing 30 to 70% of their biomass within 5 wk after application, depending on GM placement, season (wet vs. dry), and location. Soil nitrate contents increased corresponding to GM N release at all locations and seasons, with a maximum increase of 80 to 100 kg NO_3–N ha^{-1} with incorporated soybean. The peak N release occurred 2 to 6 wk after GM application in two of the three locations, and 5 to 8 wk in the third location. The apparent decline of GM N release at all locations and seasons 8 wk after application was only partly caused by tomato N uptake. At tomato harvest, 30 to 60% of the GM ^{15}N was found in the soil, and was found mostly in humins. Comparable N release dynamics across seasons and locations suggest a possible N fertilizer substitution by incorporated soybean GM for basal N application and first side dressing to tomato. With respect to season and location, GM N should be supplemented with N fertilizer starting after 8 wk to ensure optimal tomato yields.

For legume green manures (GM) to be considered as effective N sources for horticultural crops, they must supply sufficient N and their N release must be in synchrony with vegetable N demand. Green manure decomposition and subsequent N release depend largely on residue quality and quantity, soil moisture and temperature, and specific soil factors such as texture, mineralogy and acidity, biological activity, and the presence of other nutrients (Myers et al., 1994). In a previous study, 60-d-old soybean [*Glycine max* (L.) Merr.] and indigofera (*Indigofera tinctoria* L.) plants conformed to high-quality litter characteristics (Swift, 1987), releasing N quickly to two of the three soils tested (Thönnissen Michel, 1996). Legume biomass accumulation and chemical composition (e.g., C/N, N, lignin, polyphenol, and tannin) of plants of the same age varied between location and growing season (Thönnissen Michel, 1996), making it difficult to predict their decomposition when grown under different conditions. Residue decomposition can be governed to some extent by GM placement on the soil surface (mulch) or incorporation into the soil (Wilson and Hargrove, 1986). In the southeast of the USA, the greatest N release from decomposing legumes occurred 2 to 5 wk after cover crop killing in spring (Sarrantonio and Scott, 1988). Too rapid GM N release (e.g., within 15 d after incorporation of vetch; Varco et al., 1989), strong N immobilization after GM addition (Mary and Recous, 1994), or early decline of mineral N level over the growing season (Ebelhar et al., 1984) lead to poor synchronization between N release and crop N demand. Studies evaluating the fate of ^{15}N from legume residues decomposing under field conditions led to the conclusions that <30% of legume N was recovered by a subsequent nonlegume crop and large amounts of legume N were retained in soil, mostly in organic forms (Harris et al., 1994; Ladd et al., 1983; Mueller and Sundman, 1988). If, however, lower mineralization rates of mulched GM (nontillage) are responsible for reduced inorganic N accumulation, then such a system could better conserve organic N in the long term (Sarrantonio and Scott, 1988).

The objective of this study was to monitor legume GM decomposition and determine the timing and quantity of GM N release in fields grown to tomato crops (Thönnissen Michel, 1996) at three locations and two seasons (wet season, WS; dry season, DS) in Taiwan and the Philippines. In the tropical WS in Taiwan, nitrate leach-

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Abbreviations: AVRDC, Asian Vegetable Research and Development Center; BRCI, Bukidnon Resources Corporation, Inc.; DS, dry season; IRRI, International Rice Research Institute; GM, [legume] green manure; MMSU, Mariano Marcos State University; SOM, soil organic matter; WS, wet season.

ing losses were estimated in tomato plots amended with GM and N fertilizer. To trace the fate of GM N at one of the three locations, ^{15}N-labeled GM was traced in soil and labile fractions of soil organic matter.

MATERIALS AND METHODS

Field Trials

Legume GM decomposition and subsequent N release to soil grown to tomato (*Lycopersicon esculentum* Mill.) crops was monitored in six field experiments during 1993 to 1995 conducted at the Asian Vegetable Research and Development Center (AVRDC) in central Taiwan, the Mariano Marcos State University (MMSU) in northern Luzon in the Philippines, and the Bukidnon Resources Co., Inc. (BRCI), in northern Mindanao in the Philippines. Experiments were run simultaneously on two fields, each with different bed systems: raised or low beds. The raised beds were 45 cm high and 2 m wide, with 2-m furrows between the beds. The furrows were sown with rice (*Oryza sativa* L.) and were permanently flooded. The low beds were 20 cm high and 2 m wide, with 50-cm-wide irrigation furrows between beds. Both experiments (raised and low beds) were adjacent, such that the soil type, the cropping history, and meteorological conditions were the same. Soil types were a silt-loamy, mixed, hyperthermic Fluvaquentic Entochrept (AVRDC); a clayey, kaolinitic, isohyperthermic Ultisol (BRCI); and a clayey, mixed, isohyperthermic Fluvaquentic Ustropept (MMSU). A randomized complete block design with four replicates was used at all three locations. Treatments at each location were two legume species, two methods of GM application to the soil, and four N treatments (0, 30, 60, and 120 kg N ha^{-1}) applied to tomato. Legumes were grown for 2 mo, cut at the root level, chopped, and applied to the soil. The legumes were soybean and indigofera at AVRDC and MMSU, and soybean and mungbean [*Vigna radiata* (L.) Wilcz.] at BRCI. Once GM was applied to the soil, tomato crops were transplanted on the same location and grown up to harvest (2–3 mo) (Thönnissen Michel, 1996). Leguminous green manures (60 d old at AVRDC; 70 d old at MMSU) were incorporated by soil tillage down to the 10- to 15-cm soil depth or left as mulch on the soil surface (no soil tillage). The amounts of legume biomass and N present as GM varied across locations and seasons. For example, soybean GM contained between 110 and 140 kg N ha^{-1}, indigofera between 5 and 40 kg N ha^{-1}, and mungbean 26 kg N ha^{-1} (Thönnissen Michel, 1996). Tomato seedlings were transplanted immediately after GM application and remained in the field until fruit harvest.

Environmental Monitoring

Soil moisture was monitored with tensiometers placed in GM and control treatments, at the 15-, 30- and 45-cm depths following tomato transplanting at AVRDC and MMSU.

Decomposition Study

Nylon bags (mesh size 1 mm) containing 15 g fresh plant material (4.7–5.5 g dry wt.) were used to determine biomass breakdown of incorporated or mulched soybean and indigofera GM at AVRDC in both the WS and the DS and at MMSU in the DS only. Bags were filled with root and shoot material on the same day as GM application. Mulch treatments contained shoot material only. At the time of GM application, all bags were either buried 10 cm deep for incorporation treatments or left on the surface for the mulch treatments. Litter bags were sampled at the same dates as soil sampling for inorganic N: at AVRDC WS 0, 2, 5, 8, 14, 29, 42, 62 and 75 d after GM application, at AVRDC DS 0, 7, 21, 35, 56, 98 d after GM application, and at MMSU 0, 5, 21, 36, 58, 77, 113 d after GM application. On each date two randomly chosen bags per treatment were retrieved, oven-dried at 60°C for 48 h, and weighed. Samples were ashed by dry combustion in a muffle furnace (500°C) for 8 h to determine original ash-free dry weight remaining (Aber et al., 1990). Biomass loss data for soybean and indigofera were fitted into the first-order single exponential model $M_t = M_0 e^{-kt}$ described for litter decomposition by Wieder and Lang (1982). The higher the *k*-value (decomposition rate), the faster the decomposition of the organic matter. Decomposition rates were calculated for a period of 77 d in the WS and 94 d in the DS at AVRDC and 113 d at MMSU.

Inorganic Nitrogen

The effects of legume species and GM placement treatments on the quantity and the timing of N release to soil were evaluated in all six field experiments. Inorganic N in the soil was monitored in plots planted to tomato in five treatments; control (Ck0), soybean incorporation (Si), soybean mulch (Sm), and either indigofera incorporation (Ii) and indigofera mulch (Im) (at AVRDC and MMSU) or mungbean incorporation (Mi) and mungbean mulch (Mm) (at BRCI). These plots were sampled on the dates listed above for litterbag sampling and also at 0, 14, 28, 42, 56, 70, 84, 96, 110 d after GM application at BRCI. Soil samples were collected with a 5-cm-diameter auger at the 0- to 30-cm depth from the five treatments in all four blocks. Each sample was a mixed composite collected from four locations in each plot. Soil samples were passed through a 10-mm sieve and extracted with 1 *M* KCl (1:1.5 soil/water); inorganic N (NH_4–N and NO_3–N) was determined with an ammonia gas sensing electrode (Siegel, 1980). At MMSU, additional soil samples from the 30- to 60-cm soil depth were taken at −74 (legume seeding), 1, and 113 d after GM application.

To study the effect of living plants on N mineralization, the five treatment plots in Blocks I, II, and III were split into three subplot treatments after GM application: (i) unplanted, (ii) planted with tomato, and (iii) planted with cabbage (*Brassica oleracea* var. *capitata* L.) in the DS at AVRDC; and (i) unplanted, (ii) planted with tomato 1 d after GM application, and (iii) planted with tomato 2 wk after GM application at MMSU. Nitrogen mineralization was monitored in all three subplot treatments.

Estimation of Potential Nitrate Leaching

Nitrate leaching in the WS at AVRDC was estimated by the NaCl method (Cameron and Wild, 1982). Fifty grams of NaCl was broadcast on 1 m^2 in the tomato plots in the treatments Si, Sm, Ck0, and 120 kg N ha^{-1} (Ck120) in four replications in two bed systems, low or raised beds (Thönnissen Michel, 1996). Sodium chloride was applied on the respective plots after soybean incorporation and mulch on 23 June 1993. Soil samples were taken on 21 June, 23 July, and 30 August from the 0- to 50-cm layer in the raised beds and from the 0- to 30-cm layer in the low beds. In each, the soil core was separated into 10-cm sublayers. Soil samples were air-dried and extracted (1:2 soil/water). Chloride in the water extracts was determined with a chloride analyzer (Chloride Analyzer 926, Coramed AG, Dietlikon, Switzerland).

Nitrogen-15 Experiment

Tomato N response to GM was low in the DS at AVRDC (Thönnissen Michel, 1996). To understand the fate of GM N, soybean GM was labeled with ^{15}N (Thönnissen Michel, 1996) for a ^{15}N microplot experiment at MMSU. Microplots (metal

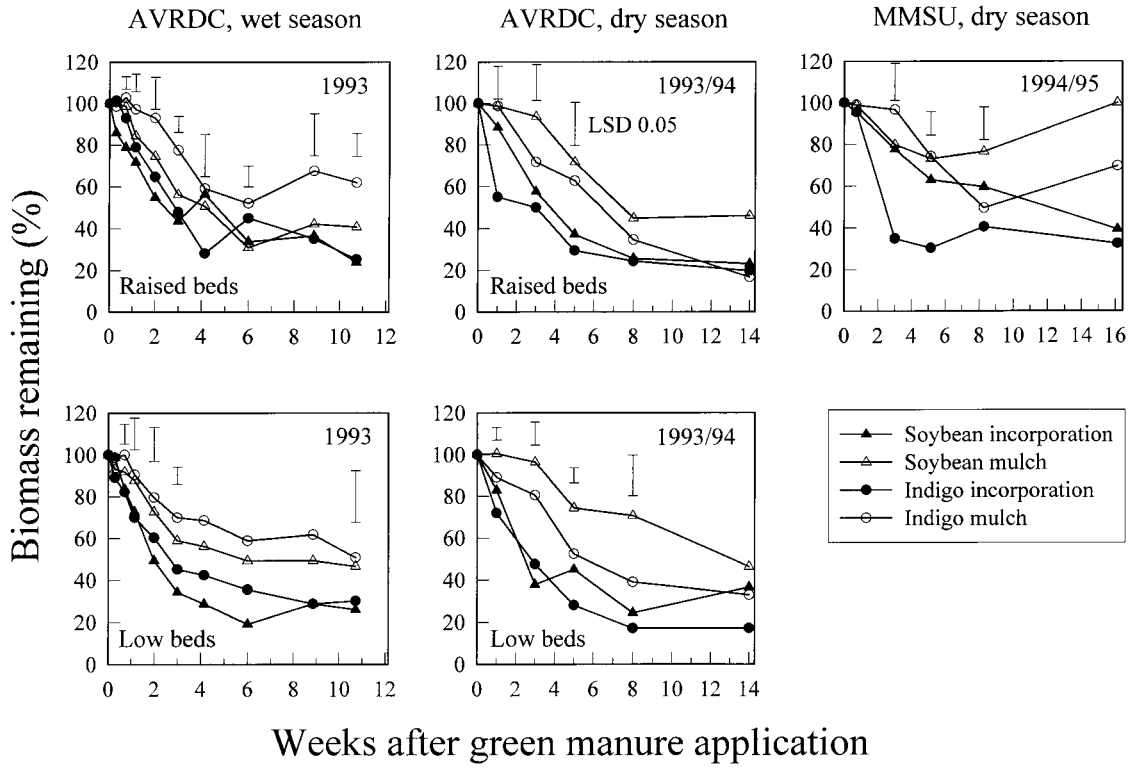

Fig. 1. Decomposition of soybean and indigofera residues when used as mulch or incorporated into the soil in the low and raised bed systems and in the wet and dry seasons at AVRDC, Taiwan, and in the dry season at MMSU, Philippines (1993–1995). Error bars indicate LSD (0.05).

frames 0.8 by 0.8 by 0.3 m, length by width by height, pushed into the soil to a depth of 25 cm) were amended with ^{15}N-labeled soybean GM. The GM was incorporated manually down to the 10- to 15-cm soil depth. Two tomato seedlings were transplanted into each microplot. Green manure ^{15}N recovery in tomato was determined (Thönnissen Michel, 1996). Soil was sampled for organic matter extraction and soil ^{15}N determination in control and soybean incorporation treatment plots at 1 and 113 d after GM application. Nitrogen-15 determination was conducted on mobile humic acids (MHA) and calcium humates (CaHA), which were considered as C pools representing early and later stages of the humification process (Olk et al., 1995).

Statistical Analysis

Data were analyzed by ANOVA procedure using JMP Version 2 (SAS Inst., 1989) and SAS version 6.03 (SAS Inst., 1991).

RESULTS

At all locations and seasons, incorporated GM decomposed significantly faster than mulched GM (Fig. 1). Biomass loss patterns and decomposition rates of both legume species and GM management practices were comparable across bed systems at AVRDC (Table 1). Soybean decomposed slightly faster than indigofera in the WS, but slower than indigofera in the DS at AVRDC. Differences in biomass breakdown between GM placement (mulch vs. incorporation) at AVRDC were larger in the DS than in the WS. While decomposition rates of incorporated GM were similar across seasons at AVRDC, those of mulched soybean GM in the DS were only half those of the WS, and slightly greater than those of the WS for indigofera. The effect of GM placement on biomass loss was similar across legume species at AVRDC, while soybean and indigofera decomposed differently at MMSU. Great differences in decomposition between incorporated and mulched indigofera occurred during the early decomposition stages (up to 6 wk) at MMSU (Fig. 1). With the exception of incorporated indigofera, GM at MMSU decomposed at reduced rates compared with those at AVRDC.

Soil Moisture and Nitrogen Release

Frequent irrigation precluded significant changes in soil moisture due to GM placement during the tomato growing season in the DS at AVRDC and at MMSU. An optimal water supply for tomato plants was ensured by maintaining soil matric potentials between −0.02 and −0.06 MPa. With the exception of typhoons that hit southern Taiwan irregularly and subsequently flooded the low beds, soil matric potentials ranged between −0.01 and −0.08 MPa in the WS. Daily rainfall led to soil moisture contents near field capacity during the tomato growing season at the BRCI location.

Nitrate was the dominant form of inorganic N in the soil soon after legume application at all three locations. Soil NH_4–N contents remained low (±5 kg NH_4–N ha^{-1} at AVRDC and MMSU; ±20 kg NH_4–N ha^{-1} at BRCI) and were comparable to those of the control (data not shown). Green manure application increased soil NH_4–N contents significantly by 10 to 15 kg NH_4–N ha^{-1} at AVRDC, 5 kg NH_4–N ha^{-1} at MMSU, and 30 kg NH_4–N ha^{-1} at BRCI in the first week after GM application, but NH_4–N declined rapidly within 3 wk. With the exception of an increase in soil NH_4–N by 1 to 8 kg NH_4–N ha^{-1} in the low beds in the DS at AVRDC, NH_4–N contents did not differ between planted and

Table 1. Decomposition rate, *k*, of legume green manures (soybean, indigofera) incorporated into the soil or left as mulch on the soil surface in field experiments at AVRDC, Taiwan (1993–1994) and at MMSU, Philippines (1994–1995). Decomposition rates were calculated using the single exponential model for decomposition (Wieder and Lang, 1982), for a period of 77 d in the wet season (WS) and 94 d in the dry season (DS) at AVRDC and 113 d at MMSU.

Species	Plant age d†	Application	Location	Season	Bed system	k ‡ d^{ms1}	r^2§
Soybean	68	incorporation	AVRDC	WS	raised	0.0272a	0.89***
					low	0.0361a	0.88***
	60			DS	raised	0.0236c	0.95***
					low	0.0251c	0.80*
	74		MMSU	DS	low	0.0099e	0.96***
	68	mulch	AVRDC	WS	raised	0.0175b	0.91***
					low	0.0144b	0.90***
	60			DS	raised	0.0094d	0.89**
					low	0.0071d	0.95***
	74		MMSU	DS	low	0.0065f	0.64*
Indigofera	68	incorporation	AVRDC	WS	raised	0.0266g	0.88***
					low	0.0262g	0.93***
	60			DS	raised	0.0313i	0.94**
					low	0.0350i	0.97***
	74		MMSU	DS	low	0.0259k	0.67*
	68	mulch	AVRDC	WS	raised	0.0098h	0.75**
					low	0.0111h	0.91***
	60			DS	raised	0.0162j	0.98***
					low	0.0147j	0.95**
	74		MMSU	DS	low	0.0059l	0.52NS

† d, days after sowing.
‡ *k*-values within the same season, location, and bed system were compared using a pairwise *t*-test for slopes. *K*-values with different letters are significantly different at $P = 0.05$.
§ *,**,***, NS, Regressions are significant at $P = 0.05$, 0.01, 0.001, or nonsignificant, respectively.

unplanted plots in the raised beds at AVRDC and at MMSU.

At all three locations, N release in soil peaked at 80 to 120 kg NO_3–N ha^{-1} with soybean GM (Fig. 2). This peak N release occurred 2 to 6 wk after GM application in both seasons at AVRDC and at BRCI. At MMSU, GM N release peaks were delayed relative to the two other locations, occurring after 5 to 8 wk. Nitrate contents declined after 5 to 8 wk at all locations. More NO_3–N was released with incorporated GM than mulched GM at AVRDC and MMSU. Far more N was released with soybean than indigofera in the WS at AVRDC; in the DS, however, differences in N release between legume species were small. Nitrate released with soybean GM was comparable to that released with mungbean GM at BRCI. Basal N mineralization (NO_3–N) in control treatment plots was low in the WS at AVRDC and at MMSU, but high in the DS at AVRDC and at BRCI.

From 10 to 50 kg ha^{-1} less of NO_3–N was measured in planted than in unplanted plots between 3 and 8 wk after GM application in the DS at AVRDC (data not shown). Nitrogen uptake by tomato or cabbage, measured by the difference of NO_3 in the soil in planted vs. unplanted plots, generally started 1 to 3 wk after transplanting. Cabbage was apparently a stronger N sink than tomato, for less soil NO_3 was found in cabbage than tomato plots. At MMSU, soil NO_3–N contents in early-transplanted tomato plots remained lower than in either later-transplanted plots or in the unplanted control plots (data not shown). No significant differences in soil NO_3–N content between GM and control plots were evident at the 30- to 60-cm soil depth at MMSU. However, nitrate contents at the 30- to 60-cm soil depth in GM treatments tended to be lower than the control before GM application and higher than the control at the end of the experiment. At tomato harvest, less soil NO_3 was found in planted than in unplanted plots, but differences were not significant. Green manure application did not affect NH_4 contents at the 30- to 60-cm soil depth.

Nitrate Leaching

The potential for nitrate leaching estimated from the movement of chloride followed similar patterns in control, 120 kg N ha^{-1}, soybean mulch and incorporation treatments. Therefore, chloride loss (%) data of these four treatments were averaged for each sampling date and bed system (Table 2). The background Cl-concentration (21 June) in the 10- to 50-cm soil depth was rather low. Of the applied chloride, 42 and 50%, had been lost by 23 July 1993 from a soil depth of 30 and 50 cm, respectively, in the raised bed only 1 mo after application. The greatest net loss occurred at the 0- to 10-cm soil depth, whereas chloride accumulation occurred at soil depths of 10 to 20 cm and 20 to 30 cm. Chloride did not accumulate at the 30- to 50-cm depth in the raised beds.

Green Manure Nitrogen-15 Recovery in Soil

Total soil C and N contents increased by about 5% between the time of soybean incorporation and tomato harvest (Table 3). Although mobile humic acid (MHA) C increased and calcium humate (CaHA) C and N decreased from the first to the second sampling, the effect of GM application on these parameters is not clear because these parameters changed similarly in the control plot between samplings.

The MHA and CaHA did not seem to be more active in short-term N cycling than the bulk soil organic matter (SOM), as the two fractions combined contained only 4.5% of the total soil ^{15}N in the soybean plot at tomato

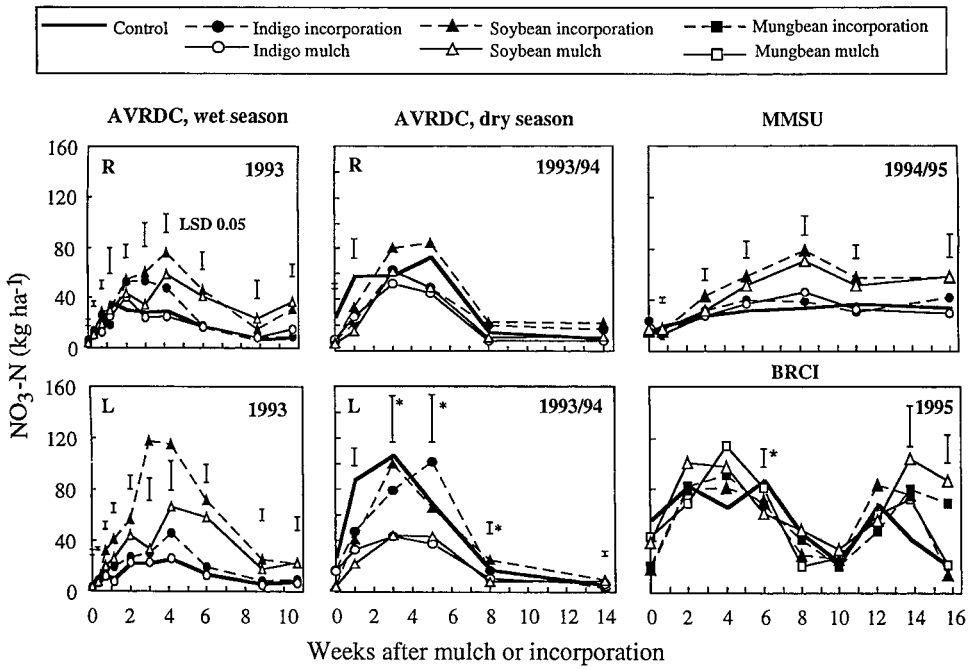

Fig. 2. Nitrate contents in soil (0–30 cm) after application of green manure (soybean, indigofera at AVRDC, Taiwan, and at MMSU, Philippines; soybean and mungbean at BRCI, Philippines) in raised (R) and low (L) beds, 1993–1995. Error bars indicate LSD (0.05); asterisk indicates significance at the 0.1 probability level.

harvest. Most of the ^{15}N was recovered in the humin (unextracted organic matter). Moreover, the ratios of ^{15}N to total N were similar for the MHA and CaHA as for the bulk soil, further suggesting that preferential accumulation of recently added ^{15}N did not occur in the extracted MHA and CaHA. The MHA and CaHA had comparable amounts of ^{15}N in the soybean plots at final tomato harvest. Nitrogen-15 in total soil was not fully recovered in the MHA, CaHA, and humin, which may be due to losses of ^{15}N during extraction as fulvic acids.

At tomato harvest, estimations of N losses were greater calculated with ^{15}N than with total N (Table 4), due to lower N recoveries of ^{15}N in both tomato and soil. Nitrogen-15 values for whole soils, MHA, and CaHA for all treatments except soybean at tomato harvest were too low to allow accurate measurement.

Table 2. Percent remaining chloride at different soil depths for three sampling dates in raised and low beds (AVRDC, Taiwan, 1993). Chloride was added on 23 June.

	Sum						
Soil depth	0–10	10–20	20–30	0–30	30–40	40–50	0–50
	% Cl†						
	Raised beds						
21 Jun	78 ± 4	6 ± 2	4 ± 1	100	7 ± 1	5 ± 1	100
23 Jul	24 ± 6	12 ± 1	6 ± 2	37	5 ± 1	4 ± 1	50
30 Aug	14 ± 2	9 ± 2	5 ± 1	25	3 ± 1	3 ± 1	35
	Low beds						
21 Jun	86 ± 3	8 ± 3	6 ± 1	100			
23 Jul	28 ± 10	19 ± 4	11 ± 2	58			
30 Aug	23 ± 1	16 ± 4	11 ± 2	50			

Values shown are means of four treatments: control, Ck 120 kg N ha^{-1}, soybean incorporation, and mulch, and standard deviation between treatment means. Treatments means are means of four replicates.

† % Cl was calculated by setting the Cl contents (g Cl/m^3) to 100% on 21 June 1993 from 0 to 30 cm (raised and low beads), and additionally 0 to 50 cm for raised beds.

DISCUSSION

Factors Affecting Green Manure Decomposition and Mineralization

Decomposition rates of incorporated GM differed less between seasons and locations than for mulched GM. Incorporated residues are in a generally more favorable environment for microbial decomposition (e.g., close soil contact, adequate soil moisture, etc.) (Wilson and Hargrove, 1986). Fast initial decomposition of soybean in both seasons at AVRDC matches findings of Broder and Wagner (1988), where incorporated soybean residues lost 68% of their total biomass within 32 d.

In most comparisons, plant chemical composition appeared to affect the decomposition rate of GM. Faster decomposition of indigofera at AVRDC was probably caused by its smaller and more tender leaves and less

Table 3. Organic C and N in total soil and in organic fractions (mobile humic acids [MHA]; calcium humates [CaHA] immediately after (1 d) and 113 d after green manure application in control and soybean incorporation plots. Standard deviation of laboratory replicates of organic C and N contents of total soil are given in parentheses, 1994–1995, MMSU, Philippines.

			Organic matter fraction			
	Total soil		MHA		CaHa	
(d†	C	N	C	N	C	N
	g kg^{-1}soil					
1						
Control	7.11 (0.01)	0.665 (0.01)	0.162	0.0163	0.448	0.0409
Soybean	7.04 (0.03)	0.707 (0.01)	0.218	0.0227	0.369	0.0346
113						
Control	6.85 (0.06)	0.669 (0.02)	0.212	0.0204	0.228	0.0243
Soybean	7.39 (0.04)	0.750 (0.02)	0.240	0.0231	0.226	0.0248

† d, days after soybean GM application.

Table 4. Comparison of total N and ^{15}N balance after tomato harvest in soybean incorporation plots at MMSU, 1995. Values within parentheses indicate standard deviation (n=3).

		Total N		^{15}N	
		kg N ha^{-1}	% recovery	kg N ha^{-1}	% recovery
Input	soybean	119.3		0.910	
Output	tomato	19.5† (10.8)	16.3	0.082 (0.02)	8.9
left	soil	64.0 (20.0)	53.7	0.315 (0.01)	34.6
not found		35.8	30.0	0.513	56.5

† Calculated by subtracting tomato N in control from tomato N in soybean incorporation.

lignified stems relative to those of soybean. The slower decomposition of incorporated soybean compared with indigofera at MMSU occurred despite similar plant chemical compositions (data not shown). Sixty-day-old soybean (maturity scale R5 to R6; Fehr et al., 1971) in both seasons at AVRDC decomposed at rates similar to those of incorporated indigofera at MMSU. The physical nature of older soybean plant material (R6 to R7) used at MMSU, with hardy stems and pods containing full size yellow beans, may have been one of the main reasons for the large differences in decomposition rates between soybean decomposition at AVRDC and indigofera at MMSU.

Many investigators have observed that organic residues decompose more slowly in soils with higher clay contents, especially clays having higher exchange capacities (Lynch and Cotnoir, 1956; Sorensen, 1975). Microbial activity is controlled by soil physical conditions such as compaction, temperature and oxygen; by chemical conditions such as substrate availability; and by biological conditions such as predatory or antagonistic organisms (Grant et al., 1993). Reduced soil aeration or oxygen in the clayey soil at MMSU compared with the loamy soil at AVRDC may have further contributed to a slower legume residue decomposition rate at MMSU.

The exponential weight loss pattern agrees with previous assumptions that residues contain labile and recalcitrant fractions having different degrees of resistance to microbial degradation. Reinertsen et al. (1984) associated the more rapid decay immediately after the burial of the residue with the decomposition of water-soluble organic constituents. Hunt (1977) described differences in decomposition patterns and rates among substrates as a function of the amount of the labile or rapidly decomposing fractions (sugars, starches, proteins) and the recalcitrant or slowly decomposing fraction (cellulose, lignin, fats, tannins, waxes). Decomposition processes can be predicted from initial litter chemistry (Aber et al., 1990; Neely et al., 1991). Seasonal effects on chemical composition of legumes (i.e., C/N, initial N, lignin, polyphenol, and tannin contents) have been shown within the same location (Thönnissen Michel, 1996). The statistical significance of each chemical component to the rate of GM degradation varied widely between seasons and locations (Thönnissen Michel, 1996). The relatively high polyphenol (3.7%) and tannin (1.6%) content of indigofera may have retarded decomposition compared with soybean (polyphenol 1.7%, tannin 0.2%) in the WS, whereas in the DS the lower C/N-ratio (10.6) and higher initial N content (4.2%) of indigofera may have determined its faster decomposition compared with soybean (C/N 12.2; N 3.9%). Results of this study confirm the complexity of decomposition processes where the interaction of both resource quality and microclimate influence the conditions and activity of decomposer communities and those in turn mediate processes of decomposition and nutrient release (Neely et al., 1991; Hunt, 1977).

High soil temperatures (20–30°C) and moisture conditions near optimum (−0.01 to −0.05 MPa; Cassman and Munns, 1980) were mainly responsible for the fast release of NO_3 following GM application in all locations and seasons. Nitrate-N release at AVRDC mirrored the initial exponential loss of biomass, evidence for the causal linkage between these two processes. Higher decomposition rates of indigofera in the DS led to N release in soil comparable to that of soybean, although far less N (33 vs. 127 kg N ha^{-1}, Thönnissen Michel, 1996) was incorporated with indigofera GM. Reduced mineralization rates of surface applied residues (mulch) can be attributed to poor soil–residue contact and drastic temperature and moisture fluctuations at the soil surface (McCalla and Duley, 1943). Numerous authors (e.g., Janzen and McGinn, 1991) have stressed the importance of volatilization losses when GM is applied as surface mulch, since drying and decomposing conditions enhance volatilization. The volatile loss of labile N from decomposing GM mulch may appreciably diminish its fertility benefit, whereas NH_3 losses from incorporated GM have been reported to be negligible (Janzen and McGinn, 1991). If, however, lower mineralization rates are the cause of reduced inorganic N accumulation under no-tillage, then such a system could better conserve organic N in the long term (Sarrantonio and Scott, 1988). Slight increases in NO_3 contents in the soil 10 wk after GM application in the WS at AVRDC and at BRCI (Fig. 2) may indicate remineralization of N that had been immobilized earlier, even though the process is considered to be relatively slow in temperate soils (Mary and Recous, 1994). Lowest NO_3–N contents in the soil with indigofera mulch were likely due to the NO_3–N uptake of the indigofera (Thönnissen Michel, 1996).

Although N release dynamics may have been driven by a combination of location and/or season-specific factors, N release patterns across locations and seasons are similar. High leaching and denitrification losses in the WS at AVRDC may have reduced the amount of GM N available to tomato plants, although temperature and soil moisture were more favorable for N mineralization than in the DS. Results of an incubation study comparing N release after addition of dry organic residues to these three soils (Thönnissen Michel, 1996) suggested that certain soil chemical and physical properties retarded N release in MMSU soil, relative to BRCI and AVRDC soil. Soil basal N mineralization was higher in the AVRDC and BRCI soils than in the MMSU soil (Thönnissen Michel, 1996). Significant amounts of inorganic N were detected in fallow plots lacking GM addition prior to vegetable crops in the DS at AVRDC and at BRCI, while leaching losses may have prevented

nitrate accumulation in the WS at AVRDC. The higher the soil N supply, the more legumes derive N from soil rather than from biological N_2 fixation. Low NO_3 contents in legume plots can be explained by the effectiveness of legumes to assimilate NO_3 derived from soil N mineralization (George et al., 1994; Ladha et al., 1996).

At all locations and seasons, the decline of soil inorganic N at 6 to 8 wk after GM application may result from a combination of the period of greatest N uptake by the tomato plants (Thönnissen Michel, 1996), lower rates of N mineralization (Griffiths et al., 1994) and biological N immobilization (Mary and Recous, 1994). The faster decline of soil nitrate in planted compared with unplanted plots suggests vegetable N uptake at AVRDC and at MMSU. Using ^{15}N-labeled residues in the absence of growing plants, Chotte et al. (1990) found net immobilization in the organic residues, but net mineralization occurred when plants were grown in these soils. Root exudates of vegetable crops may have been an insignificant energy source for soil microbial growth (Martens, 1990) in our experiments because of the high degradability of our soybean and indigofera GM, and the favorable soil temperature and moisture conditions. Reduction of microbial activity and microbial N immobilization after consumption of the labile fractions of the residue in early decomposition stages may have occurred due to the recalcitrance of the remaining crop residue. It is possible that these recalcitrant organic fractions lead to the formation of soil humus (Wilson and Hargrove, 1986). If microbial N needs were large, available soil inorganic N would be rapidly depleted and the decomposition rate of organic compounds would decline (Mary and Recous, 1994), leading to N immobilization (6–8 wk) and delayed N remineralization. In experiments by Broadbent and Tyler (1962), NO_3 was immobilized to a considerable extent when it was the only N form available to soil microorganisms. Mary and Recous (1994) described N immobilization–remineralization following organic residue incorporation as a function of the amount and nature of the residues and soil mineral N, whereas basal mineralization was explained as a function of soil texture and long-term C and N inputs.

It is probable that liming of the soil and the addition of poultry manure (*Gallus* sp.) led to a strong soil N mineralization in BRCI soil. Decay of plant residues and SOM are accelerated by liming of acid soils (Alexander, 1977).

The great loss of Cl and ostensibly NO_3 within the first month of GM and N fertilizer application in the WS at AVRDC, probably resulted from two rainfall events within that period. The soil at >30 cm depth in the raised bed system was permanently submerged due to the standing water in the rice beds (Thönnissen Michel, 1996), so that Cl may have been leached with rice bed irrigation. Improved infiltration rate through soil in the raised beds may have also increased leaching losses (Shennan, 1992). Our results confirm those of Stute and Posner (1995), that potentially leachable soil NO_3–N differed little following GM or N fertilizer.

Total Nitrogen and Nitrogen-15 Balance

The similarities of the ratios of total ^{15}N to total N for MHA and CaHA fractions compared with humin suggest that the two fractions were no more labile than the rest of the SOM in this soil. Our results are comparable to those of He et al. (1988), in that a significant proportion of recently added ^{15}N in the soil was not extractable (humin). Humin can be very young and much of it is composed of alkyl compounds and carbohydrates as microbial byproducts (He et al., 1988). Domination of soil C and N by humin may be especially pronounced in a soil where conditions are favorable for degradation. The rapid decomposition of the soybean residues and the small quantities of MHA and CaHA extracted from the MMSU soil in relation to other rice soils of the Philippines (Olk et al., 1995) demonstrate the favorable conditions for degradation in this soil. Organic molecules resulting from microbial degradation, such as microbial tissues, will be preserved in the soil only if they are stabilized and thereby are protected from further degradation. One such form of protection is chemical binding to the mineral surface of such strength that the organic material is not extractable and hence considered as humin. The extremely high Ca levels in MMSU soil may also contribute to the humin constituting a high proportion of total SOM.

Lower rates of ^{15}N recovery could be due to mineralization–immobilization turnover. The ^{15}N released from the legume residue into the soil inorganic pool could be exchanged for ^{14}N in microbial biomass, which could lead to lower ^{15}N recovery. Alternatively, lower rates of ^{15}N recovery than total N may result partly from an overestimation of apparent total N recovery and partly from the importance of soil conditions during the rapid degradation of ^{15}N-labeled material. Higher mineralization rates of labeled than of unlabeled organic materials may have contributed to lower rates of N recovery in ^{15}N compared with total N balances, in agreement with other authors (Amato and Ladd, 1980; Chichester et al., 1975). Greater loss of ^{15}N than total N (57 vs. 30%) may reflect volatilization and denitrification at the beginning of the crop cycle, as well as the low plant N uptake at that time. Total N loss would be lower on a percent basis during this time because of the low basal rate of SOM-N mineralization. Because labeled soybean was quickly decomposed, the fate of GM ^{15}N would be disproportionately determined by soil conditions early in the crop cycle. Given the relatively wet yet aerated conditions in the MMSU soil, these large amounts of $^{15}NH_4$ mineralized quickly from plant residues or young SOM fractions would be prone to losses via volatilization or nitrification–denitrification. This scenario is supported by the low total soil C and N levels, small quantities of extracted MHA and CaHA, high losses of ^{15}N from the system, and the greater relative loss of ^{15}N than total N.

Given its low total C and N contents, the MMSU soil may not have a large capacity to store added N, whether the N is added in organic or inorganic forms. We conclude that the lack of synchronization between N supply

and demand caused by a single application of GM shortly before vegetable transplanting makes this treatment less successful than split applications of inorganic N (Thönnissen Michel, 1996).

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