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Green Manure Approaches to Crop Production: A Synthesis

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ABSTRACT

A green manure (GM) is a crop used primarily as a soil amendment and a nutrient source for subsequent crops. Green manure approaches to crop production may improve economic viability, while reducing the environmental impacts of agriculture. However, such approaches are complex because they depend on interactions between the GM, the environment, and management. We suggest that the research and management techniques developed for synthetic inputs are not adequate for effective GM use. This review provides a conceptual framework to more critically evaluate GM use, and we discuss a limited number of key examples involving GM adaptation and growth, effects on soil organic matter, N release and availability for future crops, and pest control. We explore the deficiencies in our current understanding of GM approaches and argue that economic justification of GM requires provision of multiple services (such as nutrient supply, pest and weed control, and increase of soil organic matter). We propose that future research efforts make improved use of whole systems and participatory strategies to better address both the complexity of GM-based cropping systems and the obstacles preventing farmer adoption of GM approaches.

During the last century, agriculture worldwide has experienced changes in farm size, marketing strategies, and biological and economic diversity, increasing dependence on external nonrenewable resources and vulnerability to urbanization, climate change, and volatile global markets. Producers, consumers, government agencies, and researchers have, therefore, expressed increasing interest in economically viable alternatives that harness ecological and biological processes, on-farm resources, and diversification (Gold, 1999; Dinnes et al., 2002).

A GM, a crop used primarily as a soil amendment and a nutrient source for subsequent crops, may provide such an alternative. Unlike synthetic N fertilizers, legumes utilized as GM represent a potentially renewable source of on-farm, biologically fixed N and may also fix and add large amounts of C to cropping systems (Hargrove, 1986; Sharma and Mittra, 1988). Providing adequate soil N fertility with application of animal manure products may result in soil P loading (because manure N/P ratios are often much lower than those maintained by plants; Royer et al., 2003; Hao et al., 2004) or soil salinization (due to high ion concentrations in animal manure; Hao and Chang, 2003). Such excess P application and soil salinization may be avoided by use of leguminous GMs (Eigenberg et al., 2002). Green manures grown on site do not incur the often inhibitive handling and transportation costs of other organic inputs. The slow release of N from decomposing GM residues may be better synchronized with plant uptake than sources of inorganic N, possibly increasing N-uptake efficiency and crop yield while reducing N leaching losses (Abdul-Baki et al., 1996; Agustin et al., 1999; Aulakh et al., 2000; Cline and Silvernail, 2002). Green manure approaches may also drive long-term increases of soil organic matter and microbial biomass (Goyal et al., 1992, 1999; Chander et al., 1997; Biederbeck et al., 1998), further improving nutrient retention and N-uptake efficiency. When used in place of fallow, well-chosen GM may reduce erosion (Dapaah and Vyn, 1998), reduce nutrient or pesticide losses (Delgado et al., 2001; Gaston et al., 2003), and suppress weeds (Phatak et al., 1987; Dyck and Liebman, 1995; Burgos and Talbert, 1996) and specific crop pests (Bugg et al., 1990; Caswell et al., 1991). Green manures may also offer habitat or resources for beneficial organisms (Bugg et al., 1991; Nicholls and Altieri, 2001).

Historically the primary approach for maintaining soil fertility in intensive cropping systems around the world, GM use in modern agricultural systems has been nearly replaced by synthetic fertilizer, weed, and pest control inputs after the post-World War II development of the agrochemical industry (Smil, 2001; Dinnes et al., 2002). Combined with technological advancements in mechanization and (in the USA) the effects of costly government support programs created after the Great Depression, use of such agrochemical inputs increased yields while reducing farm expenses and crop-rotation requirements necessitated by many GM techniques. Economic gains from these changes, however, have not been experienced uniformly by all farmers. Large costs may also be deferred to the future through environmental degradation, farm consolidation and overspecialization, and government spending associated with reliance on current technologies (see also Schaeffer, 1997).

While organic farm surveys indicate widespread use of cover crops and GM (Organic Farming Research Foundation, 1999, 2004), it remains unclear which GM–cover crop species are used, how they are used, and the type and degree of production benefit that GM–cover crop use provides. Although ideologically favorable to GM approaches, the expansion of the organic agricultural sector has involved use of animal-based products as well as botanical extracts and a limited number of allowable synthetics. Arguably, these materials find use as simple substitutes for conventional inputs rather than employment in farm-based, diversified, whole-systems approaches to agriculture as originally envisioned by the organic movement.

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Abbreviations: GM, green manure.

Table 1. Review of green manure studies: tropical legumes and nonlegume N_2 fixers.

Green manure	Study†	Dry wt.	N content	Environment	Growth time	Management notes
		t ha^{-1}	kg ha^{-1}			
Azolla (*Azolla microphylla*)	Ladha et al. (2000)	2.1–2.3	61–75	silty clay, Philippines	6–9 wk	flooded
Pigeonpea [*Cajanus cajan* (L.) Millsp.]	Ladha et al. (1996)	6.5–9.0	154–235	clay or loam?, Philippines	~6 mo	clipped to 20–30 cm five times
Canavalia [*Canavalia ensiformis* (L.) DC.]	Ramos et al. (2001)	4.4	58	sandy loam, Cuba	8–9 wk	
Centro (*Centrosema pubescens* Benth.)	Steinmaier and Ngoliya (2001)	1.2	27	sandy loam, Zambia	14 wk (?)	
Clitoria (*Clitoria ternatea* L.)	Ladha et al. (1996)	6.9–7.7	256–306	clay or loam?, Philippines	~6 mo	clipped to 20–30 cm 2–3 times
Sunn hemp (*Crotalaria juncea* L.)	Jeranyama et al. (2000)	0.9–2.9	23–82	loamy sand, Zimbabwe	6–7 wk	
	Ladha et al. (1996)	7.6–7.8	277–279	clay or loam?, Philippines	~6 mo	clipped to 20–30 cm 2–3 times
	Mansoer et al. (1997)	4.8–7.3	120–138	sandy loam, Alabama	9–12 wk	
	Ramos et al. (2001)	11.1	195	sandy loam, Cuba	8–9 wk	
	Seneratne and Ratnasinghe (1995)	6.1–9.6	161–252	NR‡, Sri Lanka	8–9 wk	
	Steinmaier and Ngoliya (2001)	12.1	227	sandy loam, Zambia	14 wk (?)	
Crotalaria (*Crotalaria ochroleuca* G. Don)	Carsky et al. (1999)	5.0 (13 wk), 8.0 (19 wk)	114 (13 wk), 137 (19 wk)	loamy sand, Nigeria	13 and 19 wk	AAR§ = 1350 mm
	Carsky et al. (1999)	2.0 (13 wk), 3.3 (19 wk)	52 (13 wk), 63 (19 wk)	clay loam, Nigeria	13 and 19 wk	AAR = 900 mm
Curara-pea Marejea (*Crotalaria zanzibarica* Bojer) cv. Marejea	Steinmaier and Ngoliya (2001)	14.6	328	sandy loam, Zambia	14 wk (?)	
Desmanthus [*Desmanthus virgatus* (L.) Willd.]	Ladha et al. (1996)	8.0–9.1	251–283	clay or loam?, Philippines	~6 mo	
Soybean [*Glycine max* (L.) Merr.]	Thonnissen et al. (2000b)	2.8–5.8	106–141	NR, Taiwan and Philippines	2–2.5 mo	
Indigo (*Indigofera tinctoria* L.)	Agustin et al. (1999)	2.3–2.9	56–57	clay loam, Philippines	5–6 mo after death of other intercrops	
	Thonnissen et al. (2000b)	0.2–2.0	5–44	NR, Taiwan and Philippines	2–2.5 mo	
Lablab [*Lablab purpureus* (L.) Sweet] or (*Dolichos lablab* L.)	Carsky et al. (1999)	1.9 (13 wk), 2.0 (19 wk)	71 (13wk), 47 (19wk)	loamy sand, Nigeria	13 and 19 wk	AAR = 1350 mm
	Carsky et al. (1999)	0.6 (13 wk), 1.8 (19 wk)	23 (13 wk), 49 (19wk)	clay loam, Nigeria	13 and 19 wk	AAR = 900 mm
	Kouyate et al. (2000)	0.7–1.7	NR	loamy sand, Mali	NR	AAR = 619 mm
	Kouyate et al. (2000)	0.6–2.0	NR	loam, Mali	NR	AAR = 619 mm
	Steinmaier and Ngoliya (2001)	5.8	115	sandy loam, Zambia	14 wk (?)	
Siratro [*Macroptilium atropurpureum* (DC.) Urb.]	Ladha et al. (1996)	4.9–5.5	132–178	clay or loam(?), Philippines	~6 mo	
	Steinmaier and Ngoliya (2001)	2.4	62	sandy loam, Zambia	14 wk (?)	
Mucuna [*Mucuna aterrima* (Piper & Tracy) Holland]	Ramos et al. (2001)	2.1	64	sandy loam, Cuba	8–9 wk	
Velvet-bean [*Mucuna pruriens* (L.) DC.]	Carsky et al. (1999)	4.0 (13 wk), 6.2 (19 wk)	131(13 wk), 154 (19 wk)	loamy sand, Nigeria	13 and 19 wk	AAR = 1350 mm
	Carsky et al. (1999)	1.7 (13 wk), 3.4 (19 wk)	53 (13 wk), 85 (19 wk)	clay loam, Nigeria	13 and 19 wk	AAR = 900 mm
	Steinmaier and Ngoliya (2001)	9.3	183	sandy loam, Zambia	14 wk (?)	
Glycine [*Neonotonia wightii* (Wight & Arn.) J. A. Lackey]	Steinmaier and Ngoliya (2001)	0.9	21	sandy loam, Zambia	14 wk (?)	
Sesbania (*Sesbania macrantha* Welw. ex E. Phillips & Hutch.)	Steinmaier and Ngoliya (2001)	7.1	124	sandy loam, Zambia	14 wk (?)	
Sesbania (*Sesbania rostrata* Bremek. & Oberm.)	Kouyate et al. (2000)	0.7–1.4	NR	loamy sand, Mali	NR	AAR = 619 mm
	Kouyate et al. (2000)	2.3–4.6	NR	loam, Mali	NR	AAR = 619 mm
	Ladha et al. (2000)	3.2–4.6	71–88	silty clay, Philippines	6–9 wk	flooded
Stylo [*Stylosanthes guianensis* (Aubl.) Sw.]	Steinmaier and Ngoliya (2001)	4.3	88	sandy loam, Zambia	14 wk (?)	
Teramnus [*Teramnus uncinatus* (L.) Sw.]	Steinmaier and Ngoliya (2001)	3.8	80	sandy loam, Zambia	14 wk (?)	
Black gram [*Vigna mungo* (L.) Hepper]	Seneratne and Ratnasinghe (1995)	7.1–8.8 (stover)	104–155 (stover)	NR, Sri Lanka	11–12 wk	

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Table 1. Continued.

Green manure	Study†	Dry wt.	N content	Environment	Growth time	Management notes
Mung bean [*Vigna radiata* (L.) R. Wilczek]	Seneratne and Ratnasinghe (1995)	3.1–5.5 (stover)	30–88 (stover)	NR, Sri Lanka	11–12 wk	two cultivars
	Thonnissen et al. (2000b)	1.1	26	NR, Taiwan and Philippines	9–11 wk	
Cowpea [*Vigna unguiculata* (L.) Walp.]	Carsky et al. (1999)	0.6 (13 and 19 wk)	16 (13 wk), 21 (19 wk)	loamy sand, Nigeria	13 and 19 wk	AAR = 1350 mm
	Carsky et al. (1999)	1.4 (13 wk), 2.3 (19 wk)	45 (13 wk), 58 (19wk)	clay loam, Nigeria	13 and 19 wk	AAR = 900 mm
	Jeranyama et al. (2000)	0.6–4.6	15–154	loamy sand, Zimbabwe	11 wk	
	Kouyate et al. (2000)	1.5–2.5	NR	loamy sand, Mali	NR	AAR = 619 mm
	Kouyate et al. (2000)	1.1–2.4	NR	loam, Mali	NR	AAR = 619 mm
	Seneratne and Ratnasinghe (1995)	3.7–8.5	42–155	NR, Sri Lanka	11–12 wk	three cultivars

† Information is approximated from original sources.
‡ NR = not reported.
§ AAR = average annual rainfall.

Despite limited but significant successes in research and on-farm settings, GM-based cropping systems have regained little parity with current conventional and organic approaches to crop production. Conventional inputs—and many organic inputs—deliver readily known and adjustable levels of nutrients or active ingredients. Such materials often have well documented, consistent patterns of availability or action. Green manures, however, are biological organisms affected by the cropping environment, regularly confounding direct control by farm managers. Economic competitiveness of GM may thus require delivery of multiple services rather than the "one-for-one" approach more effective with chemical inputs, animal-based products, and botanical extracts. (Multiple services could include, for example, provision of biologically fixed N, pest and weed control, increase of soil organic matter, and reduction of soil erosion or agrochemical loss.) Even within such multifaceted approaches, however, procurement of particular "keystone" services may be required as an initial condition for system acceptability. Satisfying crop demand for N, often the most limiting nutrient for plant growth, frequently appears as such a keystone obstacle to GM reintroduction.

The breadth of useful species, growing environments, and management strategies summarized in Tables 1 to 4 highlight the complexity of options for GM approaches to crop production. Yet proper assessment of GM techniques requires an even greater understanding of the site-specific relationships between the life cycles of the plants used (both GM and subsequent economic crops), the production environment (climate, weather, soil, and pests), and management options (for example: type, patterns, and timing of tillage, planting, irrigation, and fertility and pest control inputs, as well as production goals). The challenge of properly reintegrating GM techniques back into our menu of agronomic options will require a cooperative effort to more systematically examine these interrelationships and develop more deliberate, knowledge-intensive support systems.

Since roughly 1990, the literature published on GM use represents a sizable dedication of resources. There exist a number of literature reviews by others (Pannell, 1995; Hartwig and Ammon, 2002; Snapp et al., 2005), as well as multiple databases (Univ. of California Sustainable Agriculture Research and Education Program, 2002) and compendia (Sustainable Agriculture Network, 1998). These review and information sources, however, have not provided a conceptual framework to critically evaluate GM use in a systematic fashion across many production scenarios and criteria. Moreover, they have not proposed improvements in our research and application approaches to better address the general disuse of GM in modern agricultural systems. Development of viable GM-based alternatives will probably not occur without refinement of whole-systems approaches within which GM secures multiple services. Given our own experiences, and the experiences of others documented in the literature, Fig. 1 represents a rough framework for assessing potential GM use. In such a framework, we first identify what environmental and management factors are preconstrained, and subsequently determine what services are desired from GM. We must then assess potential effects of environment and management on candidate GM

Table 2. Review of green manure studies: tropical nonlegumes.

Green manure	Study†	Dry wt.	N content	Environment	Growth time	Management notes
		t ha^{-1}	kg ha^{-1}			
Rhodes grass (*Chloris gayana* Kunth)	Steinmaier and Ngoliya (2001)	14	167	sandy loam, Zambia	14 wk (?)	
Japanese millet [*Echinochloa crus-galli* (L.) P. Beauv.]	N'Dayegamiye and Tran (2001)	2.3–11.2	65–139	silt loam, Canada	4 mo	30 kg N ha^{-1} applied

† Information is approximated from original sources.

Table 3. Review of green manure studies: temperate legumes.

Green manure	Study†	Dry wt.	N content	Environment	Growth time	Management notes
		t ha^{-1}	kg ha^{-1}			
Black lentil (*Lens culinaris* Medik)	Brandt (1999)	2.3–2.7	53–64	loam, Saskatchewan	NR‡	AAR§ = 359 mm
	Guldan et al. (1996)	1.0–2.2	34–58	sandy loam, New Mexico	~22 wk	interseeded in sweet corn (*Zea mays* L.) after 2 wk
	Guldan et al. (1996)	0.9–1.1	34–35	sandy loam, New Mexico	~17 weeks	interseeded in sweet corn after 7 wk
Blue lupine (*Lupinus angustifolius* L.)	Forbes (1970)	5.3–6.7	NR	NR (sandy loam?), Tifton, GA	NR	
	Gallaher (1991)	~1.0	~20	sand, Gainesville, FL	24 wk	25 plants m^{-2}
	Gallaher (1991)	~1.8	~30–35	sand, Gainesville, FL	24 wk	50 plants m^{-2}
	Gallaher (1991)	2.1	36	sand, Gainesville, FL	24 wk	100 plants m^{-2}
	Suman (in Forbes et al., 1970)	2.8–3.1	NR	NR, South Carolina	NR	
Yellow trefoil (*Medicago lupulina* L.)	Stopes et al. (1996)	0.6–20.4	15–459	clay loam, England	6–25 mo of growth	periodic mowing
Burr Medic (*Medicago polymorpha* L.)	Shrestha et al. (1999)	1.1 (cut), 1.6 (not cut)	NR	loam, Michigan	90 d	partially cut for forage at 60 d
Burr medic and snail medic [*Medicago scutellata* (L.) Mill.]	Jeranyama et al. (1998)	0.6–3.1	17–75	loam, Michigan	9–11 wk	five planting dates
	Jeranyama et al. (1998)	0.1–1.3	2–32	loam, Michigan	9–11 wk	five planting dates, intercropped with corn
Gamma medic (*Medicago rugosa* Desr.)	Shrestha et al. (1999)	1.4	NR	loam, Michigan	13 wk	
Alfalfa (*Medicago sativa* L.)	Griffin et al. (2000)	3.7–5.7	105–174	silt loam, Maine	1 yr	
	Guldan et al. (1996)	1.1–1.5	41–53	sandy loam, New Mexico	~22 wk	interseeded in sweet corn after 2 wk
	Guldan et al. (1996)	0.5–1.2	21–43	sandy loam, New Mexico	~17 wk	interseeded in sweet corn after 7 wk
	Shrestha et al. (1999)	1.6 NR		loam, Michigan 13 wk		
	Singogo et al. (1996)	2.8–5.7 107–138		sandy loam, Kansas 7–8 mo		
Barrel medic (*Medicago truncatula* Gaertn.)	Guldan et al. (1996)	2.4–4.5	72–131	sandy loam, New Mexico	~22 wk	interseeded in sweet corn after 2 wk
	Guldan et al. (1996)	1.0–2.3	37–69	sandy loam, New Mexico	~17 wk	interseeded in sweet corn after 7 wk
	Shrestha et al. (1999)	1.4 (cut), 3.2 (uncut) NR		loam, Michigan	13 wk	partially cut for forage at 60 d
Yellow sweetclover [*Melilotus officianalis* (L.) Lam.]	Blackshaw et al. (2001)	3.1–5.4	NR	sandy clay loam, Alberta	NR	AAR = 387 mm, multiple intercrops
Field pea or Austrian winter pea [*Pisum sativum* L. ssp. *sativum* var. *arvense* (L.) Poir.]	Karpenstein-Machan and Stuelpnagel (2000)	~4.8	~200	silty clay, Germany	~4 mo	
	Singogo et al. (1996)	3.2–7.6	107–230	sandy loam, Kansas	7–8 mo	
Berseem clover (*Trifolium alexandrinum* L.)	Ross et al. (2001)	6.7–10.2 (not mowed), 9.2 (mowed)	NR	silty clay loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Ross et al. (2001)	4.0–6.0 (not mowed)	NR	loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Shrestha et al. (1999)	1.9 (cut), 4.1 (uncut)	NR	loam, Michigan	13 wk	partially cut for forage at 60 d
Kura clover (*Trifolium ambiguum* M. Bieb.)	Zemenchik et al. (2000)	6.2–10.7	NR	silt loam, Wisconsin	NR	intercropped with corn, then grown alone
Alsike clover (*Trifolium* hybridum L.)	Ross et al. (2001)	3.0–4.6 (not mowed), 6.1 (mowed)	NR	silty clay loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Ross et al. (2001)	2.5–2.7 (n) NR		loam, Alberta 14–16 wk; mowed at 7–8 wk (m) and nonmowed (n)		
Crimson clover (*Trifolium incarnatum* L.)	Abdul-Baki et al. (1996)	4.2–5.7	151	sandy loam, Maryland	8 mo	
	Dyck and Liebman (1995)	5.8–7.3	130–143	sandy loam, Maine	3.5 mo	
	Dyck et al. (1995)	4.8–5.1	117–123	sandy loam and silt loam, Maine	2–2.5 mo	

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Table 3. Continued.

Green manure	Study†	Dry wt.	N content	Environment	Growth time	Management notes
	Karpenstein-Machan and Stuelpnagel (2000)	~4–10.5	~200	silty clay, Germany	~4 mo	
	Ranells and Wagger (1996)	1.4–5.0	35–134	loamy sand, Georgia	6 mo	
	Ross et al. (2001)	2.1–4.0 (not mowed), 5.7 (mowed)	NR	silty clay loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Ross et al. (2001)	3.7–5.1 (not mowed)	NR	loam, Alberta	14–16 wk	partly mowed at 7–8 wk
Crimson clover and rye (*Secale cereale* L.)	Karpenstein-Machan and Stuelpnagel (2000)	~6–12	~200	silty clay, Germany	~4 mo	three different seeding mixtures
	Ranells and Wagger (1996)	2.3–5.2 42–111		loamy sand, Georgia 6 mo		
Balansa clover [*Trifolium michelianum* Savi var. *balansae* (Boiss.) Azn.]	Ross et al. (2001)	2.5–4.5 (n), 7.2 (m) NR		silty clay loam, Alberta 14–16 wk; mowed at 7–8 wk (m) and nonmowed (n)		
	Ross et al. (2001)	2.3–3.5 (n) NR		loam, Alberta 14–16 wk; mowed at 7–8 wk (m) and nonmowed (n)		
Red clover (*Trifolium pratense* L.)	Dapaah and Vyn (1998)	2.4–3.7	NR	loam, Ontario	10 mo	intercropped with barley (*Hordeum vulgare* L.)
	Davis and Liebman (2001)	1.5–3.0	72–115	sandy loam, Maine	NR	intercropped with wheat (*Triticum aestivum* L.)
	Guldan et al. (1996)	0.8–1.9	29–49	sandy loam, New Mexico	22 wk	interseeded in sweet corn after 2 wk
	Guldan et al. (1996)	0.3–0.6	13–16	sandy loam, New Mexico	17 wk	interseeded in sweet corn after 7 wk
	N'Dayegamiye and Tran (2001)	0.6–0.7	13	silt loam, Canada	4 mo	30 kg N ha^{-1} applied
	Ross et al. (2001)	1.7–2.9 (not mowed), 5.2 (mowed)	NR	silty clay loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Ross et al. (2001)	2.1–2.2 (not mowed)	NR	loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Soon et al. (2001)	1.7–3.6	51–94	sandy loam, Alberta	NR	red clover–wheat–canola [*Brassica rapa* L. subsp. *oleifera* (DC.) Metzg.]–wheat rotation
	Stopes et al. (1996)	0.8–25.4	21–741	clay loam, England	6–25 mo of growth	periodic mowing
White clover (*Trifolium repens* L.)	Ross et al. (2001)	0.8–2.1 (not mowed), 4.0 (mowed)	NR	silty clay loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Ross et al. (2001)	2.7–3.0 (not mowed)	NR	loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Stopes et al. (1996)	0.6–25.0	17–592	clay loam, England	6–25 mo of growth	periodic mowing
Persian clover (*Trifolium resupinatum* L.)	Ross et al. (2001)	1.7–3.4 (not mowed), 7.2 (mowed)	NR	silty clay loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Ross et al. (2001)	3.7–4.6 (n) NR		loam, Alberta 14–16 wk; mowed at 7–8 wk (m) and nonmowed (n)		
Hairy vetch (*Vicia villosa* Roth)	Abdul-Baki et al. (1996)	4.4–5.2	167–197	sandy loam, Maryland	8 mo	
	Cline and Silvernail (2001)	3.5–4.0 (0 N, 140 N)	115–164 (0 N, 140 N)	silt loam, Kentucky	8 mo	0 or 140 kg N ha^{-1} for preceeding corn crop
	Guldan et al. (1996)	1.8–3.8	70–124	sandy loam, New Mexico	22 wk	interseeded in sweet corn after 2 wk
	Guldan et al. (1996)	1.5–2.8	58–88	sandy loam, New Mexico	17 wk	interseeded in sweet corn after 7 wk
	Puget and Drinkwater (2001)	4.4	NR	silt loam, Pennsylvania	~8 mo	
	Ranells and Wagger (1996)	2.9–4.8	125–182	loamy sand, Georgia	6 mo	
	Sainju and Singh (2001)	3.0–6.7	104–257	sandy loam, Georgia	~6 mo	three tillage types, two kill dates
	Singogo et al. (1996)	5.6–8.9	233–247	sandy loam, Kansas	7–8 mo	

† Information is approximated from original sources.
‡ NR = not reported.
§ AAR = average annual rainfall.

Table 4. Review of green manure studies: temperate nonlegumes and nonlegume plus legume mixtures.

Green manure	Study†	Dry wt.	N content	Environment	Growth time	Management notes
		t ha^{-1}	kg ha^{-1}			
Oat (*Avena sativa* L.)	Dyck and Liebman (1995)	3.3–4.3	80–82	sandy loam, Maine	3 mo	
Colza [*Brassicarapa* L. ssp. *campestris* (L.) A. R. Clapham]	N'Dayegamiye and Tran (2001)	2.1–4.6	59–99	silt loam, Canada	4 mo	30 kg N ha^{-1} applied
Mustard (*Brassica hirta* Moench)	N'Dayegamiye and Tran (2001)	2.3–3.8	62–72	silt loam, Canada	4 mo	30 kg N ha^{-1} applied
Buckwheat (*Fagopyrum esculentum* Moench)	N'Dayegamiye and Tran (2001)	2.1–3.7	52–65	silt loam, Canada	4 mo	30 kg N ha^{-1} applied
Ryegrass (*Lolium multiflorum* Lam.)	Dapaah and Vyn (1998)	1.3–2.5	NR‡	loam, Ontario	7 mo	intercropped with barley
	Stopes et al. (1996)	0.7–17.5	15–346	clay loam, England	6–25 mo of growth	periodic mowing
Field pea [*Pisum sativum* L. ssp. *sativum* var. *arvense* (L.) Poir.] and Rye (*Secale cereale* L.)	Karpenstein-Machan and Stuelpnagel (2000)	~6–12	~200	silty clay, Germany	~4 mo	three different seeding mixtures
Oilseed radish (*Raphanus sativus* L.)	Dapaah and Vyn (1998)	2.5–3.5	NR	loam, Ontario	3 mo	intercropped with barley
Rye	Cline and Silvernail (2001)	3.5–4.0 (0 N), 4.0–9.0 (140 N)	28–43 (0 N), 43–64 (140 N)	silt loam, Kentucky	8 mo	0 or 140 kg N ha^{-1} for preceeding corn crop
	Griffin et al. (2000)	4.1–6.6	52–66	silt loam, Maine	9 mo	
	Karpenstein-Machan and Stuelpnagel (2000)	~9–13.5	NR	silty clay, Germany	~4 mo	
	Ranells and Wagger (1996)	1.5–5.7	17–64	loamy sand, Georgia	6 mo	
	Ross et al. (2001)	2.7–3.4 (not mowed), 6.4 (mowed)	NR	silty clay loam, Alberta	14–16 wk	partly mowed at 7–8
	Ross et al. (2001)	0.5–0.6 (not mowed)	NR	loam, Alberta	14–16 wk	partly mowed at 7–8 wk
	Tollenaar et al. (1993)	1.0–6.1	NR	loam, Ontario	8 mo	four rye cultivars
Wheat (*Triticum aestivum* L.)	Singogo et al. (1996)	4.9–9.8	81–87	sandy loam, Kansas	7–8 mo	
Hairy vetch (*Vicia villosa* Roth) and Rye	Abdul-Baki et al. (1996)	5.9	120–162	sandy Loam, Maryland	8 mo	
	Cline and Silvernail (2001)	4.0 (0 N), 4.0–10.0 (140 N)	104–152 (0 N), 141–149 (140 N)	silt loam, Kentucky	8 mo	0 or 140 kg N ha^{-1} for preceeding corn crop
	Griffin et al. (2000)	3.6–6.9	57–209	silt loam, Maine		9 mo
	Ranells and Wagger (1996)	3.0–5.4	82–200	loamy sand, Georgia	6 mo	

† Information is approximated from original sources.
‡ NR = not reported.

survival, growth, and decomposition, and, next, evaluate the potential of candidate GMs to provide desired services. Finally, we should consider changes in management to better provide desired GM services. Because a GM-based, whole-systems approach to agriculture must remain site- and situation-specific to some degree, we cannot impose inflexible decision support tools. Yet GM research and eventual readoption should be rationalized using some similar approach on a case-by-case basis. An exhaustive review of all possible interrelationships within Fig. 1 remains beyond the scope of this paper; instead, our goal is to explore the most basic considerations and review their implications for key services including N supply, biological control, and soil organic matter enhancement. We discuss economic evaluations of GM systems and, finally, propose an improved strategy for future GM research efforts.

GREEN MANURE RELATIONSHIPS WITH ENVIRONMENT AND MANAGEMENT

Tables 1 to 4 summarize the dry matter and N accumulation of about 50 GM species from 40 studies and include reported information about study location, soil type, and length of growing season. Green manures generally fall into two categories: tropical ("warm weather", Tables 1–2) and temperate ("cool weather", Table 3–4). Few, if any, tropical legumes can survive hard freezes (when temperature drops below −2°C for several hours), although they can usually tolerate temperatures >35 to 40°C. Temperate legumes, on the other hand, often decline at temperatures >25 to 30°C but may persist without injury at −10°C or lower. The most widely used tropical GM legumes probably include those in genera *Crotalaria* (sunn hemp), *Glycine* (soybean), *Indigofera* (indigos), *Mucuna* (velvetbean), *Vigna* (cowpea), *Cajanus* (pigeonpea), and *Sesbania*, while the temperate GM legumes often include *Trifolium* (clovers), *Vicia* (vetches), *Medicago* (alfalfa, trefoils, and other medics), and *Lupinus* (lupins). Typical nonlegume temperate GM species consist of cereal rye (*Secale cereale* L.), mustards (*Brassica* spp.), radishes (*Raphanus* spp.), buckwheat (*Fagopyrum esculentum* Moench), millet (*Echinocloa* spp.), oat (*Avena* spp.), and wheat (*Triticum* spp.). Use of nonlegume tropical GM species such as millets and members of the *Sorghum* genus appears less common and remains relatively unstudied; in developing regions of the tropics, biomass

1) Determine pre-existing environmental factors that will affect GM function:

- ❑ Climate: temperature ranges and seasonality; rainfall amount and distribution; light levels
- ❑ Soil: texture, fertility, organic matter, and pH
- ❑ Important pest, disease, and weed pressures that may affect GM and economic crops

2) Determine pre-constrained management factors that will affect GM function:

- ❑ Choice of economic crop and its requirements for optimal stand establishment and growth
- ❑ Use of irrigation, fertility, or pest control inputs
- ❑ Requirements of the economic crop market
- ❑ Susceptibility and yield sensitivity of economic crop to pests, disease, or weed competition
- ❑ Identify the season(s) available for GM growth
- ❑ Identify if intercropping GM in, or trap cropping GM near, economic crop is desirable
- ❑ Identify tillage/residue management approach

3) Determine desired services from GM:

- ❑ N supply for subsequent crop
- ❑ Pest, disease or weed suppression
- ❑ Reduce soil erosion and agrochemical runoff losses
- ❑ Build soil organic matter
- ❑ Reduce leaching losses of residual N from previous crop
- ❑ Provide seed, forage, or other economic product

4) Evaluate effects of pre-existing environmental factors and pre-constrained management factors on potential growth & decomposition of candidate GM species/varieties:

- ❑ Eliminate GM candidates from consideration that are not adapted to environmental conditions during the time available for GM growth
- ❑ Consider how actual environment and growth time may alter GM biomass and N accumulation potential compared to values reported in other environments
- ❑ Evaluate adequacy of soil moisture for acceptable GM stand establishment
- ❑ Assess expected rate of GM decomposition and N release

5) Evaluate potential of candidate GM to provide desired services given the environment and management:

- ❑ Will the amount and timing of GM N release match subsequent crop N demand? Can soil adequately retain N in the crop rooting zone under expected precipitation?
- ❑ Will GM suppress/reduce the problem pests, disease, or weeds that affect economic crop? For what time and/or over what distance will suppression/reduction occur?
- ❑ Does GM biomass provide adequate soil coverage to reduce erosion/runoff?
- ❑ Does GM make adequate residue contributions to the soil to increase soil organic matter?
- ❑ Will GM take up residual soil N prior to leaching events?
- ❑ If GM is cut/grazed for forage or harvested for seed, can it still provide other desired benefits?
- ❑ In intercropped systems, will unacceptable competition between GM and economic crop be avoided?

6) Evaluate what additional aspects of management are required to obtain desired services from candidate GM:

- ❑ Additional irrigation, fertility, and pest/disease/weed control inputs
- ❑ Mowing/clipping of GM
- ❑ Alter GM or economic crop planting date or rate
- ❑ Change in tillage or GM residue management
- ❑ Change in economic crop species, variety, or market

Fig. 1. Six-step checklist to assess potential green manure use in cropping systems.

and grain from such nonlegumes might more likely be utilized for food, feed, or forage (Hossain, 2001).

Genetic differences (species and variety) may dictate that some legumes grow larger and accumulate more N than others. Environment (temperature, soil type, and nutrient and water availability) and management (e.g., planting density and timing, mowing, and pest control) may further alter performance of individual GM species (Kouyate et al., 2000; Ross et al., 2001; Steinmaier and Ngoliya, 2001). Because they do not derive direct sales profit, GM species are often chosen that require acceptably low levels of nutrient, irrigation, and pest control inputs and often fit into otherwise unplanted fallow periods. Legume GM species are often preferable to nonlegumes because they supply their own N, but in production scenarios where N is less limiting, where a specific GM service other than high N supply (such as allelopathy) is sought, or where legumes do not perform well, nonlegumes or mixtures of legumes and nonlegumes may be more advantageous. Desirability of GM may also include or exclude ability to reseed, growth habit (e.g., upright, prostrate, or viney), aggressiveness, and presence of toxic or allelopathic chemicals affecting livestock, crops, or plant pests; these characteristics are often controlled at the species or variety level.

Biological N fixation (for legumes) and overall N accumulation during growth are primary factors governing the adequacy of a GM as an N source (see Tables 1–4 for reports of GM N contents). Estimates of N accumulation for leguminous GMs and the relative contribution of biological N fixation in this process ranges broadly depending on soil fertility, water availability, and GM species. Generally speaking, most legumes accumulate N from biological fixation when demand cannot be met by uptake of N from the soil (Gardner, 1985). For example, sunn hemp (*Crotalaria juncea* L.) has been estimated to fix 27 to 39% (Ramos et al., 2001), 72 to 81% (Ladha et al., 1996), and 91% (Seneratne and Ratnasinghe, 1995) of its total N in different study locations and conditions. Reduction of soil N through competition generally increases rates of biological N fixation by legumes. Karpenstein-Machan and Stuelpnagel (2000) found that the relative contribution of N fixation to hairy vetch (*Vicia villosa* Roth) and crimson clover (*Trifolium incarnatum* L.) N increased when intercropped with an increasingly larger proportion of cereal rye. The same study showed greater N accumulation for optimal mixtures of legumes with cereal rye than legumes alone. However, water stress and deficiency of nutrients other than N may significantly reduce fixation (Gardner, 1985).

Climate probably limits GM species selection more than any other single factor. In very cold climates, temperate GM species survive during the spring, summer, and fall. As one moves to warmer climates, increasing winter temperatures permit temperate GM species to persist during winter months while tropical GM species become better suited during warmer months. Where the lowest temperatures remain above freezing, tropical GM species may survive all year, and high temperatures may begin to exclude the use of temperate GM species altogether. However, light levels, precipitation, soil type, and pest pressures also interact with temperature to determine how specific GM species will perform in a given location. For example, temperate legumes at higher latitudes often attain most production during the long, cool days of early fall and late spring (Cline and Silvernail, 2001). At lower latitudes, however, daylight hours with consistently cool temperatures are far more limited.

In many environments, seasonality may relate as much or more to dry or wet periods. Transpiration of soil water by GM poses a major concern for rain-fed systems in semiarid environments (Vigil and Nielson, 1998; Brandt, 1999). Especially in regions with annual precipitation around 500 mm or less, management of well-adapted GM such as wheat, pea or lentil (*Lens culinaris* Medik.) must prevent reduction of subsequent crop stand or yield due to soil water depletion (Bullied and Entz, 1999; Baumhardt and Lascano, 1999). Early termination of GM or timing of termination before periods of natural soil water recharge may or may not mitigate such problems (Schlegel and Havlin, 1997; Thiessen Martens et al., 2001). In low-rainfall climates, or in higher rainfall climates on sandy soils, establishment of small-seeded GMs such as clovers and medics may also be particularly dependent on timely rainfall when irrigation is not available. Large-seeded GMs planted at deeper depths may have better establishment potential in such environments, but are still vulnerable to periodic failure (Keeling et al., 1996). Where convenient, use of self-reseeding GM may better ensure successful establishment (Walsh et al., 2001).

Green manure performance and patterns of subsequent effects often differ based on gross differences in soil textural type. Green manure growth and N accumulation are usually greatest on loamy soils due to their relatively high inherent fertility, nutrient and water retention capacity, and microbial biomass (see Tables 1–4 for notes on soil types within studies). With their high potential to retain released N, such soils also help mediate short-term benefits from GM to subsequent crops, even when considerable lag times exist between peak GM N release (from decomposition) and subsequent crop N uptake. On sandy soils and in warm, humid climates, even short lag times between peak GM N release and subsequent crop N demand can result in significant N leaching losses (Nelson and King, 1996; Wyland et al., 1996; Weinert et al., 2002). To derive acceptable benefits, GM-based systems on such soils may need to make greater use of intercropping GM with economic crops or manipulation of GM decomposition (see discussion below). Compared with inorganic N approaches, GM approaches on sandy soils may provide benefit by temporarily increasing N immobilization potential during lag times to prevent leaching losses (Green and Blackmer, 1995), effectively requiring more massive and recalcitrant GM as well as sources of significant N (whether from GM or from supplementary sources).

Sandy soils may also present different biotic problems than related in much of the literature. Many temperate legumes that perform well on fine-textured soils are poorly adapted to low nutrient levels and pests (particularly nematodes) common in sandy soils (see below). Also, successful rhizobial inoculation of temperate leguminous GM in sandy soils is sometimes problematic. In such soils, pest, inoculation, and nutrition problems can interact in a confounding manner, creating variable GM performance within different areas of the same plot or field. Extreme clay content, on the other hand, may limit the effectiveness of GM species sensitive to restricted soil aeration (in wet climates or seasons) or low soil water potential (in dry climates or seasons). In general terms, plants used as GM may have different adaptations to soil pH and fertility that vary widely across soil textural types or climatic regions (see Tables 1–4 for notes on GM study environments).

The growing season of a GM must fit the demands of a particular crop rotation, which often means GM is planted during fallow periods with weather unfavorable for optimal production of economic crops. In temperate environments on fine-textured soils, winter-hardy legumes such as vetch, clover, and medics are capable of accumulating large amounts of biomass (7–10 t ha^{-1}) and N (150–250 kg N ha^{-1}; Table 3) and delivering substantial N benefit to subsequent spring-planted crops. A number of investigators in such environments have shown that well-managed temperate leguminous GMs can fully satisfy N requirements of subsequent crops such as sweet corn (*Zea mays* L. cv. Rugosa; Griffin et al., 2000; Cline and Silvernail, 2002). Studying fertigated, mulched tomato (*Lycopersicon esculentum* Mill.) in Maryland, Abdul-Baki et al. (1996) found that plastic mulch with 112 kg ha^{-1} inorganic N (recommended rate) produced lower yields than hairy vetch, crimson clover, and hairy vetch plus rye live mulches combined with 56 kg ha^{-1} inorganic N. In tropical environments, sunn hemp, cowpea [*Vigna unguiculata* (L.) Walp.], and mungbean [*V. radiata* (L.) R. Wilczek] may also accumulate large amounts of biomass and N (Table 1). Because no freezes occur in tropical environments, these legumes may be followed immediately by frost-sensitive crops. For example, studies in Asia have shown such GM to be capable of supplying the N requirements of rice (*Oryza sativa* L.), again on fine-textured soils (Agustin et al., 1999; Aulakh et al., 2000; Ladha et al., 2000).

However, GM–crop considerations are frequently more complex. Nutrient-demanding crops pose particular challenges to GM-based approaches, especially in soils with poor exchange capacity and when peak crop nutrient demand occurs well after release by the GM. For example, N recommendations for sweet corn on sandy soils in Florida fall between 180 and 200 kg N ha^{-1} (Hochmuth and Cordasco, 2000). This crop is generally planted in the spring to avoid pest pressures and low-light conditions that occur in the rainy summer season. Modern sweet corn varieties are bred for adaptation to high plant population and high inputs; even small reductions in N availability may significantly reduce grade for human consumption (which depends heavily on ear size and uniformity of fill, USDA, 1997) as well as ear yields (Cherr, 2004). However, providing adequate GM N supply during early spring in Florida is particularly difficult because well-adapted tropical GM species die and decompose during winter freezes (leading to potentially large N leaching losses on sandy soils) and temperate leguminous GM species appear poorly adapted to the region's variable weather, soils, and nematode pests. Options may exist to improve the effectiveness of GM for spring-grown sweet corn in Florida (e.g., intercropping or manipulation of GM decomposition). However, use of fall- or winter-grown crops, crops with lower N demand or less sensitivity to N reductions, crops better adapted to low plant populations, food crops without price premiums for large fruits, and crops grown for animal forage or feed may more readily afford integration of GM-based approaches into existing systems.

PEST CONTROL WITH GREEN MANURES

The choice of economic crop also affects the suitability of GM approaches based on crop cultural requirements and vulnerability to pests and disease. For example, increasing GM residue in the soil seedbed through use of reduced tillage may appear desirable in many environments, but crop species and varieties differ in their sensitivity to fungal attack that may occur without tillage. Some cruciferous (e.g., radish) or solanaceous (e.g., potato [*Solanum tuberosum* L.]) crops may demonstrate less adaptation to such systems than larger seeded grains and legumes (Davis et al., 1996; Cherr, 2004). With proper selection and management, however, GM may suppress pests otherwise requiring chemical or cultural intervention. A number of researchers have investigated GM-based control of weeds and nematodes through physical, biotic, and allelopathic interactions. Physically, GM may outcompete weed species for light, nutrients, and water at crucial stages and may otherwise disrupt the life cycle of nematodes by acting as nonhosts. Blackshaw et al. (2001) found yellow sweetclover [*Melilotus officinalis* (L.) Lam.] suppressed fallow weed biomass by 77 to 99% over 3 yr. However, the effectiveness of physical weed suppression by GM often depends on interaction between their environmentally mediated performance, growth habit, and management. For instance, Ross et al. (2001) found clovers to have the greatest weed suppression ability on a low-fertility site when unmowed, with the greatest suppression by tall-growing annuals such as berseem clover (*Trifolium alexandrinum* L.). In the same study, weed suppression by clovers on high-fertility sites was enhanced by mowing and did not differ among species. Green manure live mulch, when maintaining an early season advantage over competition, may provide weed suppression comparable to plastic mulch (Ellis et al., 2000). Biomass, growth habit, and developmental stage of GM intercrops and live mulches must be managed to prevent competition with economic crops. For example, low-growing GM such as red clover (*Trifolium pratense* L.) may be required to avoid shading of economic crops (Katsvairo and Cox, 2000; Bukovinsky et al., 2004). Delay of interplanting until after the establishment of an economic crop may also mitigate competitive reduction of economic crop growth (Thiessen Martens et al., 2001). Partial mechanical or chemical suppression of high-biomass GMs such as hairy vetch may alleviate competition when economic crops are planted into a preexisting living mulch (Ranells and Wagger 1993; Reddy and Kroger, 2004).

Suppression of parasitic nematodes by GM also exemplifies the importance of highly specific GM–environment–management interactions. Different crop species, and even different varieties of the same crop species, vary in their resistance to different nematode species. Plants may also show different levels of susceptibility to regional races and local isolates of nematode species. Overuse of resistant crop varieties can select for "resistance-breaking" nematodes (McSorley, 2001). Crop rotation with a nonhost or nematode-suppressant GM may help reduce such selection pressures by providing an opportunity to disrupt nematode life cycles. For example, a number of GM species act as nonhosts or suppressors of one or more *Meloidogyne* species (root-knot nematodes): castor (*Ricinus communis* L.), iron-clay cowpea (*Vigna unguicalata* cv. Iron Clay), showy crotalaria (*Crotalaria spectabilis* Roth), joint-vetch (*Aeschynomene Americana* L.), marigolds (*Tagetes minuta* L. and *T. erecta* L.), sesame (*Sesamum indicum* L. cv. Paloma), sunn hemp, barley (*Hordeum vulgare* L.), green panic grass [*Megathyrsus maximus* (Jacq.) B. K. Simon & S. W. L. Jacobs], glycine [*Neonotonia wightii* (Wight & Arn.) J.A. Lackey], horsebean [*Canavalia ensiformis* (L.) DC], velvetbean (*Mucuna* spp.), and Sudex [*Sorghum bicolor* (L.) Moench × *S.* × *drummondii* (Steud.) Millsp. & Chase; Sipes and Arakaki, 1997; Al-Rehiayani and Hafez, 1998; McSorley, 1999].

On the other hand, some GM species may exacerbate infestations of plant-parasitic nematodes by acting as hosts. In Hawaii, Sipes and Arakaki (1997) found populations of *Meloidogyne* spp. on taro [*Colocasia esculenta* (L.) Schott] increased significantly following alfalfa (*Medicago sativa* L.), cowpea (variety unreported), lablab [*Lablab purpureus* (L.) Sweet], hairy vetch, mustard (*Brassica napus* L.), oat (*Avena sativa* L. cv. Coker), Rhodes grass (*Chloris gayana* Kunth), cereal rye (cv. Danka), annual ryegrass (*Lolium multiflorum* Lam. cv. Alamo), siratro [*Macroptilium atropurpureum* (DC.) Urb. cv. Siratro] and wheat (*Triticum aestivum* L., multiple cultivars). In Florida, McSorley (1999) found high root-knot nematode populations on roots of potential GM species of pearl millet [*Pennisetum typhoides* (Burm. f.) Stapf & C.E. Hubb syn *P. glaucum*

(L.) R. Br.] and Japanese millet (*Echinochloa frumentacea* Link). Sunn hemp has been found to be a poor host of reniform nematodes (*Rotylenchulus reniformis*), yet may support a slow population increase with time (Caswell et al., 1991; Wang et al., 2003b). Some GM species known as nonhosts or direct suppressors of *Meloidogyne* spp. may have other undesirable characteristics, or may vary in their adaptability to a particular environment and management system. As discussed above, GM species well suited for control of one type of nematode may show susceptibility to others. Al-Rehiayani and Hafez (1998), working in Idaho, found varieties of buckwheat and mustard to be non- or poor hosts for a *Meloidogyne chitwoodi* race, while Sipes and Arakaki (1997) found opposite results with *Meloidogyne javanica* in Hawaii. Nematode management with GM thus requires specific information on plant host status. Generally, GM species closely related to subsequent cash crops often host similar nematodes.

Green manures may control pests indirectly by providing habitat for organisms that feed on or parasitize weeds, insects, and nematodes. Greenhouse studies in Florida using sandy soil have shown that sunn hemp can increase omnivorous and predatory nematodes on soils with low organic matter (<2%), though perhaps not enough to control parasitic nematodes such as *Meloidogyne* spp. (Wang et al., 2003a). Wang et al. (2001) found application of sunn hemp residues to a silty clay at a rate of 10 g dry residue kg^{-1} dry soil enhanced nematode-trapping fungi. Studying cucurbit crops (*Cucurbita* spp.) with buckwheat refuges, Platt et al. (1999) found numbers of insect predators and parasitoids caught on sticky traps increased by 2 to 19 times as one moved toward buckwheat refuges from 20 to 35 m away. However, the method of biological control differs among pests, with some controlled by general increases of biological activity while others require development of proper habitat for specific antagonists (Bugg et al., 1991; Davis et al., 1996; Wang et al., 2003a, 2003b). Efficacy of biological control may also depend on space and time. For example, Platt et al. (1999) found striped cucumber beetle (*Acalymma vittatum* F.) populations increased beyond the economic threshold at distances >10 m from buckwheat refuges and when buckwheat stopped flowering. Such spatially and temporally explicit information regarding the effects of GM use on both pest and beneficial arthropods remain rare, especially for field-scale studies that also quantify economic crop yields and have control treatments with standard chemical pest suppression.

Allelopathic chemicals released by specific GM species may directly inhibit weed growth, although allelopathy is highly specific to GM species, environment, residue management, and target organism (Blackshaw et al., 2001; Caamal-Maldonado et al., 2001; Inderjit, 2001). Small-seeded weeds may be particularly susceptible to growth-reducing stresses (Davis and Liebman, 2001). Allelopathic chemicals and delayed release of N from decomposing GM may thus reduce small-seeded weed growth more than that of large-seeded crops, providing such crops with a critical early season advantage (Dyck et al., 1995; Petersen et al., 2001).

BUILDING SOIL ORGANIC MATTER WITH GREEN MANURES

Although use of GM is routinely credited for its ability to increase soil organic matter (SOM) and microbial biomass pools, the actual extent of such changes depends on management and environment as well as GM biomass accumulation. Additionally, the annual contributions of GM residues may be relatively small compared with preexisting SOM pools, especially after residue losses following decomposition. For example, in a short-term study, N'Dayegamiye and Tran (2001) found that 15% of red clover N applied to maize (*Zea mays* L.) was taken up, while 19 and 28% were recovered in microbial biomass and soil organic fractions, respectively. Nonetheless, reported increases of SOM following GM use often range between 0 and 1% of total soil mass (Utomo et al., 1990; Reddy et al., 2003). The practical effects of such SOM increases may be relatively small; however, larger increases in SOM may be limited by the short-term nature of these studies or from the use of management approaches that do not obtain high biomass accumulation from GM. Because most GM research lasts for 2 to 5 yr, we have little information on the long-term potential of GM use to greatly increase SOM, especially for GM grown in place (not "cut-and-carry" studies where GM additions can be adjusted for optimal quantity and quality).

Generally, organic matter associated with the smaller size soil fractions—silt and clay—may experience more physical and chemical protection from decomposition than that associated with larger (sand) size fractions. For example, on a loam soil having about 35% sand and 1.6% soil organic C, Kandeler et al. (1999) found roughly 50 to 75% of soil organic C and microbial biomass N associated with the clay-size fraction (<2 μm) and roughly 90 to 95% of soil organic C and microbial biomass N existing within silt and clay size fractions together (<63 μm). Organic matter and microbial biomass in fine-textured soils may, therefore, show greater and more rapid response potential to GM approaches. In two similar experiments after roughly 10 yr of a pearl millet and wheat rotation on a low-organic-matter (~0.40–0.50% organic C) sandy loam (65–69% sand) in India, Goyal et al. (1992, 1999) found combinations of inorganic fertilizer and organic amendments (wheat straw, animal manure, or sesbania GM) generally increased soil organic C, total N, microbial biomass C, and enzyme activity more than inorganic fertilizer alone in the top 15 cm of soil (plow layer). Still, with manure–residue additions in these studies varying between 8 and 15 t ha^{-1} annually, relative increases in soil organic C amounted to only about 5 to 15% during the entire study periods. Realization of greater SOM increases, especially in hot, humid, sandy environments, may require greater or more consistent additions of recalcitrant residue, especially under conventional tillage (see Tables 1–4 for summary of GM biomass accumulations in literature; see also Yadav et al., 2000). In some cold environments, soils may possess large amounts of organic matter with slow turnover rates; changes in residue management may affect SOM only slowly under such conditions (Franzluebbers and Arshad, 1996; Pikul et al., 1997). Finally, while long-term and large-scale studies may demonstrate increased economic crop yield in response to higher SOM (Kanchikerimath and Singh, 2001; Majchrzak et al., 2001), the timing and amount of N mineralization from soils and residues following GM generally have major effects on subsequent economic crop yields in the short term (Vyn et al., 2000; Soon et al., 2001; see below).

MANIPULATING NITROGEN SUPPLY WITH GREEN MANURES

Matching the amount and timing of GM N release with subsequent crop N demand often remains a keystone challenge to developing integrated, GM-based crop production that is competitive with modern, chemically based approaches (Robertson, 1997). Effective manipulation of N supply in GM-based approaches to crop production requires understanding of a number of interactions between GM management, subsequent crop response, and soil, climate, and weather.

Green Manure Management

Nitrogen release from plant residues depends on a large number of interactive factors including chemical composition and N concentration, temperature, and water availability (Andren et al., 1992; Schomberg et al., 1994). These factors in turn depend on many of the subjects in Fig. 1. Additionally, GM residues may alter root growth and N uptake patterns of subsequent crops (see below).

Some researchers have found N-substitution values for GM in excess of actual GM N accumulation, suggesting that GM N is sometimes taken up more efficiently than chemical fertilizer N or that GM modifies the soil environment, crop growth, or both such that greater crop N uptake is possible (e.g., Agustin et al., 1999; Yadav et al., 2000; Prasad et al., 2002). On the other hand, GM N release can occur before (generally in warmer environments; Sainju and Singh, 2001) or after (generally in cold environments; Griffin and Hesterman, 1991; Shrestha et al., 1999) peak N demand from subsequent crops. In these cases, manipulation of residue quality through proper selection of GM or GM mixtures, tillage, and planting densities and timing may better synchronize leguminous GM-N release with subsequent crop demand.

Residue Management

Decomposition and N release generally occur faster for residues with lower C/N ratios and lignin and polyphenol contents (Seneviratne, 2000). Optimum temperature and water availability for soil-based decomposition are usually around 35°C and field capacity, respectively (Vigil and Kissel, 1995; Katterer et al., 1998; Lomander et al., 1998). Mathematically, investigators often characterize decomposition (biomass or C loss) and N loss as negative exponential declines with time, with rate directly affected by one or more decay-rate constants depending on temperature, water and N availability, and chemical quality of the residue (see also Douglas and Magdoff, 1991; Dou et al., 1996; Quemada et al., 1997). For example, Somda et al. (1991) used a litterbag study of a number of legumes and nonlegumes; C/N and lignin/N ratios were generally lower for legumes (8:1–27:1, and 2:1–9:1, respectively) than for nonlegumes (27:1–186:1, and 4:1–44:1, respectively), and decay-rate constants of both fast and slow pools were greater for legumes. Kuo and Sainju (1997) showed that mixing hairy vetch residue with increasingly large proportions of cereal rye and annual ryegrass residues slowed the relative rate of N release. Working in Georgia, USA, Ranells and Wagger (1996) also found faster decomposition and N release for hairy vetch and crimson clover grown alone than when grown with cereal rye, but still found no net N immobilization in any treatment (including rye alone).

Leaf C/N ratio and lignin content is generally much lower than for stems or roots of the same plant. In most studies, leaf decomposition and N release occurs significantly faster than for other tissues. Prolonged periods of N immobilization are often recorded for recalcitrant stems and roots (Collins et al., 1990; Cobo et al., 2002). Investigating nutrient release of about a dozen legumes, Cobo et al. (2002) found that leaves decomposed five times faster than stems, decomposition was closely related to cell wall content, and N release was most dependent on the lignin/N ratio. Both Cobo et al. (2002) and Collins et al. (1990) showed that the decomposition rates of leaf and stem mixtures were intermediate to leaves and stems decomposing alone, but faster than predicted by summing individual leaf and stem decomposition rates. These studies suggest that fungal decomposers may redistribute N from leaves to more recalcitrant tissues during decomposition.

Nitrogen contributions from belowground tissues of GM (roots and root nodules) are difficult to determine due to the rapid turnover of these tissues and possible root exudation of N. For example, Ramos et al. (2001) determined that 39 to 49% of all N accumulated by swordbean [*Canavalia ensiformis* (L.) DC.] and velvetbean [*Mucuna aterrima* (Piper & Tracy) Holland] was below ground, and 10 to 12% of all accumulated N was transferred to the soil by root and nodule turnover and root exudation. In a 3-yr study, Griffin et al. (2000) reported 56, 46, and 38% of total biomass and 32, 28, and 19% of total N in roots at final sampling for alfalfa, cereal rye, and hairy vetch plus rye intercrop, respectively; however, both of these studies occurred on soils that were fine textured, high fertility, or both. On a sandy soil, Cherr (2004) found roots accounted for as little as 10% of the total biomass and 3% of the total N content at final sampling for sunn hemp, and 13 to 22% of total biomass and 7 to 10% of total N content at final sampling for temperate legumes such as blue lupine (*Lupinus angustifolius* L.) and cahaba white vetch (*Vicia sativa* L.). Although root biomass can be relatively small, Puget and Drinkwater (2001) showed that C from lignified roots may persist in the soil longer than that of highly labile shoots, increasing the long-term importance of root contributions to SOM and possibly also soil organic N.

Soil incorporation of plant residues may speed decomposition and N release by buffering temperature and water regimes relative to the surface (Mansoer et al., 1997; Thonnissen et al., 2000a). Schomberg et al. (1994) found greater N immobilization potential for sorghum [*Sorghum bicolor* (L.) Moench) and wheat residue on the soil surface, although initial N immobilization was more rapid when the residues were buried. At peak immobilization (5 mo–1 yr or more), sorghum and wheat residues tied up 150 to 170% of their initial N content. For these low-N residues, net N immobilization lasted > 1 yr on the soil surface (study ended after 1 yr) and only 1/3 yr for buried residues. Near-complete decomposition and N release of soil-incorporated legumes has been found to require 15 to 20 wk in temperate environments (Bowen et al., 1993), but may take place in only 2 to 6 wk in tropical environments (Thonnissen et al., 2000a). Although it may slow the process somewhat, surface decomposition in warm, high-precipitation environments on sandy soils may still result in rapid N loss despite the presence of recalcitrant residue (Mansoer et al., 1997; Cherr, 2004). In such systems, it may be critical that economic crops are either planted as soon as possible after termination of GM or direct planted into adequately suppressed GM. In cool environments, however, slow surface decomposition under very dry conditions or soil cooling underneath residue mulch in wet conditions may necessitate soil incorporation of GM residue, selection of a lower biomass GM, or both (Fortin and Pierce, 1990; Holderbaum et al., 1990; Pikul et al., 1997).

Growth Management

Growth management may also exert effects on GM residue quantity and quality. Generally, leaf tissue fractions dominate shoots during early season growth, while stems become increasingly important as time goes on (Gallaher, 1991; Mansoer et al., 1997; Cherr, 2004). Low plant populations may increase the proportion of GM as stem or lignin, while higher plant population may favor greater leaf and nonstructural carbohydrate production (Gallaher, 1991; Marshall, 2002) especially in GMs with upright growth. High plant populations may facilitate early season production with earlier canopy closure, while lower plant populations may improve later production as compensatory growth takes effect; however, extremely low or high plant populations may reduce production by overcoming GM's ability for compensatory growth or exacerbating competition for nutrients, water, and light as plants become larger. Compensatory behavior may be aided by cutting plants to induce branching if and when they possess indeterminate growth habit, and competition may be reduced by mowing or grazing plants if and when they possess growing points below mowing or grazing height (Stopes et al., 1996; Shrestha et al., 1999; Ross et al., 2001; Marshall, 2002). Termination date may also affect the fraction of plant biomass and N as leaf, stem, reproductive, or senesced tissue if the GM responds to late-season changes in temperature and photoperiod; lengthening the GM growing season may or may not, therefore, increase GM biomass and N content (Cline and Silvernail, 2001; Sainju and Singh, 2001).

In addition to providing greater weed control, intercropping and live mulching with GM may help better synchronize GM N release with subsequent crop N demand, especially in warm, humid climates or on coarse soils (Dapaah and Vyn, 1998; Zemenchik et al., 2000; Jeranyama et al., 2000; Blackshaw et al., 2001). These practices, however, must be carefully managed to prevent crop–GM competition (Guldan et al., 1996; Ghaffarzadeh, 1997; Jeranyama et al., 1998; Rao and Mathuva, 2000). For example, in Georgia, USA, Phatak et al. (1999) developed a successful relay cropping system in which a cool-season GM of crimson clover is permitted to reseed itself annually and cotton is no-till planted as crimson clover declines at the onset of warm weather (see also Hartwig and Ammon, 2002).

Subsequent Crop Management

Due to different nutrient release characteristics and effects on soil water, temperature, and biota, crop root growth patterns may be markedly different following GM than chemical fertilizer. Because its N release is driven by decomposition, GM may represent a source of slow-release N. Spatial distribution of GM residue may be heterogeneous, creating localized areas of N release and other GM-mediated impacts (Mahmoudjafari et al., 1997). Green manures may have effects on soil moisture transfers, temperature, and populations of root-parasitizing organisms such as nematodes (Hartwig and Ammon, 2002).

Under conventional tillage, the use of GM or other crop residues or organic amendments appears to change crop root length density (RLD) within the plow layer. Pallant et al. (1997) and Nickel et al. (1995) reported greater RLD at depths below 12 to 15 cm for conventionally tilled corn with GM or crop residues, while chemically fertilized corn may maintain greater RLD in the upper soil depths (Nickel et al., 1995; Goldstein, 2000) and sustain greater root damage from pests (Goldstein, 2000). For potato, Opena and Porter (1999) reported that organic amendments (mixture of waste potato compost plus cattle manure and sawdust) also increased RLD in the 0- to 30-cm plow layer; however, surface-applied residues may encourage crop root proliferation near the soil surface and near the plant, especially when residues show potential for significant N release on decomposition (Thorup-Kristensen and van der Boogaard, 1999; Cherr, 2004). Altered patterns of root growth may benefit crop performance only if nutrient and water availability in root-explored areas remain adequate. Few studies, if any, have documented how changes in the amount and distribution of irrigation and supplementary fertilizer N affect uptake patterns, growth, and reproductive yield of economic crops following GM.

ECONOMIC ANALYSES OF GREEN MANURES

Economic viability of GM-based systems depends on externalities and internalities (Dobbs, 2004). Farmers (and researchers) have no direct control over factors external to their operations. Currently, low costs that farmers associate with chemical-based approaches to production may not accurately reflect the expenses passed externally to society. Existing government policies generally do not bill farmers for potential impacts of agriculturally related pollution, global warming, and ecological disruption on human health and economic activity. If government subsidies or market prices directly experienced by the farmer do not accurately reflect costs or savings passed on to society, then GM approaches may become less profitable or involve more risk to the farmer regardless of net value (Young and Painter, 1990; Ali and Narciso, 1996; Dobbs, 2004). Moreover, government policies or market prices may have different impacts regionally (Painter and Young, 1994) or on different GM approaches (Painter et al., 1995). Because farmers typically have little ability to accept economic risk, they often cannot afford short-term experimentation with GM approaches even if it leads to long-term economic profit (Painter et al., 1995). In scenarios where mechanization is not possible, GM approaches with high labor requirements for planting and residue management may become too costly, especially where synthetic fertilizers are inexpensive (Ali, 1999; Rao and Mathuva, 2000).

Internally, a particular approach to crop production will affect economic profit and risk. Farmers may also have to consider input, transition, and opportunity costs associated with GM (Ali and Narciso, 1996; Ali, 1999). External factors aside, GM approaches are more often found to be economically superior to conventional approaches when capable of providing multiple services (Young et al., 1994; Ghaffarzadeh, 1997; Ali, 1999), when GM replaces costly conventional inputs such as fallow management or plastic mulches (Wyland et al., 1996; Ellis et al., 2000), when one or more species from multispecies GM mixtures serves as an economic crop (Painter et al., 1995; Ghaffarzadeh, 1997), and when strict GM crops are replaced with crops that provide food or feed while residue is left in the field (Ali, 1999). Variable weather or other environmental patterns may also alter year-to-year profitability of GM approaches (Vigil and Nielson, 1998). Use of GM or GM plus reduced tillage approaches may also economically justify and ecologically mitigate the use of other inputs (Young et al., 1994; Painter et al., 1995).

FUTURE GREEN MANURE RESEARCH NEEDS

Needs in Data from Reductionist Studies

The amount of traditionally styled, reductionist research focused on GM use has increased dramatically during the past 15 yr. Nonetheless, several important knowledge gaps persist throughout much of this work. Simple changes in sampling procedure, treatment design, and experimental setup of traditional GM research are needed to provide essential data.

Practical information about the composition and N concentration of GM as it changes during a growing season is often lacking. Most studies report only end-of-season values for GM biomass and N content and concentration. This poses an obstacle to GM adoption because growing time in an on-farm production system differs from that studied in research, creating yet another way GM biomass and composition in an on-farm setting may differ from reported findings. Repeated sampling of GM with time provides much more meaningful information for development of appropriate GM selection and management. Additionally, repeated measurements of GM leaf area index and light interception coupled with reliable weather data (temperature and solar radiation) are needed to build simple predictive models for GM growth.

A critical need also exists for growth analysis of GM-amended crops. Final yields and crop biomasses may not reflect patterns of crop growth and N accumulation throughout a growing season. For example, in Florida, Cherr (2004) found GM had significant benefit for spring-planted sweet corn during early- to midseason; however, GM-amended corn fell behind conventionally fertilized treatments in terms of late-season ear fill. These differences led investigators to seek information about patterns of late-season corn root growth and water and N availability as affected by GM residue. In such a case, growth analysis revealed critical information necessary for understanding GM-based system behavior. To develop appropriate management techniques, information is also needed regarding how changes in the amount and distribution of irrigation and supplementary N fertilizer affect the availability and uptake of water and N by economic crops following GM.

Most existing information on GM performance comes from studies conducted in temperate or tropical environments on fine-textured soils, the results of which may not apply to regions with intermediate climates (warm but with winter freezes) or sandy soils. Studies on sandier soils in Florida, Zimbabwe, Zambia, and India have shown reduced performance for temperate GM species and low benefits from tropical GM species (Gallaher, 1993; Jeranyama et al., 2000; Steinmaier and Ngoliya, 2001; Cherr, 2004). Development of GM techniques appropriate for such regions will require approaches that better manipulate GM N accumulation and timing of N release.

If GM does not supply adequate N to meet the requirements of subsequent crops, then supplementary inorganic N may be required to prevent yield reductions. Many studies have compared the use of GM alone against synthetic fertilizers (Carsky et al., 1999), and others have also investigated GM used in combination with synthetics (Ladha et al., 2000). These studies, however, usually do not establish optimums for chemical N rate, whether used alone or with GM. This makes it difficult to assess how much (if any) chemical N is required in addition to GM for optimal production. Some studies establish optimal chemical N rates for cut-and-carry systems where GM is not grown in place (Prasad et al., 2002), but this does not reflect common agricultural practice in developed countries.

Although some studies have documented the ability of GM to host beneficial organisms or suppress insect pests (Bugg et al., 1991; Nicholls and Altieri, 2001), little field-scale data exists on insect population dynamics across space and time and the effects of pest attack on economic crop yield when GM is substituted for insecticide. Without this data, and without comparisons to control treatments with conventional or organic insecticides, it is impossible to determine when and where GM use can substitute for such insecticides in field-scale production.

Needs for Whole-Systems and Participatory Approaches to Green Manure Research

The traditional style of agricultural research and technology transfer may poorly suit the development of GM-based approaches to crop production. Such a traditional style involves separated, stepwise phases of initial planning, small-plot trials, larger scale studies under more realistic conditions, and finally the dissemination of finished technology to farmers (Wuest et al., 1999). Green manure-based alternatives to crop production are often not viable without the provision of multiple benefits. Because of the complex interrelationships between GM, management, and environment, this may demand adjustments of the entire farm system including the choice of economic crops, crop rotation, cultural practices, and marketing. The complexity of issues arising on the whole-farm level far exceeds the information gained in traditional, station-based research (Delate, 2002; Langeveld et al., 2005). Because planning and station-based research of GM usually occurs before (or without) dissemination and adoption–adaptation phases, there is little opportunity for planned feedback (van de Fliert and Braun, 2002). Application of GM in on-farm trials as a substitute technology, rather than use of appropriate GM-based systems, often fails as a result.

Our traditional research and development methods must be complemented with suitable farmer participation as well as whole-system evaluations. Effective involvement of farmers can help determine appropriate criteria for cropping-system evaluation, farmer needs and preferences, improved methods of dissemination and extension, and feedback. Such participatory elements can provide improved linkage and overlap between the planning, research, dissemination, and adoption–adaptation phases (van de Fliert and Braun, 2002). For example, this allows GM studies to be designed with complete farming systems in mind, GM research itself to become a more visible form of dissemination, and feedback from the dissemination and adoption–adaptation phases to help guide ongoing planning and research (Delate, 2002; Mueller et al., 2002).

In station-based settings, stakeholder groups have cooperatively planned and managed research and dissemination of results from fields or experimental farms (Delate, 2002; Mueller et al., 2002). Alternatively, Stoorvogel et al. (2004) describe selection of a limited number of representative, reliable, and visible farms for collaboration with academic researchers. Langeveld et al. (2005) integrated these concepts with the "nucleus and pilot" approach. Here, the performance of an entire system is evaluated on a researcher-controlled experimental farm under realistic conditions. The experimental farm (the nucleus) serves as an example for pilot farmers, who then test and evaluate the system in on-farm settings and communicate their experiences to both the researchers and other farmers.

Resource limitations restrict the number of whole systems that can be compared with each other, and management of such systems often changes continuously (Langeveld et al., 2005). Factorial studies, sometimes conducted within whole-systems studies, are important to provide an understanding of specific processes governing GM benefits (Drinkwater, 2002). Farmers make decisions based on multiple criteria that generally change with time and differ between individuals (Pannell, 1995; Kroma and Flora, 2001). Understanding how these criteria affect GM use may not be possible without on-farm, participatory, and whole-systems research approaches. On the other hand, maintenance of consistent data sets and GM evaluation may require that such approaches be complemented with on-station, researcher-controlled studies. Participatory studies often suffer from high farmer dropout rates and lack of effective communication between farmers and researchers. Bentley (1994) argued strongly that participatory research may be best suited to commercial farmers and farm sectors that have: (i) preexisting relationships with researchers and research institutions; (ii) highly organized ownership–management; and (iii) similar socioeconomic status with researchers. It may also be critical to identify early-stage farmer collaborators whose market orientation provides a benefit for the use of GM, such as those engaged in organic or direct market farming, and researchers must effectively screen GM approaches before on-farm study to reduce the risk of economic loss and discouragement for farmer collaborators. Finally, GM researchers should better involve organizations already networked with potential farmer collaborators. For example, the nearly 60 accredited organic certification agencies in the USA (USDA, 2005) have high levels of contact with farmers and other organizations with inherent interest in GM. Such agencies could provide crucial partners in the search for farmer collaborators and for subsequent dissemination, market development, and monitoring of GM approaches with other farmers.

CONCLUSIONS

Green manure-based systems may provide alternatives to current approaches to crop production; however, the use of GM may not be economically justified without the provision of multiple services such as nutrient supply, pest and weed control, and improvement of soil characteristics for crop production, among others. Provision of such services within GM-based systems requires critical and systematic assessment of the interactions between the GM, the environment, and management. Additionally, traditional styles of agricultural research and agrotechnology transfer may poorly suit the development of GM-based approaches to crop production unless complemented with effective farmer participation and whole-systems analysis going beyond mere technology substitution.

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