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REVIEW

Green and animal manure use in organic field crop systems

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Abstract

Dual-use cover/green manure (CGM) crops and animal manure are used to supply nitrogen (N) and phosphorus (P) to organically grown field crops. A comprehensive review of previous research was conducted to identify how CGM crops and animal manure have been used to meet N and P needs of organic field crops, and to identify knowledge gaps to direct future research efforts. Results indicate that: (a) CGM crops are used to provide N to subsequent cash crops in rotations; (b) CGM-supplied N generally can meet field crop needs in warm, humid regions but is insufficient for organic grain crops grown in cool and sub-humid regions; (c) adoption of conservation tillage practices can create or exacerbate N deficiencies; (d) excess N and P can result where animal manures are accessible if application rates are not carefully managed; and (e) integrating animal grazing into organic field crop systems has potential benefits but is generally not practiced. Work is needed to better understand the mechanisms governing the release of N by CGM crops to subsequent cash crops, and the legacy effects of animal manure applications in cool and sub-humid regions. The benefits and synergies that can occur by combining targeted animal grazing and CGMs on soil N, P, and other nutrients should be investigated. Improved communication and networking among researchers can aid efforts to solve soil fertility challenges faced by organic farmers when growing field crops in North America and elsewhere.

Abbreviations: CGM, cover/green manure; DM, dry matter; FM, feather meal; FSP, Farming Systems Project; PAN, plant available nitrogen; PL, poultry litter; PMN, potentially mineralizable nitrogen; SOC, soil organic carbon; SOM, soil organic matter; USD, United States dollar.

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1 | BACKGROUND

Dual-use cover/green manure (CGM) crops and animal manure can improve soil N and P (animal manure) availability and cycling when incorporated into field crop systems. This is particularly true on organic farms, where biologically driven processes (e.g., biological N-fixation and N mineralization) provide field crops with the N and P needed for optimum growth and productivity. A wide diversity of crop and animal enterprises occur on organic farms, but similarities exist in how N and P are managed. Cover/green manure crops are a common feature in organic field crop systems, regardless of the geographic region. Conversely, effects of a particular practice (e.g., growing a CGM crop prior to a maize [*Zea mays* L.] grain crop) can vary markedly among organic farms because of climatic and edaphic factors. Thus, discussing effects of CGM crops and animal manure on soil N and P fertility management should consider both general and local uses and impacts.

2 | METHODS

Agricola, CAB abstracts, Google Scholar, and Web of Science databases were used to identify previous research on soil N and P fertility management in organic grain crop systems, as described by Carr et al. (2019). “Compost,” “compost carryover,” “compost legacy,” “cover crops,” “green manure,” “manure,” “microbial diversity,” “macronutrients,” “micronutrients,” “nitrogen,” “organic,” “organic agriculture,” “organic farming,” “phosphorus,” and “soil fertility” were among the search terms used. The database search revealed >300 published papers on the use of CGM crops and animal manure in organic farming systems. The review was narrowed to organic field crop systems in North America, specifically, Canada and the United States. Papers focused on soil N and P management in organic horticultural crop systems were generally excluded from further consideration, as were those reporting research conducted in California, western Oregon, and western Washington state in the United States, and parts of Canada, where horticultural crops are widely grown. Similarly, papers summarizing research on other continents (e.g., Europe) generally were excluded, as were papers originating in countries located primarily in subtropical and tropical environments (Mexico). These restrictions resulted in ~130 published papers identified as pertinent to the review.

Additional manuscripts recommended by organic farming researchers familiar with the topic were acquired, as were new database searches using soil nutrients as key words. A general review is provided of the effects of CGM crops and animal manure on soil N and P fertility. The review addresses differences in soil N and P due to variations in climate, soil, and

Core Ideas

- CGM-supplied N can meet organic crop needs in warm, humid but not in cool, dry regions.
- Adoption of organic no-tillage can result in soil N deficiencies when growing field crops.
- Use of animal manure to supplement soil fertility can lead to soil N and P excess.
- CGM and animal incorporation into diverse rotations may enhance soil fertility status.

other factors across five important, organic field crop regions: (a) cool and humid eastern Canada; (b) the coastal and humid northeastern and mid-Atlantic United States; (c) warm and humid southeastern North America; (d) the continental and humid U.S. Midwest; and (e) the continental and sub-humid Great Plains and Intermountain West (Figure 1). Several suggestions are made for future research.

3 | DUAL-USE COVER/GREEN MANURE CROPS

3.1 | Cover/Green manure use in organic field crop systems

Readers are referred to previous reviews by Snapp et al. (2005) on cover crops and by Cherr, Scholberg, and McSorley (2006) on green manures in *Agronomy Journal*. Both reviews provided excellent summaries of the state-of-knowledge regarding cover and green manure crops at the time they were published. Recent reviews of CGMs in organic farming systems are narrow in scope and geographic area (e.g., Reberg-Horton et al., 2012). Our paper complements these earlier reviews by summarizing research results on the effects of CGM crops and animal manure on soil fertility in organic field crop systems across the five broad geographic regions in Figure 1.

Growing crops for cover and as a green manure is a mainstay in organic field crop systems in Canada and the United States (Carr et al., 2019; Table 1). Functionally, plant species are generally selected and grown that provide multiple ecosystem services. Annual legume species (e.g., hairy vetch [*Vicia villosa* Roth]) are attractive as CGM crops because they can provide plant available N (PAN) through biological-N₂ fixation to subsequent cash crops in a rotation (Olsen, Endelman, Jacobson, & Reeve, 2015). Legumes also typically have low C/N ratios (10 to 15:1) when grown as CGM crops, so residue decomposition is fast, with most of the N released within 4–8 wk of termination (Poffenbarger et al., 2015a; Ranells & Waggoner, 1996; Waggoner, 1989).

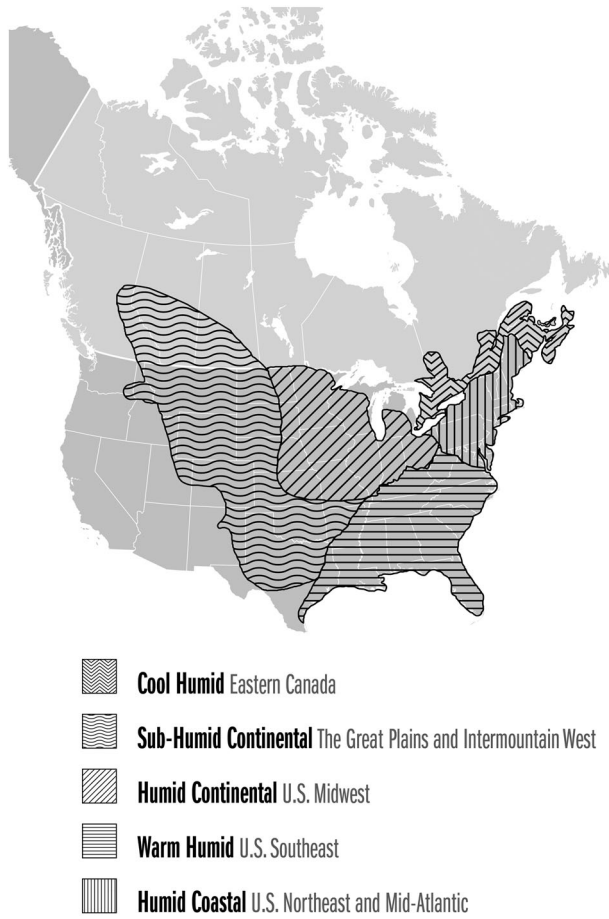


FIGURE 1 Five important organic field crop regions in Canada and the United States. (Figure created by Alison Gauthier, Univ. Communications, Montana State Univ., Bozeman, MT)

Large amounts of the N released following CGM termination can be lost via leaching and denitrification prior to N uptake by maize or other field crops that follow in a rotation (Rosecrance, McCarty, Shelton, & Teasdale, 2000). Failure to synchronize release of N by mineralization from CGMs with demand of the following cash crops is a concern (Berry et al., 2002; Cassman, Dobermann, & Walters, 2002; Dawson, Huggins, & Jones, 2008). Rapid N losses can be particularly challenging on coarse textured soils (Berntsen et al., 2006; Olsen, Askegaard, & Rasmussen, 2009). Preceding sweet corn (maize) with a pea (*Pisum sativum* L.) CGM with a low C/N ratio resulted in grain yields no different than a 0 N rate. Cover/green manure crops should be selected so that N release matches subsequent grain crop demand. Results from long-term trials showed that potentially mineralizable N (PMN) during the maize crop phase following berseem clover (*Trifolium alexandrinum* L.) peaked in July, which corresponded to maximum N demand by the maize crop (Diederich, 2018).

Nitrogen synchrony between legume CGM crop release and subsequent cash crop uptake can be improved by growing annual grass and legume species together (Poffenbarger

et al., 2015a). Grass–legume polycultures also typically produce greater amounts of aboveground dry matter (DM) than legume monocultures (Reberg-Horton et al., 2012). However, this strategy often requires supplemental applications of animal manure to meet the requirements of high N-demanding field crops such as maize (Poffenbarger et al., 2015a).

Legume crops producing >4,000 kg ha⁻¹ of aboveground DM provided large amounts of PAN to subsequent grain crops (Parr, Grossman, Reberg-Horton, Brinton, & Crozier, 2011; Teasdale, Devine, Mosjidis, Bellinder, & Beste, 2004). Hairy vetch produced up to 150 kg N ha⁻¹ in southern portions of Humid Coastal North America (Figure 1), and up to 52 kg N ha⁻¹ further north (Decker, Clark, Meisinger, Mulford, & McIntosh, 1994; Dou, Fox, & Toth, 1994; Ketterings et al., 2015; Sarrantonio & Scott, 1988; Teasdale et al., 2004, 2012). However, optimal growth of legume crops (i.e., early seeding and late termination) is not always feasible because of crop rotation considerations and other management constraints (Ketterings et al., 2015; Mirsky et al., 2017; Buckland, Reeve, Creech, & Durham, 2018). Hairy vetch produced <4,000 kg ha⁻¹ in some environments in eastern North America (Reberg-Horton et al., 2012; Teasdale & Mohler, 2000; Yenish, Worsham, & York, 1996), and DM yields exceeded 4,000 kg ha⁻¹ in only one of four years in the semi-arid Great Plains (Carr, Gramig, & Hogstad, 2016).

Nonleguminous crops such as rye (*Secale cereale* L.) and oat (*Avena* spp.) have been included as CGM crops in organic field crop systems (Table 1). Winter rye has several benefits when grown as a CGM crop; it is easy to establish, very winter hardy, can produce large amounts of above-ground DM, suppresses weeds, and can reduce N leaching (De Bruin, Porter, & Jordan, 2005; Korres & Norsworthy, 2015; Krueger, Ochsner, Porter, & Baker, 2011; Price, Reeves, & Patterson, 2006; Staver & Brinsfield, 1988; Vann et al., 2017). However, limited N release occurs if rye grows beyond the boot or Zadoks growth stage (GS) 40 (Zadoks, Chang, & Konzak, 1974), and N immobilization can result because of the high C/N ratio in straw as rye reaches advanced growth stages (Poffenbarger et al., 2015b; Ranells & Waggar, 1996). Similar concerns regarding high C/N ratios and subsequent N-immobilization exist when oat or other small-grain cereals are grown as CGM crops (Ashford & Reeves, 2003).

Growing rye or other small-grain CGM crops in combination with hairy vetch can increase the amount of PMN available to subsequent grain crops when compared to growing the grass crop alone (Poffenbarger et al., 2015b). Poffenbarger et al. (2015a, 2015b) showed that total aboveground N amounts were comparable in some rye + hairy vetch mixtures when compared with a hairy vetch monoculture. However, immobilization can reduce PAN following CGM crop termination. Poffenbarger et al. (2015) showed that N stress can be partially reduced by adjusting the seeding rate. The N-supplying ability of a rye + vetch CGM crop mixture was

TABLE 1 Selected studies that included cover/green manure crops managed organically in five important field-crop production regions in North America

Field crop-based system	Cover crop(s)	North American region	Study
Oats/LCGM ^a –wheat–soybean	Hairy vetch (<i>Vicia villosa</i> Roth)	Cool Humid	Alam et al., 2018
LCGM–wheat–soybean	Red clover (<i>Trifolium repens</i> L.)		Lynch et al., 2012
Oat+LCGM–wheat–soybean	Common vetch (<i>V. sativa</i> L.)		
Oat/LCGM–carrot–oat/LCGM–LCGM–potato	Red clover	“	Sharifi et al., 2014
Oat/LCGM–carrot–lima bean–GCGM+LCGM–potato	Red clover; oat (<i>Avena sativa</i> L.)+pea (<i>Pisum sativum</i> L.)+hairy vetch		
Oat/LCGM–lima bean–carrot–GCGM+LCGM–potato	Red clover; oat+pea+hairy vetch		
Maize/GCGM–soybean–GCGM–maize–wheat/Hay	Winter rye (<i>Secale cereale</i> L.)	Humid Coastal	Lotter et al., 2003
Maize–soybean–oat/LCGM–Maize–oat/LCGM	Red clover		
Maize–barley/soybean–oat/LCGM	Red clover		
Maize/GCGM–soybean–wheat/LCGM	Winter rye; hairy vetch		
Maize/GCGM–Wheat/Soybean/LCGM (1994–1997)	Winter rye, crimson clover (<i>T. incarnatum</i> L.)	“	Teasdale et al., 2007
Maize/GCGM–Soybean/LCGM–Wheat (1998–2002)	Winter rye, crimson clover		
Maize/GCGM–Soybean/LCGM	Winter rye, hairy vetch	“	Cavigelli et al., 2008
Maize/GCGM–Soybean–Wheat/LCGM	Winter rye, hairy vetch		
Maize/GCGM–Soybean–Wheat–Hay			
Maize–soybean–spelt/LCGM	Red clover	“	Caldwell et al., 2014
Wheat/LCGM–Fallow–LCGM–maize–Fallow	Red clover	“	Schipanski and Drinkwater (2011)
Maize–kidney bean–spelt/clover–soybean–wheat/LCGM			
Maize–kidney bean–wheat/LCGM–cabbage–spelt/LCGM			
Maize–soybean–wheat/LCGM–soybean–wheat/LCGM			
Soybean–fallow–spelt/LCGM–LCGM–LCGM			
Maize–oat+pea–barley/LCGM–soybean–spelt/LCGM			
Soybean–wheat/LCGM–snap bean–spelt/LCGM–LCGM			
Spelt/LCGM–spelt/LCGM–cabbage–LCGM–LCGM			
Maize/GCGM–soybean–oat/alfalfa	Winter rye	Humid	Delate & Cambardella, 2004
Maize/GCGM–oat/alfalfa–alfalfa		Continental	
Maize–soybean–wheat/LCGM	Red clover (1991–2004)	“	Posner, Baldock, and Hedtcke (2008)
Maize–soybean–wheat/LCGM+GCGM	Berseem clover (<i>T. alexandrinum</i> L.) + oat (2005 to 2012)		Baldock, Hedtcke, Posner, and Hall (2014)
Spring pea–wheat–LCGM–wheat	Winter pea	Sub-Humid Continental	Borrelli et al. (2014)
LCGM–wheat–LCGM–wheat	Faba bean (<i>Vicia faba</i> L.)		

(Continues)

TABLE 1 (Continued)

Field crop-based system	Cover crop(s)	North American region	Study
LCGM–LCGM–LCGM–wheat			
Wheat–LCGM–pea	Austrian winter pea (<i>P. sativum</i> L. subsp. <i>sativum</i> var. <i>arvense</i> (L.) Poir.	“	Borrelli et al. (2012)
Wheat–LCGM–LCGM	Austrian winter pea, faba bean		
LCGM–LCGM–LCGM	Austrian winter pea, faba bean		
LCGM–wheat–proso millet	Spring pea	“	Lyon & Hergert 2014
LCGM/winter wheat–spring lentil–spring barley	Austrian winter pea, chickling vetch (<i>V. villosa</i> Roth)	“	Miller et al. (2008)

^aLCGM = Legume cover green manure.

optimized at a seeding rate of 27:34 kg ha⁻¹ in Maryland (Poffenbarger et al., 2015b).

Perennials, including red clover (*Trifolium pretense* L.) and alfalfa (*Medicago sativa* L.), are grown as CGM crops, especially in areas with substantial dairy operations (Caldwell, Mohler, Ketterings, & DiTommaso, 2014; Ketterings et al., 2015). Both species generally provide more N than annual legumes, and can supply sufficient N for a succeeding maize crop (Beegle, 2018; Ketterings et al., 2015). A common practice in the U.S. Northeast and Mid-Atlantic region is to interseed red clover and other forages into an established small-grain crop (Ketterings et al., 2015; Nass, Papadopolous, MacLeod, Caldwell, & Walker, 2002; Schipanski & Drinkwater, 2011; Westra & Boyle, 1991). Typically, interseeding does not affect grain yield or protein of the small-grain crop but does provide a longer growing window for the perennial legume (Nass et al., 2002; Schipanski & Drinkwater, 2011; Zirkle, 2012), and can reduce weed biomass (Zirkle, 2012). Similar results were observed elsewhere (Amossé, Jeuffroy, Celette, & David, 2013; Buckland et al., 2018). Strip cropping may be another way to effectively extend the growing season of N₂-fixing CGM crops in organic grain systems (Buckland et al., 2018).

Soil health in organic field-crop systems is generally high (Delate, Cambardella, Chase, & Turnbull, 2015; Marriot & Wander, 2006; Teasdale, Coffman, & Mangum, 2007), in spite of a heavy reliance on tillage for weed management. Still, organic farmers are adopting conservation-tillage practices (Peigné et al., 2016; Silva & Vereecke, 2019). These practices include ridge tillage, where residue remains on the soil surface between crop rows in order to conserve soil organic carbon (SOC), with tillage limited to a slightly elevated ridge where planting occurs (PFI, 1992, 2019; UW Extension, 2019), and strip tillage, which is similar to ridge tillage except the planting furrow is not elevated (Delate, Cambardella, & McKern, 2008). Of greater interest among organic farmers is the complete elimination of tillage when growing field crops. This has led to considerable research on developing organic no-tillage

systems for field crop production in Canada and the United States.

3.2 | Cover/Green manure crops and organic no-tillage

Organic farming has been criticized for a reliance on tillage for weed management and CGM crop termination (Trewavas, 2001), while conventional no-tillage farming has been identified as an effective way to increase SOC (Marshall & Lynch, 2018; Peigne', Ball, Roger-Estrade, & David, 2007; Silva & Delate, 2017; Trewavas, 2004). More soil C has been retained in organic tilled, field crop systems than conventional no-tillage systems in some environments (Teasdale et al., 2007), but organic systems can still benefit by reducing tillage (Gadermaier, Berner, Fliessbach, Friedel, & Mäder, 2012). Developing organic no-tillage strategies may lead to increases in SOC storage, decreases in erosion and the C footprint, reduced labor requirements, and facilitate the expansion of organic farmland (Oberholtzer, Dimitri, & Jaenicki, 2013). Considerable research has explored how tillage can be eliminated when growing field crops organically in North America (Beach, Laing, Walle, & Martin, 2018; Carr, Mäder, & Creamer, 2012a; Carr, 2017; Delate et al., 2015; Halde, Gagné, Charles, & Lawley, 2017; Mirsky et al., 2013; Silva & Delate, 2017; Wallace et al., 2017). Cover/green manure crops can provide a vegetative mulch for weed suppression in no-tillage systems (Halde, Gulden, & Entz, 2014; Reberg-Horton et al., 2012; Smith et al., 2011; Teasdale & Mohler, 1993, 2000; Teasdale, Mirsky, Spargo, Cavigelli, & Maul, 2012), and PAN to cash crops that follow in a rotation (Parr et al., 2011; Stute & Posner, 1995a, 1995b).

Organic no-tillage is a rotational system where tillage is used strategically prior to, or during, some crop phases while being eliminated during others (Carr, Gramig, & Liebig, 2013a; Halde et al., 2017; Silva & Delate, 2017). Cover/green manure crops are grown during no-tillage crop phases, killed,



FIGURE 2 Roller-crimper mounted onto the front of a tractor with standing and rolled-crimped rye cover/green manure crop (Image provided by Erin Silva, University of Wisconsin, Madison, WI)

and cash crops seeded directly into the vegetative mulch. A ‘roller-crimper’ is generally used to terminate CGM crops. Various roller-crimper designs have been considered (Kornecki, Price, Raper, & Arriaga, 2009; Reberg-Horton et al., 2012), though one of the most widely used crimpers uses blunt chevron-shaped blades attached to a water-filled drum (Figure 2). Early use of a roller-crimper in organic no-tillage occurred at the Rodale Institute in Pennsylvania (Moyer, 2011), but it was quickly incorporated into organic no-tillage systems elsewhere (Carr, Anderson, Lawley, Miller, & Zwinger, 2012b; Delate, Cwach, & Chase, 2012; Halde et al., 2014; Reberg-Horton et al., 2012; Shirliffe & Johnson, 2012; Teasdale et al., 2012). Use of a roller-crimper for CGM termination can result in a dense vegetative mulch that suppresses weeds (Mirsky et al., 2012; Reberg-Horton et al., 2012).

A number of CGM crops were included in previous organic no-tillage research, with winter rye and hairy vetch the most extensively studied (Table 2). Generally, maize and soybean (*Glycine max* L.) were grown following CGMs (Delate et al., 2012; Reberg-Horton et al., 2012; Mirsky et al., 2012; Halde

et al., 2017), in part because of concerns expressed by organic maize and soybean farmers about the negative effects of high-intensity tillage (Halde et al., 2017; Mirsky et al., 2012; Reberg-Horton et al., 2012). A review of CGM crop-based, no-tillage maize and soybean production from New York through North Carolina indicated that no-tillage systems have become a viable option for organic farmers in the eastern United States (Wallace et al., 2017). These farmers incorporated rotational no-tillage practices into their cropping systems (Mirsky et al., 2012, 2013), applied animal manure, and used rye or other cereal CGM crops to trap nutrients and control weeds (Wallace et al., 2017).

Maize was planted concomitantly with termination of a hairy vetch CGM crop, and soybean with termination of a rye CGM crop, in early organic no-tillage systems (Mirsky et al., 2012; Moyer, 2011). Grain yield of both maize and soybean sometimes exceeded regional averages in Pennsylvania, although there was considerable variation in no-tillage cash crop performance, particularly with maize (Mirsky et al., 2012). Mirsky et al. (2012) attributed better performance

TABLE 2 Crop sequence/rotations and cover/green manure crops included in several organic no-tillage studies in five important field-crop production regions in North America

Field crop-based system	Cover crop(s)	North American region	Study
Wheat–soybean–LCGM ^a +GCGM ^b –LCGM+GCG	Hairy vetch+oat	Cool Humid	Marshall and Lynch (2018)
Wheat–fallow/GCGM–soybean–LCGM+GCGM	Rye, hairy vetch+oat		
Wheat/LCGM+GCGM–maize/GCGM–soybean	Triticale+hairy vetch, rye	Humid Coastal	Wallace, Keene, Curran, Mirsky, and VanGessel (2018)
			Keene et al. (2017)
LCGM–maize	Oat (nurse crop)/hairy vetch	“	Mischler et al. (2010)
Maize–soybean–spelt/LCGM	Red clover	Warm Humid	Caldwell et al., 2014
LCGM–maize	Common vetch, hairy vetch, Austrian winter pea, crimson clover, berseem clover, Balansa clover (<i>T. michelianum</i> Savi), subterranean clover (<i>T. subterraneum</i> L.), lupin (<i>Lupinus</i> spp.)	“	Parr et al. (2011)
GCGM–maize	Rye		
LCGM+GCGM–maize	Hairy vetch+rye, pea+rye		
GCGM–soybean	Rye	“	Smith et al. (2011)
LCGM+GCGM–maize	Hairy vetch, rye	“	Vann et al. (2017)
LCGM+GCGM–sweetpotato	Hairy vetch+, rye	“	Treadwell et al. (2007, 2008)
LCGM–maize	Rye+hairy vetch, wheat+ winter pea	Humid Continental	Delate et al. (2012)
LCGM–soybean	Rye+hairy vetch, wheat+winter pea		
GCGM–soybean	Rye	“	Bernstein et al. (2011)
GCGM–soybean	Rye	“	Silva and Vereecke (2019)
LCGM–wheat	Hairy vetch, pea	Sub-humid Continental	Halde and Entz (2014)
GCGM–wheat	Barley (<i>Hordeum vulgare</i> L.)		
GCMG+LCGM–wheat	Barley+pea, barley+hairy vetch		
GCGM+BCGM ^c –wheat	Barley+radish (<i>Raphanus sativus</i> L.), barley+sunflower (<i>Helianthus annuus</i> L.)		
GCGM+LCGM+BCGM–wheat	Barley+pea+radish		
Safflower/LCGM–LCGM–wheat–lentil–wheat	Yellow-flowered sweetclover (<i>Melilotus officinalis</i> Lam.)	“	Lehnhoff et al. (2017)

^aGCGM, Grass cover green manure.

^bLCGM, Legume cover green manure.

^cBCGM, Nonlegume dicot cover green manure.

of no-till soybean to greater DM production and persistence of rye residue, earlier rye maturity enabling earlier soybean planting, soybean yield plasticity when crop stands were reduced, and the biological N₂-fixing ability of soybean (Mirsky et al., 2012).

Attempts to adopt a no-tillage vetch–maize crop sequence in organic field crop systems generally were not successful outside of the U.S. Northeast and Mid-Atlantic region. Extreme yield reductions in some years ($X_{\text{yield loss}} = 65\%$) occurred when maize followed hairy vetch in Iowa (Delate

et al., 2012). No-tillage organic maize yields in southwestern Ontario, Canada, were 33% lower than tilled maize yields (Beach et al., 2018). Maize failed to produce grain following a hairy vetch CGM crop in western North Dakota (Carr, Horsley, Gunderson, Winch, & Martin, 2013b). No-tillage maize yields even lagged behind tilled maize yield in the U.S. Northeast and Mid-Atlantic region in some studies (Mirsky et al., 2012).

Legume CGM crops failed to produce adequate amounts of vegetative mulch consistently to suppress weeds in some

environments (Carr, Brevik, Horsley, & Martin, 2015; Halde, Bamford, & Entz, 2015; Reberg-Horton et al., 2012; Silva, 2014), and did not consistently supply sufficient PAN for high grain yields (Carr et al., 2012a,b; Delate et al., 2012; Halde et al., 2015). Hairy vetch is capable of producing ≥ 5 Mg DM ha⁻¹ in eastern regions of the United States (Mirsky et al., 2012; Mirsky et al., 2017; Reberg-Horton et al., 2012), but DM production can be less, as already noted. Inconsistent and sometimes low DM production (<4 Mg ha⁻¹) by hairy vetch occurred in previous research (Carr et al., 2015; Silva, 2014). Dry matter production can be enhanced by intercropping hairy vetch with rye or triticale (*Triticosecale* Wittmack), though not in all environments (Parr et al., 2011). More PAN resulted as hairy vetch comprised a greater proportion of the CGM mixture, while DM production and subsequent weed control was improved as the small-grain crop contribution was increased (Poffenbarger, 2015a; Finney, White, & Kaye, 2016; Wallace et al., 2017).

Adoption of a no-tillage rye–soybean crop sequence was successful in regions outside of the U.S. Northeast and Mid-Atlantic region (Beach et al., 2018; Bernstein, Posner, Stoltenberg, & Hedtcke, 2011; Delate et al., 2012; Silva & Vereecke, 2019), but challenges remain. Organic no-tillage soybean yields were almost 25% lower than tilled soybeans in research conducted in Wisconsin (Bernstein et al., 2011), and almost 50% less in one of two years in Iowa (Delate et al., 2012). Ironically, soybean yield loss can result from competition by rye CGM plants not killed by roller-crimping (Bernstein et al., 2011; Mirsky et al., 2013). Termination of rolled-crimped CGMs can be effective but seldom reaches 100% (Mirsky, Mortensen, Ryan, & Shumway, 2009, 2013; Mischler, Duiker, Curran, & Wilson, 2010), resulting in surviving CGM plants competing with grain crops.

Large amounts of DM must be produced by a rye CGM to suppress weeds effectively in a no-tillage rye–soybean crop sequence (Mirsky et al., 2012; Reberg-Horton et al., 2012). However, small-grain crop residue can impede the establishment of subsequent crops because of poor seed–soil contact (Mirsky et al., 2013). Crop density reductions can depress grain yield, though plant density affects grain yield more severely in crops like maize than soybean, with the latter exhibiting greater yield plasticity to plant density differences (Pedersen & Lauer, 2002). Still, planting soybean through a thick small-grain mulch can result in crop density reductions so great that grain yield is reduced (Hovermale, Camper, & Alexander, 1979; Williams, Mortensen, & Doran, 2000). Improved planter configurations and higher soybean planting rates have reduced this problem (Wallace et al., 2017).

Deficiencies in PAN can exist in an organic, no-tillage rye–soybean crop sequence. This may be due to inefficiencies in nodule formation of soybean roots, attributed to fewer nodules forming in organic no-tillage plots because of cooler and wetter soils under the thick vegetative rye mulch (Silva &

Vereeke, 2019). Cooler temperatures in organic no-tillage systems, along with nutrient tie up and allelopathic effects of rye residue, may explain the slow, early season growth of no-tillage soybeans (Silva & Delate, 2017). This delay could reduce biological N₂-fixation efficiencies in soybean (Silva & Vereeke, 2019). Plant tissue analyses indicated N deficiencies in no-tillage compared with tilled soybean (Bernstein et al., 2011), supporting the hypothesis that the rye CGM interferes with biological N₂-fixation in soybean. However, this reduction in PAN may enhance the ability of soybean to compete with weeds (Wells, Reberg-Horton, Smith, & Grossman, 2013).

The use of poultry litter (PL) as a starter fertilizer to address potential limitations and delay in the release of CGM-derived N was considered in previous research (Vann et al., 2017). A rye + vetch mixture was roller-crimped and then two surface broadcasted rates of PL (72 and 160 kg ha⁻¹ PAN) were applied along with subsurface banding of PL at 12 kg ha⁻¹ PAN and feather meal (FM) at 80 kg ha⁻¹ PAN. Grain yield was highest when PL was broadcasted at the 160 kg ha⁻¹ PAN rate, while yield was comparable when PL was broadcasted at 72 kg ha⁻¹ PAN and FM was banded at 80 kg FM ha⁻¹ PAN.

3.3 | Regional differences in cover/Green manure use and effect on soil fertility in organic field crop systems

Organic CGM crops are grown for soil N benefits and weed suppression in the five important production regions in North America (Figure 1). The ability of CGMs to maintain or enhance soil N fertility on organic farms varies across those regions due to differences in cropping systems, climate, soils, and other factors. Therefore, each region is described briefly to provide context on why CGM functionality in maintaining soil N status is inconsistent, and why animal manure is used to maintain or enhance soil fertility status, when available.

3.3.1 | Cool humid North America – Eastern Canada

The Köppen climate designation for eastern Canada is Dfb with humid, mild to warm summers and snowy winters (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). For example, annual snowfall has exceeded 300 cm in Toronto (Bolsenga & Norton, 1992). Cool temperatures limit grain crop production during most of the year, though both maize and soybean are grown in the southeast (Halde et al., 2017). Southern soils are productive and support grain as well as forage production, while those in the north are shallow and stony (Carr et al., 2019).

Organic farms are numerous in eastern Canada, despite the limitations of its northerly latitude (Figure 1). In 2015, there

were 770 organic farms in Ontario, 1,220 organic farms in Quebec, and 146 organic farms in Atlantic Canada (COTA, 2017). Interest in organic potato (*Solanum tuberosum* L.) production has grown in the region, and this is reflected in the numerous studies completed recently. Results indicated that organic tuber yields were limited by N availability in many fields (Alam, Lynch, Sharifi, Burton, & Hammermeister, 2016; Boiteau, Goyer, Rees, & Zebarth, 2014; Lynch, Zheng, Zebarth, & Martin, 2008; Nelson, Lynch, & Boiteau, 2009; Sharifi, Lynch, Hammermeister, Burton, & Messiga, 2014). Potato is shallow rooted with relatively high N and water requirements (Waddell, Gupta, Moncrief, Rosen, & Steele, 1999).

Including legume CGMs in crop rotations can introduce much-needed N into the system, especially on farms without livestock (Schmidt, Philipps, Welsh, & Fragstein, 1999). Marketable potato yields resulted following the incorporation of CGMs as an N source in Canadian soils with low residual N (Lynch, Sharifi, Hammermeister, & Burton, 2012). Potentially mineralizable N was greater in soils using red clover as a CGM compared to a mixture of oat, pea, and hairy vetch in a 3-yr rotation in Nova Scotia (Sharifi et al., 2014). Still, PAN following CGMs may be deficient for maximizing organic potato yields in eastern Canada. Lynch et al. (2012) cautioned that the PAN available from soil amendments must be matched with potato crop needs, since excess N can be leached into groundwater.

Potato-based rotations can affect soil health in addition to PAN. Meso- and macro-fauna were more abundant and soil health improved on organic farms compared to conventional farms in a comparison of conventional and organic management at 21 sites in New Brunswick (Boiteau et al., 2014). Soil physical properties were similar under pasture, organic sites, and a potato field that had been abandoned for 20 yr. Conversely, many soil biological indicators (microbial biomass C, microbial quotient, earthworm abundance) were negatively affected by the intense soil tillage during the potato crop phase in a 5-yr organic potato–grain–forage–forage–forage rotation (Nelson et al., 2009). However, these indicators rebounded to levels comparable to an undisturbed reference pasture site in the 4 yr between successive potato crops.

Considerable effort has been made to develop organic, no-tillage field crop systems that rely on CGMs for soil fertility maintenance and weed suppression in eastern Canada (Beach et al., 2018; Halde et al., 2017; Marshall & Lynch, 2018). Significant obstacles must be overcome before there will be widespread adoption. One problem is communication between English and French speaking scientists and farmers working on organic no-tillage farming systems. Much of the research was conducted in Quebec, with results reported in French, making English readers unaware of this work. However, Halde et al. (2017) reduced this communication disconnection by summarizing findings in a recent paper.

3.3.2 | Humid coastal North America – the U.S. Northeast and Mid-Atlantic region

The Köppen climate designation is Dfa and Dfb for the U.S. Northeast and Mid-Atlantic region with humid, warm to hot summers and snowy winters (Kottek et al., 2006). The region includes all or parts of 12 states, including the District of Columbia (Figure 1). The high population in this region provides marketing opportunities for organic crops with distribution through retail stores, farmers markets, and restaurants (Tobin et al., 2015). Farms are small relative to other regions, averaging only 22 ha in Rhode Island to ~81 ha in Delaware and New York (USDA NASS, 2017b). Field crop systems differ substantially across the region, where dairy plays an important role in the northern agricultural landscapes and poultry is important in the south. Dairies are typically small and widely distributed, while poultry production is generally limited to confined animal feeding operations.

Perennial forages, including alfalfa and red clover, are grown extensively in many portions of this region, with the exceptions of Delaware and Maryland. Annual grain crops are widely grown in southern portions of the region, but also contributed between 12 and 17% of total agricultural sales in New Jersey, Pennsylvania, and New York in 2017 (all values calculated from USDA NASS, 2017b). Maize is grown for grain in southern portions of the region but predominantly for silage in the north. Soybean and winter wheat (*Triticum* spp.) are important grain crops, primarily in the south.

Cover/green manure crops are limited in northern portions of the region by a short growing season, but use in the South is relatively high, in part because of nutrient management regulations and subsidies. Between 2016 and 2017, CGMs were planted on over 200,000 ha in Maryland (Ward, 2018), which was over half of the area planted to maize and soybean (USDA NASS, 2017b). By comparison, the national average amount of land planted to CGM crops versus land base planted to maize and soybean was <1% in 2013 (Wallander, 2013). Farmers in Maryland were incentivized to grow CGM crops since the state paid 111–185 U.S. dollars (USD) ha⁻¹, depending on planting and termination dates, planting method, tillage system, and CGM crop species (MDA, 2018a).

Among annual legumes, hairy vetch is adapted to growing conditions in northern areas (Ketterings et al., 2015). Crimson clover (*T. incarnatum* L.) and Austrian winter peas [*P. sativum* subsp. *sativum* var. *arvense* (L.) Poir.] are well adapted to southern portions of the region (Clark, 2007). Previous research on facilitating early planting via interseeding showed that establishing legume CGM crops is more effective in soybean than maize, but the results are not consistent (Wallace et al., 2017). Some organic farmers are flying legume + grass mixes into a standing soybean crop to provide

N for a succeeding maize crop despite high seedling spatial variability.

Scientists and farmers in this region have been leaders in developing organic no-tillage methods (Mirsky et al., 2012; Moyer, 2011; Wallace et al., 2017). Greater success occurred when growing soybean than maize, for reasons discussed previously. Researchers and farmers have investigated replacing a hairy vetch monoculture with a hairy vetch + rye mixture to improve maize performance in organic no-tillage systems. However, the vetch + rye mixture poses challenges compared with a hairy vetch monoculture. The ratio of rye to hairy vetch plants in a mixture varies from year to year, even when planted at the same rate, resulting in differences in residue N release (Poffenbarger et al., 2015b). Rye generally produces a large amount of DM whether grown alone or in a mixture, sometimes making it difficult to achieve consistent seed-soil contact when maize is planted.

3.3.3 | Warm humid North America – the U.S. Southeast

The Köppen climate designation is Cfa for much of the U.S. Southeast (Figure 1), indicating a warm, humid climate with hot summers and mild winters (Kottek et al., 2006). Precipitation is somewhat evenly distributed throughout the year. For example, annual precipitation averages 1,225 mm in North Carolina, with differences <64 mm between any two monthly means (TSRCC, 2019). Most precipitation occurs as rain in all but the northernmost region or highest elevation areas, where snowfall totals around 50 cm annually (North Carolina Climate Office, 2019).

Organic cropping systems are highly diversified in the southeastern United States, in part because the climate favors fruit and vegetable rather than field crop production. Weed pressure during the wet, mild winters and hot summers, coupled with increased disease pressure, makes production of organic grains more difficult than in drier and cooler regions. As a result, less than 1% (849 ha) of the organic wheat, 2.6% (1,309 ha) of the organic soybean, and 1.1% (925 ha) of organic maize produced domestically was grown in the southeastern United States during 2016 (USDA NASS, 2017a). However, the U.S. Southeast is an important producer of sweetpotato (*Ipomoea batatas* L.), producing 34% (1,319 ha) of the domestic crop in 2016.

An overabundance of nutrients exists in the form of animal manure in the U.S. Southeast (Carr et al., 2019). For this reason, CGMs are not relied on as heavily for maintaining soil fertility as in regions where animal manure is less available. Still, CGM crops are an integral part of most field-crop systems. A challenge in the U.S. Southeast is synchronizing N

release by CGM crops with subsequent demand by grain and other field crops in a rotation (Reberg-Horton et al., 2012), as it is elsewhere. Failure of CGM crops to supply adequate vegetative cover for erosion and weed control is a problem, particularly when legumes are grown (Reberg-Horton et al., 2012). Adequate vegetative mulch can be produced when legumes are grown with rye, but total N is likely less, and timing and rate of N release slowed, because of the larger C/N ratios of the mixtures.

Crimson clover and hairy vetch produced 5,500 and 4,900 kg DM ha⁻¹ in North Carolina, which amounts to 120 and 150 kg N ha⁻¹, when grown to maximize DM (Parr et al., 2011). Rolling, mowing, and/or incorporation must be delayed until late spring (late April to mid-May) to reach these production levels which, in turn, can delay planting the cash crop (Mischler et al., 2010; Parr et al., 2011; Reberg-Horton et al., 2012). Roller-crimping a CGM can improve weed management, but N release may be delayed (Reberg-Horton et al., 2012). Thus, if grown primarily for supplying N, CGM crops should be incorporated into the soil or mowed to increase surface area of the residue, thereby hastening the biological release of N (Reberg-Horton et al., 2012).

The impact of rolling a rye + vetch mixture was compared to conventional tillage prior to applying PL on a subsequent sweetpotato crop in Florida in 2001, 2002, and 2004 (Treadwell, Creamer, Hoyt, & Schultheis, 2008). Yields tended to be lower in the rolled plots. Differences were greatest in 2002, when sweetpotato averaged only 4.9 Mg ha⁻¹ in rolled plots compared to 16.7 to 21.8 Mg ha⁻¹ in tilled plots. Yield reductions were attributed to slower growing plants and greater weed pressure (Treadwell, Creamer, Schultheis, & Hoyt, 2007; Treadwell, Creamer, Hoyt, & Schultheis, 2008). Interestingly, the authors found no differences in total yields between plots where CGMs were incorporated and compost was applied, and in tilled plots that did not receive a compost application.

Aboveground DM production of species or mixtures was variable in many CGM studies in the southeastern United States (Parr et al., 2011; Reberg-Horton et al., 2012; Treadwell et al., 2007, 2008; Vann et al., 2017). Endemic fluctuations in weather variables help explain this variation. Cook, Gallagher, Kaye, Lynch, and Bradley (2010) found a strong positive correlation ($r^2 = .82$) between the number of growing degree days and hairy vetch DM production. Better models are needed to account for the nuances in regional weather-pattern effects on CGM DM production. Germplasm improvements are needed so CGM species and mixtures are better suited to the cropping systems that are emerging. Breeding efforts are underway to develop early maturing legume CGMs that produce large amounts of biomass without impeding the timely planting of field crops (FFAR, 2017).

3.3.4 | Humid continental North America – the U.S. Midwest

The Köppen climate designation is Dfa and Dfb in north and central portions of the U.S. Midwest (Figure 1), with humid, warm to hot summers and snowy winters (Kottek et al., 2006). In the south, the Köppen climate designation is Cfa, indicating hot and humid summers with mild winters having limited, if any, snow (Kottek et al., 2006). The greatest concentration of organic maize and soybean farms in the United States occurs in the Midwest, along with a high proportion of domestic organic dairies (USDA NASS, 2017a). There were 64,000 ha of maize and 41,000 ha of soybean grown organically in the region during 2016, along with 1,400 organic dairies (USDA NASS, 2017a). Inherently high soil fertility and sufficient rainfall support expansive production of organic grain crops, although growing season rainfall has trended below 30-yr averages in recent years (USDA MCH, 2019). Concern that climate change may reduce yields and long-term sustainability has generated a search for strategies to mitigate the deleterious effects of a changing climate on organic grain production. These include enhancing C storage in soils with perennial crops, CGMs, and composted manure, all of which are common on Midwestern organic farms (Delate et al., 2015).

Cover/green manure crops serve an important role in nutrient management on organic grain farms in the U.S. Midwest, despite the relative availability of animal manure. However, cold winter temperatures and short intervals for plant growth can limit the amount of N derived from CGMs, particularly in areas at northern latitudes. Innovative strategies have improved the integration of N management functionality of CGMs into organic grain production systems (Silva & Moore, 2017). Recent success in planting soybean directly into a rye CGM crop at the boot growth stage (Zadoks GS 45), along with rye termination when flowering ended (Zadoks GS 69), enabled earlier establishment of soybean (Silva & Vereecke, 2019). Interest continues in organic no-tillage systems because of anticipated soil-quality improvements (Mäder & Berner, 2012; Peigne' et al., 2007; Sainju, Singh, & Yaffa, 2002). An emerging concern is increased perennial weed populations under organic no-tillage (Carr et al., 2013a; Mäder & Berner, 2012; Mirsky et al., 2012), leading to the recommendation for strategic tillage (Silva & Delate, 2017).

3.3.5 | Sub-humid Continental North America – the great plains and intermountain West region

The Köppen climate designation for the Great Plains is BSh, while Dsa, Dsb, Csa, and BWk are Köppen climate designa-

tions for intermountain portions of the region (Kottek et al., 2006). The Great Plains are semi-arid with hot summers and cold winters. Intermountain areas of the region can range from cold desert (BWk) to having a warm-summer Mediterranean climate (DSa), depending on the area. Wheat is the most widely grown, organic grain crop in the region. This cereal is better adapted to cool and dry conditions than many other grain crops (e.g., maize). Furthermore, most of the organic wheat is grown without irrigation. Dryland wheat can have superior bread-making qualities compared to wheat grown under irrigation or in wetter regions because of the negative relationship between grain yield and protein concentration (Fowler, 2003; Fowler, Bryden, Darroch, Entz, & Johnston, 1990). This is a result of the N-dilution effect that high yield has on protein (Entz & Fowler, 1989; Fowler et al., 1990). Irrigation can also increase the risk of diseases or weed pressure.

Dryland farmers face several challenges when growing wheat and other field crops because of the low and erratic precipitation patterns that occur, limiting yields and increasing within-field and year-to-year yield variability (Dregne, 1976; Stuckenholtz, Koenig, Hole, & Miller, 2002; Schillinger, Papendick, Guy, Rasmussen, & van Kessel, 2003). Many soils, in turn, are relatively low in SOC, have high soil pH, and may contain high concentrations of calcium carbonate (Dregne, 1976; Schillinger et al., 2003). High concentrations of calcium carbonate can reduce the plant availability of P and several micronutrients (Dregne, 1976; von Wandruszka, 2006). Salinity and sodicity have been long-standing problems and are increasing in the region (Birru et al., 2019). Salinity and sodicity can cause soil crusting, poor water infiltration, very low yields, and high erosion rates (Dregne, 1976), and cropping should be avoided when the exchangeable sodium percentage exceeds 5 (He, DeSutter, & Clay, 2013, 2015, 2018). Many organic farms are extensive and located in remote, low rainfall areas where access to organically allowable and affordable inputs is limited (Carr et al., 2012b; Reeve, Endelman, Miller, & Hole, 2012; USDA NASS 2017b).

Yields of winter wheat on dryland organic farms can be as low as 0.2 Mg ha⁻¹ in some years due to the lack and unpredictability of adequate precipitation (Reeve et al., 2012). This perilous circumstance for dryland wheat farmers led to the development and widespread adoption of summer fallow, where cropland is idled from 14 to 21 mo to replenish plant available water and nutrients, while reducing weed populations (Hansen, Allen, Baumhardt, & Lyon, 2012; Schillinger et al., 2003). This practice continues on many organic farms in the region, even though wind and water erosion can be severe (Schillinger et al., 2003; Carr et al., 2012b, 2015; Norton, E.J., & Norton, 2012).

Previous research has documented soil N benefits when CGM crops are incorporated into dryland wheat-based cropping systems in the region (Borrelli et al., 2014; Peterson

& Westfall, 2004; Unger & Vigil, 1998), but organic wheat farmers can be hesitant to grow CGM crops because of the risk if termination timing is miscalculated. Failure to terminate CGM crops early enough can lead to soil water deficits that result in subsequent wheat yield depression (Allen, Pikul, Waddell, & Cochran, 2011; Biederbeck & Bouman, 1994; Lyon & Hergert, 2014). In practice, predicting when to terminate CGM crops in water limited environments is complicated by a highly variable climate. As a result, lack of N generally limits optimum production of wheat and other grain crops on organic farms (Miller et al., 2011).

Successful incorporation of N₂-fixing CGM crops into dryland field-crop systems has occurred when the timing of crop termination was managed effectively. Wheat grain yields were 13% greater following early (50% bloom) vs. late (50% of plants had one full-length pod) termination of a pea CGM (Miller et al., 2011). The grain yield increase was attributed to enhanced soil-water conservation and PAN. Early termination provided additional time for pea residue to decompose and resulted in a lower C/N ratio. Regardless of termination timing, grain protein concentration of the subsequent wheat crop was only 87–101 g kg⁻¹, indicating a lack of available N for optimum wheat production (Engel, Long, & Carlson, 2006).

Soil nitrate was 34% less at wheat planting following lentil (*Lens esculenta* Moench.) and pea CGMs than summer fallow across five locations in Montana (O'Dea, Miller, & Jones, 2013). However, PMN was greater following the leguminous green manures at most locations. Similarly, available soil nitrate was 41% less in a transitioning-to-organic cropping system (82 kg N ha⁻¹) than in four conventional no-tillage systems (140 kg N ha⁻¹) after 4 yr, while PMN was elevated in the organic system (97 vs. 79 kg ha⁻¹; Miller, Buschena, Jones, & Holmes, 2008). Interestingly, wheat grain and grain-N yield were equal or greater in the organic than the conventional no-tillage systems, suggesting that standard soil tests may not be a good indicator of plant nutrient availability in dryland organic systems.

Research on incorporating CGM crops into organic dryland grain systems is ongoing in the drier portions of the Intermountain West. Preliminary results indicated that yield reductions as high as 50% can occur when summer fallow was replaced by a CGM in Utah (unpublished data). Recent work showed that CGMs in Kansas could replace summer fallow successfully where grain yield potential exceeded 3.5 Mg ha⁻¹ (Holman et al., 2018). This is considerably higher than yields typically achieved by farmers in semi-arid and arid regions (Reeve et al., 2012).

Open debate exists about the suitability of organic no-tillage in the North American Great Plains and Intermountain West region (Figure 1). Attempts to develop organic no-tillage systems have been mixed, at best. Seed yield of flax (*Linum usitatissimum* L.) was greater when planted directly (i.e., no-

tillage planted) into the killed vegetative mulch of a barley (*Hordeum vulgare* L.) + hairy vetch CGM grown the previous year than following a tilled-CGM crop mulch at two of three locations in Manitoba, CA (Halde & Entz, 2014). However, organic grain yield of wheat was sometimes lower following an oat + field pea CGM crop in no-tillage than tilled plots in a separate study (Vaisman et al., 2011). Buckwheat (*Fagopyrum esculentum* Moench) and dry bean (*Phaseolus* spp.) crop yields were consistently lower when seeded directly into CGM mulch than following tilled CGMs in western North Dakota (Carr et al., 2013b). Efforts have been unsuccessful to eliminate tillage beyond a few years when growing crops organically (Carr et al., 2016; Halde et al., 2015).

Tillage will continue to be widely used by organic farmers in the Great Plains and Intermountain West region in the near-term. This suggests limited opportunities for organic farmers to increase soil organic matter (SOM) levels, unless animal manure or some other C-containing material is used. Leguminous CGM crops will continue to be relied upon to supplement soil N fertility but amounts of biologically fixed N₂ will likely be insufficient to meet the N needs of cash crops in dryland crop rotations.

3.3.6 | Summary of cover/Green manure impacts on soil fertility in organic field crop systems

Cover/green manure crops are an integral component of organic field crop systems in five important production regions in North America. They are relied on heavily to maintain soil N fertility when grown in sequences with cash grain crops. Interest in organic no-tillage systems places great value on the vegetative mulch produced by CGM crops as a growth-suppressive, physical barrier to weeds during targeted cash crop phases in rotations.

Legumes are preferred to nonlegume species when CGMs are grown to enhance PAN due to their biological N₂-fixing abilities and the relatively low C/N ratio of residue. Large amount of PAN may be available to cash crops following legume CGMs in humid environments, although cropping system constraints (e.g., early termination of CGMs) and other factors may limit the supply. The inability of CGMs to supply sufficient PAN to meet cash crop needs can be exacerbated in organic no-tillage systems, since legume species generally fail to produce enough vegetative mulch to suppress weeds, forcing nonleguminous CGM species to be grown. This latter group includes rye and other small-grain crops which can produce large amounts of DM with high C/N ratios, resulting in N immobilization for several weeks following termination.

Research is needed to better understand the effects that CGMs have on the cycling of N in organic field crop

systems, as well as other nutrients. Work is also needed to determine how the soil microbial community can be manipulated to enhance the ability of CGMs to meet the PAN needs of cash crops, and how CGMs can be used to improve access to P and other macro- and micro-nutrients. This additional insight should enhance the use of CGMs in supplying N and other plant nutrients to field crops in diverse rotations, even though additional supplementation may be needed in some environments. The remainder of this paper will focus on the use of animals, and particularly animal manure, to maintain soil fertility in organic field crop systems.

4 | ANIMAL INTEGRATION INTO ORGANIC FIELD CROP SYSTEMS

The value of integrating animal and field crop systems is documented in previous reviews (Franzluebbers, 2007; Krall & Schuman, 1996; Russelle, Entz, & Franzluebbers, 2007; Entz & Martens, 2009; Kumar et al., 2019). In part, the benefits result from incorporating forages into grain- and seed-based cropping systems (Clark, 2009; Entz, Bullied, & Katepa-Mupondwa, 1995, 2002). Nevertheless, organic farms tend to be either annual crop or animal operations in North America (Entz & Martens, 2009). For example, less than 25% of organic dairies grew the grains and forages needed to meet their dairy herd needs in a survey of farmers in the U.S. Northeast and Mid-Atlantic region (Pereira, Brito, Townson, & Townson, 2013). A similar lack of crop–livestock integration was reported on organic farms in the North American Great Plains (Entz & Martens, 2009).

Integrated crop–livestock systems have advantages over cropping systems that exclude animals. Incorporating animals into field crop systems has the potential to maintain or enhance soil fertility, as long as stocking density is optimized (Entz & Martens, 2009). Soil N and organic C were increased, and leachable N decreased, when integrated crop–animal systems were compared to cropping systems that excluded livestock in several studies reviewed by Kumar et al. (2019). Fewer weed problems occurred in crop rotations that included forages (Entz et al., 1995, 2002; Miller, Menalled, Sainju, Lenssen, & Hatfield, 2015). Field crop yield and overall system economics were improved by incorporating animal grazing into cropping schemes (Kumar et al., 2019).

Grazing can aid in the cycling of N and other nutrients through ruminant consumption of forage crops and their urine and manure excretions. Hay production and harvest removes soil nutrients and is “nutritive exhaustive” (Entz et al., 2002; Sigua, Williams, & Coleman, 2007), while soil nutrients can be balanced with succeeding crop needs when forages are grazed strategically (Unkovich, Sanford, Pate, & Hyder, 1998). Recent research showed an increase in β -glucosidase under organic rotationally grazed vs. nongrazed forage pad-

docks (Delate et al., 2018). β -glucosidase is an important soil enzyme implicated in SOM decomposition and increases in soil fertility (Delate et al., 2018). Increased dehydrogenase activities and microbial populations–biomass concentrations resulted from manure deposition in organic systems (Fraser, Doran, Sahs, & Lesoing, 1988).

Integrating forages and animals does not guarantee that soil fertility status will be enhanced on all organic farms. An assessment of the fertility status of soils on organic dairy farms in the U.S. Northeast and Mid-Atlantic region indicated that 80% of fields representing over 1,200 ha were deficient in P and K (Darby, 2017). In addition, most surveyed pastures did not have legume concentrations that were sufficient to meet the N needs of the growing plants. Forty-six percent of the fields had a soil pH < 6.0, which is considered below optimum for legume production. It is not surprising that pastures were dominated by grasses, given the low soil pH, P, and K levels. Nitrogen recommendations to meet the nutrient needs of the grass forages were high, ranging from 112 to 224 kg ha⁻¹ (Beegle, 2018). These results showed that integrated nutrient management in organic systems can have an enormous impact on the N balance and resulting crop quality.

4.1 | Use of animal manure to supplement soil fertility on organic farms

A more common practice than placing animals directly on the cropping system landscape is applying animal manure onto fields when growing organic grain and seed crops. A long-term study that compared manure-supplemented, CGM-based organic, grain-farming systems and fertilizer-supplemented, conventional grain-farming systems showed that organic grain yields were competitive with conventional grain yields (Liebhardt et al., 1989; Lotter, Seidel, & Liebhardt, 2003; Pimentel, Hepperly, Hanson, Douds, & Seidel, 2005). Grain yields were greater in the organic manure-based system than the CGM-based organic system (relying on hairy vetch as the primary N source), as was soil C (981 vs 574 kg ha⁻¹; Pimentel et al., 2005). Both organic systems retained more soil C than the conventional system (293 kg ha⁻¹).

The long-term USDA-ARS Farming Systems Project (FSP) in Beltsville, MD provides a unique perspective on short- vs. long-term effects of nutrient management in manure-based organic cropping systems. The FSP compares three organic systems with two conventional cash-grain operations. A conservative approach to using animal manures (mostly PL) during the early years of the FSP resulted in N limitations that reduced yields (Cavigelli, Teasdale, & Conklin, 2008). A more consistent, albeit still conservative, use of PL (approximately 2 Mg ha⁻¹ for high N-demanding maize and wheat crops) created soils with substantial N-supplying power, resulting in organic maize yields of about 10 Mg ha⁻¹

in micro-plots to which no exogenous form of N was applied (Spargo, Cavigelli, Mirsky, Maul, & Meisinger, 2011). Soils with a history of manure applications in Maryland often have substantial N reserves; maize grain yields of 7.4–8.7 Mg ha⁻¹ on silt loam soils (Spargo, Cavigelli, Mirsky, Meisinger, & Ackroyd, 2016), and 7.6–12.9 Mg ha⁻¹ on silt and sandy loam soils, occurred on an irrigated organic farm when no other N source was applied (Ackroyd et al., 2019).

Crop rotation length and diversity affected long-term P balance (P inputs minus harvested P outputs) in manure-based, organic cropping systems in the FSP. The P balance was only 0.2 kg P ha⁻¹ yr⁻¹ for a 6-yr diverse rotation that included grain, CGM, and forage crops compared with 12 kg P ha⁻¹ yr⁻¹ and 18 kg P ha⁻¹ yr⁻¹ for 2- and 3-yr rotations that included only grain and CGM crops (White & Cavigelli, 2019). In all three rotations, PL-supplemented legume CGM crops produced sufficient N for maize, while PL was the sole N input for wheat. Similarly, maize and soybean yields were comparable, and SOC and PMN were greater relative to nitrate-N, in a diverse organic cropping system that included forages and animal manure applications to those in a conventional cropping system in Iowa (Delate & Cambardella, 2004; Delate et al., 2015).

Results from the FSP and the study in Iowa suggest that diverse rotations which include forages and animal manure applications store and cycle nutrients more efficiently than fertilizer-based, conventional systems. Marriott and Wander (2006) verified these findings and reported that organic systems had higher SOC and total N concentrations, with 30–40% greater particulate organic matter C and N than conventional systems. Likewise, C stocks, aggregate-associated C, and concentrations of particulate organic matter C fractions were all greater in an organic grain system that relied on cattle manure and alfalfa inputs than in a fertilizer-based, conventional system, particularly in the upper 15-cm soil layer (Blanco-Canqui, Francis, & Galusha, 2017).

Crop N demands are not always met with green or animal manure additions. In those cases, alternative N sources should be considered. Organic farmers have explored other cost-effective fertility sources such as those produced from soybean, peanut (*Arachis hypogaea* L.), and canola (*Brassica* spp.) meals that have higher N (50–80 g kg⁻¹) than P (10–30 g kg⁻¹) concentrations (Darby, 2017). These options helped farmers meet the N requirements of cash grain crops without over applying P. Over 50% of the total N content (80 g kg⁻¹ N) of soybean meal was mineralized within 70 d of application in incubation studies (Darby, 2009). Canola, along with soybean meal, released a significant portion of N within 30 d when both were applied along with sunflower (*Helianthus annuus* L.) meal and Chilean nitrate in field-based studies (Darby et al., 2014). Sweet corn (maize) yields were comparable when canola meal, soybean meal, and Chilean nitrate were applied. These results indicate that

oilseed meals can be viable N sources. Since there are many factors influencing N release from legume CGM crops and animal manures, efforts to improve N-use efficiency from these organic sources will likely benefit from modern GPS-guided tractors and applicators that are designed to provide field-by-field, fine-tuned N and P soil fertility management (Morris et al., 2018), and from models that are custom designed (Melkonian, Poffenbarger, Mirsky, Ryan, & Moebius-Clune, 2017; White et al., 2017, 2018).

Annual legume CGMs can provide most, if not all, of the PAN needed when followed by maize in warm, humid regions (Spargo et al., 2016). Animal manures combined with legume-based CGM crops can be used to meet crop demand when CGM-derived N is insufficient, and can balance crop N and P inputs and outputs in organic systems (Buckland et al., 2018; Olsen et al., 2015; Spargo et al., 2016). Poultry litter applied at crop P removal rates and supplemented with CGM-derived N met maize crop needs in Maryland (Ackroyd et al., 2019). Animal manures may need to be applied at greater rates at more northern latitudes since legumes accumulate biomass (and therefore N) more slowly in cooler climates (Mirsky et al., 2017). However, maize grain yields were similar when following red clover and following red clover plus 2 Mg ha⁻¹ PL compost over 6 yr in New York, including 2 yr when maize grain yields were >10 Mg ha⁻¹ (Caldwell et al., 2014).

Excess applications of manure can result in the runoff and leaching of N and other nutrients, thus leading to surface and groundwater pollution. Applications of animal manure and other fertilizer sources containing N and/or P contributed to the eutrophication of Chesapeake Bay waters (Boesch, Brinsfield, & Magnien, 2001; Stout, Weaver, Folmar, & Schnabel, 2000). Animal manure applications can be an important source of excess P when based on crop N requirements, since animal manures generally contain low amounts of N relative to P for meeting crop needs (Toth, Dou, Ferguson, Galligan, & Ramberg, 2006). Adjusting application rates so manure provides sufficient P reduced the risk of P runoff from fields (Toth et al., 2006). However, this also increases the likelihood that crop N needs are not met, increasing the reliance on CGMs to supply the additional N for cash crops that follow.

Weed growth can be stimulated over crop growth by heavy application of plant nutrients (Little, Mohler, Ketterings, & DiTommaso, 2015). Researchers found that maize grain yields in an organic maize–soybean–spelt (*Triticum spelta* L.) + red clover rotation were similar over 4 yr in high- and low-fertility systems, but the application of composted poultry manure in the high fertility system resulted in greater weed biomass (Caldwell et al., 2014). Animal manures can affect weeds directly since animal manures are a known source of weed introductions on farms (Mt. Pleasant & Schlather, 1994 as cited by Gallandt, Liebman, & Huggins, 1999). Caldwell

et al. (2014) suggested that animal manure and compost applications should be targeted at the spelt crop phase of the rotation, since spelt yields increased by 76% following application of composted poultry manure in 2 of 4 yr. However, they noted that the optimal timing of the nutrient inputs requires further research.

Improvements in soil health conferred by compost and animal manure applications may improve a crop's ability to compete with weeds. Weed biomass was 75% lower under an animal manure and compost amended, organic soil fertility system than a conventional fertilizer-based system in a potato-based rotation (Gallandt, Liebman, Corson, Porter, & Ullrich, 1998). Potato leaf area and yield in the organic amended treatment were equal to, or greater than, those in the nonamended treatment, and in 1 of 2 yr, yield loss due to weeds was 12% in the amended and 37% in the nonamended treatment. Similarly, studies with maize (Dyck & Liebman, 1994) and dry bean (Liebman & Gallandt, 2002) demonstrated that weed biomass was reduced and crop yields were improved by an incorporated CGM crop. Gallandt et al. (1999) posited that the effects observed in these and other CGM crop studies may be due to differences between large-seeded crops and small-seeded weeds in their susceptibility to the allelopathic effects of CGM crop residues.

4.2 | Regional differences in animal manure use and effect on soil fertility management in organic field crops

Greater disparity exists in the use of animal manure than CGMs on organic farms in five North American production regions (Figure 1). This difference is explained largely by the availability of animal manure across regions, although other factors, such as the ability of CGMs to meet crop N needs, affect animal manure use. As a result, the use of animal manure applications to supplement soil fertility in organic field crop systems in each region is discussed, followed by summary comments.

4.2.1 | Cool humid North America – Eastern Canada

Dairy operations are common in eastern Canada, yet few studies have focused on integrating animals into potato and other field crop systems. Swine waste–sawdust compost was compared to pelletized PL as an N source when growing potato over 2 yr in Prince Edward Island and Nova Scotia (Lynch et al., 2008). Both organic amendments were applied at rates of 300 and 600 kg total N ha⁻¹. The compost elicited a yield response in only one year, while the PL improved yields at both the 300 and 600 kg total N ha⁻¹ rates. However, the heav-

ier PL application rate left a large amount of residual inorganic N (61 kg N ha⁻¹) in the field after harvest.

Eutrophication of lakes and rivers due to N-enrichment is a growing concern in Eastern Canada (Rasouli, Whalen, & Madramootoo, 2014). Much of this N can be traced to agriculture and, in turn, animal enterprises and the manure that is produced (Janzen et al., 2003). Nitrogen provided in excess of crop needs is susceptible to leaching and runoff, where it can reduce water quality. Various strategies have been proposed to limit animal manure applications, including the planting of catch crops after harvest (Rasouli et al., 2014; Thapa, Mirsky, & Tully, 2018).

Combining CGMs with pelletized PL improved organic wheat yields compared to only using CGMs in Nova Scotia and Quebec (Alam, Lynch, Tremblay, Gillis-Madden, & Vanasse, 2018). In that study, more consistent yield improvements occurred following an oat + hairy vetch mixture than red clover, red clover + oat and oat CGM crops. An application of 80 kg N ha⁻¹ of pelletized PL could be substituted for the legume CGM crop without a change in wheat yield (Alam et al., 2018). Supplementing red clover and hairy vetch CGMs with municipal solid-food waste composts consistently increased potato yield in a 3-yr study conducted in Nova Scotia (Lynch et al., 2012).

4.2.2 | Humid Coastal North America – the U.S. Northeast and Mid-Atlantic region

Agricultural nutrient management in the U.S. Northeast and Mid-Atlantic region is regulated, largely due to declining water quality in many estuaries, including the Chesapeake Bay (Tobin et al., 2015). The Chesapeake Bay watershed encompasses a large portion of six states and the District of Columbia (Tobin et al., 2015). Regulations and subsidy programs are targeted at reducing N, P, and sediment losses from agriculture. These regulations can affect nutrient management on organic farms. For example, the amount of PL that can be applied in the fall is limited in Maryland, which could reduce winter wheat yields on organic farms (MDA, 2017). At the same time, state-level water quality statutes include unique programs that can benefit organic farmers, such as CGM crop and animal manure-transport allowances, both of which are subsidized in Maryland (MDA, 2018b).

Perennial legume and grass species are the primary components of organic dairy rations and can contribute agronomic and environmental benefits when incorporated into rotations in the region (Cavigelli, Teasdale, & Spargo, 2013) and elsewhere (Entz et al., 1995, 2002). Nitrogen management has been documented as a major challenge associated with growing high-yielding organic crops, including perennial forages (Cormack, Shepherd, & Wilson, 2003). Adding legumes to grass stands increases feed protein concentrations and

biologically fixes N_2 in the soil, so it may be possible to obtain sufficient N from legume forages to meet the requirements of associated grass crops, but minimal data exist to support this common claim on organic farms in the region.

Compost is used widely in organic vegetable production in this and other regions (Gaskell & Smith, 2007), but is considered too expensive for grain crop production. However, organic grain farmers reportedly used compost at a rate of 2 Mg ha^{-1} in conjunction with a red clover CGM crop in central New York (Caldwell et al., 2014). The N/P ratio of compost usually is less favorable than that of raw manure relative to crop N and P needs (Heckman et al., 2003; Preusch, Adler, Sikora, & Tworowski, 2002). For this reason, raw animal manures generally are the best option for supplementing N from legume CGM crops. Other sources of N, such as blood meal, FM, grain meals, and Chilean nitrate, are approved for use in organic systems (Grubinger, 2011), but most have not been assessed extensively for use in grain cropping systems within the region.

The agronomic and economic value of pelletized PL, FM, and PL+ FM in concert with a hairy vetch CGM was assessed in a 2-yr study conducted in Maryland (Spargo et al., 2016). Maize N uptake and grain yield were similar for all products when applied at the same time as hairy vetch termination. The researchers concluded that raw PL was the best choice to supplement the N supplied by hairy vetch since cost per unit of N was substantially less (2.67 USD kg^{-1} of N) than for the other products (7.39 , 13.60 , and $21.80 \text{ USD kg}^{-1}$ of N for FM, pelletized PL, and PL + FM, respectively; Spargo et al., 2016). However, in a situation where regulations restrict the application of PL, or where manures are not readily available, FM may serve as an acceptable source of PAN.

Some unique challenges of relying on local animal manure for organic grain production in the U.S. Northeast and Mid-Atlantic region are illustrated by a niche market that is developing in northern New England. Increasing demand for locally grown, organic bread wheat has prompted soil fertility research in the region. Dairy dominates in northern areas, but poultry manure and PL tended to produce greater increases in yield when compared to dairy manure, which had considerably lower inorganic N concentration (Englander, 2014). However, pre-plant N sources rarely produced wheat with a protein content that was sufficient for high quality breads (Englander, 2014; Mallory & Darby, 2013; Roche, Mallory, & Darby, 2017). As a result, many organic grain farmers include an in-season application of N to produce the grain protein levels required for the bread flour market. Typical N sources for topdressing include dehydrated animal manures, FM, plant meals, and Chilean nitrate. Mallory and Darby (2013) found that spring-applied topdress N increased grain protein up to 20 g kg^{-1} . Applying N at the wheat boot stage (Zadoks GS 41–49) produced a greater increase in grain protein than when applied at tillering (Zadoks GS 20–29) and flag

leaf (Zadoks GS 37) stages, and Chilean nitrate was almost twice as effective at raising grain protein level as dehydrated chicken manure.

4.2.3 | Warm humid North America – the U.S. Southeast

Animal manure is abundant in the U.S. Southeast (Carr et al., 2019), where it is used as the sole nutrient source when growing crops organically. However, the use of manure as the primary source of N, can increase soil P levels that could adversely affect the environment. Much of the land in the southeastern United States has high amounts of residual P (legacy P) from centuries of row cropping. For example, over 48% of the soil samples collected across North Carolina contained between 60 and 120 mg dm^{-3} P (Cahill, Johnson, Osmond, & Hardy, 2008). The potential for P leachate or runoff entering groundwater or sensitive estuaries is high at these levels (Endale, Cabrera, Steiner, Radcliffe, & Vencill, 2002). With an abundance of legacy P, using a CGM crop as the primary supplier of N can be an attractive alternative to P-rich, manure-derived products.

Sweetpotato thrives in the subtropical summers and coarse-textured soils within this region. This crop requires $56\text{--}67 \text{ kg N ha}^{-1}$ for optimum production in the southeastern United States, and it is sensitive to over- and under-application, as well as excess N late in the growing season (Phillips, Warren, & Mullins, 2005). Traditionally, fertilizer applications 2–4 wk after transplanting meet N needs (Phillips et al., 2005; Treadwell et al., 2008). Differences in N requirements exist among commercial sweetpotato cultivars (Phillips et al., 2005). Treadwell et al. (2008) investigated the effects of CGM crops and composted PL applied at a rate of 20 Mg ha^{-1} ($47\text{--}49 \text{ kg ha}^{-1}$ of PAN) as N sources for ‘Beauregard’ sweetpotato in North Carolina. Total yields from the PL treatments did not differ from those receiving the synthetic fertilizer control of $48 \text{ kg NH}_4\text{NO}_3 \text{ ha}^{-1}$ of PAN. The results indicated that any potential delayed or continual N mineralization of composted PL did not affect yields negatively, and that organically grown sweetpotato can produce yields that are comparable with conventionally grown sweetpotato.

Subsurface versus broadcast applications of various rates of PL were compared in cotton (*Gossypium hirsutum* L.) over 3 yr in Mississippi (Tewolde, Armstrong, Way, Rowe, & Sistani, 2009). Broadcasting 6.7 Mg ha^{-1} of PL resulted in lower lint yields (984 kg ha^{-1}) compared to applying the same amount in a subsurface strip ($1,053 \text{ kg ha}^{-1}$ lint yields). The subsurface treatments had greater leaf chlorophyll indices than broadcast treatments. The researchers suggested that these results were due to minimizing the N volatilized through subsurface applications, thereby conserving PL nutrients for plant use.

4.2.4 | Humid Continental – the U.S. Midwest

Animal production is extensive in the U.S. Midwest (USDA NASS, 2017b), and animal manure is an important nutrient source for organic grain crops. In addition, forage crops are widely grown to provide feed for livestock and for hay markets (Chase, Topolff, & Delate, 2016). Alfalfa, red clover, and other perennial forages are the main soil-building components of organic crop rotations (USDA AMS NOP, 2019), with longer rotations (up to 9 yr) leading to improved weed management, which is considered one of the more challenging issues on midwestern organic farms (Anderson, 2010). According to Wortman, Galusha, Mason, and Francis (2011), the addition of a perennial forage, such as alfalfa, in crop rotations was found to mitigate soil C loss from tillage practices in organic field crop systems.

No reports of animal manure over-application have occurred on Midwestern organic grain farms, but nutrient leaching and run-off remain concerns. Experiments confirmed greater soil nitrate-N concentrations in a fertilizer-based, conventional maize–soybean rotation than an organic maize–soybean–oat + alfalfa–alfalfa rotation in Iowa (Delate & Cambardella, 2004). Trends in soil nitrate-N and P levels between organic and conventional farms in Nebraska were inconsistent (Liebig & Doran, 1999), indicating that off-site effects from nutrient loss should be closely monitored. Cambardella, Delate, and Jaynes (2015) reported 50% greater N losses under a conventional maize–soybean rotation than the organic maize–soybean–oat + alfalfa–alfalfa rotation supplied with approximately 170 kg N ha⁻¹ from manure.

4.2.5 | Sub-humid Continental North America – the great plains and intermountain West region

Animal production is extensive across the Great Plains and Intermountain West region, particularly beef cattle (*Bos taurus*) and sheep (*Ovis aries*). However, most organic farms tend to be stockless in the region (Entz & Martens, 2009), with forages underrepresented among the field crops grown (Entz, Guilford, & Gulden, 2001). Obstacles such as low carrying capacity, limited fencing and watering ponds (stock), lack of animal managerial skills, and certification limitations must be overcome before there is wide-scale adoption of integrated animal–crop organic systems. In addition, local markets for organic beef and other animal products generally are lacking, as are local processing facilities.

Despite these and other challenges, integrating crop and animal enterprises is the best strategy for long-term soil fertility maintenance and improvement on organic farms in the Great Plains and Intermountain West region. Soil nutrient deficiencies are common on organic farms in the region even

when CGMs are grown (Carr et al., 2019), leading researchers to suggest that long-term maintenance of soil fertility will require applications of animal manure or some other nutrient-containing input (Lehnhoff et al., 2017; Miller et al., 2008; Reeve et al., 2012). Animal manure can be an excellent source of not only N and P but also other macro- and micro-nutrients (Araji, Abdo, & Joyce, 2001; Wadman, Sluijsmans, & De La Lande, 1987). In addition to soil fertility improvements, animal manure can improve soil structure, thus increasing moisture infiltration and retention and reducing erosion (Arthur, Cornelis, Vermang, & De Rucker, 2011; Williams, 2004; Wortmann & Shapiro, 2008). These non-nutritive benefits may be as important in maintaining grain yield as soil fertility benefits in moisture constrained systems like those in this region (Stuckenholtz et al., 2002).

Less than 15% of fields received animal manure applications in a survey of organic farms in the northern Great Plains (Entz & Martens, 2009). This is not surprising since animals generally are not found on organic grain farms in the region. The upfront costs can be prohibitive for hauling and applying animal manure, even on organic farms where both crop and animal enterprises exist. Organic farms tend to be large in the region, making it necessary to apply manure strategically and foregoing applications to many fields where nutrient deficiencies are not especially acute. For example, organic grain farms average >800 ha with over 20% being >2,000 ha in Montana (OAE, 2017). Manure applications can be limited further by antiquated equipment and other constraints.

Composted animal manure can have a considerable carryover or legacy effect which may offset application costs and some other challenges posed when considering manure (Endelman, Reeve, & Drost, 2010a, 2010b). Research conducted on the long-term effects of composts and manures indicates that these materials influence nutrient requirements for 1–6 yr at typical agronomic rates (Eghball, Ginting, & Gilley, 2004; Lund & Doss, 1980; McAndrews, Liebman, Cambardella, & Richard, 2006; Mooleki, Schoenau, Charles, & Wen, 2004; Mugwira, 1979; Nyiraneza, Chantigney, N'Dayegamiye, & Laverdiere, 2010; Wallingford, Murphy, Powers, & Mangers, 1975). However, because most of this research was done in humid environments, confirmation of these findings is needed in semi-arid and arid climates. Eck (1988) showed that in Texas there was higher available P and SOC 12 yr after three consecutive manure applications of 67 Mg ha⁻¹ yr⁻¹. Carryover effects were detected 16 yr after a single application of compost at 50 Mg ha⁻¹ DM on an organic dryland wheat farm in Utah (Reeve et al., 2012).

Composted animal manure can be applied to supplement the reservoirs of N, P, and other nutrients in soils on dryland farms without depleting soil moisture (Rasmussen & Parton, 1994; Ghimire, Machado, & Bista, 2018). Annual additions of steer manure at 11 Mg DM ha⁻¹ since 1931 to the long-term

dryland wheat experiment in Pendleton, OR, have proven to be more effective at maintaining yields and slowing the loss of SOM more than either pea residue or additions of synthetic fertilizers (Ghimire et al., 2018). The slow mineralization of nutrients associated with composts can improve plant uptake in calcareous soils (Braschi, Ciavatta, Giovannini, & Gessa, 2003). Organic acids present in manures and composts have also been shown to coat soil particles, potentially inhibiting precipitation of plant available P (Doner & Grossl, 2002; Grossl & Inskeep, 1991).

The effect of animal manure applications on organic grain yield can be difficult to predict on dryland organic farms in sub-humid North America. Organic wheat yield was unaffected when composted cattle manure was applied at rates up to 23 Mg ha⁻¹ when compared with an unfertilized check in experiments in the central U.S. Great Plains (Lyon & Hergert, 2014). Lyon and Hergert (2014) speculated that dry conditions following manure application and the short time between application and planting limited the amount of N mineralized and made available to the wheat crop. In contrast, organic wheat yield was increased over 200% following cattle manure applications of up to 75 Mg ha⁻¹ in Utah (Stuckenholtz et al., 2002). In this experiment, the greatest incremental increase in wheat yield was gained at the lowest manure application rate (10 Mg ha⁻¹). A follow-up study documented that there was a large positive legacy effect on organic wheat yield (200% increase) and soil properties (160% increase in soil C and available P) 16 yr after the initial manure application (Reeve et al., 2012). Such long-term residual effects may make compost application on organic dryland farms an economically viable option. However, research is limited, and more information is needed to improve the prediction of which sites may or may not be responsive to compost additions and when upfront costs are most likely to be recouped.

4.3 | Summary of animal impacts on soil fertility in organic field crop systems

Animals are generally not integrated into organic field crop systems in North America, despite many ecosystem services that livestock enterprises can offer. More common is the application of animal manure to supplement native soil fertility, either alone or in combination with CGMs prior to planting cash crops. Animal manure is an excellent source of N, P, and other macro- and micronutrients, while CGMs are grown almost exclusively for soil N supplementation.

Eutrophication of water bodies caused by N- and P-enrichment can occur when nutrient supplementation exceeds cash crop needs. For this reason, animal manure applications to farmland are carefully regulated in eastern Canada and the northeastern United States. Over-application of animal manure is a concern in all regions except the Great Plains

and Intermountain West, where animal manure is generally in short supply. The relative unavailability of manure in this region is not because animals are not encountered, but because most organic grain farms are stockless. The large size and associated hauling costs of bulky organic material, lack of animal managerial skills and infrastructure, low carrying capacity, and lack of local markets for organic animal products help explain the limited use of animal manure when growing organic field crops in this region.

Animal manure will remain an important source of N, P, and other nutrients for organic field crops in most regions, despite challenges with availability and when over-application occurs. Research is needed to refine best management practices when applying animal manure so crop nutrient needs are met and both soil and water are protected from misapplication and associated environmental problems. Combining CGMs with the judicious application of animal manure is recommended to optimize the use of both nutrient sources when growing organic field crops.

5 | CONCLUSIONS AND RESEARCH NEEDS

Cover/green manure crops are ubiquitous in organic field-crop systems. Past research has focused on the ability of CGMs to provide PAN to cash crops in diverse rotations. Efforts were made to determine how CGM crops affect soil health, but our understanding remains incomplete. Work is needed to elucidate how functional members of the microbial community can be manipulated to improve synchrony between PAN release from CGMs and the N demand of cash crops. The effect of CGM crop selection on the cycling of N and other nutrients is a ripe area for research. Results from this work can guide the management of CGMs in rotation with cash crops. Well-informed management should improve the health of soil macro- and micro- fauna and flora, and in the functions that the soil microbial community can execute.

Leguminous CGMs can provide most, and sometimes all, of the N needs of subsequent cash crops in humid areas in North America. Generally, animal manure is readily accessible in these regions as well. The over-application of animal manure is possible, particularly when applied at rates based on crop N rather than P needs. This problem can be exacerbated when animal manure is applied and leguminous CGMs are grown, as is common in organic field crop systems. Prediction models are needed which accurately estimate mineralization of N contained in CGMs so, when coupled with animal manure applications, N (as well as P) are not under- or over-applied. Research is needed which quantifies how CGMs and animal manure, alone and in combination, affect not only N and P supply but other macro- and micro-nutrients in organic field crop systems. Finally, future work is needed which

determines how the timing of animal manure applications interacts with CGM-supplied N to affect field crop quality.

Biological N₂-fixation by legume CGMs can be inefficient in the North American Great Plains, leading to failure of CGMs to supply adequate PAN to meet N demands of wheat and other grain crops. Low yields and poor crop quality can result. Animal manure can be applied to supplement the PAN provided by CGMs, but access to animal manure is limited in much of the region. Past research suggests that there are legacy effects from animal manure applications which can last for years or even decades. Economic analyses are needed to determine the benefits-to-costs of hauling and applying animal manure to remote locations. A positive benefits-to-costs ratio will indicate that a single heavy application of animal manure may be a long-term strategy for supplementing CGM-derived PAN in dryland field crop systems, though this must be balanced with the environmental costs that this application may have.

Integrating animals directly into organic cropping systems has not been studied to any great extent. However, integrated crop–livestock systems are likely to have profound effects on crop nutrient cycling and other ecosystems services provided by organic farming systems. Integrated crop–livestock research requires significant resources, is costly, and must have buy-in from inter-disciplinary teams of scientists to be successful. A sustained funding stream for integrated crop–livestock research is needed to motivate scientists to participate.

The emergence of organic no-tillage creates the need for CGMs that produce large amounts of vegetative mulch for weed suppression while almost simultaneously supplying PAN to meet cash crop needs. Thus far, CGM selection has focused on rye, hairy vetch, and mixtures of both species in no-tillage systems, with only limited success in meeting dual weed suppression and soil N fertility needs. Additional legume and nonlegume species and species mixtures are needed which can fulfill both functions. A concerted CGM breeding effort is underway in the eastern United States, but this should be expanded to include other regions and additional plant species. This breeding effort should incorporate innovative strategies and techniques, such as the use of cross-slot openers on planters, to improve CGM establishment in high residue seedbeds.

Considerable research has been done on CGMs and animal manure effects in organic field crop systems, as indicated by this review. What is lacking is a well-established network enabling scientists to exchange information and coordinate research efforts. This limitation impedes progress in overcoming obstacles to improving nutrient management within organic field crop systems. Our hope is that this review not only increases the knowledge of organic researchers on work that has been completed, but that it prompts the develop-


ment of more active forums for sharing information and ideas among scientists working in this area.

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