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Optimizing Legume-Based Nitrogen Fertility For Organic Small Grain Systems

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OPTIMIZING LEGUME-BASED NITROGEN FERTILITY

FOR ORGANIC SMALL GRAIN SYSTEMS

By

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Thesis Advisor: Dr. Ellen Mallory

An Abstract of the Thesis Presented
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In the past decade, Maine has witnessed a steady rise in consumer demand for organic small grain products, accompanied by the swift creation of new businesses that cater to this demand, including bakeries, flourmills, malt houses, and distilleries. Maine's farmers have been slower to respond; only a small percentage of the 40,000+ acres of oats and barley being grown in the state, for example, is certified organic (National Agricultural Statistics Service, 2012). Given this combination of land resources, infrastructure, and consumer demand, Maine has the potential to become a regional leader in organic small grain production. According to our region's growers, one of the biggest hurdles associated with growing small grains organically is accessing reliable, affordable nitrogen fertility to support their crop systems. This thesis employs both quantitative, field-based methods and qualitative tools to help tackle this issue by exploring the use and management of legume green manures (LGMs) in production.

Chapter 1, "Alternative Methods for Terminating Green Manures in Organic Small Grain Systems," describes a field experiment in Maine and Vermont that aimed to evaluate potential alternatives to the standard method of terminating LGMs in our region,

moldboard plowing. This study assessed four different LGM termination methods for kill efficacy, winter soil cover, and N supply to a subsequent crop. Plowing resulted in the highest early season N uptake and grain crude protein in wheat at one site, though wheat yields were statistically similar among termination treatments at all but one site. We found that undercutting, as practiced in this trial, increased protective winter soil cover relative to moldboard plowing, but failed to adequately kill the LGM. Skim plowing, which uses the same implement as the standard method but involves less soil disturbance, increased soil cover relative to plowing at one site, and resulted in similar kill efficacy to plowing, making it a promising alternative.

Chapter 2, "Challenges, Strategies, and Research Priorities in Legume-Based Nitrogen Management for Organic Small Grain Producers in the Northeastern U.S." describes a qualitative investigation of organic small grain farmers and agricultural advisors regarding issues encountered in general nitrogen management, and use of LGMs in particular. Through semi-structured interviews, farmers and advisors revealed major challenges to be cost, overdependence on external nitrogen sources, diversifying rotations, weed management, and predicting nitrogen mineralization of organic residues. Market-based challenges, such as the cost of LGM seed and limited cash crop markets, represent significant barriers not easily solved through research and programming. This study highlights the need for on-farm, participatory research aimed at assessing potential alternatives to external nitrogen sources, addressing field-based challenges associated with LGMs, and bolstering grower confidence in legume-based nitrogen management.

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LIST OF ABBREVIATIONS

BP	Burial period
C	Carbon
C:N	Carbon-to-nitrogen ratio
CtlM	Cattle manure
GCP	Grain crude protein
GS	Growth stage (wheat)
K	Potassium
LGM	Legume green manure
N	Nitrogen
NHI	Nitrogen harvest index
NUtE	Nitrogen utilization efficiency
OFB	Organic fertilizer blend
OSG	Organic small grain
P	Phosphorus
PL	Plow treatment
PltM	Poultry manure
PNU	Plant N uptake
PRS	Plant Root Simulator® (probe)
SK	Skim plow treatment
SN	Sodium nitrate
UC	Undercutter treatment
WK	Winterkill treatment

CHAPTER 1: ALTERNATIVE METHODS FOR TERMINATING GREEN MANURES IN ORGANIC SMALL GRAIN SYSTEMS

1.1 Chapter Abstract

Legume green manures (LGMs) are a vital source of nitrogen (N) for many organic grain systems. A common practice among organic growers in the Northeast and other parts of the U.S. is to undersow a LGM into a small grain, harvest the grain crop, and terminate the LGM stand in late fall by moldboard plowing. While fall plowing offers excellent LGM kill, growers increasingly seek an alternative termination method that reduces tillage intensity and bare winter soil. This study, performed at three sites in Maine and Vermont, evaluates three LGM termination methods for kill efficacy, winter soil cover, spring soil conditions, and N uptake and yield of a subsequent test crop of hard red spring wheat (*Triticum aestivum* L., var. Glenn). The experiment was a split-plot randomized complete block design, with green manure treatment as a split-plot factor and termination treatment as a main plot factor. A no-clover check treatment and a red clover (*Trifolium pratense* L., var. Freedom) treatment were established as an intercrop with spring barley (*Hordeum vulgare* L., var. Newdale) and terminated in late fall by moldboard plowing (PL), skim plowing (SK), or undercutting (UC). An additional termination treatment, winterkill (WK), was evaluated at one site. SK, UC, and WK increased soil cover relative to PL, though UC resulted in low red clover kill efficacy, and is in need of improved design. Early and mid-season plant N uptake in the wheat test crop was higher following PL and SK than UC in Maine, though yield was unaffected by termination method. Grain crude protein following PL was higher than UC in two of three sites, indicating a more favorable delivery of N

associated with PL. SK is particularly promising as an alternative termination method, meeting or outperforming PL for nearly all measures, and offering a potential balance between soil conservation, LGM kill efficacy, and N supply.

1.2 Introduction

In organic agriculture, productivity is typically restricted by nitrogen (N) (Berry et al., 2002). For farmers without consistent access to animal manure, or those unable to afford costly organic fertilizer blends, legume green manures (LGMs) can be a viable N fertility option (Cherr et al., 2006). LGMs are leguminous crops grown primarily to produce soil N for a subsequent crop and to improve overall soil health and quality. The work described in this chapter aims to address a key management challenge associated with the use of LGMs in organic small grain systems, LGM termination, such that nitrogen contribution and associated soil health benefits are maximized.

LGMs produce N via biological N fixation, accomplished through symbiosis with rhizobia soil bacteria. When LGMs are terminated and incorporated into the soil, LGM plant tissue is broken down by soil microbes, and the organic N within the tissues is converted into an inorganic form, available for subsequent crops to use. The potential N contribution of a LGM is dependent on species (Ross et al., 2009; Liebman et al., 2018), life-cycle traits (ie, annual or perennial), and length of LGM growing period (Stute and Posner, 1995). Previous studies have estimated that the aboveground biomass of red clover, established as an intercrop with a small grain in northern climates, contains between 10-108 kg N ha^{-1} (Gaudin et al., 2013).

Generally, a LGM is either used to replace summer fallow or is sown as a companion crop in spring or winter grains. LGMs accumulate the most biomass when competition from

other plants is limited and the growing season is as long as possible (Stute & Posner, 1995). However, the opportunity cost of growing a full-season, full-field GM instead of a cash crop is often not compensated for by the associated fertility benefits (Olesen et al., 2002). Particularly in regions with a limited growing season, intercropping small grains with LGMs, like the widely used red clover (*Trifolium pratense* L.), allows a grower to take advantage of field space (between grain rows) that would otherwise be underutilized (Gaudin et al., 2013), avoiding the opportunity cost of a sole-cropped LGM. Previous work has suggested that intercropping a small grain with a legume can improve yield and quality of the associated small grain (Bedoussac et al., 2015), although not consistently (Hesterman et al. 1992, Amossé et al., 2013).

In a typical red clover-small grain intercrop, the clover germinates and establishes between cereal rows before the cereal crop produces a full canopy, at which point clover growth is greatly slowed (Queen et al., 2009). Following harvest of the grain nurse crop, LGMs respond to increased solar radiation with a rapid accumulation in biomass (Blaser et al., 2007). In northern growing regions, LGMs are typically terminated and incorporated into the soil by moldboard plowing in mid- to late-fall, as termination the following spring may result in insufficient decomposition of residues prior to planting a subsequent crop. Plowing, while effective at killing LGMs, leaves the soil with little to no surface residue through the winter and early spring, making it vulnerable to wind and water erosion (Lal et al., 2007), and growers concerned with soil health and quality may prefer an alternative method of termination. High-residue, non-chemical methods of cover crop termination have been the focus of recent studies, particularly in reduced-tillage systems using a roller-crimper (Mirsky et al., 2012; Parr et al., 2014; Wayman et al., 2014; Liebman et al., 2018).

Creamer et al. (2002) demonstrated that undercutting, a termination method that severs cover crop roots while leaving aboveground biomass intact, was successful in killing a range of legume and non-legume cover crops in the spring in Ohio, and resulted in an even soil surface mulch prior to a tomato crop. As red clover is too vigorous to be terminated by roller-crimper (Clark, 2007), undercutting may offer a successful, low-disturbance alternative to plowing for northern growers.

There is also a need to investigate how different methods of fall termination affect the supply of N from LGM residue to the subsequent crop, as well as other potential yield-limiting factors, such as weed pressure. In general, N mineralization rate of organic residue is affected by residue quality (i.e., carbon to nitrogen ratio, C:N) (Wagger et al., 1998), soil temperature, moisture, oxygen availability, and pH (Liebman & Davis, 2000). Termination method can impact the pattern of N release of LGM residues by altering the residue particle size, as well as the degree to which residue is incorporated or left on the soil surface at termination (Olesen et al., 2009; Wortman et al., 2012). Moldboard plowing, for example, entails complete or near complete inversion and incorporation of LGM plants, exposing most or all of the plants' surface area to soil microbes. Stute and Posner (1995) observed rapid decomposition of red clover buried to simulate full incorporation, with 50% of total N released in the first 4 weeks after clover mortality, and N release continuing for 10 weeks in total (Stute and Posner, 1995). Tillage of the soil itself can also encourage the N in soil organic matter to mineralize more rapidly than in untilled soil (Balesdent et al., 2000).

In contrast, termination methods that disturb less of the soil profile, and leave LGM residues on the soil surface, lead to slower residue decomposition and a more gradual release of N (Holland and Coleman, 1987; Van Den Bossche et al., 2009). Yield and quality

in small grain crops are greatly impacted by both the amount and timing of N supply (Mallory and Darby, 2013), and therefore could be expected to be influenced by LGM termination method. For example, high grain crude protein (GCP), an important quality parameter in bread wheat, is strongly linked to N availability during grain fill (Fowler, 2003). If lower-disturbance termination methods are successful in delivering N at a slower, more gradual rate throughout the growing season, it is possible that this could have positive effects on farmers' crop quality.

Different termination methods may also result in different degrees of weed pressure for a subsequent crop. Blackshaw et al. (2010) demonstrated that higher-residue termination of sweet clover, (mowing and leaving residues on the soil surface) led to reduced weed pressure relative to low-residue termination (mowing and removing residue as hay). The authors theorized that high-residue termination, which left a mulch on the soil surface, buffered the soil from temperature oscillations, perhaps preventing the onset of weed seed germination (Sarrantonio and Gallandt, 2003). A mulch of legume residue may also prevent or delay weed seed germination due to its phytotoxic properties (Ohno et al., 2000). High disturbance termination in the fall, such as moldboard plowing, may succeed in burying weed seeds deeper in the soil profile prior to winter, resulting in reduced apparent weed pressure the following spring. However, this does not guarantee a long-term reduction of weed pressure in the system, as seeds may resurface upon subsequent tillage events (Gruber and Claupein, 2009).

The goal of this study is to evaluate different methods of LGM termination for winter and early spring soil cover, LGM kill efficacy, spring soil conditions, weed pressure, and supply of N to a subsequent crop. We hypothesized that lower-disturbance, higher-residue

forms of LGM termination would lead to N release that is better timed to the N uptake needs of a subsequent wheat crop, while enhancing soil protection in the winter through increased surface residues.

1.3 Materials and Methods

1.3.1. Study Site and Experimental Design

The field experiment was conducted from 2016-2018 at two sites in Maine and one site in Vermont. In Maine, the sites were located at the University of Maine Rogers Farm Forage and Crop Research Facility (44°56'N, 68°42'W) in Old Town. The first Maine site (ME17) was initiated in May 2016 and concluded in November 2017. The experiment was preceded by tilled fallow. At ME17, the soil was a silt loam (Pushaw-Swanville complex, fine-silty, mixed, semiactive, nonacid, frigid Aeric Epiaquepts) with a pH of 6.0, 3.6% organic matter, and 19.5 kg ha^{-1} soil test phosphorus (P) and 151.4 kg ha^{-1} soil test potassium (K), determined using the standard methods of the Maine Soil Testing Service (Hoskins, 1997). The second Maine site (ME18) was initiated in May 2017 and concluded in November 2018. The experiment was preceded by tilled fallow. The soil at ME18 was a very fine sandy loam (Nicholville, coarse-silty, isotic, frigid Aquic Haplorthod) with a pH of 5.9, 4.3% organic matter, and 11.9 kg ha^{-1} soil test P and 174.9 kg ha^{-1} soil test K, determined as above (Hoskins, 1997). In Vermont, the experiment was located at Borderview Research Farm in Alburgh (45°0'N, 73°18'W). The Vermont site (VT17) was initiated in April 2016 and concluded in August 2017. The soil was a Benson silt loam (loamy- skeletal, mixed, active, mesic, Lithic Eutrudepts) with a pH of 7.2, 4.2% organic matter, and 13.0 kg ha^{-1} soil test P and 132.0 kg ha^{-1} soil test K, determined as above. The VT17 experiment was preceded by corn (*Zea mays* L.).

The experimental design was a split plot, randomized complete block design, with termination method as the main plot factor and LGM as the split-plot factor. At ME17, five replications were used, and at ME18 and VT17, four replications were used. In Maine, field plots were 1.8 by 24.4 m with two 1.8 by 12.2 m subplots, and in Vermont, plots were 3.7 by 18.4 m, with two 3.7 by 9.2m subplots. The experiment had two phases: a LGM establishment phase and a test crop phase (Table 1). In the LGM establishment phase, red clover (*Trifolium pratense* L., var. Freedom) was established as an intercrop with spring barley (*Hordeum vulgare* L., var. Newdale) in one of the two subplots. The other subplot was left unplanted as a no-clover control. Originally, an additional subplot was included in each main plot, and planted to a mixture of red clover and perennial ryegrass (*Lolium* perenne L., var. Linn) intercropped with barley. This treatment was intended to provide a higher carbon-to-nitrogen (C:N) LGM relative to the red clover LGM, in order to determine whether an interaction existed between termination treatment and LGM C:N. Due to poor ryegrass establishment, this treatment was abandoned.

Table 1.1. Summary of field operations and samplings in the green manure establishment phase and test crop phase in Maine and Vermont.

Operation	Wheat growth stage†	ME17	ME18	VT17
Green manure establishment phase		**2016**	**2017**	**2016**
Manure application	-	12 May	5 May	12 May
Barley seeding	-	12 May	6 May	12 May
LGM seeding	-	13 May	6 May	13 May
Barley and LGM heights measured	-	10 Aug.	2 Aug.	10 Aug.
Barley harvest	-	11 Aug.	3 Aug.	11 Aug.
Fall-established LGM seeding‡	-	-	-	22 Aug.
LGM biomass sampling	-	31 Oct.	18 Oct.	1 Nov.
LGM termination	-	2 Nov.	28 Oct.	14 Nov.
Test crop phase		**2017**	**2018**	**2017**
Ground cover measure	-	20 Apr.	22 Apr.	25 Apr.
LGM biomass sampling	-	17 May	24 Apr.	27 Apr.
Pre-tillage soil sampling	-	19 May	24 Apr.	27 Apr.
Tillage	-	20 May 24 May 30 May	24 Apr. 7 May 11 May	2 May
Bone meal and potassium sulfate application	-	1 June	6 May	-
Wheat seeding	-	2 June	17 May	4 May
Post-plant soil sampling	-	6 Jun.	28 May	-
PRS§ probe set 1 installed	-	7 June	17 May	-
PRS probe set 1 retrieved	-	19 June	29 May	-
PRS probe set 2 installed	-	21 June	6 June	-
Cultivation	-	27 June	30 May	-
PRS probe set 2 retrieved	-	3 July	18 June	-
Wheat, soil sampling #1	Stem extension, GS30-32	5 July	20 June	14 June
PRS probe set 3 installed	-	14 July	-	-
Wheat, soil sampling #2	Ear emergence, GS55-59¶	17 July	5 July	26 June
PRS probe set 3 retrieved	-	26 July	-	-
Wheat, soil sampling #3	Soft dough, GS85	13 Aug.	1 Aug.	31 July
Wheat harvest	Maturity, GS91	30 Aug.	9 Aug.	10 Aug.
Oat seeding	-	5 Sept.	28 Aug.	-
Oat, soil sampling	-	23 Oct.	15 Oct.	-

† Zadoks scale for growth staging cereals (Zadoks et al., 1974).
‡ At ME18, an additional treatment was added consisting of field pea following barley harvest.
§PRS®, Plant Root Simulator
¶ In Vermont, this sampling took place at GS40-49, booting.

Three termination treatments (standard moldboard plowing, PL; skim plowing, SK; undercutting, UC) were applied across the LGM and control subplots prior to the first killing frost in the LGM establishment phase. The PL treatment, employing a 450 International 3-bottom moldboard plow (Navistar International Co, Lisle, IL), disturbed soil to a depth of 20-30 cm, with complete inversion and burial of LGM plants. SK, also performed using a moldboard plow, disturbed 13-18 cm of soil, with partial inversion and burial of LGM plants. The UC treatment was completed using an experimental undercutter implement. In Maine, the undercutter consisted of five overlapping, V-shaped flat sweeps, each 30 cm wide, staggered on two tool bars and mounted on a three-point hitch. The tool bar was weighed down with tractor weights as necessary to hold the undercutter sweeps in the ground as the implement was moved forward. In Vermont, the undercutter implement was comprised of a single angled blade, 1.5 m wide, with a center gauge wheel for controlling depth, mounted on a three-point hitch. At ME18 only, an additional LGM treatment and termination treatment combination was included, consisting of field pea (*Pisum sativum* L.) established following barley harvest in the LGM establishment phase using a conventional grain drill and left to winterkill (WK).

1.3.2. Management Practices

Prior to experiment initiation, one composite soil sample was obtained at each field site to ensure adequate P and K levels (Hoskins, 1997). A summary of field operations and sampling, and their respective dates for each site, is provided in Table 1.1. Manure was applied no more than one day prior to barley seeding at the start of the LGM establishment phase, and incorporated using a Perfecta® II field cultivator (Unverferth Manufacturing Co, Inc., Kalida, OH). Spring barley (var. Newdale) was planted at a target density of 300 live

plants m^{-2} (326 live plants m^{-2} at ME18) using a Massey-Harris 2.6 m drill with single disc openers (Massey Ferguson Ltd., Duluth, GA) in Maine, and a Sunflower 9412, double disc opener, 3.0 m grain drill (Sunflower Manufacturing, Beloit, KA) in Vermont. Red clover was seeded within one day of barley planting using a calibrated drop spreader at a rate of 11 kg ha^{1} in Maine and 13 kg ha^{-1} in Vermont. Barley was harvested with plot combines. Plots were treated with the 3 termination treatments prior to the first killing frost.

At the initiation of the test crop phase at both Maine sites, one composite soil sample was obtained in each block to assess P and K levels. Plots were tilled with a heavy disk to prepare a seedbed, using one to three passes depending on the amount of plant residue present prior to planting. Following disking in Maine, bone meal and potassium sulfate were applied by hand according to the results of the soil test to achieve target availability of 11-26 kg ha^{-1} for P and 3-5% saturation for K (Table 1.2). Plots were harrowed using a Perfecta® II field cultivator (Unverferth Manufacturing Co, Inc., Kalida, OH) to incorporate fertilizers. Spring wheat (var. Glenn) was planted in Maine using an Almaco cone seeder with double-disk openers (Almaco Inc., Nevada, IA) at a row spacing of 17.8 cm. In Vermont, wheat was planted using a John Deere 750 double-disc opener grain drill (John Deere, Moline, IL) at a row spacing of 15.5 cm. Target seeding rate for wheat was 380 live plants m^{-2} for ME17 and VT 17, and 500 live plants m^{-2} at ME18. At the three-leaf stage in Maine, plots were cultivated using a rear-mounted 2.5 m-wide hoe (Schmotzer Agrartechnic, Bad Windsheim, Germany) in 2017, and tine harrowed using a Williams tool system (Market Farm Implement, Friedens, PA) in 2018. Wheat was harvested with plot combines. Following wheat harvest in Maine, straw was removed, stubble was mowed and rototilled, and oat (*Avena sativa* L.) was seeded with a conventional grain drill.

Table 1.2. Material and nutrient application rates for manure applied prior to barley planting in the LGM establishment phase, and fertilizer applied prior to wheat planting in the test crop phase.

Materials and nutrients	**Pre-plant manure†**			**Bone meal‡**		**Potassium sulfate§**	
	ME17	ME18	VT16	ME17	ME18	ME17	ME18
Material application rate, Mg ha^{-1}	49	49	4.6	0.61	0.61	0.29	0.13
Organic N, kg ha^{-1}	148	157	-	0	0	0	0
Inorganic N, kg ha^{-1}	45	27	-	0	0	0	0
Estimated available N, kg ha^{-1}	59	53	67	0	0	0	0
P, kg ha^{-1}	94	63	106	78	78	0	0
K, kg ha^{-1}	161	125	125	0	0	146	63

† Pre-plant manure for Maine was dairy manure, and estimated available N was calculated as 25% of the organic-N and 50% of the inorganic-N based on Klausner and Bouldin (1983). Pre-plant manure was poultry manure in Vermont (2.9% N, 2.3% P, 2.7% K), and estimated available N was assumed to be 50% of total N.

‡ Bone meal, 16% P. Estimated available P was assumed to be 80%.

§ Potassium sulfate, 50% K. Estimated available K was assumed to be 100%.

1.3.3. Measurements and Analytical Procedures

Prior to barley harvest in the LGM establishment phase, the heights of six randomly selected barley plants and LGM plants were recorded in each LGM plot to assess the potential for the undersown LGM to interfere with barley grain harvest. Barley yield and moisture (GAC 2100, DICKEY-john Corp., Auburn, IL) were determined on cleaned samples. Yield was adjusted to 135 g kg^{-1} grain moisture. A subsample was taken from each sample and ground using a 2 mm mesh. Total N concentration was determined using combustion of a 250-mg sub-subsample with a Leco CN2000 analyzer (Leco Corp., St. Joseph, MI), corrected to a grain moisture of 120 g kg^{-1}. Grain protein concentration was determined by multiplying total N concentration by a factor of 5.7 (Am. Assoc. of Cereal Chem. Method 46-30). Biomass of LGM and weeds was collected from all plots within a one-week period prior to termination. LGM density was measured in each plot by counting the number of living clover plants in two, 30 by 33 cm quadrats. Aboveground biomass was clipped at 2 cm from

the soil surface in four, 30 by 33 cm quadrats in each plot. Subsequent biomass sampling in the test crop phase avoided the location of this initial sampling. Belowground biomass was collected from the same four quadrats by pitchforking around each sampling area and excavating biomass rooted within the bounds of each quadrat to a depth of 30 cm. Roots were sorted into LGM and weed fractions, and gently sprayed with water on top of a fine mesh screen to remove all soil. Plants were dried at 60°, weighed, and ground using a 2 mm mesh. Total N and C concentration was determined by combustion of a 250-mg subsample using a Leco CN2000 analyzer (Leco Corp., St. Joseph, MI).

Following snowmelt, and prior to any field operations in the test crop phase, spring soil cover was determined in each plot using the line transect method (Laflen et al., 1981). Any living LGM or weed biomass was collected by clipping plants at 2 cm from the same quadrats where LGM density was determined the prior fall. Plants were dried at 60°, weighed, and ground using a 2 mm mesh. Total N was determined using the methods described above. In Maine, volumetric soil moisture was measured at 6.4 cm in each plot at weekly intervals starting three weeks before wheat planting at ME17 and one week before planting at ME18 using a soil probe (ML3 ThetaProbe, Delta-T Devices Ltd., Cambridge, UK). Plant Root Simulator (PRS)® ion resin probes (Western Ag, Saskatoon, SK, Canada) were used to measure extractable inorganic N at Maine sites. At ME17, probes were installed in a series of three consecutive burial periods in all PL, SK, and UC plots that had contained the LGM. At ME18, probes were installed in two consecutive burial periods in PL and UC plots only. PRS® probes act as an ion sink, measuring NO_3^- and NH_4^+ availability in the soil by adsorbing ions onto a resin membrane over time, simulating the effect of plant roots in soil (Qian and Schoenau, 2005). For each burial period, probes were buried

vertically such that the center of each membrane was located 10.2 cm below the soil surface, and the probe tip at 20.3 cm. At ME17, two probe pairs, each consisting of one ion probe and one anion probe, were installed at opposite ends of each plot between the 3rd and 4th crop rows. At ME18, the same procedure was followed, but with four probe pairs per plot. At the end of each burial period, probes were brushed off, rinsed with deionized H_2O, and shipped to Western Ag Innovations for analysis. At Maine sites, Thermochron iButton® temperature loggers (Dallas Semiconductor, Maxim Integrated Products, Sunnyvale, CA), logging temperature every 30 minutes, were installed in soil at 10.2 cm one week after wheat planting, and remained installed until after all PRS® probes were retrieved. Temperature means were calculated as mean daily temperatures for a span of five days surrounding each sampling date (e.g., temperature value for 30 Apr. 2017 was calculated by averaging the daily temperature from 27 Apr. to 3 May).

Wheat stand counts were performed at the three-leaf stage by counting the number of wheat plants in four, 1-ft sections in each plot. Wheat and weed aboveground biomass was collected three times throughout the growing season, at Zadoks growth stages 30-32 (stem extension), 55-59 (head emergence), and 85 (soft dough, or "peak biomass") (Zadoks et al., 1974). In Vermont, secondary sampling occurred during growth stages 40-49 (booting), rather than head emergence. All aboveground biomass was collected from two, 30 by 33 cm quadrats from opposite ends of each plot, squared over the 4th and 5th crop rows from one plot edge. On consecutive sampling dates, the sampling areas were placed at least 0.3 m from preceding sample location. Plants were clipped at 1.3 cm above the soil surface, separated into wheat and weeds fractions, dried at 60°, weighed, and ground using a 2 mm mesh. Total N concentration was determined using the procedure described above.

Plant N uptake was determined by multiplying total biomass of wheat and weeds by total N. At maturity (GS91), wheat was harvested using plot combines. Grain was cleaned and its moisture determined (GAC 2100, DICKEY-john Corp., Auburn, IL), and yield was adjusted to 135 g kg^{-1} moisture. Grain subsamples were ground using a 2 mm mesh, and grain protein was determined according to the procedure described above. Grain N yield was calculated by multiplying grain yield by total grain N. Nitrogen utilization efficiency (NUtE) and N harvest index (NHI) were determined by dividing yield and grain N yield, respectively, by wheat N uptake at the soft dough stage (Dawson et al., 2008). In Maine, oats were sampled 1 to 2 d prior to the first killing frost at the end of the test crop phase, using the sampling procedure described above.

Soil was sampled in the test crop phase prior to initial tillage (within 10 days of wheat seeding) and at the start and end of each PRS probe burial period, each wheat biomass sampling, and the oat sampling (ME17 only). Six soil cores (2 cm diameter) were taken to a depth of 20 cm within each biomass sampling area, three next to the crop row and three between crop rows. Cores were bulked by plot, mixed, and sieved to 2 mm. A 200 g subsample was air-dried rapidly on paper plates using fans, and stored until inorganic N analysis was performed. A 3 g subsample of the dried soil was measured into a 50 mL polypropylene centrifuge tube with 30 mL of 2.0 M KCl and shaken for 1 h. The solution was filtered through 2 μ paper filters and kept frozen until analysis. The supernatant was analyzed for NH_4^+ and NO_3^- colorimetrically (ALPKEM model FS3000, O.I. Analytical, College Station, TX).

1.3.4. Statistical Analysis

Data were analyzed using the statistical program JMP v. 14 (JMP, SAS Institute, Cary, NC, USA). Each site was analyzed separately due to significant treatment by site interactions, as well as occasional differences in sampling times and frequencies. Analysis of variance (ANOVA) was used to test the significance of termination treatment on experimental parameters using LGM subplots only, since termination treatment was not relevant for control subplots. For most parameters, a separate ANOVA was used to test for differences between LGM ("Clover") and control ("No clover") treatments using data from Plow (PL) only. ANOVA assumption of equal variance was tested using Levene's test, and residuals were tested for normality using the Shapiro-Wilk test. All means were separated using Fisher's protected LSD at $p=0.05$. In the event that data did not conform to the assumptions of ANOVA, log transformations were performed.

1.4. Results and Discussion

1.4.1 Weather

Monthly mean temperatures and precipitation for each site and year of the experiment are presented in Table 1.3. During the LGM establishment years (2016 and 2017 in Maine, 2016 in Vermont), mean temperatures from May to August were similar to the 30-year average for all three sites, followed by slightly higher than average temperatures in September and October of these years. Rainfall in June and September of the LGM establishment year was generally lower than the 30-year average for all three sites. At ME18 and VT17, this was followed by higher than average rainfall in October of the LGM establishment year. During the wheat test crop years (2017 and 2018 in Maine, 2017 in Vermont), mean temperatures for all sites were close to the 30-year average until

September, when all sites experienced higher than average temperatures. Precipitation in Maine was 27% higher than normal in May 2017, and 58% lower than normal in May 2018, followed by generally lower-than-normal rainfall for the remainder of the wheat-growing season. In Vermont, rainfall was higher than average during the test crop year (2017).

Table 1.3. Monthly mean temperature and total rainfall from March to November of each year of the experiment in Old Town, Maine and Alburgh, VT, compared with average climate data (1981-2010).

Mean temperature and rainfall	Maine				Vermont		
	2016	2017	2018	30-yr avg.	2016	2017	30-yr avg.
Mean temperature, °C							
March	-	-3.5	-0.3	-1.4	-	-3.9	-0.6
April	-	6.9	4.4	5.3	-	8.4	7.1
May	12.2	11.4	13.2	11.4	14.5	13.1	13.5
June	15.9	17.0	15.9	16.4	18.8	18.6	18.8
July	20.2	19.2	21.0	19.7	21.5	20.4	21.4
August	19.9	18.1	20.7	18.6	22.0	19.8	20.4
September	15.6	16.6	15.0	13.9	17.4	18.0	15.9
October	9.1	12.0	6.1	7.8	10.0	14.1	9.0
November	3.8	2.1	-0.5	2.2	4.4	1.8	3.4
Rainfall, mm							
March	-	72	81	80	-	40	56
April	-	104	108	95	-	133	72
May	77	124	41	98	38	105	88
June	65	68	108	103	71	143	94
July	119	47	69	90	46	124	106
August	62	43	65	84	76	141	99
September	33	82	79	96	64	47	93
October	99	135	114	101	127	84	91
November	92	64	165	112	76	58	80

1.4.2. Green Manure Effect on Barley Yield and Grain Quality

Barley grain yield was highest at ME18, averaging 4.3 Mg ha^{-1} (Table 1.4), perhaps due to the 9% increase in target seeding rate relative to ME17, as well as higher early season precipitation in 2017 relative to 2016. Mean barley test weights were above the USDA's official weight per bushel for highest grade barley (618 kg m^{-3}) in both Maine sites, but Vermont test weights fell below this threshold for both clover and no-clover plots, indicating late-season crop stress (Mallory and Darby, 2013).

Table 1.4. Barley mean grain yield, test weight, and grain crude protein in the LGM establishment phase, and ANOVA results.

	df	Grain yield			Test weight			Grain crude protein		
		ME17	**ME18**	**VT17**	**ME17**	**ME18**	**VT17**	**ME17**	**ME18**	**VT17**
Green manure		——— Mg ha^{-1} ———			——— kg m^{-3} ———			——— g kg^{-1} ———		
Clover		2.8	4.1	2.6	636	646	489	99	108	112
No clover		2.9	4.4	2.7	638	644	497	94	114	117
Source of variation						**ANOVA**				
Green manure	1	ns†	ns	ns	ns	ns	ns	ns	*	ns
CV, %		10.7	16.6	18.8	1.2	1.7	4.7	9.7	1.9	9.9

*, significant at $p<0.05$.
† ns, not significant.

Despite the potential ecological advantages outlined by Bedoussac et al. (2015), intercropping spring barley with a legume did not significantly increase yield or grain quality, nor did the clover LGM significantly reduce yield in any of the three sites, unlike what has been observed in previous studies (Brandt et al., 1989; Kunelius et al., 1992). Overall, barley test weight was unaffected by the intercropped LGM. Barley grain crude protein was significantly impacted by the LGM at ME18 only; mean protein for barley grown without clover was 6% higher than barley grown with clover. It is possible that this is the result of relatively low precipitation during stem extension and grain filling (43 mm lower than the 30-yr average in July 2017 and 41 mm lower than the 30-yr average in August 2017), which may have led to increased competition for water resources from the

intercropped green manure, restricting late-season N uptake (Unger et al., 1998). On average, the green manure grew to 37%, 26%, and 44% of the height of the barley crop at ME17, ME18, and VT17, respectively, well below the barley spikes (data not shown). The clover did not interfere with grain harvest but would have reduced straw yields.

1.4.3. Green Manure Treatment Characteristics

A summary of green manure treatment characteristics is presented in Table 1.5. Density and biomass of the red clover green manure, measured prior to termination, were lower at ME18 than ME17, perhaps due to increased barley seeding rate and the much lower midsummer rainfall, both of which may have restricted clover establishment (Kunelius et al., 1992; Gaudin et al., 2013). Red clover aboveground dry matter biomass was 2456, 1782, and 1613 kg ha^{-1} at ME17, ME18, and VT17, respectively, falling within the range of fall red clover biomass reported by Gaudin et al. (2013) in their review of red clover intercropping (600 to 4200 kg ha^{-1}). On average, the aboveground N content of the green manure prior to termination was 74, 58, and 43 kg N ha^{-1} at ME17, ME18, and VT17, respectively, which also fall within the range reported by Gaudin et al. (2013) for aboveground N content of red clover established as an intercrop with a small grain (10-108 kg N ha^{-1}).

The aboveground biomass and N content of plants growing in no-clover plots was higher than expected at ME17 and VT17 (30 kg N ha^{-1} for ME17 and 40 kg N ha^{-1} for VT17), due to the presence of white clover as a weed at all sites. At ME17, white clover (*Trifolium repens* L.) composed, on average, 69% of total weed biomass in no-clover plots, but aboveground biomass and N content were substantially higher in the clover treatment. At ME18, white clover was hand-weeded from no-clover plots at the seedling stage, and made

up less than 1% of no-clover plot weed biomass prior to termination. We would therefore expect a slight, unintentional "green manure" effect in no-clover plots at ME17 and VT17. The carbon to nitrogen ratio (C:N) of the clover treatment biomass was significantly lower than that of the no-clover treatment at all sites, as expected.

Table 1.5. Mean green manure biomass, nitrogen content, and C:N for red clover green manure and weeds incorporated prior to wheat planting.

	df	Aboveground biomass			N content			C:N		
		ME17	ME18	VT17	ME17	ME18	VT17	ME17	ME18	VT17
Green manure		kg DM ha^{-1}			kg N ha^{-1}					
Clover		2456	1782	1613	74	58	43	14	13	14
No clover		1055	802	1427	30	23	40	15	16	17
Source of variation						ANOVA				
Green manure	1	***	***	ns‡	***	***	ns	***	**	**
CV, %		19.6	33.3	44.0	19.7	31.8	49.1	5.2	16.1	16.9

,*, significant at p<0.01 and <0.001.
† Not measured.
‡ ns, not significant.

1.4.4. Soil Cover, Kill Efficacy, and Spring Soil Conditions

The undercutter consistently resulted in significantly higher overwinter soil cover, as measured in early spring, than either SK or PL (Table 1.6). The SK treatment increased soil cover relative to PL only at ME17. Termination treatment had a substantial impact on green manure kill efficacy at both Maine sites. At ME17, PL resulted in the highest kill, followed by SK and UC. The undercutter performed the worst at ME18, killing only 38% of red clover plants on average, though much less living biomass was present prior to first spring tillage at ME18 relative to ME17. PL, SK, and WK kill efficacy was effectively 100% at ME18, with no living biomass present in the spring prior to tillage, likely due to drier spring soil conditions relative to the previous year. In Vermont, UC resulted in significantly higher living spring biomass than PL or SK treatments.

Table 1.6. Mean early spring soil cover, percent LGM kill, and living spring biomass for all sites, and ANOVA results.

	df	Early spring soil cover			Percent LGM kill			Living spring biomass		
		ME17	**ME18**	**VT17**	**ME17**	**ME18**	**VT17†**	**ME17**	**ME18**	**VT17**
Termination method		————%————			————%————			———kg ha^{-1} ———		
PL		2 c‡	3 b	4 b	98 a	100§	-	0§	0§	37 b
SK		20 b	5 b	21 b	85 b	100§	-	535	0§	91 b
UC		84 a	81 a	62 a	66 c	38	-	1453	201	842 a
WK		-	81 a	-	-	100§	-	-	-	-
Source of variation						**ANOVA**				
Termination	2,3,2¶	***	***	**	***	-	-	*	-	***
CV, %		10.8	8.0	34.7	8.4	-	-	41.8	-	30.3

*, **, ***, significant at p<0.05, p<0.01, and p<0.001.

† Not measured.

‡ Within columns, means followed by the same letter are not significantly different according to Fisher's LSD (0.05).

§ Value based on ocular estimate; ANOVA not performed.

¶ Degrees of freedom for ME17, ME18, and VT17.

To the authors' knowledge, no previous work has been published on the efficacy of undercutting for cover crop termination in the Northeast U.S., though previous work has evaluated using an undercutter to terminate various legume cover crops elsewhere in the United States. Creamer et al. (1995) reported high kill efficacy using an undercutter in late spring in Ohio to terminate vetch (*Vicia villosa* Roth.), subterranean clover (*Trifolium subterranneum* L.), and crimson clover (*Trifolium incarnatum* L.) planted the previous summer, but inadequate kill efficacy for medium red or mammoth red clover. The authors attributed these differences in undercutter performance in part to plant maturity, with the undercutter more easily killing species that had reached mid-bloom or beyond at the time of termination. The species' drought tolerance and root-to-shoot ratio were also discussed as potential explanations for the discrepancy in kill efficacy. We postulate that UC's relatively low kill efficacy, and high degree of living spring biomass, resulted from a combination of these factors. Red clover is a drought tolerant species with ample root biomass, and was terminated prior to bloom in this experiment, while its roots were still fairly pliable. The undercutter design used was likely not optimized to effectively and consistently sever red clover roots at this growth stage, and allowed for LGM survival. Spring LGM regrowth was highest at ME17 and VT17, largely due to very wet spring soil conditions in these years (Table 1.3), which delayed field operations and wheat planting.

Soil moisture and temperature were affected by termination method at ME17 but not ME18 (and were not measured in VT17). At ME17, UC resulted in significantly higher soil moisture than PL at 3 weeks prior to first spring tillage (30 Apr.) (Table 1.7). In their study comparing disking to undercutting to kill cover crop mixtures, Wortman et al. (2012) also found that undercutting increased surface soil moisture following termination in late

spring, which they attributed to the cover crop mulch that remained on the soil surface after undercutting. However, in the present study, a statistical difference in soil moisture was not observed at subsequent samplings in the weeks leading up to tillage. At ME17, UC also resulted in statistically lower soil temperature than PL at 3 weeks (30 Apr.) as well as at 2 weeks (5 May) and immediately (17 May) prior to tillage. Just prior to tillage in this year, soil moisture in SK was also lower than in PL but higher than in UC. One week after wheat planting (8 June), soil moisture in UC and SK was still lower than in PL, and equal to each other. At ME18, no differences in soil moisture or temperature were detected pre-tillage or post-planting, likely due to more normal spring weather conditions, which allowed for timely planting of wheat. At ME17, it is unclear whether the increased soil moisture and decreased soil temperature in UC plots would have delayed planting relative to PL or SK because spring field operations were commenced at the same time for all treatments, but it is a clear possibility. As experts have begun to predict wetter spring conditions and fewer field-working days in northern New England due to climate change (Wolfe et al., 2018), farmers may be even less inclined to risk delaying field operations in the future, despite the benefits of the enhanced spring soil cover offered by the undercutter.

Table 1.7. Mean volumetric soil moisture and soil temperature measured prior to first spring field operations at 6.4 cm, and post-wheat planting at 10 cm, at Maine sites, and ANOVA results. Temperature values represent the mean daily temperature at 10 cm for 5 days surrounding the soil moisture sampling date.

	df	**ME17**				**ME18**	
		30 Apr. 2017	5 May 2017	17 May 2017	8 Jun. 2017	23 Apr. 2018	25 May 2018
				Mean soil moisture			
Termination method		———————————	———————	————— % —————	———————	———————	———————
PL		30 b †	31	29	17	17	13
SK		32 ab	31	27	16	18	13
UC		40 a	36	36	17	22	13
Source of variation				**ANOVA**			
Termination	2	*	ns	ns	ns	ns	ns
CV, %		14.4	12.1	16.6	13.3	17.0	5.3
				5-day mean soil temperature			
Termination method		———————————	———————	————— °C —————	———————	———————	———————
PL		11.6 a	10.9 a	15.1 a	17.0 ab ‡	9.0 §	16.9
SK		11.5 a	10.7 a	14.5 b	17.2 a ‡	-	16.8
UC		11.2 b	10.3 b	13.5 c	16.6 b ‡	9.0 §	16.6
Source of variation				**ANOVA**			
Termination	2	**	**	***	*	ns	ns
CV, %		1.4	1.6	2.1	1.5	3.0	3.0

*, **, ***, significant at $p<0.05$, $p<0.01$, and $p<0.001$.

† Within columns, means followed by the same letter are not significantly different according to Fisher's LSD (0.05).

‡ Mean of 8 Jun. to 11 Jun. '17.

§ Mean of 23 Apr. to 27 Apr. '18.

1.4.5. Wheat Plant Density

Wheat plant density (Table 1.8) was significantly impacted by termination method at ME17 but not at ME18. UC resulted in 81% lower stand counts than PL and SK, due perhaps to plant material on or near the soil surface following undercutting, impeding seed-soil contact at wheat seeding, or that newly incorporated red clover material having allelopathic effects on emerging wheat seedlings (Ohno et al., 2000). Plant density differences did not significantly affect final yield at ME17, suggesting that sufficient tillering took place between seeding and harvest in UC plots to compensate for lower initial plant density. At ME18, the target seeding rate was increased by 32% in response to poor stands the previous year and this appears to have led to improved crop densities across termination methods.

Table 1.8. Mean wheat stand counts for all sites, and ANOVA results.

		Wheat stand counts	
	df	**ME17**	**ME18**
Termination method		——plants m^{-2}——	
PL		352 a †	535
SK		323 a	539
UC		186 b	580
WK		-	579
Source of variation		**ANOVA**	
Termination	2,3‡	**	ns§
CV, %		19.6	8.6

** Significant at $p < 0.01$.

† Within columns, means followed by the same letter are not significantly different according to Fisher's LSD (0.05).

‡Degrees of freedom for ME17 and ME18.

§ ns, not significant.

1.4.6. Weed Biomass

Weeds at both Maine sites were primarily summer annuals: *Chenopodium album, Galinsoga ciliata*, *Digitaria sanguinalis*, and *Amaranthus retroflexus* dominated, as well as *Trifolium repens* at ME17. In Vermont, major weeds species included *Taraxicum officinale* and *Silene vulgaris*. High CVs for weed biomass reflect the characteristic patchiness of weed emergence, and may have masked possible treatment effects at all sites (Table 1.9). Variability at VT17 data was considered too high to reliably evaluate treatment effects. Mean weed biomass at this site was 461, 664, and 1673 kg ha^{-1} at stem extension (GS30-32), boot stage (GS40-49), and soft dough (GS85), respectively.

Table 1.9. Mean weed biomass at three growth stages of the wheat crop, and ANOVA results, for Maine sites.

	df	**Weed Biomass**					
		GS30-32		**GS55-59**		**GS85**	
		ME17	**ME18**	**ME17**	**ME18**	**ME17**	**ME18**
Termination method		kg ha^{-1}					
PL		502	97 b †	1081	648	1127 b	2433 b
SP		589	217 a	1120	637	1949 a	3906 a
UC		475	230 a	1329	653	2041 a	2198 b
WK		-	31 b	-	369	-	750 c
Source of variation		ANOVA					
Termination	2,3‡	ns §	**	ns	ns	**	**
CV, %		22.7	39.1	24.2	19.4	15.2	31.1
Green manure							
Clover		502	97	1081	648	1127	2433
No clover		524	89	998	577	1431	1390
Source of variation							
Green manure	1	ns	ns	ns	ns	ns	**
CV, %		19.2	20.5	15.7	30.7	42.9	8.6

*, ***, significant at p<0.05 and p<0.001.

† Within columns, means followed by the same letter are not significantly different according to Fisher's LSD (0.05).

‡ Degrees of freedom for ME17 and ME18.

§ ns, not significant.

At ME17, termination method affected weed biomass at soft dough stage (GS85) only, with UC and SK resulting in 73% and 81% higher weed biomass, respectively, relative to PL. At ME18, weed biomass was affected by termination method at both stem extension (GS30-32) and soft dough (GS85) stages. SK and UC resulted in significantly higher weed biomass than PL and WK at stem extension. Superior weed control following PL at both Maine sites may be linked to depth of disturbance, with fall moldboard plowing burying weed seeds deeper in the soil profile (Gruber and Claupein, 2009). At soft dough at ME18, SK resulted in significantly higher weed biomass than all other treatments, and PL and UC had significantly higher weed biomass than WK. Green manure treatment affected weed biomass only at soft dough at ME18, where the clover treatment resulted in 75% higher weed biomass than the no-clover treatment. This in an unexpected result, given that use of LGMs is linked to lower overall weed pressure in organic systems (Liebman and Davis, 2009).

1.4.7. Plant Nitrogen Uptake

Plant root simulator (PRS)® probes installed in consecutive burial periods after wheat planting in Maine detected no differences in extractable inorganic N among termination treatments (Table 1.10). Extractable inorganic N, as determined using PRS® probes, is influenced by both soil N dynamics and the depth at which the probes are buried in relation to the placement of the incorporated LGM residue within the soil profile. Future studies would benefit from placing probes at various depths to better understand the spatial variability of N mineralization resulting from these different termination methods. Soil inorganic N, measured sampling soil from a full 0-20 cm profile, revealed no significant effect of termination method at either site, though $p = 0.05$ at the start of BP1 at ME17

(Table 1.11). At this point in the season, which is less than one week after wheat planting, soil inorganic N is appreciably lower in SK and UC relative to PL, potentially indicating an early season burst in N mineralization from LGM residue in PL plots.

Table 1.10. Mean extractable inorganic N, retrieved from Plant Root Simulator® probes, for both Maine sites at consecutive burial periods (BPs), and ANOVA results. BPs were, for ME17, 7 June–19 June (BP1), 21 June-3 July (BP2), and 14 July-26 July (BP3), and for ME18, 17 May-29 May (BP1) and 6 June-18 June (BP2).

	df	**ME17**			**ME18**	
		BP1	**BP2**	**BP3**	**BP1**	**BP2**
Termination method		——————µg 10cm^{-2} 12 days^{-1}——————				
PL		517	303	23	229	148
SK		488	338	18	-	-
UC		514	381	22	385	155
Source of variation				**ANOVA**		
Termination	2	ns†	ns	ns	ns	ns
CV, %		9.7	26.4	30.0	23.2	13.8

† ns, not significant.

Table 1.11. Soil inorganic N, as determined by KCl extraction, at the start and end of BP1 and BP2 for both Maine sites, and ANOVA results.

	df	**ME17**				**ME18**			
		BP1		**BP2**		**BP1**		**BP2**	
		Start	**End**	**Start**	**End**	**Start†**	**End**	**Start**	**End**
Termination method		————————————kg N ha^{-1}————————————							
PL		73	69	69	21	-	57	56	30
SK		53	65	55	18	-	-	-	
UC		49	63	69	19	-	62	47	33
Source of variation						**ANOVA**			
Termination	2	ns‡	ns	ns	ns	-	ns	ns	ns
CV, %		23.1	29.2	18.7	23.0	-	32.1	28.5	63.2

† Not measured.
‡ ns, not significant.

Early season PNU was affected by termination treatment at both Maine sites (Table 1.12). At ME17, PL led to significantly higher PNU than SK and UC at both stem extension (GS30-32) and head emergence (GS55-59). The heightened PNU resulting from PL at ME17 may be due to the high degree of soil-to-residue contact achieved at the time of

termination, which may have hastened mineralization the following season relative to the other termination treatments, resulting in more inorganic soil N available for the wheat crop earlier in the season. This pattern does not hold at ME18, however, where SK results in significantly higher PNU than PL at stem extension. One possible explanation is that the SK treatment resulted in LGM residues concentrated closer to the soil surface, and ensuing N mineralization led to a pool of inorganic N more proximal to the roots of growing wheat plants than that of PL plots. Perhaps the relatively dry conditions at stem extension at ME17 stunted N mineralization across all treatments, and prevented this from being observed. More detailed data is needed about the spatial distribution of LGM residues following each termination method to more fully understand these N dynamics.

Green manure treatment affected PNU at ME17 at head emergence (GS55-59) and soft dough (GS85), with the clover treatment resulting in significantly higher PNU than the no-clover treatment at both stages. This was expected, as the clover treatment introduced an additional 3-44 kg N ha^{-1} into the system relative to the no-clover treatment (Table 1.5).

Table 1.12. Mean plant nitrogen uptake at stem extension, early head emergence, and soft dough stages, and ANOVA results, for all sites. Data for ME18 at head emergence (GS55-59) were log10 transformed meet assumptions of ANOVA, with back-transformed values presented in parentheses.

	df	Plant N Uptake								
		GS30-32			GS55-59			GS85		
		ME17	**ME18**	**VT17**	**ME17**	**ME18**	**VT17**	**ME17**	**ME18**	**VT17**
Termination method		kg ha^{-1}								
PL		66 a †	52 b	54	89 a	2.0 (90)	-	93	121	182
SK		51 b	65 a	41	64 b	2.0 (100)	-	73	120	143
UC		48 b	50 b	46	69 b	1.9 (84)	-	79	113	116
WK		-	44 b	-	-	1.9 (80)	-	-	88	-
Source of variation		**ANOVA**								
Termination	2,3‡	*	**	ns	*	ns	-	ns	ns	ns
CV, %		16.1	10.3	64.6	13.0	3.2	-	15.8	15.7	33.1
Green manure										
Clover		66	1.7 (52)	54	89	90	-	93	121	182
No clover		46	1.6 (41)	18	61	77	-	74	113	68
Source of variation		**ANOVA**								
Green manure	1	ns§	ns	ns	*	ns	-	*	ns	ns
CV, %		14.8	6.8	81.4	16.7	17.9	-	9.1	23.6	59.7

*, **, significant at p<0.05, p<0.01.

† Within columns, means followed by the same letter are not significantly different according to Fisher's LSD (0.05).

‡ Degrees of freedom for ME17 and ME18.

§ ns, not significant

1.4.8. Wheat Yield, Quality, and Grain Nitrogen Yield

Termination method and green manure treatment significantly affected wheat grain yield and quality (Table 1.13). Wheat grain yields averaged 2.6 Mg ha^{-1}, 1.9 Mg ha^{-1}, and 0.9 Mg ha^{-1} in ME17, ME18, and VT17, which are generally within the range of yield obtained for the Glenn variety in four years of variety trials at the same sites in Maine (2.3-3.9 Mg ha^{-1}) and Vermont (0.7-3.3 Mg ha^{-1}) (Mallory et al., 2012). The exception was ME18. Despite a higher seeding rate and higher crop density, yields at ME18 were lower than ME17, likely because of very high late-season weed biomass (Table 1.9), which may have also contributed to the high CVs observed in yield data from this site.

Table 1.13. Mean grain yield, test weight, grain protein concentration, grain N yield, and ANOVA results for wheat grown following termination for all sites. Grain yield data for ME17 and ME18, and grain N yield at VT17, were log10 transformed to meet the assumptions of ANOVA, with back-transformed values presented in parentheses.

		Grain yield			Test weight			Grain crude protein			Grain N yield		
	df	**ME17**	**ME18**	**VT17**	**ME17**	**ME18**	**VT17**	**ME17**	**ME18**	**VT17**	**ME17**	**ME18**	**VT17**
Termination method		——— Mg ha^{-1} ———			— kg m^{-3} —			—— g kg^{-1} ——			— kg ha^{-1} —		
PL		0.4 (2.8)	0.3 (1.9)	1.4 a †	806	750	725 ab	142 a	165	181 a	72 a	58	27
SK		0.4 (2.6)	0.3 (2.1)	0.9 ab	811	743	730 a	133 b	171	175 a	65 a	70	24
UC		0.4 (2.3)	0.2 (1.5)	0.4 b	799	745	705 b	131 b	161	163 b	52 b	44	29
WK		-	0.3 (2.1)	-	-	758	-	-	166	-	-	60	-
Source of variation							**ANOVA**						
Termination	2,3,2‡	ns§	ns	*	ns	ns	*	*	ns	*	**	ns	ns
CV, %		13.8	54.1	33.6	0.9	1.6	1.5	3.3	5.0	3.4	9.9	34.9	50.6
Green manure													
Clover		2.8	1.9	1.4	806	750	725	142	165	181	72	58	1.4 (27)
No clover		1.9	2.4	0.4	810	764	705	132	162	153	44	68	1.2 (17)
Source of variation							**ANOVA**						
Green manure	1	***	ns	***	ns	*	ns	*	ns	*	**	ns	ns
CV, %		6.7	18.2	24.5	1.0	0.3	13.6	2.6	3.5	5.4	9.2	17.7	15.7

*, **, ***, significant at p<0.05, p<0.01, and p<0.001.

† Within columns, means followed by the same letter are not significantly different according to Fisher's LSD (0.05).

‡ Degrees of freedom for ME17, ME18, and VT17.

§ ns, not significant.

At ME17, the higher early season PNU in PL did not translate into significantly higher yields for this treatment, nor were differences detected in ME18 yields. A similar finding was observed by Sainju and Singh (2001) in an investigation of N dynamics following different cover crop termination methods in a corn silage system. Despite greater N mineralization of cover crop residue following moldboard plowing and chisel plowing relative to a no till treatment, the authors detected no significant differences in silage corn yield (Sainju and Singh, 2001). Termination treatment did affect wheat yield at VT17, where UC resulted in 71% lower yield than PL, but this effect cannot be attributed to differences in PNU, as none were observed.

Test weights were highest at ME17, followed by ME18 and VT17. ME17 was the only site to achieve mean test weights above the USDA's official weight per bushel for highest grade wheat (772 kg m^{-3}). Low test weights in wheat are typically caused by insufficient fertility, significant pest and weed pressure, or lodging events, and can lead to a reduction in crop sale price (Lyon and Hergert, 2012). High weed biomass during grain fill at ME18 and VT17 (Table 1.9) may help to explain this result. Test weight was affected by termination treatment at VT17 only, where UC resulted in significantly lower test weight relative to SK, a difference of 3%.

Mean grain crude protein (GCP) values were highest at VT17, averaging 168 g kg^{-1}, and lowest at ME17, averaging 135 g kg^{-1}. This is likely due to the negative relationship between yield and protein, as documented by Fowler et al. (1990). GCP, an important quality parameter for bread wheat, was affected by termination treatment at ME17 and VT17. At ME17, SK and UC resulted in significantly lower GCP relative to PL (by 7% and 8% lower for SK and UC, respectively). At VT17, GCP following UC was significantly lower than

both PL (by 11%) and SK (by 7%). Grain N yield was affected by termination treatment at ME17 only. At this site, mean grain N yield following UC was significantly lower than that following PL (by 38%) or SK (by 25%). Again, high CVs may have masked treatment effects at ME18 and VT17.

While no differences in yield were detected among termination treatments at ME17, the observed differences in GCP and grain N yield suggest that N dynamics were impacted by termination method. GCP is strongly tied to soil N availability during crop growth, particularly late-season, during grain fill (Mallory and Darby, 2013). Given that higher GCP resulted from PL at ME17, we would therefore have expected to see such a pattern mirrored in soft dough PNU, though no such difference was detected. Differences were detected, however, in stem extension and head emergence PNU, with PL resulting in higher values than UC and SK. Taken together, it appears as though the heightened early- and mid-season N uptake exhibited by the crop following PL was enough to significantly boost GCP relative to the other termination treatments. At VT17, the difference observed in GCP, in which UC GCP is significantly lower than PL or SP, cannot be explained by PNU at any growth stage based on our analyses. Furthermore, contrary to the negative yield-protein relationship typically observed in wheat (Fowler, 2003), the treatment with the lowest yield (UC) also has the lowest GCP at VT17. The difference detected in grain N yield at ME17 was not mirrored in grain yield, unlike what has been observed in previous studies (Fowler and Brydon, 1989; Mallory and Darby, 2013), suggesting that another factor (i.e., weed pressure) may have impacted the relationship between yield and protein.

In most measures, the clover treatment had a positive or neutral effect on grain yield and quality. At ME17 and VT17, the clover treatment resulted in higher yields (by

47% at ME17 and 250% at VT17) and higher GCP (by 8% at ME17 and 13% at VT17) than the non-clover treatment. Grain N yield was also significantly higher following clover at ME17 relative to non-clover. While studies on the impacts of red clover on hard red wheat are scarce, the positive impact of red clover on subsequent corn yield has been well-documented (Stute and Posner, 1995; Vyn et al., 2000; Liebman et al., 2011). As with yield, the observed effect of the green manure on GCP and grain N yield likely stem largely from the additional N introduced into the system. However, non-N benefits associated with incorporated red clover, such as increased soil microbial activity and soil organic matter (Sarrantonio and Gallandt, 2003; Henry et al., 2010), may also be at play. The only measure in which the non-clover treatment outperformed the clover treatment was test weight at ME18, where the clover treatment resulted in 2% lower test weight than non-clover.

1.4.9. Nitrogen Utilization Efficiency and Nitrogen Harvest Index

Nitrogen utilization efficiency (NUtE) and N harvest index (NHI) express the response of grain yield and grain N yield, respectively, to wheat N uptake at peak biomass (Dawson et al., 2008), and are used as measures of the overall efficiency of N use under different agronomic conditions (Huggins and Pan, 1993). Mean NUtE and NHI were higher at ME17 (41 g g^{-1} N and 0.99%, for NUtE and NHI, respectively) than ME18 (22 g g^{-1} N and 0.63%, respectively) (Table 1.14). High variability at VT17 data precluded statistical tests, and therefore data is not displayed. NUtE and NHI were impacted by termination treatment at ME17 only, where PL resulted in significantly lower mean NUtE and NHI relative to SK. At ME18, no differences were detected among termination treatments for either measure.

Table 1.14. Nitrogen utilization efficiency (NUtE) and N harvest index (NHI) for wheat at Maine sites, and ANOVA results.

	df	**NUtE**		**NHI**	
		ME17	**ME18**	**ME17**	**ME18**
Termination method		——g g^{-1} N——		———%———	
PL		37 b †	20	0.89 b	0.57
SK		49 a	24	1.20 a	0.72
UC		45 ab	17	1.08 ab	0.48
WK		-	25	-	0.73
Source of variation			**ANOVA**		
Termination	2,3‡	*	ns§	*	ns
CV, %		13.8	24.3	12.0	22.6
Green manure					
Clover		37	20	0.89	0.57
No clover		33	22	0.78	0.63
Source of variation			**ANOVA**		
Green manure	1	ns	ns	ns	ns
CV, %		18.8	24.1	18.2	23.7

*, **, significant at p<0.05, p<0.01.
† Within columns, means followed by the same letter are not significantly different according to Fisher's LSD (0.05).
‡ Degrees of freedom for ME17, ME18.
§ ns, not significant.

1.4.10. Winterkill Termination of Field Pea

At ME18, an additional termination treatment was included to assess the efficacy and N dynamics of winterkilled field pea relative to original treatments. The potential advantages to using winterkill (WK) relative to PL, SK, or UC include the lack of fall soil disturbance, and the retention of maximum soil surface residue through the winter. This "climatic termination" method has been shown to be successful in no-till vegetable systems (Grimmer and Masiunas, 2004; Lounsbury and Weil, 2015). In the present study, prior to the first killing frost in 2017, the field pea LGM had an aboveground biomass of 2334 kg ha^{-1}, an N content of 95 kg ha^{-1} (31% higher aboveground biomass and 64% greater N content than red clover in ME18) and a C:N of 10. Overwinter soil cover in this treatment equaled

that provided by UC, which was substantially greater than either PL or SK. Due to its low C:N, pea residue is apt to decompose quickly on the soil surface, which may allow farmers to avoid difficult spring residue management in preparation for planting, but may also lead to early season N loss in the event of heavy spring rain. Winterkill resulted in statistically similar yield and grain protein to other termination methods.

1.5. Conclusions

Results from this study indicate that low-disturbance, high-residue LGM termination methods hold promise for organic small grain growers in northern New England. UC successfully enhanced winter soil cover at all sites, fulfilling a need for growers concerned about off-season soil erosion. Poor kill efficacy was the chief tradeoff associated with UC, leading to a high degree of spring LGM regrowth. This suggests that further research is needed to determine optimal undercutter design for severing clover taproots. Additionally, alternative termination timings and LGM species should be explored in conjunction with UC to hone this method. PL outperformed SK and UC with regard to early and mid-season PNU and GCP only at ME17, and differences in grain yield were only detected at VT17. SK may be an attractive alternative termination method growers, as it requires only a simple adjustment to an implement many farmers already own, though in most cases this method did not outperform PL, our region's "standard" termination method.

Further work is needed to determine the minimum soil working depth required for SK to perform optimally, to arrive at a favorable balance between soil conservation, termination efficacy, and efficient N use efficiency for a subsequent crop. WK is promising as another potential alternative LGM termination method for growers in this region, offering enhanced overwinter soil cover, significantly lower late season weed biomass, and similar grain yield and quality when compared to other treatments. Future studies should seek to identify LGM species that produce ample biomass and winterkill readily.

CHAPTER 2: CHALLENGES, STRATEGIES, AND RESEARCH PRIORITIES IN LEGUME-BASED NITROGEN MANAGEMENT FOR ORGANIC SMALL GRAIN PRODUCERS IN THE NORTHEASTERN U.S.

2.1. Chapter Abstract

Successful nitrogen (N) management is essential for ensuring high yields and crop quality in organic small grain (OSG) operations. Experienced farmers and advisors in the Northeastern U.S. were asked to identify and discuss the most pressing challenges in organic N management for OSG systems, with a particular focus on legume green manures (LGMs). Eighteen semi-structured interviews with 20 participants were conducted between December 2017 and March 2018. Growers employed a range of materials and practices for fulfilling the N fertility needs of their crops, including LGMs, animal manures, and organic fertilizers. Farmers and advisors identified cost, overdependence on external N sources, N source access, diversifying rotations, weed management, and predicting N mineralization of organic residues as major challenges in N management. Results indicated that cost-effectiveness in N management is essential, but that growers consider additional factors, such as weed pressure, long-term soil health effects, and their overall level of economic stability, when choosing N sources or practices.

We found evidence that practice perceptions, including observability and complexity, may also impact decision-making, though more targeted qualitative investigation would help to elucidate farmers' decision-making process. Given the recent loss of a major poultry manure source in Maine, growers require support shifting from input-based N management to a legume-based system, which may necessitate system redesign. However, structural challenges, such as the lack of animal agriculture proximal to

grain operations, and limited cash crop markets, impede the development of diverse rotations that feature long-term legume sods. Additional field-based research and economic analysis is needed to determine whether farm-grown legume seed meals provide a suitable N alternative to imported animal manures. On-farm, participatory LGM research may harness farmer innovation to help remove in-field barriers associated with intercropping and termination, and better predict N outcomes in local climatic conditions. Programming and educational outreach should focus on bolstering grower understanding of N mineralization of incorporated LGM residues, potential sources of variability in LGM systems, and how to leverage the multiple ecosystem benefits of LGMs to provide the greatest environmental and economic impacts.

2.2. Introduction

The recent rise in consumer demand for organic small grain (OSG) products in the Northeastern U.S. has created a significant economic opportunity for organic growers to produce small grains, including wheat, oats, rye, and barley. The growth and sustained success of this emerging organic sector relies on the existence of affordable sources of nitrogen (N) and N-building practices that are compatible with small grain-based cropping systems. N management can present a formidable challenge for organic producers, who are restricted from using chemical fertilizers in their production, and must instead rely on animal manures, legumes, soil organic matter, and organically-approved fertilizer blends to supply N to their crops (Watson et al., 2002). N is yield-limiting in most organic systems (Berry et al., 2002), and as such, failing to successfully manage N can result in economic consequences. In this study, we investigate the N management practices of OSG producers

using a qualitative approach, with the goal of identifying major challenges and optimizing future research and programming.

Prior research regarding N management in OSG systems has focused primarily on assessing agronomic performance of small grains under various nitrogen management regimes (Olesen et al., 2007; Dawson et al., 2008; Olesen et al., 2009; Mallory and Darby, 2013; Roche et al., 2017) including the use of legume green manures (LGMs) (Vaisman et al., 2011; Tamm et al., 2016). LGMs are leguminous plants established primarily to amend soil and provide nutrients to subsequent crops (Cherr et al., 2006). The atmospheric N fixed by LGMs is released in an inorganic form into the soil when the plant tissues degrade. In regions where farmers' access to animal manure is limited, which describes an increasingly large swath of the U.S., LGMs can provide an affordable N supply for OSG crops, capable of producing between 10-108 kg N ha^{-1} (Gaudin et al., 2013). The use of LGMs is often characterized as an agroecological practice, as it is associated with multiple ecosystem services, including weed control (Amossé et al., 2013), pest and disease suppression (Gaudin et al., 2013), and building soil organic matter (Cherr et al., 2006). Success in LGM use, however, can be compromised by management-related challenges, including failure to establish even LGM stands (Queen et al., 2009; Muñoz et al., 2014) and issues with termination (Creamer et al., 1995; Clark, 2007).

As OSG production continues to expand in the Northeast, it is essential for agricultural advisors, such as extension personnel, to tailor future programming and research to meet the unique needs of OSG producers with regard to N management. A key area in need of investigation is the adoption and use of LGMs by growers. Past studies focused on adoption of agroecological practices have identified factors such as

socioeconomic status and education level (Kim et al., 2005), ecological awareness (Blesh & Wolf, 2014; Wilson et al., 2014), social norms (Cranfield et al., 2010), and past experiences (Chongtham et al., 2016; Corselius et al., 2003) as influential in predicting use of such practices among farmers. However, meta-analyses of literature on the adoption of agricultural innovations have failed to identify variables that successfully, and universally, predict use or disuse (Knowler and Bradshaw, 2007; Carlisle, 2016), in large part due to the lack of homogeneity across farming communities. It has been suggested, therefore, that in order to be successful, efforts to remove barriers to the adoption of these practices should be based on locally-specific research (Knowler and Bradshaw, 2007). Research has also highlighted the importance of looking beyond basic agronomic field challenges experienced by farmers, to potential structural challenges, such as those related to market diversity and economics, that might inhibit practice adoption (Carlisle, 2016; Roesch-McNally et al., 2017).

Qualitative research methods, and interviews in particular, have the potential to offer an in-depth understanding of farming challenges (Prokopy, 2011), and can lead to the development of more targeted research, programming, and outreach with which to serve the agricultural community (Llewellyn et al., 2005; Garst and McCawley, 2015). In this study, we use interviews to identify current challenges encountered by OSG producers in the Northeast U.S. with regard to N management, and highlight successful grower strategies, from the perspectives of farmers and their advisors. In particular, we assess the role of LGMs in N management, and uncover potential barriers faced by growers wishing to increase their usage of legume-based N on-farm. We conclude with suggestions for future research and programming.

2.3. Methods

In order to capture a range of perspectives on N management and LGM use in Northeastern U.S. OSG systems, both farmers and agricultural advisors were interviewed for this study. Farmer interviewees (10 male and 2 female) from 11 individual operations were selected based on the recommendations of advisor participants, who were asked to identify experienced, successful OSG growers in their region. Two of the farmer participants were co-owners of the same operation, and were interviewed together; this interview is treated as a single sample to avoid confusion and artificial inflation of results. Farmers' operations were located in Maine (n=5), Vermont (n=2), New York (n=1), New Jersey (n=1), and Pennsylvania (n=2), and varied in acreage (Table 2.1) and types of crops grown (Table 2.2). With one exception, all operations were certified organic, though the one uncertified farmer described using strictly organic growing methods. Two growers owned split operations, with part of their total acreage in conventional production. The majority of growers operated on land that was mostly or entirely rented, and all but two farmed full-time. Five of eleven operations owned cattle, and six of eleven had the capacity to add value to their OSG product on-farm by milling or grinding. Growers varied in their choice of primary and supplementary sources of N fertility, with a majority (63%) using a combination of animal manure and LGMs.

Advisors included extension personnel, university faculty members, and technical service providers from the Northeast region. Advisor participants (6 male and 2 female) were selected based on their expertise in the field of soil fertility and OSG systems in the Northeastern U.S. Individuals from Maine (n=2), Vermont (n=1), Massachusetts (n=1), New York (n=1), New Jersey (n=1), and Pennsylvania (n=2) participated. All but two described

working closely with OSG farmers on a regular basis, and all had previously led, or contributed to, formal research and/or outreach efforts focused on the enhancement of OSG systems. In one interview, an advisor was accompanied by his graduate student, who is also an organic grain farmer. This interview is treated as a single sample.

Table 2.1. Farmer interviewees and operation characteristics (LGM = legume green manure; CtlM = cattle manure; PltM = poultry manure; SN = sodium nitrate; OFB = organic fertilizer blend; on/off-farm indicates whether material originates from grower's operation or is imported).

Sta.	**Years Organic**	**Full-time Farmer?**	**Cropped Organic Acreage**	**Split Operation?**	**% Rented Cropland**	**# Cattle**	**Value added on-farm?**	**Primary N Source**	**Secondary N Source(s)**
ME	8	No	15	No	<50%	0	Yes	PltM	LGM
ME	15	Yes	70	No	>50%	15-20	No	CtlM	CtlM (on-farm)
ME	10	No	200	No	>50%	0	No	PltM	N/A
ME	21	Yes	300	No	>50%	0	Yes	LGM	PltM, SN
ME	10	Yes	1500	Yes	<50%	0	No	OFB	LGM
VT	11	Yes	50	No	>50%	30	Yes	CtlM (on-farm)	PltM
VT	6	Yes	100	No	>50%	32	Yes	LGM	CtlM (on-farm)
NY	27	Yes	1200	No	100%	0	Yes	LGM	PltM, SN
PA	28 †	Yes	8	No	100%	0	No	LGM	OFB
PA	10	Yes	60	No	100%	60-80	Yes	CtlM (on-farm)	LGM, PltM
NJ	-	Yes	300	Yes	>50%	-	No	CtlM (on-farm)	PltM, LGM

†This grower is not certified organic, but describes using strictly organic growing practices.

Table 2.2. Crops grown by farmer participants.

Small grain crops	**Operations reporting**
Wheat (spring or winter)	9
Oats (spring)	8
Rye (winter)	7
Barley (spring)	3
Spelt	3
Emmer	1
Other field crops	
Buckwheat	5
Corn	4
Soybeans	4
Field peas	3
Dry beans	2
Potatoes	1

Following approval from the University of Maine Institutional Review Board for the Protection of Human Subjects, eighteen telephone interviews, with 20 total participants, were conducted between December 2017 and March 2018 by one of the authors. Separate interview guides were created for farmer and advisor participants, in order to target the experiences and expertise of the two groups, though significant overlap existed between the questions in each guide. Questions for farmers focused on their experience with LGMs, such as, "How has using LGMs affected production of your cash crops?" and "Can you think of anything that would make your use of LGMs more successful?" Farmers were also asked about the challenges they faced with N fertility management in general, and about their experience using other N sources. Advisors were asked a similar set of questions, based on their experience working with the growers in their region. In addition, they were asked about the level of success of any previous programming and outreach efforts in N management they had been involved in producing.

Interviews were typically 60 minutes in duration, and were semi-structured, allowing for occasional follow-up questions from the interviewer (Bernard, 2011). Farmer participants were offered US$50 to reimburse them for their time. With participant permission, interviews were digitally recorded, and audio recordings were transcribed verbatim and checked for accuracy by one of the authors. Analysis was performed using MAXQDA (VERBI Software, 2018). An initial round of open coding was performed on all transcripts, followed by subsequent, targeted coding to identify major challenges, strategies, and needs regarding N fertility.

2.4. Results

Farmer and advisor responses are discussed together, as in most cases, the responses from these two groups were similar and complement each other well. However, advisors tended to discuss trends that existed among multiple growers with whom they worked, and farmers typically spoke exclusively about their own operations. Quotations have been edited lightly for grammar.

2.4.1. Description of Nitrogen Management Systems

Farmer participants employed a range of materials and practices for supplying N fertility to their small grain crops, but most favored one in particular (Table 2.1). At the time of the interviews, six operations used predominantly animal manure, with three using primarily cattle manure generated on their own farms, and three importing poultry or cattle manure from off-farm. Raw manures were typically broadcast and incorporated prior to small grain planting, or applied to a cover crop preceding a small grain. Pelletized and granulated poultry manure products were also used by growers, and these were typically banded in-row at planting. One farmer used an organic fertilizer blend (NatureSafe, 10-2-8)

as the primary N source for his small grain crop, which he applied at planting using a standard grain drill.

The remaining four farmers used legume green manures (LGMs) to supply the majority of their crops' N needs. Most growers who utilized LGMs favored red clover (*Trifolium pratense*, L.), a short-lived perennial that overwinters in most of the Northeast U.S. In most cases, red clover was established as an intercrop by planting between the rows of small grains. Clover establishment was achieved through frost-seeding in winter grains, or broadcasting at or following crop planting for spring grains. Two spring grain growers described waiting to underseed clover until their crop reached three-to-four-leaf stage in order to minimize LGM-crop competition. Two growers used crimson clover (*Trifolium incarnatum*, L.) and one used yellow sweetclover (*Melilotus officinalis*, (L.) Pall.) as green manures, though these were typically established as sole crops or mixed with a grass, rather than intercropped with a small grain. Farmers described growing LGMs for as little as several months, or up to several years, before incorporation. All but one used a moldboard plow to terminate the green manure, with the remaining grower using a heavy disk.

Two growers, both of whom used LGMs as their predominant N source, reported using sodium nitrate ('Chilean nitrate') as a supplementary N source. These farmers described broadcasting the product onto spring and winter wheat at tillering or flag-leaf stage for yield or grain protein enhancement, respectively. Sodium nitrate, a mined product containing high soluble N, is currently permitted by National Organic Program regulations, though its use in organic production is prohibited in several countries (McEvoy, 2012).

2.4.2. Challenges in Nitrogen Management

Farmers and advisors identified a range of challenges regarding N management for organic small grains (Table 2.3). In general, significant overlap existed between the major challenges identified by farmers and advisors, suggesting a high level of communication between these two groups. Cost of N management was the most cited general challenge, followed by overreliance on, and inconsistent availability of, off-farm N sources, rotation diversity, weed pressure related to N management, and predicting N mineralization. Top challenges in legume-based management included termination timing and method, and the cost and availability of high-quality LGM seed. In manure-based systems, participants identified material access, transport, and application as top challenges, followed by perceived negative impacts of chicken manure use on soil health and weed pressure. Material cost was the only challenge identified in fertilizer-based N systems, mentioned by the sole farmer who used primarily organic fertilizer blends for N fertility. Fertilizer-based systems were underrepresented in this study. Some challenges raised were crop-specific, such as growers of wheat expressing concern about achieving high grain protein.

Table 2.3. Major challenges in nitrogen management, as identified by farmers and advisors, and number (fraction) of interviews in which challenge is mentioned for each participant group.

Coded Challenge	**Overall mentioning (n=18)**	**Farmers mentioning (n=11)**	**Advisors mentioning (n = 7)**
GENERAL			
Cost of N management	13	6 (0.55)	7 (1.00)
Dependence on off-farm N sources	10	4 (0.36)	6 (0.86)
Reliable N source access	10	5 (0.45)	5 (0.71)
Rotation-building	7	3 (0.27)	4 (0.43)
Weed pressure resulting from N mgmt.	6	4 (0.36)	2 (0.28)
Predicting N mineralization of organic materials	4	2 (0.18)	2 (0.28)
Weather unpredictability	4	3 (0.27)	1 (0.14)
Meeting grain quality parameters	4	1 (0.09)	3 (0.43)
Underusing N	3	0	3 (0.43)
Balancing high yields with lodging risk	3	2 (0.18)	1 (0.14)
Long-term thinking	3	1 (0.09)	2 (0.28)
New farmer/no capital	2	1 (0.09)	1 (0.14)
Poor soil health	2	1 (0.09)	1 (0.14)
LEGUME-BASED			
LGM termination timing and method	6	4 (0.36)	2 (0.28)
LGM seed availability and cost	5	4 (0.36)	1 (0.14)
LGM issues with intercropping	4	3 (0.27)	1 (0.14)
LGM phytotoxicity and disease	3	3 (0.27)	0
MANURE-BASED			
Access and transport	11	7 (0.63)	4 (0.57)
Difficulty with application	7	4 (0.36)	3 (0.43)
Poul. manure detrimental to soil health	6	2 (0.18)	4 (0.57)
Poul. manure encourages weeds	5	4 (0.36)	1 (0.14)
Poul. manure hosts diseases	2	1 (0.09)	1 (0.14)
Poul. manure N synchrony	2	1 (0.09)	1 (0.14)
Poul. manure variable N content	2	1 (0.09)	1 (0.14)
Poul. manure ethical/philosophical	2	2 (0.18)	0
FERTILIZER-BASED			
Material cost	3	1 (0.09)	2 (0.28)

2.4.2.1. Cost of Nitrogen Management

The cost of N management was mentioned in six out of eleven farmer interviews, and all advisor interviews. Farmers and advisors cited the cost of high-quality LGM seed, as well as the opportunity cost of growing a LGM rather than a cash crop, as major expenses in legume-based systems. Costs incurred in material purchase, transportation, and application were identified as the greatest expenses associated with manure-based systems, while upfront material cost was reported as a formidable expense in the one fertilizer-based system in this study.

In general, farmers described N fertility as costly, but worthy of investment. One farmer described how his willingness and ability to invest in N fertility for his crops grew as his farm business accrued capital through expansion and diversification:

> *When you're starting out...you don't have any cows, you don't have any nutrients, so you're trying to make a living, but inputs are expensive. Only in recent years have we been able to start adding inputs like wood ash, chicken litter. Now we have enough of our own animals that we have really awesome compost[ed manure]. Now the yields are coming up, the quality is improving, because now we have the money to actually put some fertility and inputs in a serious way back onto our land* (Farmer, Vermont).

Farmers often paired their acknowledgement that N management was expensive with a justification for that cost. For example, several described a strong link between their investment in fertility and heightened crop yield and quality:

You buy some of these cheaper nitrogen sources, and it's a hit or miss if you put the right amount of nitrogen on per acre. The more expensive nitrogen sources can be calibrated pretty much 100%. And to get maximum yields, you need that exact right amount of nitrogen (Farmer, Maine).

Advisors perceived that farmers' N management decisions were highly dependent on cost. Several advisors described N fertility as "*a major out-of-pocket expense*" each year for OSG growers, who could not expect to achieve the same high economic return for their crop as their vegetable-growing counterparts. Two advisors suspected that, as a result, many growers regularly under-applied N, to the detriment of crop yield and quality. This was compounded, they said, by the difficultly of identifying nitrogen deficiency as a yield-limiting factor in complex organic systems; one advisor observed that growers with whom he worked tended to prioritize addressing more "visible" issues on-farm, such as weeds:

Nitrogen could be a major yield-limiting factor, but you wouldn't necessarily know that. If you drive by a field and it's loaded with weeds, you can say, 'I've got a major weed problem that's limiting my yield, I know it is' (Advisor, Maine).

Three advisors, in Maine and Pennsylvania, said that raw poultry manure was favored by the majority of growers in their respective states as a major N source because of its high N content and affordability relative to other available N sources. The advisors in Maine explained that growers in their state had recently and abruptly lost access to their main supply of the manure, leaving many without a viable substitute for the coming season, and presenting a pressing need to identify alternative solutions.

2.4.2.2. Dependence on Off-Farm Nitrogen Sources

Dependence on external sources of N was presented as a challenge in four out of eleven farmer interviews and six out of seven advisor interviews. Only one farmer in this study described using exclusively on-farm sources of N, though three others expressed a desire to eliminate their use of external N sources in the future. Farmers described that overreliance on off-farm N made their operations vulnerable; reliable N source access was described as a challenge in five out of eleven farmer interviews. Three of the five interviews with Maine farmers included references to the impending loss of a major poultry manure source:

> *If that manure source becomes unavailable, I think we're going to be in for a challenge on finding something that's both economical and effective as fertilizer* (Farmer, Maine).

Farmers also described how their desire to limit their use of off-farm N stemmed from economic considerations, citing high transportation costs and difficulty with application. Others described how reliance on external N did not align with their farming ideals:

> *I'm not trying to make my organic farm mimic a conventional farm, where I can just add 'x' amount of nitrogen per acre and get it to work. I want to build a soil that can feed a low-feeding crop year after year, with minimal inputs.* (Farmer, Maine)

Growers without their own livestock appeared to encounter difficulty accessing locally produced animal manures. Indeed, two farmers and four advisors referred to the dearth, or ongoing decline, of animal agriculture operations within grain growing regions, indicating that market forces were not currently supportive of growth in those industries, and presenting a barrier to regional livestock integration. Four farmers expressed a desire to increase their usage of LGMs as a way to enhance their supply of on-farm N, but identified field-based challenges, such as intercropping issues, as potential barriers:

We have gone in and done some frost-seeding, or mud-seeding really, because the frost-seeding thing, while great in theory, I realized it's not too many years that you can consistently get out there on ground that is frozen without snow on it. (Farmer, Maine)

We have had years where the [intercropped] clover has grown [up] through the wheat crop [canopy], and we've either lost the wheat crop or it was kind of a mess. So that is definitely a risk. (Farmer, New York)

Like farmers, advisors expressed that relying heavily on off-farm N sources left growers vulnerable to abrupt changes in access, compromising their operation's resilience: "*That's a terrible trap to run into, because those supplies are not inexhaustible, just as they're finding out*" (Advisor, New York). Indeed, reliable access to N sources was cited in five out of seven advisor interviews as a major challenge. They expressed that overreliance on external N sources was a wide-scale problem in OSG production, not limited to the Northeast US:

When I was in Sweden, it was a yeast [byproduct]. So that whole region was really reliant on this source of nitrogen. What happens if that yeast factory went away? The growers would be in trouble. (Advisor, Maine)

Advisors also observed that importing nutrients cheaply had encouraged growers to decouple their N management from soil-building practices that they saw as fundamental to lasting success in organic agriculture:

My overall feeling from the farmers is that [imported] poultry manure isn't building soil health at all. It's allowing growers to get along with that as a crutch. (Advisor, Maine)

In three advisor interviews and one farmer interview, participants expressed that the long-term use of poultry manure led to negative environmental consequences, namely the buildup of excess soil phosphorus.

2.4.2.3. Diversifying Rotations

Diversifying rotations, in the context of efficient and economical N management, was cited as a challenge in three out of seven advisor interviews and three out of eleven farmer interviews. Three farmers indicated that they wished to improve their crop rotation by increasing or diversifying their use of legume crops and LGMs, but felt they lacked information about how to do so in a way that made sense economically:

> *We're hoping for a rotation that's good for soil-building and nitrogen accumulation, and also profitable…We're thinking of maybe trying to introduce soy[beans] into the system, but we're not sure yet if there would be a market for it. [And] there isn't that large of a market for peas.* (Farmer, Maine)

An advisor in Maine echoed this, noting that options for OSG-based crop rotations were limited by the lack of different cash crops with existing local markets, which thereby limited the rotational windows in which soil-building crops like LGMs could be planted: "*I think that's really the thought we've been challenged with, is finding other markets for things that give us some [rotational] options*" (Advisor, Maine).

2.4.2.4. Weed Pressure Resulting From Nitrogen Management

All farmer participants described issues with weed pressure in their production, and four out of eleven farmers linked past or current weed issues to their management of N. Most of the discussions surrounding weed pressure and N management involved the use of animal manures. Two farmers described past experiences in which they'd applied poultry manure too aggressively, inadvertently stimulating weed growth to the detriment of their crop:

I thought, well, I have some chicken litter, let's put this on. And it was early. And the weeds grew like crazy! Got ahead of the wheat, and I couldn't harvest it. I never had weeds like that in wheat. Oh! That was a mistake. (Farmer, New Jersey)

One grower made the connection between using poultry manure and seeing an overall increase in pernicious perennial weeds in his system:

The manures, they have a lot of organic salt, and you'll get a weed like quackgrass, which thrives in that situation. And quackgrass can overwhelm you if you give it too good an environment to grow in. (Farmer, Maine)

These negative experiences encouraged farmers to alter their N management, such that the use of raw poultry manure was greatly limited or completely eliminated in their production.

Weed pressure was also discussed in relation to utilizing cover crops and green manures. Four farmers cited weed control as a significant benefit to undersowing a LGM into the understory of a small grain, and one farmer who expressed interest in increasing his use of LGMs stated that enhancing weed control was his primary goal for doing so. An advisor from Maine, however, noted that the threat of perennial weeds developing in a long-term LGM sod could dissuade new farmers, or farmers working new land, from establishing LGMs in their rotation:

If [the land] has been in CRP (Conservation Resource Protection), and you can't use glyphosate to control the perennial weeds, you're dealing with a perennial weed problem for a while. I think [growers are] sometimes reluctant to go back into a perennial system, which would allow those weeds to build back up again. (Advisor, Maine)

2.4.2.5. Predicting Nitrogen Mineralization from Organic Residues

The prediction of N mineralization from organic materials, such as LGM residues, was identified as a challenge by three farmers and two advisors. Farmers without significant prior experience in legume-based N management expressed uncertainty that LGMs or other legume N sources could adequately supply their crop with N, citing an inability to "quantify" N release rate and overall N contribution:

> *You can grow an alfalfa [green manure], and say it can produce a hundred forty pounds of N, right? How is that broken down?...If I wanna go and buy a bag of triple-10, then I pretty much know that 10% of that's gonna be available nitrogen. But when you go and use soybean meal, is it [broken down] that way? You know, I don't know that.* (Farmer, Maine)

> *I've had some really good stands of clover. I'm sure it's doing something good, but I don't really count on it [as a nitrogen source] for my next crop…I do it because I think it helps, but I don't know that I can necessarily quantify exactly how it helps and how much it helps.* (Farmer, Maine)

A farmer who relies almost entirely on LGM-based N offered a contrasting perspective regarding the need to predict N mineralization from his incorporated residue, considerably more laid-back: "*Our attitude is to just try to build good, healthy soil and don't worry about it*" (Farmer, Vermont).

Farmers growing bread wheat tended to be more concerned about the timing of N release from incorporated residues, citing that this was likely to affect the protein content of their grain: "*Where we've had problems is during certain periods of plant development [in winter wheat] when we don't have good mineralization [of LGM residues] in the soil, when the*

soil is cold…when the soil microbes aren't doing much for me" (Farmer, New York). In response to this, several wheat growers described employing sodium nitrate as a supplemental N source.

Advisors described how uncertainty was inherent in legume-based N management, and that farmers yearning for simple, straightforward guidance regarding the expected N contribution of LGMs were often disappointed. An advisor explained that, while simplicity was elusive in LGM-based systems, bolstering farmers' understanding of underlying biological concepts could enable them to make more informed decisions, minimizing risk in their unique operation and helping them to better cope with variability:

> *People are still asking the same questions. You know, how much nitrogen do you get from this or that. And the answer is "it depends"... If it's a good stand, it can be as good as this, and if it's a bad stand, it can be as low as this. So, [growers] have to take basic information on [N] mineralization, so that they understand the process and can make decisions for their farm. It's never going to be perfect.* (Advisor, Vermont)

Another advisor suggested that harnessing grower innovation through on-farm, participatory research could help increase grower confidence in using legume sources of N:

> *I'd like to see some of this [research] done on-farm in very simplified systems. Getting farmers to work these legumes into their systems. Because, inevitably, it's their system, and they're going to do everything they can to not let it fail. So a lot of innovation can come from the growers themselves.* (Advisor, Maine)

2.4.3. Strategies for Successful Management of Legume Green Manures

Farmer and advisor participants presented strategies for the successful management of LGMs (Table 2.4) . The major expenses associated with LGM management were identified as the cost of high quality seed, and the opportunity cost garnered by using field space to grow a cover crop rather than a cash crop. To allay the cost of seed, five farmers described growing their own LGM seed on-farm. One advisor described that the development of farmer-led LGM seed cooperatives could provide both control over seed costs, as well as an additional market to which farmers could sell their excess seed as a cash crop, and one farmer mentioned his participation in such a cooperative, located in Maine. To reduce the opportunity cost associated with using field space to grow LGMs rather than cash crops, five farmers described taking cuttings of their LGM for hay, either to sell or to feed to their own animals.

Farmers and advisors identified local and regional livestock integration, use of locally-produced legume meals, and increased usage of LGMs as ways to reduce grower reliance on off-farm sources of N. Five of the farmer interviewees owned their own livestock, and several described how having animals not only provided a direct a source of N-rich manure for their crops, but helped to offset the opportunity costs of growing long-term LGMs, which they could harvest as supplemental feed for their animals, or to sell to neighboring farms:

> *We might get a cut of hay off of [the clover green manure] before we have to roll it back down for grains in the fall. And we're not losing those nutrients. We'll just put them back on in the form of manure.* (Farmer, Vermont)

Two farmers and one advisor proposed producing legume meals on-farm, from field peas (*Pisum sativum* L.) or sunn hemp (*Crotalaria juncea* L.), as a way to reduce reliance on external inputs, while avoiding some of the field-related challenges encountered with traditional LGM establishment. One farmer explained how this strategy provided an ideal work-around to the lack of animal manure sources nearby:

> *You know, manure is simply a plant that went through an animal. And so you don't necessarily need the animal if you can source it in the plant. Fundamentally, it's all plant-based. So you go direct to the source.* (Farmer, Maine)

Table 2.4. Challenges associated with legume green manures, and corresponding strategies, as identified by participants.

Challenges	Strategies
Plowing to terminate LGMs is inefficient	1. Replace plowing with mowing + chisel plowing
Plowing to terminate LGMs negatively impacts soil health	1. Delay fall LGM plowing until spring to allow LGM to act as an overwinter cover crop 2. Replace plowing with heavy disk
High-quality LGM seed is expensive and difficult to access	1. Produce seed on-farm 2. Develop farmer-led LGM seed cooperative in Northeast
N mineralization of LGM residue is slow in early spring	1. Supplement LGM N with early season Chilean nitrate application
Difficulty aligning LGM N release with subsequent crop N uptake	1. Delay LGM incorporation as much as possible prior to subsequent crop planting
Intercropped LGMs grow into grain canopy	1. Select tall crop varieties 2. Avoid delayed grain crop planting 3. Ensure grain crop receives enough N to support early season growth, through topdressing if necessary 4. Seed LGM when grain crop is at 3-4 leaf stage 5. Harvest grain crop before completely dried down
Too much red clover in system leads to disease issues	1. Diversify LGM species in rotation 2. Plant non-legume cover crop between LGMs in rotation

2.5. Discussion

The objectives of this study were to investigate major challenges in N management encountered by Northeast U.S. OSG growers, and to identify ways in which advisors could provide targeted support to growers on this topic, with particular focus on legume-based N sources. Farmer and advisor participants identified cost, dependence on external N sources, rotation-building, weed management, and predicting N mineralization of organic materials to be major challenges. Identifying economical, alternative N sources was presented as an especially pressing need for Maine growers, given a recent and abrupt loss of poultry manure accessibility. Increased usage of LGMs and locally-produced legume meals, as well as livestock integration, were presented as key opportunities for bolstering on-farm and local N production.

2.5.1. Potential Drivers of Nitrogen Fertility Decision-Making

In assessing participants' discussions of major challenges regarding N management, we gain insight into growers' decision-making processes. In this study, the cost of N management was the most cited challenge by both farmer and advisor participants. Traditional economic theory suggests that individuals make decisions based on what they expect will maximize profit or utility (Edwards -Jones, 2006), and may discount future benefits in favor of immediate gains (Frederick et al., 2002). It is unsurprising, then, that many growers in Maine and Pennsylvania have relied heavily on raw poultry manure as a N source for their small grain crops, given the relatively low upfront cost and high available N content of the material. Our results suggest, however, that some farmers view this economic equation differently, and factor in the long-term effects of their N management, often relying on past experiences, when choosing what they perceive to be the most cost-

effective N source for their system, similar to studies by Bergtold et al. (2012) and Chongtham et al. (2016). For example, several farmers were dissuaded from using raw poultry manure due to experiences with increased weed pressure, and the perceived risk of soil health decline.

Farmers expressed that with increasing capital comes greater decision-making power regarding N fertility, and that new growers may gradually come to invest more in N fertility as their business expands and diversifies. Farmers also linked greater investment in N fertility to improved yield and crop quality. While cost-effectiveness presented itself as a key component of successful N management, our data suggest that growers consider factors beyond upfront cost and short-term N supply in choosing a N source, particularly if they believe investing more in N management will benefit their farm in other ways. Previous work has found that nutrient management strategies depend on growers' level of experience (Chongtham et al., 2016). It is likely, then, that our findings regarding farmers' economic attitudes on N management may be influenced by our pool of farmer interviewees, who were all experienced organic farmers.

The results of this study suggest that practice characteristics beyond perceived economic benefit may also play an important role in guiding decision-making in N management. Advisors suggested, for instance, that farmers preferentially address "visible" issues on-farm, such as weeds, over N fertility, which may not present itself as a yield-limiting factor so readily. In other words, N fertility management, as a practice, may suffer from a lack of what Rogers (2003), within the Diffusion of Innovation Theory, termed "observability." or the extent to which the benefits of a practice are easily observable. Observability has been demonstrated to be a driver of farmer decision-making regarding

conservation practices (Reimer et al., 2012; Liu et al., 2018); the more observable the benefits of a practice, the more likely farmers are to adopt it. Advisors also described how growers' perception of complexity, particularly regarding the use of LGMs and other legume sources of N, presented a potentially formidable barrier to adoption of sustainable N practices. Larger, more in-depth investigations are needed to understand the N management decision-making of OSG growers more robustly. This study provides evidence, however, that decision-making in this arena is more nuanced than a simple, short-term, cost accounting equation.

2.5.2. Comparing Farmer and Advisor Responses

Significant overlap existed between the challenges discussed by farmers and advisors, indicating a high level of farmer-advisor communication within the population interviewed. This was expected, given that farmer interviewees were selected based on the recommendations of advisors, and as such, had a pre-existing relationship with the advisors interviewed. For these reasons, comparison between the two groups is not of central interest to this study. However, several discrepancies were observed, and are worth mentioning as areas of potential improvement in future communication efforts. For instance, a higher proportion of the farmers interviewed mentioned weed pressure, as a result of past N management, as a major challenge (0.36), relative to advisors (0.28). In particular, farmers mentioned weeds as a direct result of poultry manure use more often than advisors (0.36 and 0.14, for farmers and advisors, respectively). Farmers were more likely to name unpredictable weather, and its effect on timely field operations, as a challenge to N management (0.27), relative to advisors (0.14). These areas are well-known, perennial challenges in organic farming (Liebman and Davis, 2009; Jerkins and Ory, 2016),

and it is unlikely that they are neglected as part of wider programming and outreach efforts. However, an opportunity may exist to better integrate these topics into future programming specifically in the context of managing N.

2.5.3. Supporting Growers Transitioning To Legume-Based Nitrogen Management

The sudden loss of a major poultry manure source in Maine spurred discussion about the long-term reliability of different N sources. Several growers affected by the loss expressed a need to shift away from using inexpensive, external sources of N, in part because such dependence compromised their long-term resilience. Berkes and Turner (2006) describe that adoption of conservation thought and practice in communities often follows a resource crisis, which serves not only to demonstrate the exhaustibility of resources, but also forces communities to adapt to a new reality through innovation. If growers' N management decisions are considered through this lens, it follows that that abrupt loss of poultry manure in Maine may serve as a powerful impetus for OSG growers to innovate, and develop the skills necessary to shift from an input-based system to one that relies more heavily on legume sources of N and, perhaps, local sources of manure. Future programming and outreach should be primed to support growers to innovate in such a way.

The myriad benefits to using LGMs are well documented, though this study identifies a number of potential barriers that may be anticipated as growers prepare to shift to legume-based N management. Similar to previous studies investigating barriers to agroecological practices (Blesh and Wolf, 2014; Roesch-McNally et al., 2017), our data suggest that barriers to LGM practice extend beyond simple field-based challenges like termination and intercropping issues. For example, interviewees expressed that growers'

embrace of LGM-based rotations may be limited by what Roesch-McNalley et al. (2017) describe as "structural challenges", or those influenced by market forces. In our study, structural challenges include the cost of high-quality LGM seed, a dearth of animal agriculture operations that might provide a market for clover hay, and a lack of diverse cash crop markets that could provide ample windows for LGMs in growers' rotations. Structural challenges are market-driven, and therefore require solutions beyond the scope of individual farmer actions or those of extension personnel. The lack of diverse cash crop markets, which could hinder growers' ability to build robust, legume-based rotations, for instance, cannot be fully addressed through programming and research. However, opportunities may exist for leveraging farmer and advisor action to help lessen or circumvent major barriers. Farmers producing their own LGM seed on-farm provides a good example of this, as does the establishment of farmer-owned seed cooperatives. Previous research has documented the success of this type of collaborative, farmer-led initiative for spurring innovation and cultivating resilience within the agricultural community (Kroma, 2006).

Livestock integration, of individual farms and wider grain-growing regions, was discussed as a way to lessen the opportunity costs associated with using arable land to grow LGMs rather than cash crops. Study participants who owned their own livestock, or who farmed within proximity to livestock operations, explained that taking cuttings of their LGM as hay helped to allay the opportunity costs of growing an LGM, encouraging the use of long-term legume sods, and potentially improving nutrient cycling. Several studies have described this complementary relationship between animal integration and the use of cover crops and legume sods (Franzluebbers, 2007; Sulc and Tracy, 2007; Clark, 2008). For

operations that cannot or will not integrate, previous research has also demonstrated the value of collaborative efforts between arable and livestock operations for achieving such a relationship (Hoshide et al., 2007; Oelofse et al., 2013; Andersson et al., 2018; Asai et al., 2018). Many participants in this study, however, observed that animal agriculture was generally in decline in parts of the Northeast US, or that animal operations were no longer proximal to crop-producing regions, consistent with the national trend (MacDonald and McBride, 2009). As such, future on-farm animal integration, or collaborative partnerships between arable and livestock operations, would be feasible only given a certain degree of reversal of this market-driven trend. In the meantime, growers wishing to increase their use of LGMs must utilize other tactics to offset the opportunity costs associated with this practice.

A number of farmers and advisors proposed that using legume meals, made of field peas or sunn hemp grown on-farm, could introduce locally-produced, legume-derived N into cropping systems while avoiding some of the field-related challenges associated with traditional LGM establishment, and providing a workaround to the lack of local animal agriculture. Using legume seed meals as a N fertility source has been shown to be effective (Katroschan et al., 2012) and economical (Cabilovski et al., 2011) in vegetable production, as has using "mobile green manures", or dried, chopped legume tissue moved from one field to another (Nygaard Sorensen and Thorup-Kristensen, 2011). As study participants indicated, field-based research is needed to determine ideal growing conditions, meal consistency, and meal application rates for grain production in the Northeast U.S. growing climate. More in-depth economic analysis is also needed to determine whether this practice will contribute to a financially viable alternative to animal manures over the long term.

Finally, the results of this study indicate that supporting growers in a shift to legume-based N management must include bolstering their confidence in this practice's ability to adequately meet the fertility needs of small grain crop. This is particularly important for wheat growers, who may be especially concerned with the timing of N release and its effect on grain protein concentration, an important quality parameter (Mallory and Darby, 2013). The link between farmer confidence level and practice adoption has been demonstrated in previous research on cover crop adoption (Arbuckle and Roesch-McNally, 2015), as has the negative relationship between perceived risk and the adoption of agroecological practices by farmers (Constance and Choi, 2010; Wilson et al., 2014). Our interviews revealed that predicting N mineralization from LGM residues was a top challenge, and that growers new to using LGMs had reservations about the efficacy of substituting legume-derived N for animal manures and fertilizers. The same issue was documented in Denmark by Oelofse et al. (2013), as the country prepared to phase out conventional nutrients from organic agriculture.

While advisors in the present study described LGM systems as inherently complex, they proposed several strategies for addressing grower uncertainty. These focused on training growers to expect, and respond to, a certain level of variability within legume-based systems, using knowledge of their unique operation and the scientific principles surrounding LGM residue breakdown and subsequent N release. A similar sentiment was observed by Jabbour et al. (2014), in which advisors emphasized the importance of embracing ecological complexity to achieve successful organic weed management, while farmers tended to view complexity in a negative light. On-farm LGM trials and participatory research were suggested by advisors in the present study as ways to harness grower

innovation, boost confidence in the practice, and demonstrate its benefits. Participatory research, in which farmers are part of research design and execution, has been shown to be useful in addressing on-farm challenges (Kroma, 2006; Lefèvre et al., 2014). Research on cover crop adoption has also demonstrated farmers' willingness to tolerate a certain level of risk associated with a new technology if they can identify clear benefits to its use (Mallory et al., 1998; Bergtold et al., 2012; Wayman et al., 2016), providing additional support for participatory, or demonstrative-style learning.

More research is needed to determine the characteristics of successful transitions to legume-based N management. Advisors in this study suggested that farmers dependent on inexpensive, external N sources may be neglecting key aspects of organic management by substituting an input for soil-building cultural practices, as has been observed by others (Guthman, 2004; Lockie and Halpin, 2005; Oelofse et al., 2011; Chongtham et al., 2016). Some studies suggest that a key component to the successful use of LGMs may be a "whole-systems approach" (Cherr et al., 2006), in which LGMs are not simply inserted into cropping systems as substitutes for manures and fertilizers, but are integrated into the farm system in such a way that their multiple benefits, such as weed and pest control, are maximized. Cherr et al. (2006) note that this may necessitate "adjustments of the entire farm system, including the choice of economic crops, crop rotation, cultural practices, and marketing," a process referred to in agroecological literature as *system redesign* (MacCrae et al., 1990; Rosset and Altieri, 1997; Carlisle, 2016). This study, however, has indicated that growers' development of diverse rotations is limited by available cash crop markets, and the dearth of livestock operations close to grain-growing areas can make it difficult for growers to justify the opportunity costs of long-term legume sods. As such, growers require

a roadmap for system redesign that takes into account these structural limitations, while addressing field-level barriers to N management.

2.6. Conclusions

Successful N management is crucial for achieving high yields and crop quality in OSG production. This study identifies key areas of need in research, programming, and educational outreach to assist OSG growers in optimizing their N management strategies, particularly for growers who wish to transition away from high-input N management to legume-based N systems. We've demonstrated that growers' decision-making regarding N source and management style takes into account a suite of factors extending beyond upfront cost, and that LGM adoption can be impacted by both field-based and market-related challenges. A limitation to this study was its small sample size, and this topic area would benefit from a wider-scale investigation of farmer decision-making regarding N, as well as characterization of successful N management strategies in different regional contexts. The majority of farmers interviewed in this study had some experience, and in some cases, extensive experience, using LGMs. In order to fully grasp the challenges of shifting to LGM-based N management, further studies should include beginning farmers, as well as famers with little to no experience with LGMs, akin to Bergtold et al. (2012).

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