ABSTRACT
Organic farmers are challenged by increasing soil P levels resulting from the use of manure to meet cash crop N needs. The use of a legume cover crop may address this challenge. In a 2-yr study at three organic production sites in Maryland, we examined the combination of a winter annual legume cover crop (hairy vetch, crimson clover, Austrian winter pea, and a no-cover control) at three poultry litter (PL) application rates (to meet the N requirement of corn, to replace P removed by corn grain harvest, and a no-PL control). Cover crop biomass varied by site and by year, ranging from about 600 to 6100 kg ha$^{-1}$ for crimson clover. Cover crop N accumulation ranged from 15 to 169 kg N ha$^{-1}$. Corn yields, which ranged from 2.9 to 14.2 Mg ha$^{-1}$, tended to be lowest in the control (0 PL) no-cover treatments and similar in the N-based and P-based treatments irrespective of the cover crop species. These results indicate that when legume cover crops are used, PL can be applied at a P-replacement rate on sites with a history of PL application to meet crop production and environmental stewardship goals.

Core Ideas
• Legume cover crop N accumulation ranged from 15 to 169 kg N ha$^{-1}$.
• Corn yield after legume crops was not affected by poultry litter application rate.
• Legume cover crops provide opportunity to reduce poultry litter application rates.

Despite increasing interest worldwide in organic production by farmers, adequate information on organic grain crop management is lacking to address the unique challenges associated with soils with low native soil fertility. Production challenges have restricted the success of some operations that have transitioned to organic methods and may be limiting the number of operations considering adoption of these practices. The issues of greatest concern to organic grain producers are nutrient management, weed control, and soil conservation/soil quality (Jerkins and Ory, 2016; Sooby et al., 2007). Over the last decade, research has been conducted to address weed control and soil quality in organic cropping systems in the mid-Atlantic region, but there has been limited attention given to nutrient management (Liebman et al., 2018; Mirsky et al., 2013; Ryan et al., 2009).

Organic production seeks to maintain soil fertility and meet crop nutrient needs using animal industry byproducts, such as manure and compost and legume cover crops, while factoring in nutrient release from soil organic matter. Many organic grain farmers rely on animal manure or compost for a substantial portion of cash crop nutrient needs (Watson et al., 2002). However, there are environmental concerns associated with the application of animal byproducts (King, 1990; Phillips, 2007). The ratio of plant-available N/P in manure and compost is approximately 2:1 and 1:2, respectively, whereas the N/P ratio in most crops is between 7:1 and 10:1 (Eck and Stewart, 1995; Heckman et al., 2003; Preusch et al., 2002). Soils that receive repeated applications of animal manure or compost sufficient to meet crop N needs accumulate soil P in excess of crop needs, thereby increasing the risk of P enrichment of soil runoff (Delate and Cambardella, 2004; Maguire et al., 2008; Spargo et al., 2006). Due to the concentration of confined animal feeding operations and the resultant overapplication of manure, much of the cropland in the mid-Atlantic is now considered to have “excessive” levels of soil P (Ator and Denver, 2015; Sims et al., 2002). This is particularly of concern in the Chesapeake Bay...
and other watersheds, where estuarine water quality continues to
decline due to high nutrient inputs and other pollution (Ator
and Denver, 2015). To protect water quality, many mid-Atlantic
states have laws that require manure application rates to be
based on the results of soil P tests and the estimated P removal
of harvested cash crops (MDA, 2017; Sims et al., 2005). This
situation creates a challenge for organic grain producers seeking
approved sources of N fertility because P-based application of
manure or compost will only meet a portion of crop N needs
(Berry et al., 2002; Spargo et al., 2016).

The use of legume cover crops in organic cropping systems
capitalizes on plant biological N fixation and is an effective
practice to help reduce off-farm inputs and to improve nutrient
use efficiency. The N value of a legume to a following cash crop
depends on cover crop species traits (e.g., biomass production
and N fixation), seeding and termination dates, time between
cover crop termination and cash crop planting, and tillage sys-
tem (Ketterings et al., 2015; Mirsky et al., 2017). Nonetheless,
the legume species adapted to the mid-Atlantic region often fail
to supply enough plant-available N (PAN) to satisfy the needs
of a subsequent corn (Zea mays L.) crop in most seasons (Clark,
2007; Lawrence Roth.) or crim-
son clover (Trifolium incarnatum L.) (Clark, 2007; Lawrence
et al., 2009; Teasdale et al., 2004; Wagger, 1989). Hairy vetch
is one of the most adaptable and productive cover crops in
the region (Clark, 2007; Decker et al., 1994; Teasdale et al., 2004).
It can produce more than 150 kg N ha⁻¹ (Decker et al.,
1994; Teasdale et al., 2004), although only a portion (30–60%  

fertilizer N equivalence) of this total N is typically available to a
succeeding crop (Clark et al., 2007; Seo et al., 2006). In a study
in Georgia, McVay et al. (1989) estimated that hairy vetch pro-
vided an average fertilizer equivalent of 123 kg N ha⁻¹ averaged
across six site-years. However, most organic grain farmers in the
mid-Atlantic are reluctant to plant hairy vetch on their farm due
to its reputation for becoming an invasive weed (Ed Fry, Corey
Spies, Nick Marvell, and Bill Mason, personal communication,
2010). Mid-Atlantic organic farmers prefer crimson clover,
which is less winter hardy and generally produces less PAN
than hairy vetch but which can provide rapid fall ground cover
and has lower seed cost than hairy vetch (Clark, 2007; Duiker,
calculated a crimson clover fertilizer N equivalent value of 99
kg N ha⁻¹, averaged across six site-years in Georgia. Farmers in
the mid-Atlantic United States have also begun to experiment
with Austrian winter pea (Pisum sativum var. arvense (L.) Poir)
as a cover crop, which has comparable hardness to crimson
clover and can accumulate 168 to 208 kg N ha⁻¹ (Clark, 2007;
Parr et al., 2011). McVay et al. (1989) estimated that Austrian
winter pea produces a fertilizer N equivalent of 85 kg N ha⁻¹.
Our objective was to determine which combination(s) of annual
legume cover crop and PL application rate maximized corn yield
to minimize the application of excessive P.

MATERIALS AND METHODS

Study Sites

The experiment was conducted from fall 2010 to summer 2012 at three sites, two of which were located on farms of coop-
erating growers. Sites were selected to represent the range of
environmental conditions and organic grain cropping manage-
ment systems found in the mid-Atlantic region. This region
has a humid subtropical climate (Cfa, according to the Köppen
climate classification [Kottek et al., 2006]), with hot summers,
generally mild winters, and abundant precipitation relatively
evenly distributed throughout the year. On the Eastern Shore
of Maryland, the grower cooperatives sites were Mason Heritage

Table 1. Overview of experimental sites and cropping systems.

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Latitude and longitude</th>
<th>Typical Rotation</th>
<th>Previous Crop 2011</th>
<th>Soil Test P 2011, mg kg⁻¹‡</th>
<th>Pre-plant Soil [NO₃⁻ + NH₄⁺]-N, mg kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beltsville</td>
<td>39.03 N, 76.93 W</td>
<td>Corn-rye-soybean</td>
<td>Soybean</td>
<td>95 (E)</td>
<td>2011 7.00 3.06 2.73 3.92</td>
</tr>
<tr>
<td>Eden</td>
<td>38.32 N, 75.72 W</td>
<td>Corn-rye-soybean</td>
<td>Soybean</td>
<td>193 (E)</td>
<td>2012 4.84 3.41 3.50 3.92</td>
</tr>
<tr>
<td>Queen Anne</td>
<td>39.01 N, 75.95 W</td>
<td>Corn-rye-soybean</td>
<td>Crimson clover</td>
<td>101 (E)</td>
<td>2011 3.87 2.80 3.50 3.92</td>
</tr>
</tbody>
</table>

† AWP, Austrian winter pea; B, barley; CC, crimson clover; HV, hairy vetch; NC, no cover crop.
‡ Values in parentheses are Maryland ratings (E, excessive; M, medium).

‡ Values in parentheses are Maryland ratings (E, excessive; M, medium).
Farm (Queen Anne, MD) and Cutfresh Organics, LLC (Eden, MD) (Table 1). At the Queen Anne site, the soil was an Ingleside sandy loam (coarse-loamy, siliceous, semiactive, mesic Typic Hapludult) with 2 to 5% slopes in 2011 and a Nassawango silt loam (Fine-silty, mixed, semiactive, mesic Typic Hapludult) with 0 to 2% slopes in 2012. Research at the Eden site was conducted in different portions of the same field both years, where the soils were a Hambrook sandy loam (fine-loamy, siliceous, semiactive, mesic Typic Hapludult) with 0 to 2% slopes and a Woodstown sandy loam (fine-loamy, mixed, active, mesic Aquic Hapludult) with 0 to 2% slopes. The USDA–ARS Beltsville Agricultural Research Center (BARC) (Beltsville, MD), which served as the third site, sits on the western edge of the Atlantic Coastal Plain; the soil is a Codorus-Hatboro silt loam (fine-loamy, mixed, active, mesic, Fluvaquentic Dystrudepts and Endoaquepts) with 0 to 3% slope. The preceding crops and typical crop rotations are listed in Table 1. Average and yearly weather data are provided in Fig. 1. Average annual precipitation at BARC and Maryland Wye Research and Education Center is 1063 and 1188 mm, respectively. Average annual temperature at BARC and Maryland Wye Research and Education Center is 13.0 and 14.3°C, respectively.

**Experimental Design**

The experiment used a split-split plot design with four replications. At each site, studies were conducted in adjacent fields on soils with similar characteristics and management history. Because the experimental design for on-farm research was developed in collaboration with cooperating producers to address key issues relevant to their specific cropping systems, cover crop treatments varied by site (Table 1). Main plots consisted of 4.6-m-wide
Data collection and P-based (3.4 Mg PL ha–1) rates prior to corn planting and aerially seeded at 22 kg ha–1 in combination with barley typical cultivation used at each farm, including by rotary hoeing winter pea, and 22 kg ha–1 for crimson clover. All legumes were (respectively; crimson clover was planted at 17 kg ha–1 in 2010 soil pH levels. At Beltsville, K2SO4 (0–0–60) was applied at was applied prior to corn planting when recommended to adjust was incorporated into the soil within 24 h of application. Lime Rhizobium Austrian winter pea was planted at 112 kg ha–1 and hairy vetch were insufficient.

Field operations and data collection dates.

<table>
<thead>
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<tbody>
<tr>
<td>(HV†, AWP, CC)</td>
<td></td>
<td></td>
<td>(AWP and HV)</td>
<td>(AWP and AWP)</td>
<td>(AWP)</td>
<td>(AWP and B/CC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(replanted 17 May 2012 (cutworms))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data collection</td>
<td></td>
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</tbody>
</table>

† AWP, Austrian winter pea; B, barley; CC, crimson clover; HV, hairy vetch; PPN, pelleted poultry litter applied at the N rate; PPP, pelleted poultry litter applied at the P rate.

Field Operations

Field equipment varied by site because we relied on equipment available at a given farm. At the Queen Anne site, Austrian winter pea was planted at 84 and 112 kg ha–1 in 2010 and 2011, respectively; crimson clover was planted at 17 kg ha–1 in 2010 and aerially seeded at 22 kg ha–1 in combination with barley (Hordeum vulgare L.) at 84 kg ha–1 in 2011. At the Eden site, Austrian winter pea was planted at 112 kg ha–1 and hairy vetch was planted at 34 kg ha–1 both years. At the Beltsville site, planting rates were 34 kg ha–1 for hairy vetch, 112 kg ha–1 for Austrian winter pea, and 22 kg ha–1 for crimson clover. All legumes were first inoculated with the appropriate Rhizobium species.

Poultry litter was applied at the N-based (6.7 Mg PL ha–1) and P-based (3.4 Mg PL ha–1) rates prior to corn planting and was incorporated into the soil within 24 h of application. Lime was applied prior to corn planting when recommended to adjust soil pH levels. At Beltsville, K2SO4 (0–0–60) was applied at recommended rates at the same time as the pre-plant PL treatments when soil tests collected in the spring indicated K levels were insufficient.

Corn varieties and planting dates varied by site according to farmer preferences. At the Queen Anne site, corn was planted at 74,100 seeds ha–1 using BRH 57H36 (Blue River Hybrids Organic Seed, Kelley, IA) (104-d) corn was planted at 71,630 seeds ha–1. Weeds were controlled mechanically using irrigation (13–15 cm yr–1), but the other two sites did not.

Data Collection

Three aboveground cover crop biomass subsamples were collected from each cover crop strip immediately prior to termination in the spring from quadrats that were either 0.25 or 0.5 m2 in size located in representative areas; the same quadrat size was used in both years at a given site (Table 2). Weed biomass was separated from cover crop samples and collected from control plots when present in notable amounts. At the Queen Anne site, barley and crimson clover plants were separated prior to sample processing. Cover crop biomass was oven dried (60°C), weighed, and ground to pass a 1.0-mm screen. Total tissue N content was determined on each of three analytical replicates for each sample using total combustion analysis (ECS 4010 CHNSO Analyzer; Costech, Valencia, CA).

Three grab samples of PL were collected immediately prior to field application, placed in 2-L polyethylene bags, and frozen within 12 h of collection. Analyses were conducted on the three samples independently by A&L Eastern Laboratories (Richmond, VA). Dry matter was determined by oven drying at 105°C to a constant weight, according to SM 2540 G (APHA, 2005). Samples were extracted with 1 M KCl and analyzed for [NO3 + NH4]–N colorimetrically using a QuickChem Automated Ion Analyzer (Lachat Instruments, Milwaukee, WI). Total C and N were determined on oven-dried samples using total combustion analysis using a vario MAX CN Analyzer (Elementar Americas, Inc., Mt. Laurel, NJ). Organic N concentration was calculated as total-N minus [NO3 + NH4]–N. The concentrations of P and K were determined by inductively coupled plasma emission spectroscopy after samples were prepared by microwave-assisted digestion (Wolf et al., 2003).

Whole aboveground corn plant samples were collected at the black layer (physiological maturity) stage by cutting and weighing plants from one 3.1-m row-length in each weed-free treatment plot. Six representative plants were further subsampled and between-row cultivation. The Queen Anne site received irrigation (13–15 cm yr–1), but the other two sites did not.
for tissue analysis. Corn tissue samples were oven dried (60°C), weighed, and ground to pass a 1.0-mm screen. Total tissue N content was determined on duplicate samples using total combustion analysis using a Vario MAX cube (Elementar Americas, Inc.). Corn grain yield was determined by hand-harvesting two 3.1-m row lengths in each plot, except at the Beltsville site where corn was harvested with a small-plot combine in 2012 (ALMACO, Nevada, IA). In 2011, due to hurricane damage at the Beltsville site, corn biomass and grain yield data were collected by hand from the same plants. Poultry litter properties are provided in Table 3.

To assess basal soil fertility, soil samples were collected in early spring (March) and analyzed for pH and Mehlich 3-extractable P and K (Table 2). One composite sample consisting of 12 soil cores (0–15 cm depth) was collected in each site-year using a 1.9-cm-diameter stainless steel push probe. Samples were air-dried and ground to pass a 2-mm sieve prior to submission to A&L Eastern Laboratories (Richmond, VA) for analysis. Additional soil samples were collected at the same time as spring cover crop biomass samples to test for potentially confounding residual soil \([\text{NO}_3^- + \text{NH}_4^+]\)-N levels. Two soil cores were collected from each of the no-cover crop treatments in each replication to form a composite (eight cores total) for each site-year. Soil cores were collected from each depth (0–30, 30–60, and 60–90 cm) using a nickel-plated push-probe (1.9 cm diameter) at all locations except at the Beltsville site, where samples were collected with a 5-cm-diameter augur to account for a stony soil. Samples were held at 4°C until transported to the laboratory, air-dried within 24 h, and then ground to pass a 2-mm sieve. Soil samples were also collected at corn black layer from each plot using the same protocol as for the pre-plant \([\text{NO}_3^- + \text{NH}_4^+]\)-N samples except that a composite of eight (30-cm deep) cores was collected per plot. Samples were analyzed for \([\text{NO}_3^- + \text{NH}_4^+]\)-N colorimetrically using a QuickChem Automated Ion Analyzer (Lachat Instruments) after extraction with a 1 M KCl solution.

### Calculations and Statistical Analyses

Total available N (TAN) was calculated as the sum of 0 to 30 cm soil nitrate (kg NO$_3^-$-N ha$^{-1}$) (assuming a soil bulk density of 1.5 g cm$^{-3}$) and corn N uptake (kg N ha$^{-1}$) collected at corn black layer (Spargo et al., 2016). Measurements were conducted using the \texttt{lsmeans} package in R (Lenth, 2016). We fit linear mixed models for the response variables cover crop biomass, cover crop N content, TAN, and corn grain yield separately to each site and year. For each model, we used cover crop, PL application rate, and their interactions as categorical fixed effects. The random effects were cover crop subplot nested within field replicate block. Model fitting was conducted using the \texttt{nlme} package in R, and means separations were conducted using the \texttt{lsmeans} package. When data were collected prior to the imposition of another factor (e.g., cover crop biomass collected before PL application), data were collected in the lowest number of plots possible, and the same values were used for all equivalent treatments. Data were analyzed by site-year due to varying cover crop species at each site and interactions among treatment, site, and year.

### RESULTS AND DISCUSSION

**2010–2011 Season**

Due to the use of different cover crop treatments across sites (Table 1), site-years were analyzed separately. In spring 2011 at Beltsville, there was approximately the same amount of volunteer wheat (labeled weed biomass in figure) as cover crop biomass in each treatment (Fig. 2). Total cover crop biomass (including weeds) was similar for all three species treatments; all cover crop treatments produced more total biomass than the no-cover crop control. At the Eden site, weed pressure was low, so weeds were not collected or separated from the cover crop biomass. We found no differences in cover crop biomass between Austrian winter pea and hairy vetch. At the Queen Anne site, total crimson clover biomass was almost double that of Austrian winter pea; there was considerable volunteer barley in this site-year. There was no difference between the Austrian winter pea and the no-cover crop control.

Legume cover crop biomass production was similar to that found in other studies in the mid-Atlantic region for fall-planted, spring-terminated cover crops, ranging from 5400 to 6100 kg ha$^{-1}$ for crimson clover, from 3600 to 4700 kg ha$^{-1}$ for hairy vetch, and from 2800 to 4900 kg ha$^{-1}$ for Austrian winter pea (Duiker, 2014; Mirsky et al., 2017; Parr et al., 2011). Duiker (2014) observed hairy vetch to be more productive than crimson clover in a planting by termination date trial in Pennsylvania. Differences in relative biomass production among studies are likely the combined result of differing germplasm (e.g., varying rates of germination and seedling growth), environmental conditions (e.g., winter low temperatures, soil type), and management (e.g., planting date). Cover crop N accumulation mirrored cover crop biomass production in spring 2011, with high-biomass treatments accumulating more N than low-biomass treatments (Fig. 2 and 3). Nitrogen accumulation ranged from 81 to 166 kg N ha$^{-1}$ in the cover crop fraction of treatments to 105 to 242 kg N ha$^{-1}$ in combined cover crop and weed N fractions in all treatments (Fig. 3).

Total available N (the sum of soil NO$_3^-$ and corn N accumulation at black layer) is an estimate of the N provided by a given treatment (Spargo et al., 2016). At the Beltsville site, TAN was greater in the hairy vetch than in the no-cover crop control. At the Eden site, TAN was greater in the Austrian winter pea than in the no-cover crop treatment (248 vs. 169 kg N ha$^{-1}$) when 0 PL was applied (Table 4). Total available N was also greater under the N-based than the P-based and 0 PL treatments (265, 204, 169 kg N ha$^{-1}$, respectively) when no cover crop was present. No other significant differences in that site year were detected. At the Eden site in 2011, TAN was greater in the hairy vetch than in the no-cover crop treatment at all PL application rates. The N-based
Fig. 2. Cover crop dry above ground biomass prior to spring termination in 2011 and 2012 at the Beltsville, Eden, and Queen Anne, MD, sites. Mean total biomasses labeled with different letters within site-years are significantly different ($p < 0.05$). Bars represent 1 SEM. *Weed biomass was sufficiently low that we did not separate weed from cover crop biomass. The weedy bar at the Beltsville site in 2011 represents volunteer wheat and at Queen Anne site represents volunteer barley in 2011 and overseeded barley in 2012.

Fig. 3. Cover crop N accumulation prior to spring termination in 2011 and 2012 at the Beltsville, Eden, and Queen Anne, MD, sites. Bars represent 1 SEM. *Weed biomass was sufficiently low so as to not be separated from cover crop biomass. The weedy bar at the Queen Anne site represented volunteer barley in 2011 and overseeded barley in 2012.
Table 4. Mean total available N (corn N uptake plus soil NO\textsubscript{3}–N at black layer) and standard error resulting from two poultry litter rates (subplots) applied to corn that followed a legume cover crop or no cover crop (whole plots) in 2011 and 2012.

<table>
<thead>
<tr>
<th>Cover crop</th>
<th>Total available N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg N ha\textsuperscript{-1}</td>
</tr>
<tr>
<td></td>
<td>0 P-based</td>
</tr>
<tr>
<td>Beltsville 2011†</td>
<td></td>
</tr>
<tr>
<td>No cover</td>
<td>169 (11.8)Bz†</td>
</tr>
<tr>
<td>Austrian winter pea</td>
<td>248 (31.7)A</td>
</tr>
<tr>
<td>Crimson clover</td>
<td>238 (8.36)AB</td>
</tr>
<tr>
<td>Hairy vetch</td>
<td>222 (11.9)AB</td>
</tr>
<tr>
<td>Beltsville 2012</td>
<td></td>
</tr>
<tr>
<td>No cover</td>
<td>69.8 (25.0)Bz</td>
</tr>
<tr>
<td>Austrian winter pea</td>
<td>86.3 (19.6)Bz‡</td>
</tr>
<tr>
<td>Hairy vetch</td>
<td>155 (7.79)Az</td>
</tr>
<tr>
<td>Queen Anne 2011</td>
<td></td>
</tr>
<tr>
<td>No cover</td>
<td>99.6 (17.5)z</td>
</tr>
<tr>
<td>Austrian winter pea</td>
<td>90.2 (12.8)z</td>
</tr>
<tr>
<td>Crimson clover + barley</td>
<td>108 (10.8)z</td>
</tr>
<tr>
<td>Queen Anne 2012</td>
<td></td>
</tr>
<tr>
<td>No cover</td>
<td>119 (12.5)zB</td>
</tr>
<tr>
<td>Austrian winter pea</td>
<td>174 (9.17)AB</td>
</tr>
<tr>
<td>Hairy vetch</td>
<td>190 (13.8)A</td>
</tr>
<tr>
<td>Eden 2011</td>
<td></td>
</tr>
<tr>
<td>No cover</td>
<td>2.89 (0.259)Bz‡</td>
</tr>
<tr>
<td>Austrian winter pea</td>
<td>4.61 (1.02)Az</td>
</tr>
<tr>
<td>Hairy vetch</td>
<td>6.09 (0.943)A</td>
</tr>
</tbody>
</table>

† Beltsville 2012 data were not collected.
‡ Means followed by the same uppercase letter within columns and site years or lowercase letters within a given row are not significantly different (p < 0.05).

PL rate resulted in greater TAN values than the 0 PL application rate across cover crop treatments. Total available N at the P-based rate was equivalent to that at the 0 PL rate under the hairy vetch and no-cover crop treatments. At the Queen Anne site in 2011, TAN was consistently greater in the N-based and P-based PL treatments than in the 0 PL treatment. These results show that both PL application rate and (to a lesser extent) cover crop have a considerable (if variable) effect on TAN.

At the Beltsville site in 2011, the 0- to 30-cm pre-plant N [NO\textsubscript{3} + NH\textsubscript{4}]–N was 7.00 mg kg\textsuperscript{-1}, compared with 3.87 and 4.78 mg kg\textsuperscript{-1} at the Eden and Queen Anne sites, respectively (Table 1). Consistent with these data, fewer differences in TAN were detected at the Beltsville site than at the other two sites (Table 4). Greater pre-plant [NO\textsubscript{3} + NH\textsubscript{4}]–N could mask or obviate treatment differences, in line with our hypothesis that at high-fertility sites PL application can be reduced to the P-based rate, especially when applied in conjunction with use of a cover crop. The corn N accumulation portion of the TAN equation also influences interpretation: luxury N consumption of N means that N uptake does not necessarily translate into higher grain yield (Blackmer and Schepers, 1994).

We detected relatively few differences in corn grain yield (Table 5). There were no differences at the Beltsville site, again perhaps due to the high level of pre-plant [NO\textsubscript{3} + NH\textsubscript{4}]–N (Table 1). At the Eden site, corn at the N-based PL rate with Austrian winter pea and at the N-based PL rate with no cover crop produced more grain than corn in the 0 PL treatment under the same cover crop treatments (Table 5). At the Queen Anne site, corn grain yield was similar in the N- and P-based PL treatments and greater in those treatments than in the 0 PL treatment across cover crop treatments. Under the 0 PL treatment, grain yield was greater under crimson clover than the no-cover crop treatment. Considering corn grain yield in tandem with TAN (Tables 4 and 5) suggests that luxury N consumption occurred in our study. Corn grain yield in 2011 site-years supports our hypothesis that N-based PL rates can be reduced to P-based PL rates without compromising corn yield—sometimes in the absence of, but particularly in combination with—a legume cover crop.

### 2011–2012 Season

In the 2011–2012 season, weeds were scarce at the Beltsville site, so spring biomass was not separated into fractions; crimson clover again produced more biomass than Austrian winter pea and hairy vetch (Fig. 2). At the Eden site, Austrian winter pea and hairy vetch again produced similar amounts of biomass (5000 and 4200 kg ha\textsuperscript{-1}, respectively). At the Queen Anne site, crimson clover was seeded with barley; this crimson clover/barley combination produced a similar amount of biomass as the winter pea, almost entirely due to barley biomass production. Crimson clover did not establish well in 2012, likely due to a...
November planting date (Table 2). Variable establishment success of crimson clover in the mid-Atlantic United States due to hardiness constraints has been reported in the literature; earlier planting dates improve establishment success, as might the use of regionally adapted germplasm (Duiker, 2014). Currently, hairy vetch, crimson clover, and Austrian winter pea are the focus of an intensive germplasm refinement effort to select and breed cover crops that better meet organic farmer needs, including improved winter hardiness and maximum N fixation (USDA–ARS, 2015). The large amount of barley biomass mixed with clover at the Queen Anne site in 2012 also helps to explain the much lower N accumulation compared with 2011 (Fig. 3).

We did not collect soil mineral N data at black layer in Beltsville in 2012. At the Eden site in 2012, TAN was lower in the 0 PL than in the N-based PL treatment under both the no-cover crop treatment and Austrian winter pea cover crop; no significant differences were detected under the hairy vetch cover crop across PL rates (TAN ranged from 190 to 220 kg N ha⁻¹). In the 0 PL treatment, TAN was higher in the hairy vetch treatment than in the no-cover crop control (190 vs. 119 kg N ha⁻¹). At the Queen Anne site, TAN was lower under the 0 PL treatment than the N-based PL treatment under the no-cover crop and crimson clover + barley treatments. Unsurprisingly, given the low N accumulation of the crimson clover + barley treatment (Fig. 3), TAN was lower in the crimson clover + barley treatment compared with the Austrian winter pea treatment when 0 PL was applied (Table 4).

Few differences in corn grain yield were detected in the 2011–2012 season (Table 5). At the Beltsville site, corn grain yield in the crimson clover treatment at the P-based rate (6.91 Mg ha⁻¹) was greater than at the 0 PL rate (3.35 Mg ha⁻¹) and equal to that at the N-based rate (4.79 Mg ha⁻¹). At the Eden site, grain yield was greater in the N- and P-based treatment than in the 0 PL treatment when no cover crop was present (9.22, 9.98, and 4.77 Mg ha⁻¹, respectively). Yield was also greater in the hairy vetch and Austrian winter pea treatments than in the no-cover crop control at the 0 PL rate (9.20, 8.64, and 4.77 Mg ha⁻¹, respectively). At the Queen Anne site, corn yield was greater in the no-cover crop, N-based PL treatment than the P-based PL treatment but was statistically the same in the P-based and 0 PL treatments, possibly due to underlying variability not detected in our soil sampling regime. No other differences were detected in this site-year. Not surprisingly, corn grain yields were consistently greater at the irrigated Queen Anne site than at the other two nonirrigated sites. As in the 2010–2011 season, grain yields compared with TAN suggested the presence of luxury N need to a rate equivalent to the P removed in the corn grain both under irrigation and in dryland settings. In three of six site-years, grain yield was significantly lower in the control (0 PL) no-cover treatment than in the N-based and P-based no-cover treatments, indicating the value of including a winter annual legume cover crop in rotation prior to corn. In the other two site-years, it is likely that basal soil N fertility filled the gap in N need, demonstrating the fertility of such sites and providing “insurance” against the occasional unsuccessful cover crop establishment. Longer-term studies are needed to determine PL plus cover crop strategies for drawing down soil P levels in organic corn cropping systems and to determine the threshold number of years after which PL application could be raised from a P-based rate back to an N-based rate if needed.

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**REFERENCES**


