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# Cover Crop Mixture Effects on Maize, Soybean, and Wheat Yield in Rotation

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### Core Ideas

- Few studies report the effects of cover crop mixtures on crop yields in rotation.
- Cover crop C/N ratio was negatively correlated with maize yield.
- Multispecies mixtures did not affect maize, soybean, or wheat yields.
- Cover crops with high biomass and C/N ratios provide unique ecosystem services.
- Both mixtures and diverse rotations may enhance cover crop ecosystem services.

**Abstract:** Despite the popularity of multispecies cover crop mixtures, there is little published evidence of their effects on subsequent crop yields, especially for multiple crops grown in rotation. We examined the effects of fall-planted cover crops—both mixtures and their component monocultures—on subsequent crop yields in an organically managed maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–winter wheat (*Triticum aestivum* L.) rotation in central Pennsylvania. We hypothesized that cover crop biomass C/N ratio would be negatively correlated with crop yields. This held true for maize ($R^2$ = 0.134, $p$ < 0.0001), but there was no cover crop effect on soybean or wheat yields. All multispecies mixtures produced high biomass, and none affected maize yield relative to fallow. Our findings suggest that both multispecies cover crops and diverse crop rotations may increase opportunities to gain the benefits of cover crops with high biomass and C/N ratio—such as erosion control, weed suppression, N retention, and soil C accumulation—without compromising yield.

Multispecies cover crop mixtures are quickly gaining popularity in the United States. According to a national survey of cover crop users, adoption of multispecies mixtures increased 38% between 2012 and 2016 (CTIC and SARE, 2013; CTIC, 2017). Compared with traditional mono- and biculture cover crops, mixtures have the potential to optimize across a wider range of ecosystem services, such as building soil organic matter, reducing N leaching, and improving yield of the following crop (Creamer et al., 1997; LaChance et al., 2015; Finney and Kaye, 2016). However, there is little published evidence of the effects of cover crop mixtures on subsequent crop yields, especially for multiple crops grown in rotation (Welch et al., 2016; Chu et al., 2017).

A recent meta-analysis (Marcillo and Miguez, 2017) found that maize (*Zea mays* L.) yield increased an average of 13% following cover crop mixtures compared with no cover crop, but these were predominantly bicultures. Most studies of multispecies cover crops have found little or no effect on the yield of the following cash crop (Smith et al., 2014; Welch et al., 2016; Appelgate et al., 2017), except when cover crops affected soil water availability (positively or negatively) in semiarid environments (Wortman et al., 2012; Reese et al., 2014; Nielsen et al., 2016). However, Chu et al. (2017) showed that soybean [*Glycine max* (L.) Merr.] yield was higher following 3 yr of a diverse cover crop mix, potentially due to increased soil moisture content.

A small body of literature indicates that cover crop mixtures can strongly influence the yield of the following crop by affecting soil N availability, particularly for crops with high N demand, such as maize (Kuykendall et al., 2015; Finney et al., 2016; White et al., 2016, 2017). Plant residue with a C/N ratio below 25 is likely to result in net N mineralization when returned to the soil, increasing N supply, while residue with a C/N ratio higher than 25 is likely to result

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**Abbreviations:** 3SppN, three species nitrogen management; 3SppW, three species weed management; 4Spp, four species; 6Spp, six species.

in net N immobilization, reducing soil N supply (White et al., 2016). In a tilled system with no fertilizer added, Finney et al. (2016) found that cover crop mixtures with low-C/N biomass increased maize yield by up to 47%, while high-C/N mixtures decreased maize yield by up to 70%.

If the risk of yield loss deters adoption of high-C/N cover crops, some potential benefits of cover cropping may be lost, because the C/N ratio typically increases as plants gain biomass and approach physiological maturity. High-biomass cover crops can maximize important services such as erosion control (Blanco-Canqui et al., 2015), N scavenging (Finney et al., 2017), weed suppression (Baraibar et al., 2018), and C sequestration (Poeplau and Don, 2015). In addition, allowing insect-provisioning species such as canola (*Brassica napus* L.) to mature to flowering stage may help promote pollination and biocontrol services (Ellis and Barbercheck, 2015). Understanding individual crops' yield sensitivity to the C/N ratio of the cover crop mixture is therefore an important step toward maximizing cover crop benefits.

We examined the effect of diverse cover crop mixtures, and their component monocultures, on crop yields in an organically managed maize–soybean–winter wheat (*Triticum aestivum* L.) rotation in central Pennsylvania. We hypothesized that cover crop mixtures with low-C/N biomass would increase yields of the following cash crops, while high-C/N cover crops would decrease yields.

# Materials and Methods

This study was conducted from 2012 to 2015 at the Pennsylvania State University Russell E. Larson Agricultural Research Center, Rock Springs, PA (40°43′ N, 77°56′ W). The field site is dominated by Murrill channery silt loam soil (fine-loamy, mixed, semiactive, mesic Typic Hapludult), and the typical slope is 0 to 3% (Soil Survey Staff, 2017). Average annual precipitation at the site is 1020 mm, and mean monthly temperatures range from −3°C (January) to 22°C (July) for 1980 to 2016 (Xia et al., 2012).

## Experimental Design and Management

Treatment plots were established in a randomized complete block design with four replications. Crops were planted in the following 3-yr rotation: maize silage–cover crop–soybean–winter wheat–cover crop. All phases of the rotation were present in each year. Since wheat was grown without a preceding cover crop, cover crop legacy effects on wheat plots were minimal until the final year. Organic management was initiated in July 2012.

Cash crops were planted in 24-m by 348-m strips. Dairy bed pack manure was applied on a wet-weight basis at rates designed to meet the P demand of the system. This supplied an average of 128 and 57 kg ha$^{-1}$ of plant-available N and an average of 94.2 and 89.6 kg ha$^{-1}$ of $P_2O_5$ before maize and wheat, respectively (Hunter, 2018). Cash crops were managed according to organic practices (White et al., 2015), including mechanical weed control. Mean planting and harvest dates, respectively, were as follows: maize: 31 May and 13 September; soybean: 6 June and 10 October; wheat: 22 October and 19 July (Hunter, 2018, Table 3-1).

All cover crop treatments were planted on the same day into tilled soil in 24-m by 29-m plots. Cover crops were terminated by flail mowing and incorporated by moldboard plowing 2 to 4 wk prior to planting maize or soybean. Mean cover crop planting and termination dates, respectively, were as follows: before maize: 16 August and 7 May; before soybean: 30 September and 16 May (Hunter, 2018, Table 3-1).

Six monoculture species were planted prior to both maize and soybean. Species were chosen with contrasting functional traits: two legumes (Fabaceae), medium red clover (*Trifolium pratense* L.) and Austrian winter pea (*Pisum sativum* L.); two brassicas (*Brassicaceae*), canola (*Brassica napus* L. 'Wichita') and forage radish (*Raphanus sativus* L. 'Tillage Radish'); and two grasses (Poaceae), cereal rye (*Secale cereale* L. 'Aroostook') and spring oat (*Avena sativa* L. 'Jerry'). One species from each family is known to be winter-hardy in central Pennsylvania (clover, canola, and rye), while the other is known to be susceptible to winter kill (pea, radish, and oat). A tilled fallow served as a control.

These component species were combined into four mixtures of increasing species and functional diversity. Prior to maize, the mixtures were as follows: three species N management (3SppN): rye, pea, clover; three species weed management (3SppW): rye, oat, clover; four species (4Spp): rye, pea, clover, canola; six species (6Spp): all monocultures. Prior to soybean, the compositions of 3SppN and 4Spp were adjusted to focus on N scavenging rather than N fixation, resulting in the following mixtures: 3SppN: rye, oat, radish; 4Spp: rye, pea, radish, canola. The 3SppW and 6Spp mixtures were the same in both planting windows. However, as reported below, only cereal rye reliably overwintered in this window, so there were effectively two treatments: rye and no rye. Further details of cover crop establishment, seeding rates, and mixture design are available in Murrell et al. (2017) and Hunter (2018).

## Data Collection

Cover crop biomass was sampled as reported in Murrell et al. (2017). Briefly, living aboveground biomass taller than ~2 cm was sampled in both fall and spring in three 0.25-m$^2$ quadrats per plot. Biomass was sorted to species, dried, weighed, and analyzed for C and N concentrations by the combustion method as described in Finney et al. (2016). Weeds were included in biomass and C/N ratio calculations. The C/N ratio of weed biomass was not directly measured for all samples, but seasonal means were applied based on a subset of samples taken prior to maize in the fall (mean of 20.0) and spring (19.8) and prior to soybean in the spring (20.2). To represent total cover crop effects prior to maize, fall and spring cover crop biomass were summed and the weighted average of fall and spring C/N ratio was calculated. Prior to soybean, due to limited fall growth, only spring values were used.

Maize was harvested for silage at 60 to 70% moisture from two subsamples of crop row at least 5.3 m in length, dried, and weighed. Soybean and wheat were harvested at physiological maturity with a small-plot combine pass along the full length of the plot. Soybean and wheat yields were adjusted to 13 and 13.5% moisture, respectively.

## Statistical Analyses

All statistical analyses were performed in R (R Core Team, 2013). Mixed-effect linear models were specified with the lmer function (Bates et al., 2015). Pairwise comparisons were evaluated with the emmeans function (Lenth, 2018) with a Tukey adjustment for multiple comparisons. Explanatory power of fixed effects in mixed models was assessed with marginal $R^2$ ($R^2_m$) calculated with the r.squaredGLMM function (Bartoń, 2016). An $\alpha$ value of 0.05 was used to assess statistical significance.

# Results and Discussion

## Cover Crop Performance

Prior to maize, the 3SppN and 4Spp mixtures produced more biomass than any of the monocultures other than rye (Fig. 1A), primarily due to the combination of fall pea biomass and spring rye biomass (see Fig. 1 in Murrell et al., 2017). Radish and clover produced less biomass than all mixtures. Cover crops that were dominated by grasses (oat, rye, and 3SppW) had the highest C/N ratios (~30; Fig. 1B). The other mixtures and the brassica monocultures had moderate C/N ratios (~20), and the legume monocultures had the lowest (~12).

Prior to soybean, late planting resulted in minimal fall biomass production (Murrell et al., 2017; Hunter, 2018). Only cereal rye reliably overwintered, which reduced the effective treatments in this window to two: rye and no rye. In the rye-containing treatments, mean spring biomass was 2870 kg ha$^{-1}$ and C/N ratios were ~26 to 40; in the no-rye treatments, biomass was 207 kg ha$^{-1}$ and C/N ratios were ~11 to 22.

## Cash Crop Yields

Mean maize silage yield was 12.9 Mg ha$^{-1}$. Cover crop treatment explained 21.7% of the variability in annual maize yield across all 3 yr ($p < 0.0001$; Fig. 1C). In pairwise comparisons, only pea increased yield relative to fallow and only rye decreased yield. None of the mixtures affected maize yield relative to fallow, but yield following 3SppN and 4Spp was equivalent to that following pea, and yield following 3SppW was equivalent to that following rye. Spring cover crop C/N ratio was negatively correlated with maize yield and explained 13.4% of yield variability ($p < 0.0001$; Fig. 1D). These results are in keeping with previous findings that the mean effect of cover crop mixtures (mostly bicultures) on maize yield is relatively small (Marcillo and Miguez, 2017) and that there is a risk of maize yield loss following high-C/N cover crop mixtures (Kuykendall et al., 2015; Finney et al., 2016; White et al., 2016, 2017).

Mean soybean yield was 3.1 Mg ha$^{-1}$. There were no cover crop effects on soybean yield, either by treatment or between the rye-containing and no-rye treatment groups ($p = 0.948$ and $p = 0.949$, respectively), despite relatively high spring rye biomass production (2870 kg ha$^{-1}$). Likewise, spring cover crop C/N ratio did not explain soybean yield ($p = 0.877$), likely due to soybean's ability to symbiotically fix

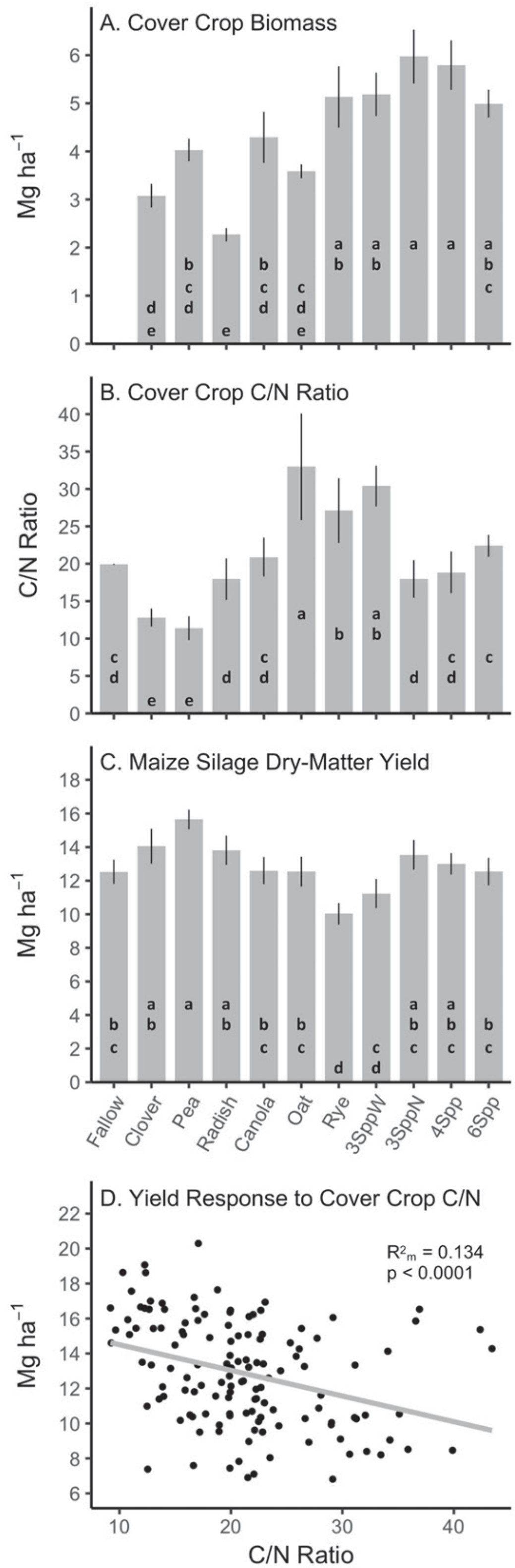


**Fig. 1. Combined spring and fall cover crop (A) biomass and (B) C/N ratio prior to maize. (C) Resulting maize silage dry-matter yield and (D) the relationship between maize silage dry-matter yield and cover crop biomass C/N ratio. In A, B and C, bars represent means and whiskers represent standard error; means that share a letter are not significantly different at the $\alpha = 0.05$ level with a Tukey correction for multiple comparisons. 3SppN: rye, pea, clover; 3SppW: rye, oat, clover; 4Spp: rye, pea, clover, canola; 6Spp: all monocultures.**

atmospheric N, which limits its N responsiveness to high-yield-potential environments (Salvagiotti et al., 2008).

Likewise, wheat yield did not differ by cover crop ($p$ = 0.859); mean yield was 2.4 Mg ha$^{-1}$. Even in 2015, the only year in which the wheat plots had a 2-yr legacy of cover cropping, there were no yield effects of cover crop treatment ($p$ = 0.789) or between the rye-containing and no-rye groups ($p$ = 0.867). This is likely due to the temporal separation between cover crop termination and wheat planting, as well as the manure applied prior to wheat.

## Management Implications

Overall, multispecies cover crop mixtures did not significantly affect the yield of cash crops grown in this organically managed maize–soybean–wheat rotation, relative to a fallow control. This finding has strong implications for the potential of cover crop mixtures to provide multiple ecosystem services without compromising yield.

Prior to a sequence of soybean and wheat, cover crops with high biomass (>2.5 Mg ha$^{-1}$) and C/N ratios (>25) did not jeopardize cash crop yield. However, this tradeoff may be more difficult to navigate for cover crops planted immediately before cash crops with high N demand, such as maize. Two of the mixtures in this study, 3SppN and 4Spp, achieved maximum biomass and led to maize yields that did not differ from those following pea, the treatment with the highest mean yield. This indicates that appropriately constructed mixtures (in this case, those that contained pea to balance the effects of rye) can optimize ecosystem services and cash crop yield. However, the 3SppW mixture resulted in equivalent maize yields to those following rye, the treatment with the lowest mean yield. This highlights the risk of planting high-C/N cover crops prior to maize, even in mixture. Adjusting seeding rates to increase the proportion of legume biomass in mixtures or applying additional N fertilizer could help mitigate the risk of yield loss, while still reaping the benefits of high-biomass cover crops.

Overall, our results show that well-designed cover crop mixtures can strike a balance between high cover crop biomass production and the yield of N-responsive crops, such as maize. Moreover, our findings indicate that diverse crop rotations that include less-N-responsive cash crops, such as soybean, may provide farmers with additional cover cropping options and thereby help them achieve multiple agronomic and environmental goals.

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