Ecosystem Services and Disservices Are Bundled in Simple and Diverse Cover Cropping Systems

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Core Ideas

- Cover crop monocultures and mixtures support multiple ecosystem services.
- Service interactions can lead to bundling, or co-occurrence, of certain services.
- Service interactions also create trade-offs among services and disservices.
- Cover crop mixtures can mitigate disservices to increase multifunctionality.

Abstract: Agroecosystems are increasingly expected to provide multiple ecosystem services. We tested whether and how cover crop selection (identity and number of species) affects provisioning of multiple services (multifunctionality). In a 3-yr study of 10 cover crop treatments and eight ecosystem services, certain services consistently co-occurred. One such service "bundle" included cover crop biomass production, weed suppression, and nitrogen retention. Another set of bundled services included cash crop production, nitrogen supply, and profitability. We also identified trade-offs: as some services increased, other disservices arose, limiting multifunctionality. However, functionally diverse mixtures ameliorated disservices associated with certain monocultures, thereby increasing cover crop multifunctionality.

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COVER CROPS are widely used to improve soil quality, weed management, pest regulation, nutrient cycling, and crop yield (Snapp et al., 2005; Blanco-Canqui et al., 2015; CTIC, SARE, and ASTA, 2016). This array of ecosystem services suggests that cover crops are "multifunctional," although current knowledge is primarily derived from studies of single or disciplinary-focused subsets of services (Schipanski et al., 2014). Furthermore, processes that enable cover crop multifunctionality are not well understood. Increasing cover crop diversity, for example, can enhance multifunctionality (Finney and Kaye, 2017), but not all services respond in the same manner (Finney et al., 2016). Cover crops can also introduce disservices, leading to an outcome worse than not planting a cover crop (Finney et al., 2016).

Managing cover crops for multifunctionality requires knowledge of how service interactions are influenced by species identity and diversity (Carpenter et al., 2009). Interactions arise when the provisioning of one service leads to changes in another or when the same factor drives a change in multiple services, leading to co-occurring or "bundled" services (Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Storkey et al., 2015; Finney et al., 2016). As one example of linked services, high nitrogen (N) retention in grass cover crops can lead to low N supply (low residue mineralization) and low yields in the subsequent cash crop (Finney et al., 2016; White et al., 2017).

Common approaches to analyzing multifunctionality do not highlight interactions that lead to service synergies or trade-offs. Multifunctionality is typically calculated as an average of standardized values (Maes et al., 2012; Byrnes et al., 2014; Storkey et al., 2015; Finney and Kaye, 2017). Yet, averaging masks how individual services respond to diversity because increases and decreases in individual services can average each other out (Byrnes et al., 2014).

Here, we evaluate cover crop multifunctionality based on eight ecosystem services measured for three consecutive years in 10 cover crop treatments using

Abbreviations: PCA, principal components analysis.

a quantitative approach to assess multifunctionality and service interactions. We expect that (i) interactions among services lead to service bundles and trade-offs, (ii) mixtures provide greater multifunctionality than monocultures, and (iii) increasing functional diversity in mixtures enhances multifunctionality.

Materials and Methods

From 2012 to 2015 on land transitioning to organic certification in Rock Springs, PA (40°43′ N, 77°55′ W), 10 cover crop treatments (Table 1) and a no-cover crop control (hereafter, "control") were planted after wheat (*Triticum aestivum* L.) and terminated prior to planting maize (*Zea mays* L.; Murrell et al., 2017). We quantified eight ecosystem services provided by cover crops for three consecutive years. The cover crop biomass (hereafter, "biomass") production service was the fall plus spring aboveground biomass (kg ha^{-1}) sampled as in Murrell et al. (2017). The weed suppression service was the fall plus spring weed biomass minus weed biomass in the control (Baraibar et al., 2017). The N retention service was nitrate (NO_3^-–N) accumulation on anion exchange resin bags (169 cm^2 surface area buried at 25 cm) from cover crop planting to termination (kg NO_3–N ha^{-1}) minus NO_3–N accumulated in the control (Finney et al., 2016). Pest suppression was indexed by infection of sentinel insects by *Metarhizium* (Order: Hypocreales; Family: Clavicipitaceae), an entomopathogenic fungus widely researched as a control agent against soil-inhabiting arthropod pests. For 7 to 10 d prior to cover crop termination, we placed 15 last instar greater wax moth, *Galleria mellonella* (Zimmermann, 1986), in a lidded container with soil from the plot. The pest suppression service was the percentage of sentinel insects infected by *Metarhizium* in the cover crop minus the control. The active soil carbon (C) service was calculated as permanganate oxidizable C (mg C kg^{-1} soil; Weil et al., 2003; Culman et al., 2012) in each cover crop treatment minus the control. Eleven soil cores (2.5 cm diam. by 20 cm deep) per plot were collected and composited for analysis on two dates, before (May) and after (July) cover crop termination. Nitrogen supply was calculated using a previously calibrated model that predicts the effects of cover crop residues

and N uptake on N availability to subsequent maize crops, relative to a no-cover control (White et al., 2016). The model inputs were fall and spring cover crop biomass N per unit area, spring biomass C/N ratio, and spring soil NO_3^- concentrations for each plot. The cash crop production service (Mg ha^{-1}) was corn silage yield (hand harvested from two 5.3-m row lengths per plot) at 65% moisture following each cover crop minus yield in the control, both grown without supplemental fertility inputs. Using annual enterprise budgets for each treatment, the short-term profitability service was calculated as annual profit associated with each cover crop minus the control.

The measured value of each service proxy was relativized to the control within the same year (Finney et al., 2016) so that a higher value always indicates greater provision. Positive values indicate that the cover crop performed better than the control (hereafter, "service"). Negative values indicate that the cover crop performed worse than the control (hereafter, "disservice"). Service values were divided by their standard deviation to put values on a comparable scale while retaining directionality (positive = service; negative = disservice). To identify interactions among ecosystem services, we performed principal components analysis (PCA) on standardized values (R package vegan; Oksanen et al., 2016).

To create an average multifunctionality index for each cover crop treatment, standardized values for services exhibiting a significant response to cover crop treatment ($P < 0.05$, mixed-model ANOVA, R package lmer4; Bates et al., 2015) were averaged together. Treatment differences for average multifunctionality were determined by ANOVA with year and block as random effects using Tukey's adjustment (PROC MIXED, SAS v. 9.4 [SAS Institute, 2014]). Preplanned contrasts detected differences between monocultures and multispecies mixtures. The effect of species richness (*S*, the number of cover crop species in aboveground biomass) on multifunctionality for all treatments was analyzed using a mixed model (R package lmer4; Bates et al., 2015) with block and year as random effects. Multifunctionality and *S* were log-transformed to provide the best fit for the model and marginal R^2 calculated following Nakagawa and Schielzeth (2013). Functional diversity of cover crop mixtures was

Table 1. Cover crop monoculture and mixture seeding rates planted after wheat in a 3-yr wheat–maize silage–soybean rotation in central Pennsylvania. Average multifunctionality value is based on seven ecosystem services. Modified from Murrell et al. (2017).

Cover crop	Medium red clover	Winter canola 'Wichita'	Forage radish 'Tillage radish'	Cereal rye 'Aroostook'	Oat 'Jerry'	Austrian winter pea	Average multifunctionality
	plants m^{-2}						
Red clover	600						0.66de†
Canola		400					0.64de
Radish			60				0.92bcd
Rye				500			0.34e
Oat					300		0.92bcd
Pea						60	1.47a
3 species nitrogen	300	0	0	100	0	30	1.09b
3 species weed	300	0	0	250	150	0	0.77cd
4 species	300	200	0	100	0	30	1.08bc
6 species	150	100	20	100	75	15	0.94bcd

† Letters denote statistical differences based on Tukey's HSD (α = 0.05).

estimated using relative Rao's quadratic entropy (rRao; Rao, 1982). Relative Rao was calculated in FDiversity software (Casanoves et al., 2011) based on four cover crop characteristics: fall growth potential, spring growth potential, peak C/N ratio, and taxonomic family (Finney and Kaye, 2017). We used mixed models (PROC MIXED, SAS 9.4), with block and year as random effects, to test the relationship between rRao and (i) average multifunctionality, (ii) mean service (standardized service scores > 0), and (iii) mean disservice (standardized service scores < 0) in cover crop mixtures.

Results

Biomass production, weed suppression, and N retention services were provided by all treatments (Fig. 1) and bundled in the PCA (clustered in Fig. 2). Cash crop production, N supply, and profitability formed a second bundle (clustered in Fig. 2). There was a trade-off between these two bundles as they differentiated along principle component (PC) 1, which explained 40% of the variation in cover crop services (Fig. 2). Principle component 2, which explained 16% of variation in services, was driven by active soil C and pest suppression (Fig. 2).

Multifunctionality was based on seven services: biomass production, weed suppression, N retention, pest suppression, N supply, cash crop production, and profitability. Active soil C was not different among treatments ($P = 0.18$) and was excluded from the index. Although mixtures on average outperformed monocultures (estimate = 0.15, $P = 0.002$), the pea (*Pisum sativum* L.) monoculture exhibited the highest multifunctionality of all treatments (Table 1). There was a positive relationship between S and multifunctionality (log[multifunctionality + 1] = 0.22 + 0.10*log[S + 1], marginal $R^2 = 0.03$). Within mixtures, average multifunctionality increased ($P = 0.01$) with increasing functional diversity (rRao) because disservices (scores < 0 in Fig. 1) decreased as rRao increased ($P < 0.001$). In contrast, services (scores > 0 in Fig. 1) were not related to changes in rRao ($P = 0.71$).

Discussion

The temporal and spatial co-occurrence, or bundling, of ecosystem services is typically evaluated at landscape scales, frequently with differentiation among land uses (Raudsepp-Hearne et al., 2010; Maes et al., 2012). Within our field-based study, ecosystem services provided by cover crops were bundled into groups linked to aboveground biomass production and those linked to N supply. In general, we found few cover crop treatments that provided all ecosystem services because of a central trade-off between the biomass (biomass production, N retention, and weed suppression) and nutrient (N supply, cash crop production, and profitability) service bundles (PC1, Fig. 2). In legume monocultures, both bundles were supported, but there was
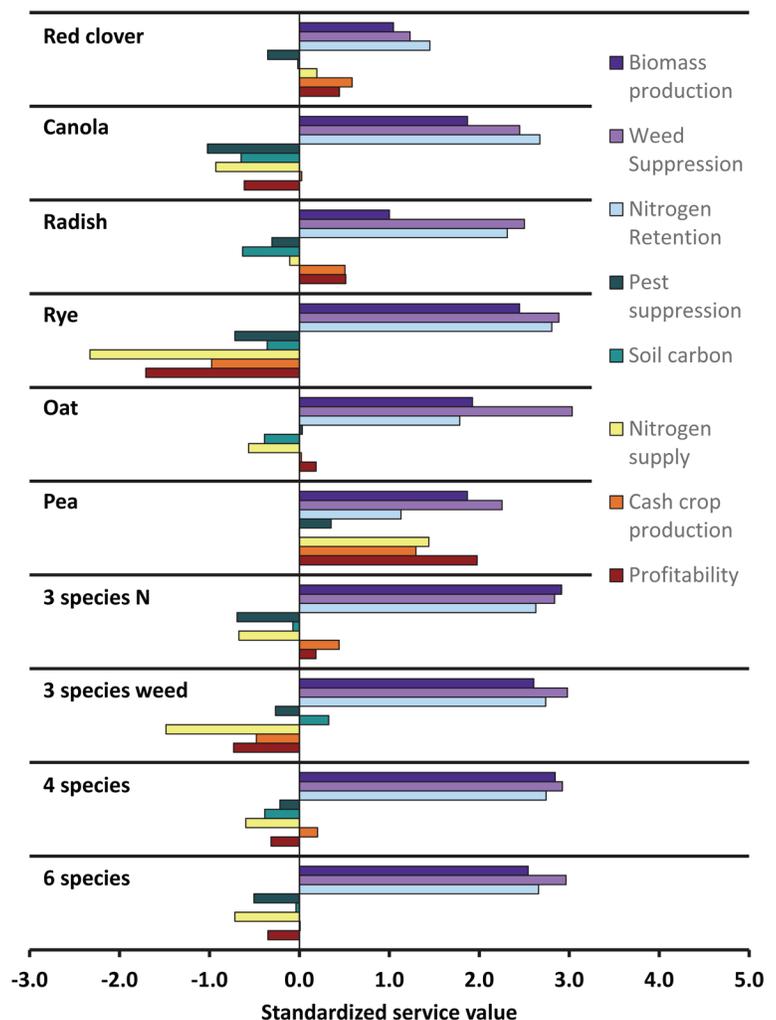

Fig. 1. Ecosystem services (values > 0) and disservices (values < 0) provided by 10 cover crop treatments incorporated in a wheat–maize silage–soybean rotation in a 3-yr field study in central Pennsylvania. See Table 1 for species included in each cover crop mixture.

large variation between species, as pea exhibited the highest multifunctionality index across all treatments whereas red clover (*Trifolium pretense* L.) was among the lowest. The high multifunctionality of pea was due to adequate provisioning of many services with no significant disservices. Red clover also provided many services and only one disservice, but the magnitude of individual services was low, leading to low multifunctionality (Fig. 1).

Overwintering nonlegume monocultures exhibited more extreme trade-offs, in which robust provisioning of the biomass bundle was accompanied by disservices in the nutrient bundle. This is consistent with disciplinary studies showing that legume cover crops that supply N retain less N than nonlegume cover crops (Tonitto et al., 2006). Conversely, cover crops with high N retention potential (e.g., cereal rye [*Secale cereale* L.]) are often associated with N immobilization leading to cash crop provision disservices (Wagger, 1989; Finney et al., 2016). An important implication of our results is that managing a trade-off like that between N supply and N retention by manipulating the cover crop C/N ratio (Finney

et al., 2016) may have implications for other nontarget services in the bundle.

Although increasing species richness had a positive effect on multifunctionality, it explained only 3% of the variation in multifunctionality. This outcome, coupled with the variable performance of monocultures, suggests that species number is less important to multifunctionality than the variety of traits present in a cover crop mixture. Functional diversity measures like rRao are commonly used to quantify trait variation (Cadotte et al., 2011). Consistent with previous research on the effects of pre-maize cover crop diversity on multifunctionality (Finney and Kaye, 2017), increasing functional diversity increased multifunctionality of cover crop mixtures. The fact that rRao reflects both the diversity of species traits and their relative abundance in a mixture indicates that multifunctionality was not based solely on the presence or absence of a particular species (Gagic et al., 2015). Notably, more functionally diverse mixtures increased multifunctionality by ameliorating disservices associated with component species, not by enhancing services. In this study, cereal rye was included in all mixtures and comprised 20 to 40% of fall and 70 to 90% of spring aboveground biomass (Murrell et al., 2017). Rye was exceptional in providing services in the biomass bundle, but it had high disservice scores for the nutrient bundle. Multispecies mixtures were an effective tool for managing these trade-offs because mixing rye with other species ameliorated the strong nutrient bundle disservices.

Awareness of common service bundles and trade-offs among them can help farmers and agronomists design multifunctional cover crop treatments that avoid damaging disservices. Our study demonstrates that while cover crop mixtures tend to have greater multifunctionality than monocultures, certain monocultures may provide similar (oat [*Avena sativa* L.], radish [*Raphanus sativus* L.]) or greater (pea) multifunctionality than diverse mixtures. Selecting a monoculture cover crop to support a single management goal will likely lead to provision of additional, bundled services but may also introduce disservices. This research demonstrates that mitigation of such trade-offs can be achieved with the use of functionally diverse cover crop mixtures.
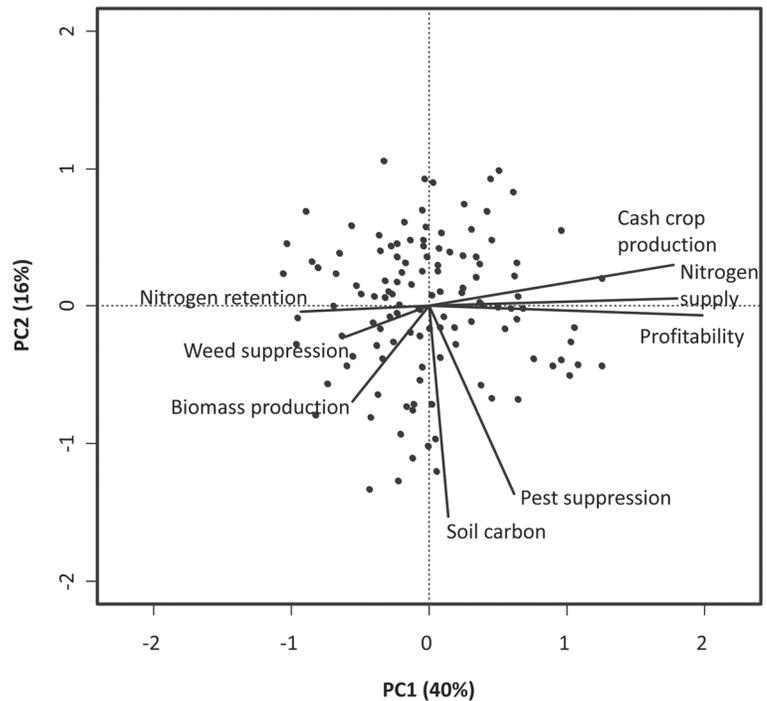
Acknowledgments

Fig. 2. Principle component analysis of eight ecosystem services provided by cover crops in a 3-yr field study of 10 cover crop systems incorporated in a wheat–maize silage–soybean rotation in central Pennsylvania. Values in parentheses indicate the percentage of variation explained by each principle component (PC) axis.

References

Baraibar, B., M.C. Hunter, M.E. Schipanski, A. Hamilton, and D.A. Mortensen. 2017. Weed suppression in cover crop monocultures and mixtures. Weed Sci. (in press). doi:10.1017/wsc.2017.59

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67(1):1–48. doi:10.18637/jss.v067.i01

Bennett, E.M., G.D. Peterson, and L.J. Gordon. 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12(12):1394–1404. doi:10.1111/j.1461-0248.2009.01387.x

Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, and G.W. Hergert. 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agron. J. 107(6):2449–2474. doi:10.2134/agronj15.0086

Byrnes, J.E., L. Gamfeldt, F. Isbell, J.S. Lefcheck, J.N. Griffin, A. Hector, B.J. Cardinale, D.U. Hooper, L.E. Dee, and J.E. Duffy. 2014. Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions. Methods Ecol. Evol. 5(2):111–124.

Cadotte, M.W., K. Carscadden, and N. Mirotchnick. 2011. Beyond species: Functional diversity and the maintenance of ecological processes and services. J. Appl. Ecol. 48(5):1079–1087.

Carpenter, S.R., H.A. Mooney, J. Agard, D. Capistrano, R.S. Defries, S. Diaz, T. Dietz, A.K. Duraiappah, A. Oteng-Yeboah, H.M. Pereira, C. Perrings, W.V. Reid, J. Sarukhan, R.J. Scholes, A. Whyte, S. Díaz, T. Dietz, A.K. Duraiappah, A. Oteng-Yeboah, H.M. Pereira, C. Perrings, W.V. Reid, J. Sarukhan, R.J. Scholes, and A. Whyte. 2009. Science for managing ecosystem services: Beyond the millennium ecosystem assessment. Proc. Natl. Acad. Sci. USA 106(5):1305–1312. doi:10.1073/pnas.0808772106

Casanoves, F., L. Pla, J.A. Di Rienzo, and S. Díaz. 2011. FDiversity: A software package for the integrated analysis of functional diversity. Methods Ecol. Evol. 2(3):233–237. doi:10.1111/j.2041-210X.2010.00082.x

CTIC, SARE, and ASTA. 2016. Annual report: 2015–2016 cover crop survey. CTIC, SARE, and ASTA.

Culman, S.W., S.S. Snapp, M.A. Freeman, M.E. Schipanski, J. Beniston, R. Lal, L.E. Drinkwater, A.J. Franzluebbers, J.D. Glover, A.S. Grandy, J. Lee, J. Six, J.E. Maul, S.B. Mirksy, J.T. Spargo, and M.M. Wander. 2012. Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. Soil Sci. Soc. Am. J. 76(2):494–504. doi:10.2136/sssaj2011.0286

Finney, D.M., and J.P. Kaye. 2017. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. J. Appl. Ecol. 54(2):509–517. doi:10.1111/1365-2664.12765

Finney, D.M., C.M. White, and J.P. Kaye. 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from diverse cover crop mixtures. Agron. J. 108(1):39–52. doi:10.2134/agronj15.0182

Gagic, V., I. Bartomeus, T. Jonsson, A. Taylor, C. Winqvist, C. Fischer, E.M. Slade, I. Steffan-dewenter, M. Emmerson, S.G. Potts, T. Tscharntke, W. Weisser, and R. Bommarco. 2015. Functional identity and diversity of animals predict ecosystem functioning better than species-based indices. Proc. Biol. Sci. 282:20142620. doi:10.1098/rspb.2014.2620

Maes, J., M.L. Paracchini, G. Zulian, M.B. Dunbar, and R. Alkemade. 2012. Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe. Biol. Conserv. 155(October):1–12. doi:10.1016/j.biocon.2012.06.016

Murrell, E.G., M.E. Schipanski, D.M. Finney, M.C. Hunter, M.H. Burgess, J.C. Lachance, B. Baraibar, C.M. White, D.A. Mortensen, and J.P. Kaye. 2017. Achieving diverse cover crop mixtures: Effects of planting date and seeding rate. Agron. J. 109(1):259–271. doi:10.2134/agronj2016.03.0174

Nakagawa, S., and H. Schielzeth. 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4(2):133–142. doi:10.1111/j.2041-210x.2012.00261.x

Oksanen, J., F.G. Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGlinn, P.R. Minchin, R.B. O'Hara, G.L. Simpson, P. Solymos, M.H.H. Stevens, E. Szoecs, and H. Wagner. 2016. vegan: Community ecology package. R Packag. version 2.4-1.

Rao, R. 1982. Diversity and dissimilarity coefficients: A unified approach. Theor. Popul. Biol. 21:21–43.

Raudsepp-Hearne, C., G.D. Peterson, and E.M. Bennett. 2010. Ecosystem services bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. USA 107(11):5242–5247. doi:10.1073/pnas.0907284107

SAS Institute. 2014. Base SAS 9.4 procedures guide. 7th ed. SAS Inst., Cary, NC.

Schipanski, M.E., M.E. Barbercheck, M.R. Douglas, D.M. Finney, K. Haider, J.P. Kaye, A.R. Kemanian, D.A. Mortensen, M.R. Ryan, J. Tooker, and C. White. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric. Syst. 125:12–22. doi:10.1016/j.agsy.2013.11.004

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, and J. Nyiraneza. 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agron. J. 97:322–332.

Storkey, J., T. Doring, J. Baddeley, R. Collins, S. Roderick, H. Jones, and C. Watson. 2015. Engineering a plant community to deliver multiple ecosystem services. Ecol. Appl. 25(4):1034–1043. doi:10.1890/14-1605.1

Tonitto, C., M.B. David, and L.E. Drinkwater. 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112(1):58–72. doi:10.1016/j.agee.2005.07.003

Wagger, M.G. 1989. Cover crop management and nitrogen rate in relation to growth and yield of no-till corn. Agron. J. 81(3): 533–538. doi:10.2134/agronj1989.00021962008100030028x

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Leibig. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. Am. J. Altern. Agric. 18:3–17.

White, C.M., S.T. DuPont, M. Hautau, D. Hartman, D.M. Finney, B. Bradley, J.C. LaChance, and J.P. Kaye. 2017. Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agric. Ecosyst. Environ. 237:121–133. doi:10.1016/j.agee.2016.12.016

White, C.M., D.M. Finney, A.R. Kemanian, and J.P. Kaye. 2016. A model-data fusion approach for predicting cover crop nitrogen supply to corn. Agron. J. 108(6):2527–2540. doi:10.2134/agronj2016.05.0288

Zimmermann, G. 1986. The "Galleria bait method" for detection of entomopathogenic fungi in soil. J. Appl. Entomol. 102:213–215. doi:10.1111/j.1439-0418.1986.tb00912.x