WEED RESEARCH An International Journal of Weed Biology, Ecology and Vegetation Management

DOI: 10.1111/wre.12334

Weed interference with no-till soyabeans influenced by fine-scale covariation between soil properties and cover crop performance

S V ESLAMI* & A S DAVIS†

*Department of Agronomy & Plant Breeding, Faculty of Agriculture, University of Birjand, Birjand, Iran and †USDA-Agricultural Research Service, Urbana, IL, USA

Received 13 March 2018
Revised version accepted 8 August 2018
Subject Editor: Matt Liebman, IA, USA

Summary

Balancing trade-offs in conservation agriculture between the conflicting impacts of soil disturbance on crop yield and soil quality is complicated by the need for adequate weed management, especially in production systems with low, or no, reliance upon herbicides. Production of soyabeans no-till planted into a rolled-crimped cereal rye cover crop is attracting increasing farmer interest. Experimental work on this approach to date has provided inferences at the field scale and above, helping to identify broad recommendation domains for best management practices. For individual growers, however, fine-scale information may also be helpful for making in-field adjustments to refine the system. In a three-year field study in Illinois, USA, we quantified key associations among no-till soyabean performance in a rolled rye system and decametre-scale variation in soil characteristics, cover crop performance and weed growth. Subfield variation in soil properties had both direct and indirect effects on soyabean yield. Local soil potassium limitation was linked to reduced rye height, which in turn indirectly reduced soyabean yields through decreased weed suppression by the cover crop. Slow-draining field areas that were still moist at the time of cover crop termination were associated with lower soyabean stands, directly reducing yields. Although the subfield characteristics influencing soyabean and cover crop performance may vary from farm to farm, this study highlights potential gains to be realised in this production system from a better understanding of how such properties covary at fine spatial scales and taking steps to create an environment conducive to maximising cover crop establishment and growth.

Keywords: precision agriculture, roller-crimper, structural equation modelling, ecological weed management, *Secale cereale*, *Glycine max*.

Eslami SV, Davis AS. Weed interference with no-till soyabeans influenced by fine-scale covariation between soil properties and cover crop performance. *Weed Research*. https://doi.org/10.1111/wre.12334.

Introduction

Conservation agriculture systems hold promise for combining improvements in soil quality and weed management without becoming overly reliant on herbicides. Cover cropping, as one of the main pillars of conservation agriculture, provides numerous well-known ecological and agronomic benefits in crop production systems, notably water conservation, improving soil and water quality, enhancing soil productivity and weed suppression (Mirsky *et al.*, 2011, 2013; Wells *et al.*, 2014; Hill *et al.*, 2016). Cereal rye has specific

Correspondence: A S Davis, Department of Crop Sciences, University of Illinois, AW-115 Turner Hall, 1102 S. Goodwin Ave., Urbana, IL 61801 USA. Tel: (+1) 217 333 9654; E-mail: asdavis1@illinois.edu

© 2018 European Weed Research Society

traits that make it an ideal fall(autumn)-planted cover crop in many agronomic systems, such as possessing appropriate agronomic traits as a cover crop, soil and water quality improvements and suppressing weeds (Barberi & Mazzoncini, 2001; Smith *et al*., 2011; Teasdale *et al*., 2012; Mirsky *et al*., 2013). To obtain the most benefits from including cover crops in cropping systems, and also to facilitate the planting operations of the main crop, the cover crop plants should be terminated before they set seed and become a nuisance in the main crop. A commonly practiced method in no-till soyabean production systems across the United States is to sow cereal rye in fall and terminate the cover crop in early spring with a burndown herbicide. For organic and low-external-input farmers, who need to partially or completely replace herbicides with physical, cultural and biological practices (Liebman *et al*., 2016), one approach to achieving this is through physical termination of cover crops in no-till systems with a roller-crimper.

Since the early 2000s in the USA and early 1970s in Brazil (Khatounian, 2004), no-till soyabean production systems featuring rolled-crimped cover crops have attracted farmers who wish to balance soil conservation and weed management benefits (Wells *et al*., 2014). The roller-crimper, a heavy metal cylinder with protruding fins that rotates on a lengthwise axis as it is drawn over the soil, is commonly used to kill winter annual cover crops before no-till planting of cash crops and deposits residues uniformly on the soil surface (Ashford & Reeves, 2003; Kornecki *et al*., 2006). The cover crop roller-crimper uniformly lays the cover crop down, crimps the vascular tissue and leaves plants intact and attached to their roots. Managing the residue in this way creates many benefits such as slow decomposition of cover crop residue, increased longevity of weed suppression (Creamer & Dabney, 2002), inhibition of cover crop regrowth and consistent ground cover due to even distribution of residues (Kornecki *et al*., 2006). In addition, a roller-crimper requires less energy to operate compared with some mechanical implements such as a flail mower (Smith *et al*., 2011). There have been improvements in roller-crimper operation through reducing vibrations, increasing planting efficiency and improving efficacy in terminating cover crops (Kornecki *et al*., 2006). Although this management system has several benefits, there are some drawbacks as well. The roller-crimper does not control emerged weed seedlings, so successful weed management is dependent upon prevention of weed seedling emergence through the production of large amounts of rye biomass (Mirsky *et al*., 2013). Moreover, the cover crop must mature to a growth stage where it is susceptible to mechanical control, which can delay cash crop planting and reduce crop yield (Nord *et al*., 2012). This production system is still being refined and scientific insights are needed to improve its performance.

The rolled rye no-till management system, like other agricultural management practices, interacts with baseline variation in soil physical and chemical properties in a field. Thus, it is not just the average soil conditions in a field that are of interest for evaluating this management practice, but the spatial distribution of soil properties (Peukert *et al*., 2016). Spatial variability in soil properties, occurring at scales varying from 10^{-2} to 10^{3} m, often causes spatial variability in the growth of both crop and non-crop vegetation (Dieleman *et al*., 2000; Kravchenko *et al*., 2017). Conservation agricultural systems rely heavily on cover crops and rotational diversity; therefore, the impacts of spatial variation on these systems can be particularly pronounced (Kravchenko *et al*., 2017). In addition, subfield variation in weed abundance can result from soil property interactions with applied weed control practices (Gerhards *et al*., 2012). Therefore, to understand the performance of this management system and its effects on soil functions and its associated ecosystem services at subfield scales, we need to explicitly consider corresponding spatial variation in soil properties and cover crop performance.

The objective of this study was to highlight important subfield site associations, occurring at the decametre spatial scale, between soyabean performance and rye growth, weed pressure, soil physical properties and soil chemical properties in a no-till rolled rye soyabean production system. Within this framework, we hypothesised that variation in soil properties would influence soyabean yield in two ways: through direct effects on the soyabean crop itself and through indirect effects mediated through soil associations with either cover crop performance or weed growth, or both.

Materials and methods

Field study design

We conducted the field study at the University of Illinois Crop Sciences Research and Education Center in Savoy, Illinois, USA (40°3′, −88°15′). The soil type was a Flanagan silty clay loam (Fine, smectitic, mesic Aquic Argiudoll) with 56% silt, 27% clay, pH 6.0 and 4.8% soil organic matter. The experiment took place from fall 2007 to fall 2010 within the soyabean phase of a soyabean-spring oat crop rotation (to facilitate timely cereal rye planting before the soyabean phase) on two adjacent 0.80 ha study sites, fields A and B (together making up two halves of a larger production

© 2018 European Weed Research Society

field). Prior to initiation of the experiment, fields A and B were part of the same larger production field planted to maize and soyabean and managed using practices typical of local commercial operations. The study was initiated in September 2007 by drilling a cereal rye winter cover crop in field A at 135 kg seed ha^{-1} on 15-cm row spacing. Two levels of the experimental factor *cover crop cultivar* ('Aroostook' and 'HiRye') were established in a randomised complete block design with three replicate blocks in field A. Study plots were 9.1 m wide and 123 m long, to make it possible to sample across relevant soil environmental gradients. In early April of 2008, oat was planted in field B in 15-cm rows at 67 kg seed ha^{-1}. In late May of 2008, rye was mechanically terminated in field A with a roller-crimper at 95% anthesis (Ashford & Reeves, 2003), operating the roller parallel to the long axis of the plots. Soyabean (Pioneer 93M61) was then no-till planted into terminated rye residues at a population of 425 000 seeds ha^{-1} in 0.76-m rows parallel to the direction of crimping. No additional weed management (besides the rolled-crimped rye residue) was performed in the soyabean crop. This process of planting a soyabean crop into a mechanically terminated cereal rye cover crop was repeated within field B in 2009 and field A in 2010 (during which time, oats were grown in fields A and B respectively). The experimental design and plot dimensions were the same for fields A and B, and management practices for the rye cover crop and soyabean crop were also held constant across both fields. No fertiliser was applied to either the oat or the rye phases of the crop rotation during the study, in order to reveal underlying variation in soil fertility associated with subfield soil heterogeneity.

To quantify subfield decametre-scale variation in soil and plant properties in each of the growing seasons, we overlaid, upon each whole-field randomised complete block design, a matrix consisting of 60 sampling stations on a 9.1-m grid, analogous to the precision experimental design of Gerhards *et al.* (2012). Within each plot, 10 sampling stations were located at 9.1-m intervals along the length of the plot. Sampling stations consisted of two paired 1 m^2 quadrats assigned to the factor *weed management* (ambient vs. weed-free). Weeds were removed every two weeks by hand from the weed-free quadrats, plus a 0.5-m weed-free buffer area for each quadrat, from soyabean planting through to harvest.

Plant and soil variables

At each station, we measured soil chemical and physical properties and variables related to cover crop, weed and soyabean growth (Figs 1–4). Soil samples were collected two weeks prior to cover crop termination by taking ten 2.5-cm-diameter soil cores to a depth of 30 cm from each sampling quadrat and bulking the cores to form a composite sample. Soil chemical properties included NO_3, NH_4, P, K, Ca, Mg, CEC, pH and SOM, and were analysed through standard protocols by a commercial soil testing laboratory. Soil compaction was measured with a hand-held penetrometer. Gravimetric soil moisture content was determined by weighing subsamples before and after drying to a constant mass at 100°C.

Cereal rye ground cover and population were measured in each sampling quadrat in late March, at the early tillering stage (approximately stage 22 on the Zadoks scale; Zadoks *et al.*, 1974). Rye height and tiller number were measured in sampling quadrats just prior to rye termination, at late anthesis (Zadoks 65–67). Rye biomass was measured at the same time in 0.5 m quadrats placed to the outside of the sampling quadrats, to avoid altering soyabean and weed growth within the quadrats. Transmittance of photosynthetically active radiation (PAR) through the rye canopy was measured just prior to rye termination and at two weeks following termination. At each measurement date, PAR transmittance was measured by placing a point sensor above the rye canopy and a line quantum sensor at the ground surface below the rye canopy (pre-termination) or beneath the flattened rye residues (post-termination).

Weed populations within the sampling quadrats were counted just prior to rye termination and weed biomass within the quadrats was measured at the time of soyabean harvest. Weed populations and biomass were separated to the dominant three species (*Amaranthus tuberculatus* (Moq.) J.D.Sauer, *Erigeron canadensis* (L.) Cronquist and *Setaria faberi* Herrm.) and the unclassified remainder added into the totals. Two of the three weed species, *A. tuberculatus* and *E. canadensis*, are also the most commonly reported dominant weed species in commercial soyabean production systems in the Midwest USA (Van Wychen, 2016).

Soyabean stand was quantified two weeks after planting within the 2 m of row represented at each sampling station. Soyabean was hand-harvested at maturity, air-dried at room temperature under continuous air flow for three weeks. The grain was machine threshed and cleaned with a seed cleaner, moisture content determined and yield quantified at a 13% grain moisture equivalent. Soyabean yield loss due to weed interference was determined at each station for each ambient/weed-free pair.

Statistical analyses

Our approach to statistical analyses of the data involved a series of steps that progressed from

© 2018 European Weed Research Society

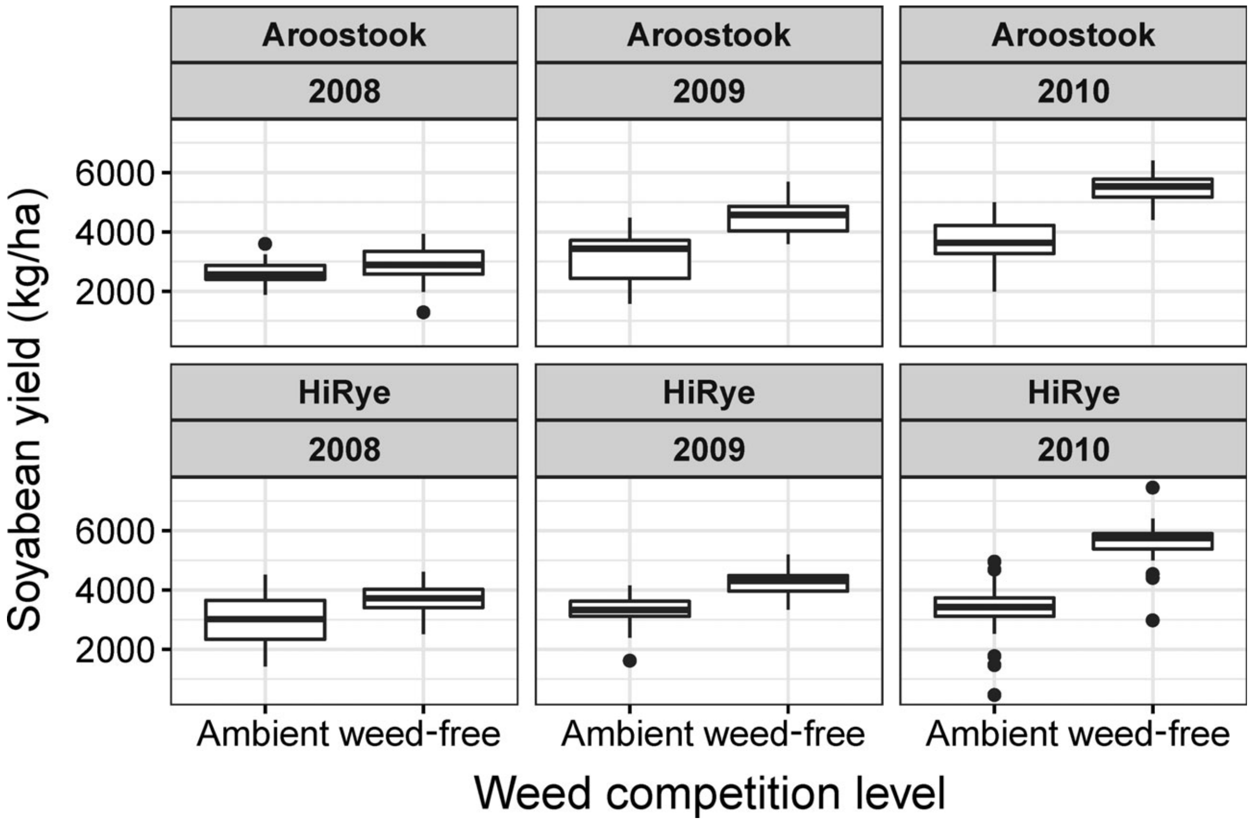

Fig. 1 Yield of soyabean in Savoy, Illinois, USA, under two weed competition treatments (weed-free and ambient weed populations), no-till planted into rolled residues of the Aroostook and HiRye cultivars of cereal rye.

attempting to characterise more general, field-scale knowledge about the system (mixed effects linear models), to increasingly specific understanding of the spatial covariances among variables. These latter analyses addressed three types of questions. First, how does the amount of variation in soil and plant properties among sampling locations change with interlocation distance; or, at what sampling distance does the amount of variation become more or less constant, indicating spatial independence [semivariance analysis]? Second, which of the many possible spatial associations among soil, cover crop and weed properties are most related to variation in soyabean performance, and which should we focus on in more explicit detail [Random Forests]? Finally, what are the specific associations among soil, cover crop and weed properties in relation to soyabean performance at the decametre spatial scale [Structural Equation Modelling]? The statistical methods addressing each of these questions are described in more detail below.

We tested for effects of field-scale factors on soyabean yield using hierarchical linear mixed effects models containing fixed effects for cereal rye cultivar, weed competition level and year, and their interaction terms, and a random effects nesting structure consisting of year{replication{rye cultivar{station}}}. To quantify effects of rye cultivar and year on soyabean yield loss due to weed interference, we fitted generalised linear mixed effects models with binomially distributed errors and the same random effects structure as above (Zuur *et al*., 2009). Mixed effects models were implemented in the *nlme* and *lme4* packages of R v3.3.1 (R Development Core Team, 2017).

We used a three-step process to quantify multivariate subfield associations among soil, cover crop, weed and soyabean variables. First, we performed variable selection using Random Forest (Breiman, 2001), an iterative procedure that uses a random starting seed to generate hundreds of tree models that best minimise prediction error (regression trees) or node impurity (classification trees). Tree models are a non-parametric approach to multivariate data analysis that recursively split data sets into smaller subsets, stopping when metrics of model performance stabilise. In contrast to Classification and Regression Tree analysis, in which a single tree is built from a pre-selected set of candidate variables, with measures of model parsimony related to global and reduced models, the Random Forests approach builds many different tree models from a candidate pool of variables, providing a means of

© 2018 European Weed Research Society

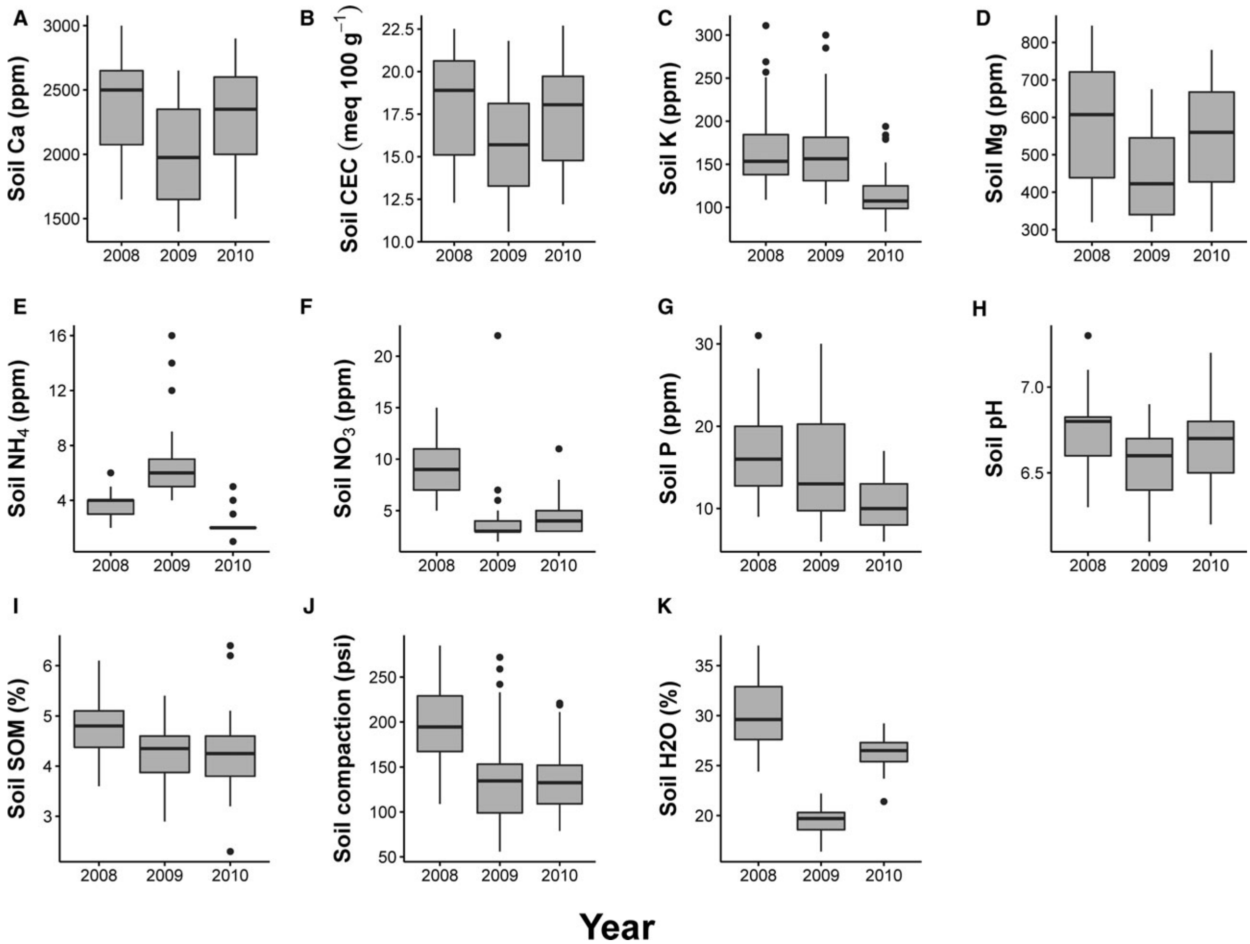

Fig. 2 Descriptive statistics for soil characteristics measured two weeks prior to cover crop termination in Savoy, Illinois, USA field study. Within years, distributions represent observations from a 10-m grid (n = 60). Bold horizontal line represents population median.

assessing the relative strength ('Variable Importance') of different variables in improving the model predictions (Breiman, 2001). Model output included variable importance rankings (Table 1); we selected the top predictor variables common to cover crop and soyabean performance tree models as candidates for building structural equation models in the next step.

Second, the spatial domain of subfield variation in soil and plant properties highlighted by Random Forests variable selection was quantified through a geostatistical approach (Brunsdon & Comber, 2015). Semivariograms were fitted for each variable using an iterative least squares approach in the *gstat* and *sp* packages of R v3.3.1. Values for range (the distance at which semivariance among sampling locations stabilised) and sill (semivariance value at the range) were extracted from fitted semivariograms.

Finally, we modelled covariance and regression relationships among soil and plant variables using structural equation models. Structural equation modelling is a multivariate statistical modelling method that is descended from path analysis; in that, it explicitly considers the covariance and variance relationships (causal pathways) among variables in a multiple regression. It extends upon the path analysis framework by including latent (conceptual; represented as factors) variables, in addition to manifest (directly measured) variables, and is sometimes described as a hybrid between multiple regression and factor analysis (Smith *et al.*, 2014). By accounting for covariance relationships among the exogenous variables in the model, in addition to their relationships to the dependent variable of interest, structural equation models allow the analyst to weigh the relative importance of indirect and direct causal pathways between independent and dependent variables.

Candidate structural equation models included both latent (conceptual factors) and manifest (directly measured) variables for soil, cover crop, weed and soyabean (Figure S1). To avoid confounding interannual variation with spatial variation at the subfield scale, variables for SEM analyses were rescaled, within cultivar and year, so that their range was constrained between 0 and 100, using the 'rescale' subroutine of

© 2018 European Weed Research Society

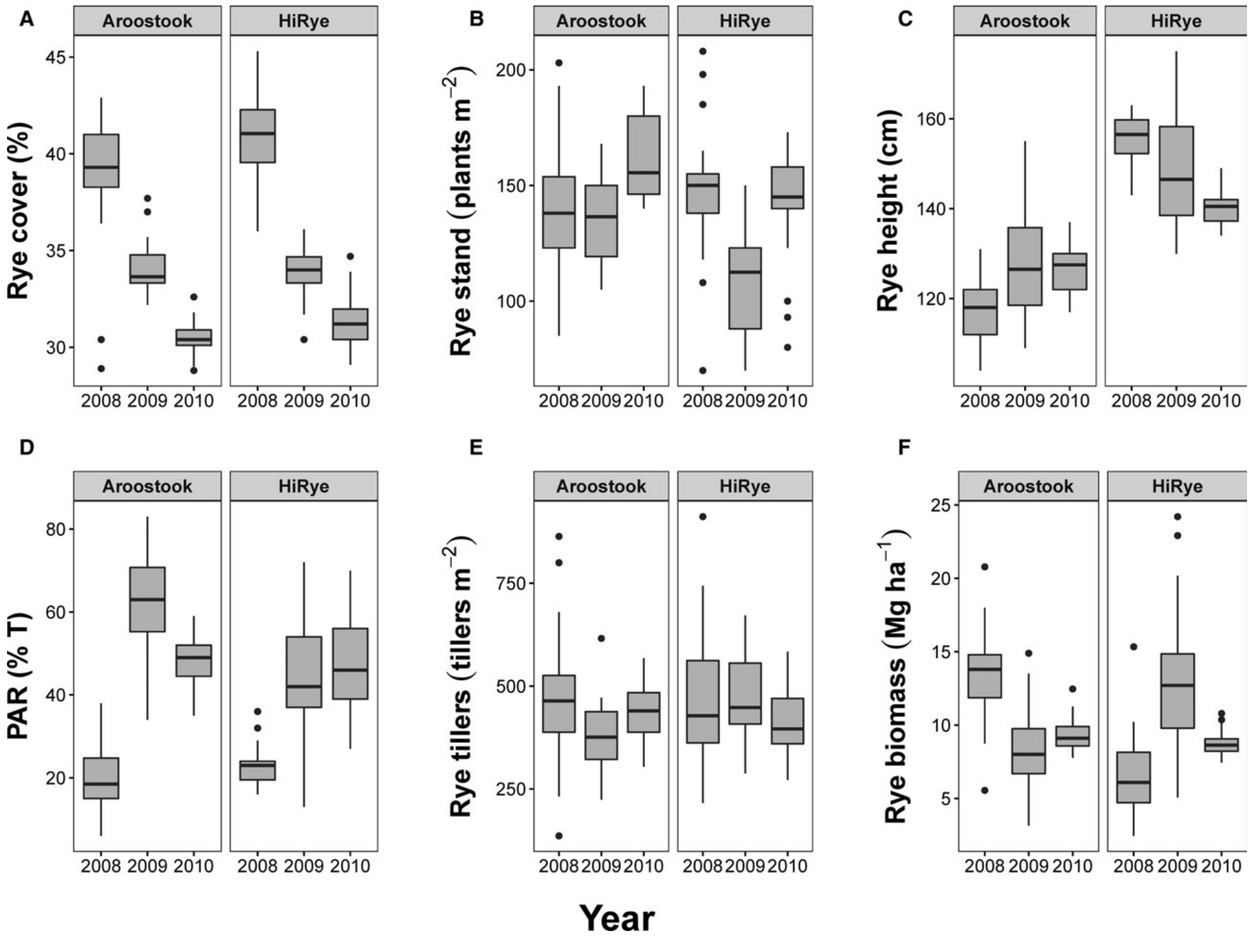

Fig. 3 Descriptive statistics for cereal rye cover crop at time of mechanical termination in Savoy, Illinois, USA field study. Within years, distributions represent observations from a 10-m grid (n = 30 for each rye cultivar). Bold horizontal line represents population median.

the *scales* package in R v3.3.1. Model selection to identify the most parsimonious models was based on goodness of fit between the modelled and observed covariance matrices ($\chi^2 > 0.05$) and minimisation of maximum likelihood criteria (Table S1). Random Forest and SEM models were implemented in the *randomForest* and *lavaan* packages of R v3.3.1.

Results

Soyabean yield: field-scale factors

Model selection indicated that the most parsimonious linear mixed effects model for explaining field-scale variation in soyabean yield contained main and interaction effects for cover crop cultivar, weed competition and year, compared with the no interaction model ($\chi_4^2 = 29$, $P < 0.001$). Weed competition ($F_{1,294} = 335$, $P < 0.001$) and year ($F_{1,294} = 340$, $P < 0.001$), but not cereal rye cultivar ($F_{1,2} = 2.9$, $P = 0.23$), showed significant main effects on soyabean yield (Fig. 1). The interactive effects of rye cultivar by year ($F_{1,294} = 20$, $P < 0.001$) and weed competition by year ($F_{1,294} = 95$, $P < 0.001$) on soyabean yield were also significant. Soyabean yield ranged from 2790 to 5530 kg ha^{-1} and increased over the years of the study under both ambient and weed-free competition levels. Soyabean yield loss to weed interference was lowest in 2008 (8.2 to 19%), intermediate in 2009 (21 to 30%) and greatest in 2010 (33 to 41%). The overall marginal R^2 for the model (R_m^2, fixed effects only) was 0.65, and the overall conditional R^2 for the model (R_c^2, fixed and random effects) was 0.70. Considering each of the main effects separately, R_m^2 for cover crop cultivar, weed competition and year were 0.01, 0.27 and 0.28 respectively.

Soyabean yield: decametre-scale factors

Spatial variability for many of the soil characteristics studied was greater than interannual variability, with two- to threefold variation between the minimum and maximum values at subfield locations (Fig. 2). There was also considerable spatial variability observed in

© 2018 European Weed Research Society

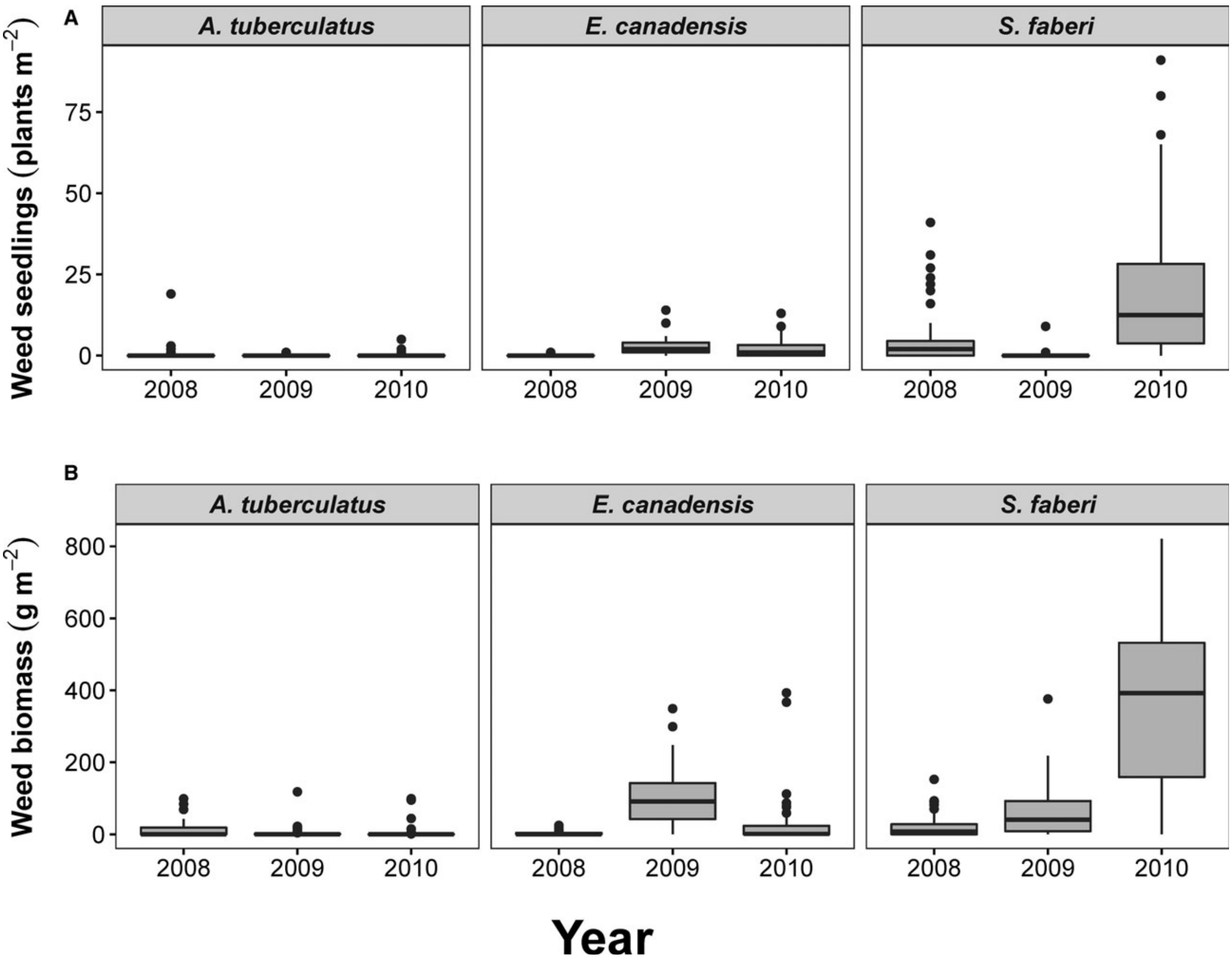

Fig. 4 Descriptive statistics for weed population density and biomass in Savoy, Illinois, USA field study. Populations *of Amaranthus tuberculatus, Erigeron canadensis and Setaria faberi* were censused at cover crop termination, and biomass was collected one day prior to soyabean harvest. Within years, distributions represent observations from a 10-m grid (n = 60). Bold horizontal line represents population median.

cover crop performance, but with smaller ranges than for most of the soil variables (Fig. 3). Weed population densities and growth showed a greater amount of spatial variability within years than either soil or cover crop characteristics, ranging from null values to more than 10 times the mean (Fig. 4).

As a means of preliminary variable selection for subsequent covariance analyses, decametre-scale variation in soyabean and cover crop performance was modelled in relation to the soil, weed and cover crop spatial variation described above using Random Forest regression. Random Forest model performance stabilised between 100 and 150 runs (out of 500 runs) indicating that we included enough iterations to observe maximum model performance. Models explained between 0.30 and 0.35 of observed variation in soyabean and cover crop performance. Variable importance measures obtained from Random Forest models are presented in Table 1. Across the five response variables modelled, a consistent set of independent variables relating to soyabean yield variability was identified, including soil nutrient availability (CEC, K, Mg and NO_3), soil moisture at the time of rye termination, rye cultivar and height, *S. faberi* biomass and seedling population density, total weed biomass and soyabean population.

Semivariance modelling for the subset of variables selected by Random Forest regression returned range values that mostly varied between 4.6 and 9.1 m (the grid spacing chosen for the sampling stations in this study), with the exception of soyabean yield in 2009 and rye height at rolling in 2010 and 2011, which had slightly larger ranges (Table 2). These results indicated that these field characteristics were largely spatially independent among sampling stations (i.e. soil and plant properties at two neighbouring grid locations were not correlated simply because they were near each other). We therefore did not include an explicit

© 2018 European Weed Research Society

Table 1 Variable importance measures from Random Forest regression models for soyabean and cover crop performance

Independent variable type	Independent variable	Rye stand (March)	Rye height (pre-roll)	Soyabean stand (June)	Soyabean yield loss	Soyabean yield
		Dependent variables for Random Forest models				
		Variable importance* (reduction in model MSE from adding each independent variable)				
Soil chemical	Ca	4.7	3.3	−0.1	−0.5	1.8
	CEC	6	3.2	0.1	1	2.2
	K	7.8	**12.6**	4.8	3.5	**5.8**
	Mg	5.6	**8.3**	−1	1.5	2.9
	NH_4	8.7	4.6	0.2	−0.5	3.7
	NO_3	**9.7**	5.4	**9.2**	**6.5**	**5.8**
	Total inorganic N	9.6	7.2	4.9	4.3	5.2
	P	7.3	7.3	0	2.9	4.7
	pH	−0.3	0.9	−2.6	2.4	−0.5
	SOM	3.6	3.3	−3.7	1	0
Soil physical	H_2O, pre-roll	**11.8**	6.3	**12.4**	3.4	4
	Penetrometer psi, post-roll	3.4	0.5	0.5	−1.6	3
	Year	**21.1**	7.1	**21.2**	1.8	1.3
Crop	Rye cultivar	5.7	**33.1**	2.9	1.6	2.2
	Rye height, pre-roll	—	—	1.8	**6.8**	**11**
	Rye ground cover	—	—	—	3.5	4.8
	Rye PAR transmittance, post-roll	—	—	—	−1.6	2.9
	Rye PAR transmittance, pre-roll	—	—	—	4.8	3.6
	Rye stand, Mar.	—	**9.2**	**10.3**	1.6	**8.9**
	Rye biomass, pre-roll	—	—	—	0.3	2.5
	Rye tillers, pre-roll	0.1	3.3	−2.6	4.4	−0.3
	Soyabean stand, June	**11.6**	**8.5**	—	**0**	**14.5**
Weed	*A. tuberculatus* plants m^{-2}, pre-roll	1.2	−0.9	0.4	0.1	0.8
	C. canadensis plants m^{-2}, pre-roll	3.1	4	2.2	0.8	1.7
	S. faberi plants m^{-2}, pre-roll	4.4	1.3	1.9	**6.3**	3
	Total weeds m^{-2}, pre-roll	5.6	2.4	4.4	4.9	3.9
	A. tuberculatus biomass, harvest	—	—	—	−2.6	1.3
	C. canadensis biomass, harvest	—	—	—	−0.4	2.7
	S. faberi biomass, harvest	—	—	—	**10.9**	4.9
	Other weed biomass, harvest	—	—	—	1.5	1.3
	Total weed biomass, harvest	—	—	—	**13.9**	4.5

*Independent variables selected for subsequent covariance analyses through structural equation modelling are highlighted in bold. Variable selection was based on model parsimony with respect to ranked variable importance values; retention of variables ceased when the per cent difference in variable importance between two subsequent independent variables was <5%.

measure of spatial autocorrelation for the subfield variables sampled here (Table 2).

The subset of variables identified in Table 1 as having the greatest consistent impact on decametre-scale variation in soyabean yield were then used to populate a conceptual model (Fig. 5) as a starting point for modelling spatial covariance among them using structural equation models (SEM). Within each of the boxes in Fig. 5, the bulleted lists of variables denote manifest (directly measured) variables associated with latent (conceptual) variables of interest. Because cereal rye cultivar was one of the important factors highlighted during variable selection with Random Forest regression, SEM were constructed separately for each rye cultivar. The pool of candidate SEM included models containing both latent and manifest variables, latent variables only and manifest variables only (Figure S1).

The most parsimonious SEM retained manifest variables only and showed the same basic pattern for both rye cultivars: soil properties affected soyabean yield via indirect and direct pathways (Fig. 6). Models that included the association between variation in soyabean population and weed growth were less well supported (Figure S1, Table S1). Subfield variation in soil moisture directly affected soyabean yield through the negative impacts of excessive soil moisture in slow-draining areas of the field on soyabean population. This association was stronger for soyabean no-till planted into residues of the HiRye cereal rye cultivar (Fig. 6B) than for those planted into residues of the Aroostook cereal rye cultivar (Fig. 6A). In the other

© 2018 European Weed Research Society

pathway, decametre-scale variation in soil K influenced soyabean yield through indirect effects mediated through the cover crop: soil K limitation was associated with lower cereal rye height at rolling, which reduced rye's weed suppressive ability, resulting in less soyabean yield. Since cereal height at rolling was measured two weeks after soil properties, it is likely that variation in soil properties was driving variation in rye height, rather than vice versa. For both rye cultivars, the decametre-scale variables examined here explained a modest, but significant, amount of variation in soyabean yield (15 and 22%, respectively, for the Aroostook and HiRye cereal rye cultivars).

Discussion

As seen elsewhere, interannual variability in environmental conditions and weed interference accounted for most (approximately 70%) of the observed variation in soyabean yield (Teasdale & Cavigelli, 2017). Despite the large amount of subfield spatial variation quantified for soil properties, this variability explained <20% of soyabean yield variation, corroborating the findings of Robertson *et al.* (1997). As hypothesised, the impacts of subfield decametre-scale variation in soil properties on soyabean yield worked both directly through impacts on soyabean stand, and indirectly through impacts on the weed suppressive ability of the cereal rye cover crop. What was unexpected was that subfield variation in cereal rye suppression of weed growth would be mediated through rye height rather than accumulation of rye biomass.

Subfield cereal rye biomass variation in this study was high, spanning a range previously reported in the literature (Ryan *et al.*, 2011; Wells *et al.*, 2014). However, biomass variation was not associated with variation in weed suppression. Instead, the main source of subfield variation in weed suppression by the cereal rye

Table 2 Spatial statistics from fitted semivariograms for selected site characteristics in Savoy, Illinois, USA field study

	2008		2009		2010	
Selected variable	Range m	Sill* γ	Range m	Sill γ	Range m	Sill γ
Soyabean yield	7.6	3×10^5	12.2	3×10^5	4.6	3×10^5
Soyabean population	4.6	8	4.6	8	4.6	30
Final weed biomass	6.1	2300	6.1	4000	9.1	3×10^4
Rye height at rolling	9.1	600	10.7	150	10.7	60
Soil K	9.1	2000	9.1	1600	9.1	600
Soil H_2O	9.1	13	9.1	1.3	4.6	3

*The range and sill values reported here represent, respectively, the distance in metres at which the semivariance (γ), from a Gaussian semivariogram model fit by the least squares method, stabilised.

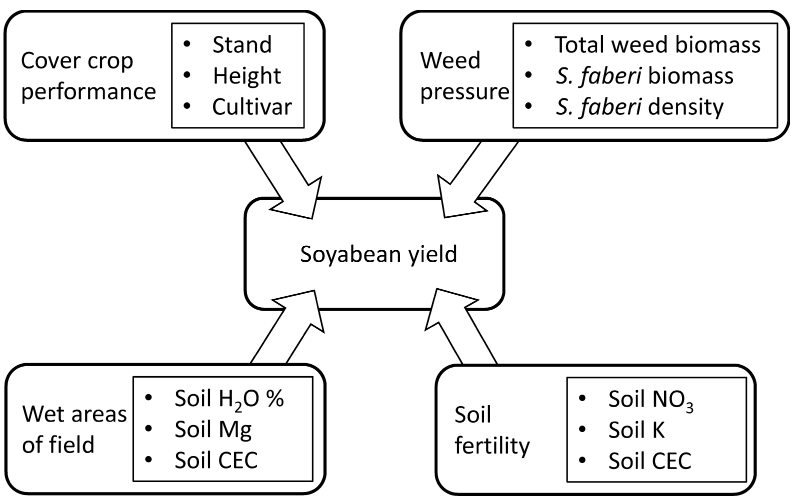

Fig. 5 Conceptual model of soyabean yield associations with soil, cover crop and weed variables selected through Random Forest regression modelling. The bullet lists within each box show manifest (measured) variables used to define latent (conceptual) variables for subsequent structural equation modelling.

© 2018 European Weed Research Society

cover crop was cereal rye height. Previous work has highlighted the importance of cereal rye biomass for weed suppression in rolled-crimped systems, through controlled studies of impacts of rye seeding rate, planting date and soil inorganic N availability on rye biomass production and associated weed suppression (Ryan *et al.*, 2011; Smith *et al.*, 2011; Mirsky *et al.*, 2013; Wells *et al.*, 2014). The multivariate statistical approaches employed in the present study accounted for covariation among rye ground cover, biomass and height, thereby allowing us to quantify the relative importance of these variables in weed suppression, factoring out overlapping effects. Our results suggest that managing variation in cereal rye height should be a grower priority, from a weed management perspective. The strong associations between soil microsite fertility levels and cereal rye height suggest that soil testing at the subfield level would be a well-justified expense for growers, so that they may adjust soil fertility levels accordingly. For cover crop improvement programmes, cereal rye height appears to be a trait that warrants further attention.

Pockets of excessive soil moisture consistently created problems for soyabean stand establishment. Much of the agricultural land in central Illinois was converted to this use from wet prairies more than a century ago (Anderson, 1970), making efficient drainage systems an essential feature of crop production in this area. Although the land used for this field experiment is tile-drained, wet spots evidently persist due to low areas and proximity to an adjoining drainage ditch. Improving agricultural drainage is a routine expense for Illinois crop producers, and additional investment appears to be warranted for this parcel of land. A more unexpected finding was the consistent positive association between subfield soil K levels and cereal rye height, which has not been reported before. Indeed, the role of soil nutrients, other than inorganic N, in cereal rye cover crop performance has not been explored in the scientific literature. The value of soil K in soyabean production has been recently called into question, in contrast to common extension recommendations to growers to apply K fertilisers to meet crop nutritional demands (Khan *et al.*, 2014). Therefore, the potential utility of fertiliser K additions in improving yields of soyabean no-till planted into a rolled-crimped cereal rye cover crop would likely need to be evaluated through empirical tests of the economic trade-off between gains in soyabean yield through improved weed suppression by cereal rye and costs of fertiliser additions.

The low variable importance of *A. tuberculatus* and *E. canadensis* seedling recruitment or biomass in predicting soyabean yield or yield loss was surprising, given their ubiquity and consistent rankings as the top two commercially important weeds of soyabean production systems in Illinois and other states of the Midwest USA (Van Wychen, 2016). The low recruitment and biomass of *A. tuberculatus* and *E. canadensis* was not due to lack of a seedbank. Both species were represented at seedbank population densities above 10 000 seeds m^{-2} in both study fields (Davis, 2010). Rather, the crimped-rolled rye system appeared to successfully inhibit the establishment and growth of *A. tuberculatus* and *E. canadensis*, whereas *S. faberi* was able to increase its representation in the field over time, producing prodigious amounts of biomass by the third year of the study (Fig. 4B). These results suggest that

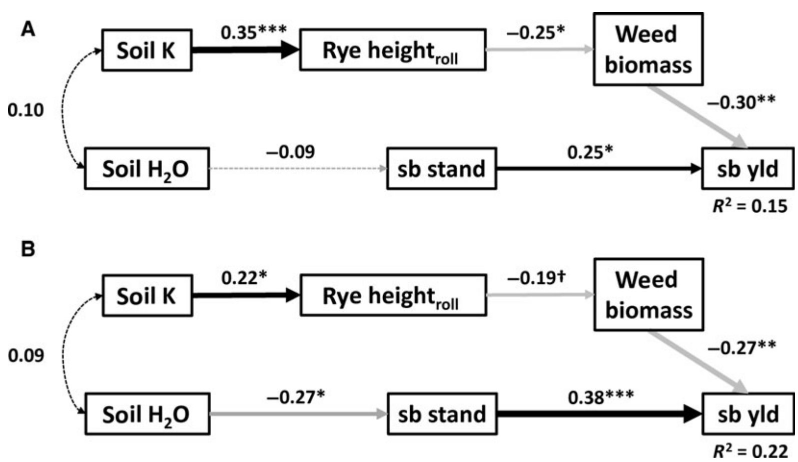

Fig. 6 Structural equation models identified as most parsimonious for explaining decametre-scale associations among soyabean yield and soil, cover crop and weed variables in (A) Aroostook and (B) HiRye cultivars of cereal rye. Black and grey arrows denote positive and negative relationships respectively. Standardised regression coefficients b_i are reported (n = 90 for each model). The symbols †, *, ** and *** represent significant b_i at 0.10, 0.05, 0.01 and 0.001 α levels.

© 2018 European Weed Research Society

soyabean producers concerned with increasingly intractable herbicide-resistant populations of *A. tuberculatus* and *E. canadensis* (Westhoven *et al.*, 2008; Evans, 2016) should consider including cereal rye cover crops in their cropping system in at least some soyabean production years.

Because agriculture is a particularly site-dependent activity, the subfield variables identified as important in this study may not be the same ones that are found to be most important at other locations. However, there are some key management insights from these results that may be more broadly useful. The robust subfield spatial associations we detected among variation in soil K, cover crop height growth and weed suppression in soyabean highlight the importance of understanding and ameliorating subfield spatial deficiencies in soil fertility levels. In this study, we did not provide any external fertiliser to either the soyabean or the oat crops in any of the growing seasons. Prior to the initiation of the study, the experimental fields had been in a conventional maize–soyabean crop sequence, receiving recommended amounts of macronutrients at the start of each growing season. The steady decline in soil macronutrient levels over the three years of the study (Fig. 2C,F,G) indicates that we were depleting our soils of N, P and K. This was accompanied by a consistent decline in cereal rye ground cover over time (Fig. 3A) and decline in height of the HiRye cereal rye cultivar (Fig. 3C). Taken together, these results indicate the fundamental importance of treating a cover crop as a crop in its own right, deserving of management attention tailored to its needs, and not as a place-holder between main crops.

Conclusion

Observational studies in agriculture can play an important role as sensors for previously unconsidered relationships (Schipanski *et al.*, 2014), highlighting new associations for closer scrutiny in controlled trials, and ultimately providing novel management recommendations. Our results indicated that subfield scale variation in soil properties affected soyabean yield through direct impacts on soyabean stand and indirect impacts mediated through soil K effects on cover crop performance. Cost-benefit analyses of the contribution of soil K to soyabean yield in cover-cropped systems will help to evaluate the overall utility of such an approach. More fundamentally, these results indicate the need to refine agronomic recommendations that focus on maximising cover crop performance and achieving robust results in variable environments.

Acknowledgements

Many thanks to the research technicians and undergraduate research assistants who made this work possible. This study was funded by USDA-ARS CRIS Project #5012-12220-008. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture. USDA-ARS is an equal opportunity provider and employer.

References

Anderson RC (1970) Prairies in the prairie state. *Transactions of the Illinois Academy of Sciences* **63**, 214–221.

Ashford DL & Reeves DW (2003) Use of a mechanical roller-crimper as an alternative kill method for cover crops. *American Journal of Alternative Agriculture* **18**, 37–45.

Barberi P & Mazzoncini M (2001) Changes in weed community composition as influenced by cover crop and management system in continuous corn. *Weed Science* **49**, 491–499.

Breiman L (2001) Random forests. *Machine learning* **45**, 5–32.

Brunsdon C & Comber L (2015) *An Introduction to R for Spatial Analysis and Mapping*. 343. SAGE Publications Ltd., Los Angeles, CA.

Creamer NG & Dabney SM (2002) Killing cover crops mechanically: review of recent literature and assessment of new research results. *American Journal of Alternative Agriculture* **17**, 32–40.

Davis AS (2010) Cover-crop roller–crimper contributes to weed management in no-till soybean. *Weed Science* **58**, 300–309.

Dieleman JA, Mortensen DA, Buhler DD, Cambardella CA & Moorman TB (2000) Identifying association among site properties and weed species abundance I. Multivariate analysis. *Weed Science* **48**, 567–575.

Evans CM (2016) Characterization of a novel five-way resistant population of waterhemp (*Amaranthus tuberculatus*), M.S. Thesis, University of Illinois, Urbana, IL. Available at: http://hdl.handle.net/2142/92670 (last accessed 21 May 2018).

Gerhards R, Gutjahr C, Weis M *et al*. (2012) Using precision farming technology to quantify yield effects attributed to weed competition and herbicide application. *Weed Research* **52**, 6–15.

Hill EC, Renner KA, Sprague CL & Davis AS (2016) Cover crop impact on weed dynamics in an organic dry bean system. *Weed Science* **64**, 261–275.

Khan SA, Mulvaney RL & Ellsworth TR (2014) The potassium paradox: implications for soil fertility, crop production and human health. *Renewable Agriculture and Food Systems* **29**, 3–27.

Khatounian CA (2004) Weed control in no-till organic soybean in southern Brazil, Ph.D. Dissertation, Iowa State

© 2018 European Weed Research Society

University, Ames IA. Iowa State University, Available at: http://lib.dr.iastate.edu/rtd/957 (last accessed on 7 December 2017).

Kornecki TS, Price AJ & Raper RL (2006) Performance of different roller designs in terminating rye cover crop and reducing vibration. *Applied Engineering in Agriculture* **22**, 633–641.

Kravchenko AN, Snapp SS & Robertson GP (2017) Field-scale experiments reveal persistent yield gaps in low-input and organic cropping systems. *Proceedings of the National Academy of Sciences of the United States of America* **114**, 926–931.

Liebman M, Baraibar B, Buckley Y *et al.* (2016) Ecologically sustainable weed management: how do we get from proof-of-concept to adoption? *Ecological Applications* **26**, 1352–1369.

Mirsky SB, Curran WS, Mortensen DM, Ryan MR & Shumway DL (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. *Weed Science* **59**, 380–389.

Mirsky SB, Ryan MR, Teasdale JR *et al.* (2013) Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the eastern United States. *Weed Technology* **27**, 193–203.

Nord EA, Ryan MR, Curran WS, Mortensen DA & Mirsky SB (2012) Effects of management type and timing on weed suppression in soybean no-till planted into rolled-crimped cereal rye. *Weed Science* **60**, 624–633.

Peukert S, Griffith BA, Murray PJ, Macleod CJA & Brazier RE (2016) Spatial variation in soil properties and diffuse losses between and within grassland fields with similar short-term management. *European Journal of Soil Science* **67**, 386–396.

R Development Core Team (2017) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Robertson GP, Klingensmith KM, Klug MJ *et al.* (1997) Soil resources, microbial activity, and primary production across an agricultural ecosystem. *Ecological Applications* **7**, 158–170.

Ryan MR, Mirsky SB, Mortensen DA, Teasdale JR & Curran WS (2011) Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. *Weed Science* **59**, 238–246.

Schipanski ME, Smith RG, Gareau TLP *et al.* (2014) Multivariate relationships influencing crop yields during the transition to organic management. *Agriculture Ecosystems and Environment* **189**, 119–126.

Smith AN, Reberg-Horton C, Place GT *et al.* (2011) Rolled rye mulch for weed suppression in organic no-tillage soybeans. *Weed Science* **59**, 224–231.

Smith RG, Davis AS, Jordan N *et al.* (2014) Structural equation modeling facilitates transdisciplinary research on agriculture and climate change. *Crop Science* **54**, 1–9.

Teasdale JR & Cavigelli MA (2017) Meteorological fluctuations define long-term crop yield patterns in conventional and organic production systems. *Scientific Reports* **7**, 688.

Teasdale JR, Rice CP, Cai G & Mangum RW (2012) Expression of allelopathy in the soil environment: soil concentration and activity of benzoxazinoid compounds released by rye cover crop residue. *Plant Ecology* **213**, 1893–1905.

Van Wychen L (2016) 2015 baseline survey of the most common and troublesome weeds in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. Available at: http://wssa.net/wp-content/uploads/2015_Weed_Survey_Final.xlsx (last accessed 21 May 2018).

Wells MS, Reberg-Horton SC & Mirsky SB (2014) Cultural strategies for managing weeds and soil moisture in cover crop based no-till soybean production. *Weed Science* **62**, 501–511.

Westhoven AM, Davis VM, Gibson KD, Weller SC & Johnson WG (2008) Field presence of glyphosate-resistant horseweed (*Conyza canadensis*), common lambsquarters (*Chenopodium album*), and giant ragweed (*Ambrosia trifida*) biotypes with elevated tolerance to glyphosate. *Weed Technology* **22**, 544–548.

Zadoks JC, Chang TT & Konzak CF (1974) Decimal Code for Growth Stages of Cereals. *Weed Research* **14**, 415–421.

Zuur AF, Ieno EN, Walker NJ, Saveliev AA & Smith GM eds. (2009) *Mixed Effects Models and Extensions in Ecology with R*. Springer, New York, NY.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Candidate structural equation models to describe variation in soyabean yield from decametre-scale variation in soil, cover crop and weeds.

Table S1. Maximum likelihood model selection for structural equation models.

© 2018 European Weed Research Society