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ARTICLE

Interactive effects between cover crop management and the environment modulate benefits to cash crop yields: a meta-analysis

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Abstract: Several governmental programs have been established throughout Canada to foster agriculture sustainability. As a best management practice, cover crops (CCs) limit soil erosion and prevent nutrient losses in agroecosystems. Yet, the variable effects of CCs on cash crop productivity previously reported may limit their large-scale adoption by farmers. To address this variability, we conducted an unweighted meta-analysis including 2274 observations from 86 field studies conducted under humid temperate climate to evaluate yield response to CCs for three annual cash crops. Overall, CCs increased corn and small grain cereal yields by 13% and 22% respectively, but did not affect soybean yield. Legume CCs alone or mixed with grasses provided the highest small grain cereal and corn yield increases compared with non-legume broadleaf and grass CCs. CC benefits increased with nitrogen (N) content in CC aboveground biomass but decreased when N fertilizer inputs applied to corn exceeded 60 kg N ha^{-1}. Greater precipitation and N fertilizer inputs reduced the negative effect of grass CCs on corn yield, while benefits of legume CCs were highly resilient to precipitation variations. CC benefits on corn yield increased through time and at low soil organic matter content, especially at low N fertilizer inputs. These results evidence the complex interplay between cash crop productivity, CC management, and environmental factors — related to N inputs from CCs, changes in soil properties (e.g., increased organic matter, improved soil structure or microbial activity), or potential competition for water under drier conditions — which provide new perspectives to promote CC inclusion in cropping systems.

Key words: best management practices, ecosystem services, nitrogen, catch crops, sustainable agriculture.

Résumé : Plusieurs programmes gouvernementaux ont été instaurés au Canada pour favoriser l'agriculture durable. Les cultures de couverture (CC) freinent l'érosion du sol et la perte de nutriments dans les agroécosystèmes. Pourtant, les agriculteurs hésitent à les adopter en raison de leur incidence sur le rendement des cultures. Les auteurs ont effectué une méta-analyse non pondérée de 2 274 observations extraites de 86 études réalisées en climat tempéré humide afin d'évaluer la réponse du rendement de trois cultures commerciales aux CC. Les CC augmentent respectivement le rendement du maïs et des céréales de 13 % et de 22 %, mais pas celui du soja. Les CC de légumineuses, seules ou combinées à des graminées, fournissent les hausses de rendement les plus élevées pour les céréales et le maïs, comparativement aux CC de graminées ou de crucifères. Les avantages de la CC s'accroissent avec la teneur en azote de sa biomasse aérienne, mais diminuent quand l'apport d'engrais azoté au maïs dépasse 60 kg de N par hectare. Des précipitations et un apport d'azote plus

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élevés atténuent l'incidence négative des CC de graminées sur le rendement du maïs, alors que l'effet des CC de légumineuses s'avère très résilient à la variation des précipitations. L'effet bénéfique d'es CC sur le rendement du maïs augmente avec le temps et est plus important sur les sols pauvres en matière organique. Ces résultats soulignent les interactions complexes entre la productivité des cultures commerciales, la gestion des CC et les facteurs environnementaux, et ouvrent de nouvelles pistes pour l'adoption des CC.

Mots-clés : pratiques agroenvironnementales, services écosystémiques, azote, cultures de couverture, agriculture durable.

Introduction

The implementation of best management practices is currently a salient issue to promote agriculture sustainability. Throughout Canada, several governmental programs have been established recently in this objective at both federal and provincial levels including the Agriculture and Agri-Food Canada Agricultural Climate Solutions program, the Quebec Sustainable Agriculture Plan or the Ontario's Agricultural Soil Health and Conservation Strategy. Cover crops (CCs) are usually an integral part of these programs given the multiple environmental and soil benefits they provide (Schipanski et al. 2014; Blanco-Canqui et al. 2015; Daryanto et al. 2018; Daryanto et al. 2019; Lavergne et al. 2021). Integrating CCs in cropping systems is indeed recommended to reduce soil erosion and nutrient losses in agroecosystems (Dabney et al. 2001; Lal et al. 2011; Thapa et al. 2018; Kaye et al. 2019). By trapping post-harvest nutrients, CCs can also considerably improve soil conditions for subsequent cash crops, hence maintaining or enhancing crop yields (Bullied et al. 2002; Stavi et al. 2012; Cicek et al. 2014; N'Dayegamiye et al. 2015). Broad variations of cash crop productivity response to CCs, however, have been reported in previous quantitative studies and meta-analyses (Tonitto et al. 2006; Delgado and Gantze, 2015; Marcillo and Miguez 2017; Daryanto et al. 2018; Abdalla et al. 2019; Florence and McGuire 2020). Thus, even though CCs can provide many benefits, farmers might be reluctant to adopt them if they perceive an increased risk of reduced yields (Arbuckle and Roesch-McNally 2015; Basche et al. 2016*a*; Seidel et al. 2017; Daryanto et al. 2019; Jian et al. 2020). Quantifying the effect of CCs on cash crop yields among various cropping systems would be useful for promoting the use of CCs in Canada.

There is considerable variation among CC systems (Blanco-Canqui et al. 2015; N'Dayegamiye et al. 2015; Thilakarathna et al. 2015), which are highly dependent on the timing of CC seeding and its integration into annual crop rotations, such as: (*i*) the intercropping system in which CCs are directly seeded into the cash crop, (*ii*) the successive system in which CCs are grown between two cash crops, sometimes called an intermediate crop, and (*iii*) the full-season system in which CCs are grown as a green manure during an entire season (typically observed in organic agriculture). A wide range of CC species can be used in pure or mixed stands under these different systems. Most commonly cultivated CCs include: (*i*) grasses such as oat (*Avena sativa* L.) (Johnson et al. 1998; Thilakarathna et al. 2015), winter cereal rye (*Secale cereale* L.) (Baggs et al. 2000; De Bruin et al. 2005), and annual (*Lolium multiflorum* L.) or perennial ryegrass (*L. perenne* L.) (Chen et al. 2006; Løes et al. 2011); (*ii*) legumes like common (*Vicia sativa* L.) or hairy vetch (*V. villosa* L.) (Rosecrance et al. 2000; N'Dayegamiye et al. 2015; Alam et al. 2018), red clover (*Trifolium pratense* L.) (Abdallahi and N'Dayegamiye 2000; Jokela et al. 2009) and alfalfa (*Medicago sativa* L.) (Badaruddin and Meyer 1990; Thiessen Martens et al. 2005); and (*iii*) non-legume broadleaves, especially oilseed and forage radish (*Raphanus sativus* L.) (Baggs et al. 2000; Vyn et al. 2000). Although variations in cash crop productivity could depend on CC management (Blanco-Canqui et al. 2015; Daryanto et al. 2019), no meta-analysis has yet compared CC effects between CC systems which makes comparison between studies difficult and therefore challenging to provide recommendations to farmers.

The potential benefits of CCs to crop productivity are largely determined by CC biomass production and composition (e.g., nitrogen (N) content and carbon (C)/N ratio), which can be managed through planting date, inter-row spacing, timing, methods of CC termination, and more importantly, CC species selection (Dabney et al. 2001; Coombs et al. 2017; De Notaris et al. 2019). In particular, legumes can add N to cropping systems through the fixation of atmospheric N, and generally reduce the need for external N inputs (Alam et al. 2018; De Notaris et al. 2019), provided that synchrony between crop N demand and CC mineralization is adequate (Crews and Peoples 2005). Benefits of CCs to crop productivity are strongly modulated by weather conditions and soil properties besides management practices (Dabney et al. 2010). Nevertheless, the influence of pedo-climatic factors (e.g., precipitation, soil organic matter (SOM)) as well as their interaction with management practices on the relationships linking CCs to cash crop productivity has not been extensively investigated, making it difficult to identify CC best management practices (Blanco-Canqui et al. 2015).

Cash crop types greatly differ in their response to CCs. In corn production, Marcillo and Miguez (2017) have reported a neutral to positive contribution of winter CCs (i.e., CCs providing a ground cover over winter) to subsequent yield. For instance, on average, winter CC grasses neither increased nor decreased corn yield, whereas a 30% yield increase has been reported following legume winter CCs or CC mixtures. Both no-till implementation and late termination of legumes (0 to 6 d before subsequent corn) often positively impact corn yield (Marcillo and Miguez 2017), while the positive effects of legume CCs generally decrease with increasing inputs of N fertilizers. Tonitto et al. (2006) reported a 10% decrease of legume-fertilized cash crop yields (corn, sorghum, or vegetables) compared with conventional N fertilization. Diversified systems with winter legume CCs providing at least 110 kg N ha^{-1} can, however, ensure similar crop yields than conventional systems applying recommended inorganic N fertilizer inputs (following a bare fallow; Tonitto et al. 2006). Given the impact of soil temperature and moisture on N dynamics and the influence of CCs on these soil characteristics, a better understanding of the interactive effects of management and environment is necessary.

Less information is available in soybean and small grain cereal production for which contrasting effects of CCs have been reported (Warnes et al. 1991; Samson et al. 1992; De Bruin et al. 2005). More than 20% yield increases in spring and winter wheat planted into legume mulches have been reported, while non-legume CCs (especially grasses) can result in a 30% yield decrease in organic systems (Halde et al. 2014). Highest gains in small grain cereal productivity were reported in Europe and Canada with more than 50% yield increases following full-season legume CCs such as alfalfa, common vetch, hairy vetch, or red clover (Thiessen Martens et al. 2005; Ross et al. 2009; Alam et al. 2018). In soybean, variable results of winter cereal rye CC seeded before soybean harvest have been reported in the past. De Bruin et al. (2005) reported comparable soybean yields whether a cereal rye CC was grown or not but reduced economic returns with CCs. According to Warnes et al. (1991), soybean response to winter cereal rye CC depends on soil water content, while Basche et al. (2016*b*) showed that long-term cultivation of winter cereal rye CC increased soil water storage during both wet and dry years. Corn and small grain cereal productivity following CCs might therefore mostly depend on CC types, whereas soybean yield was more related to water availability (Warnes et al. 1991; Samson et al. 1992).

Variation in CC performance can be largely explained by the large diversity in cover cropping systems, the specific cash crop type, and the management practices (including the duration of cover cropping system), as well as environmental and climatic factors, making comparison between studies difficult. To date, no meta-analysis attempted to assess CC effects on a wide range of CC systems and cash crop types with the consideration of possible multiple interactions between crop management practices and pedo-climatic factors (precipitations, SOM, etc.). In addition, few studies have investigated long-term yield trends (i.e., cash crop yield response to multiple years of cover cropping) as they mostly focussed on crop yield changes when transitioning from conventional to CC systems, and there are relatively few long-term CC experiments in Ontario and North America (Norris et al. 2020).

Our objective was to attain a comprehensive quantitative understanding of crop yield response to CCs for three major annual cash crops (corn, small grain cereals, and soybean) across humid temperate climates based on a meta-analysis. More precisely, we investigated changes in yield ratios (YRs) (i.e., the ratio of crop yield with CCs over crop yield without CCs) in response to management practices (CC system, CC type, CC duration, N inputs) alone or in interaction with major environmental factors (precipitation, initial SOM of the site). Based on our results, we discuss the key mechanisms underlying CC effects on cash crop yields, and finally propose strategies for improved CC management as well as future key directions for CC research.

Materials and Methods

Data survey and selection

A literature survey was carried out in July 2015 using the *CAB Abstracts* (1910 to 2015) database using the keywords listed in Appendix A. This survey retrieved 288 peer-reviewed research articles. Seven inclusion criteria were then applied to uniformly screen references for the meta-analysis, i.e.:

1. The study was performed under humid temperate climate (i.e., North American areas between the 40th and 50th parallels, and European areas between the 45th and 60th parallels);
2. The study was conducted under field conditions (hence, excluding experiments in controlled environments);
3. Cash crop corresponded to corn, small grain cereals (i.e., wheat, barley, oat or cereal rye) or soybean cultivated either under intercropping, successive, or full-season CCs;
4. A control treatment without CC was included in the experiment, and crop yields were reported for both the CC and control plots.
5. Cash crop yield or CC data averaged on several years or across sites were excluded to consider pedo-climatic variability;
6. Total N inputs to the cash crop were provided and similarly applied to both the CC and control plots;
7. The treatments were spatially replicated.

Different institutions, governments, industries, and parapublic agencies from Quebec, Nova Scotia, Ontario, Manitoba and the north-eastern United States were further contacted from January 2015 to January 2016 to collect unpublished data from research projects on CCs using similar screening criteria. The database was completed in July 2016, including grey literature and missing information from published articles (such as weather data obtained from the Canadian national weather data server). The software Engauge Digitizer version 3.0 was used to extract data from figures if not provided in tables or in the text.

Overall, 66 published articles and 20 research reports (Appendix B) were selected for meta-analysis which corresponded to 2450 observations from plots with CCs. From this dataset, 171 CC observations were excluded to avoid pseudo-replication when CC biomass was measured more than once in the experiment, and only the CC observation corresponding to the highest biomass was included in these studies. In addition, five extreme CC observations with YRs higher than 10 (i.e., three observations from Huntington et al. 1985 in corn, and two observations from Halde et al. 2014 in small grain cereals) were excluded. Therefore, 2274 CC observations were analyzed in this meta-analysis.

Calculation of effect size

The effect of CCs on the cash crop yield was estimated from log-transformed YRs calculated as:

$$ln(\text{YR}) = ln\left[\frac{Y_{\text{CC}}(N_i)}{Y_{\text{CC}_0}(N_i)}\right]$$

where Y_{CC} is the yield of the cash crop following CCs, and Y_{CC_0} the yield of the cash crop without CCs (control plot) at the same fertilizer N rate (N_i). For full-season CCs, control plots corresponded to conventional cash crop rotation, either without CCs and bare soil during winter, or with a fallow in replacement of full-season CCs. These full-season cover cropping systems represented 47% (n = 201) and 3% (n = 47) of the observations in small grain cereals and corn respectively, but were not observed in soybean. Published grain yields were adjusted to 15.5% moisture content for corn, and 13.0% for small grain cereals and soybean to avoid biases among studies reporting crop yields at different moisture levels.

Explanatory variables

In addition to cash crop type (corn, small grain cereals, soybean), 13 variables were selected to assess cash crop yield response to CCs (Table 1). The following management and environmental variables were considered:

- CC management practices: CC type (LEG: legumes, MIX: mixes with legumes, GRASS: grasses, and NLB: non-legume broadleaves), CC system (intercropping, successive, full-season), duration of CC integration to the crop rotation (in years) and CC termination timing (winter, spring, summer or fall);
- N inputs: N content in CC biomass (classified into four categories: <50 kg N ha^{-1}, 50–99 kg N ha^{-1}, 100–199 kg N ha^{-1}, and ≥200 kg N ha^{-1}) and N fertilizer inputs applied to the cash crop (classified into five categories: 0 kg N ha^{-1}, 1–60 kg N ha^{-1}, 61–120 kg N ha^{-1}, 121–180 kg N ha^{-1}, and >180 kg N ha^{-1});
- crop rotation, farm management, and tillage: preceding cash crop (corn, small grain cereals, soybean, other), farming system (organic, nonorganic), and soil tillage system (conventional tillage, reduced tillage, no-till);
- soil properties: initial SOM content for the site (classified into four categories: SOM ≤ 20 g kg^{-1}, 20 < SOM ≤ 50 g kg^{-1}, 50 < SOM ≤100 g kg^{-1}, and SOM > 100 g kg^{-1}) and soil texture, (classified as fine-, medium-, and coarse-textured soils based on Shirazi and Boersma 1984 and CRAAQ 2010);
- weather parameters: 30-yr annual mean air temperature (i.e., yearly mean temperature averaged over 30 yr) and total precipitation expressed as the abundant and well-distributed rainfall (AWDR) index that reflects the amount of total precipitation corrected for evenness of rainfall and snow events (calculated as the product of cumulative precipitation and the Shannon diversity index of precipitation; see Tremblay et al. 2012) occurring from the date of CC seeding to the date of the cash crop harvest. A shorter time period was used for precipitation compared with temperature (i.e., AWDR during the growing season vs. 30-yr annual mean air temperature) given that precipitations are generally more variable among years than temperature.

Statistical analyses

First, we compared the response of cash crop yields to CCs between the three cash crop type studied (i.e., corn, small grain cereals, soybean). Second, we investigated the effects of agricultural management practices and environmental factors on YRs for each cash crop separately. More precisely, YR responses to each of the 13 explanatory variables (Table 1) were evaluated separately in order to maximize the total number of observations used from the database; the interactions of CC type with (*i*) CC system, (*ii*) CC duration, and (*iii*) CC termination timing were also tested. Third, a multiple regression was conducted to assess interactions between the most significant agricultural management practices and environmental variables revealed from univariate models (i.e., CC type and N fertilizer inputs as well as initial SOM content and AWDR), hence testing whether practices, soil properties, or weather parameters modulate CC effect on cash crop yields. CC type effect on YRs were further compared for three values of AWDR (i.e., 500, 1000, and 1500). This multiple regression approach, which maximizes the statistical power and provides more robust estimates by considering multiple interactions, was only conducted for corn due to insufficient number of observations for small grain cereals and soybean.

All analyses were additionally conducted by excluding full-season CC systems given that the longer growing period of full-season CCs may have a greater influence on

Table 1. Management and environmental variables investigated in relation to cash crop yield ratios.

	Code	Levels or units
Management variables		
Cover crop management		
Type of cover crop species	CC type	Legumes (LEG)
		Mixes with legumes (MIX)
		Grasses (GRASS)
		Non-legume broadleaves (NLB)
Management system of cover crops	CC system	Intercropping
		Successive
		Full season
Duration of cover crop integration to the crop rotation	CC duration	First year
		2 to 5 yr
		More than 5 yr
Timing of cover crop termination	CC termination timing	Winter
		Spring
		Summer
		Fall
Nitrogen (N) inputs		
N content in the cover crop aboveground biomass	N content CC biomass	<50 kg N ha^{-1}
		50–99 kg N ha^{-1}
		100–199 kg N ha^{-1}
		≥ 200 kg N ha^{-1}
N fertilizer inputs applied to the cash crop	N fertilizer inputs	0 kg N ha^{-1}
		1–60 kg N ha^{-1}
		61–120 kg N ha^{-1}
		121–180 kg N ha^{-1}
		> 180 kg N ha^{-1}
Crop rotation, tillage and farm management		
Crop during the cover crop year (preceding crop or companion crop in intercropping system)	Preceeding crop	Corn
		Small grain cereals (barley, oat, rye, wheat)
		Soybean
		Other (dry bean, grazed green manure, green pea, sweet potato, tilled fallow)
Farming system	Farming system	Non-organic
		Organic
Soil tillage system	Tillage system	Conventional
		Reduced tillage
		No-till

Table 1. (*concluded*).

	Code	Levels or units
Environmental variables		
Soil properties		
Initial soil organic matter content for the site	SOM	≤ 20 g kg^{-1}
		> 20 - ≤ 50 g kg^{-1}
		> 50 - ≤ 100 g kg^{-1}
		> 100 g kg^{-1}
Soil texture	Soil texture	Fine (clay, clay loam, loam to clay loam, sandy clay loam, silty clay, silty clay loam)
		Medium (gravelly loam, loam, silt loam)
		Coarse (loamy sand, sand, sandy loam, sandy loam/loamy sand)
Climate parameters		
Annual mean air temperature (30-year normal)	AMAT	°C
Abundant and well-distributed rainfall	AWDR	mm

cash crop yields than intercropped and successive CCs. All analyses were conducted using linear mixed-effects models with PROC MIXED on SAS version 9.2 (SAS Institute, Cary, NC, USA) including "study" and "site nested in study" as random effects, followed by Fisher's Least Significant Difference tests ($\alpha = 0.05$). As measures of yield variability (e.g., standard deviation) were not provided for 30% of the observations, we conducted an unweighted meta-analysis, hence allowing to maximize the number of observations analyzed. YRs were log-transformed prior to analysis to meet residual normality and homoscedasticity conditions and compute F values, p values, and group separation, while estimates (i.e., mean and standard error) from models based on original (i.e., untransformed) YRs were presented in the text and figures given the difficulty of back-transforming standard errors (Gaétan Daigle, personal communication, Université Laval).

Results

Data summary

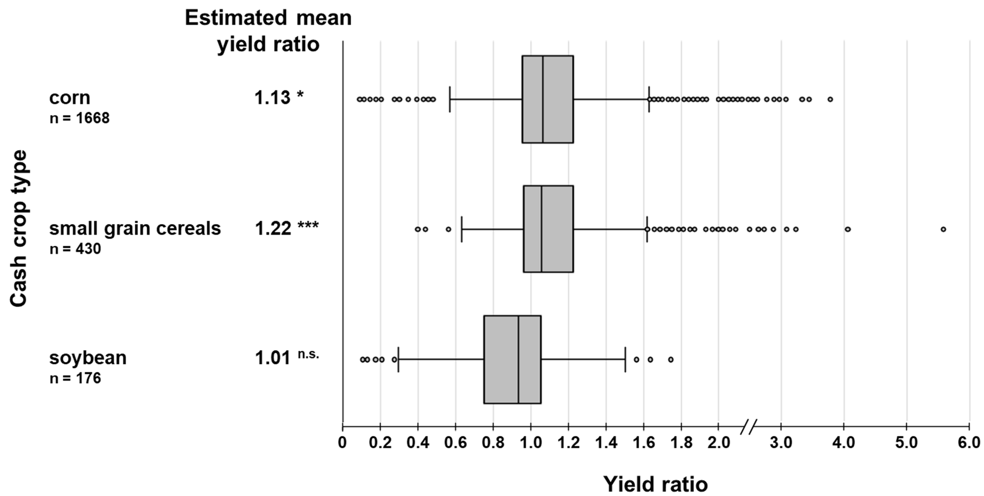
Among the 86 studies that met the criteria for meta-analysis (Appendix B), 37 were located in Canada across four provinces (including 11 research reports from Quebec and 8 from Ontario), 37 from 13 states in the USA (including one research report), and 13 from nine European countries (Appendix C). Peer-reviewed articles were published from 1977 to 2015 with a large percentage after 1990 (i.e., 88% of the 66 selected articles: Appendix B). Research reports were published from 1989 to 2017 among which 65% were published after 2010 (Appendix B).

Corn was the most represented cash crop in the database representing 73% of the 2274 observations analyzed, followed by small grain cereals (19%) and soybean (8%). Most of the studies focussed on successive CC system (61%), while intercropping and full-season CC system represented 28% and 11% of the observations, respectively. Regarding CC type, legumes (LEG) were well represented (53% of observations), as well as grasses (GRASS 26%), while a smaller number of observations were available for CC mixtures with legumes (MIX 14%) and non-legume broadleaves (NLB 7%). In successive CC systems, GRASS and LEG CCs were equally represented (38% and 36% of the observations, respectively), while intercropping and full season systems mostly included LEG CCs (77% and 84% of the observations, respectively).

Main effect of CCs on cash crop yields

On average, CCs increased cash crop yields by 14% ± 3% as compared with the control without CCs ($p = 0.0001$; $n = 2274$ observations). Cash crop types, however, largely differed in their response to CCs ($p = 0.0007$; Fig. 1). Specifically, CCs increased corn yield by 13% ± 3% ($p = 0.0011$), small grain cereal yield by an average of 22% ± 4% ($p < 0.0001$), whereas soybean yield did not respond to CCs ($p = 0.2678$). More precisely, YRs varied from 0.09 to 3.78 in corn and from 0.40 to 5.58 in small

Fig. 1. Effect of cover crop on distribution of cash crop yield ratios for each crop type studied. Boxes represent the 25th percentile (left box side), median (solid interior line), and 75th percentile (right box side). Error bars on the sides of the box indicate the 10th and 90th percentiles. Circles correspond to extreme observations. Asterisks indicate differences of yield ratio estimates from 1 (i.e., no cover crop control) (***: $p \leq 0.0001$; *: $0.001 < p \leq 0.05$; ns: $p > 0.1$).



grain cereals. For both these cash crop types, 64% of the observations depicted a yield increase with CCs (i.e., a YR higher than 1). When excluding full-season CCs from analyses, CCs increased cash crop yields by 9% ± 2% on average (i.e., for all cash crops together; $p = 0.0119$; $n = 2026$ observation), by 11% ± 4% in corn ($p = 0.0250$) and by 11% ± 2% in small grain cereals ($p = 0.0024$), while CC effect on soybean yield remained non-significant ($p = 0.0862$; Appendix D).

Effects of management practices on cash crop yield response to CCs

The YRs were influenced by CC management and N inputs to cash crops, but the effects largely differed among cash crop types (Table 2). In contrast, the effects of variables related to crop rotation (i.e., preceding crop: corn, small grain cereals, soybean, others), tillage (i.e., conventional tillage, reduced tillage, no-till), and farming system (i.e., organic, non-organic) did not influence YRs for the three cash crops studied. Overall, corn yields were most responsive to the effects of CC management and N inputs followed by small grain cereal yields (with respectively six and three significant factors evidenced; Table 2); while in soybean, none of the management practices investigated significantly influenced YRs (albeit fewer observations were available). Thus, we focused on understanding interactive effects of CC management and environment on corn and small grain cereals only.

Corn crop

In corn, CC duration, CC type (alone or in interaction with CC system and CC termination timing), and N inputs (both N content in CC aboveground biomass and N fertilizer input to the cash crop) significantly influenced YRs (Table 2). Independent of CC type, corn yield increased from 10% with CC use in the first year to 25% after more than one to five consecutive years of CC inclusion to the cash crop rotation (Fig. 2*a*). Corn yield was significantly higher in presence of LEG or MIX with a 21% to 20% increase respectively, while GRASS decreased corn yield by 6% and NLB had no effect (Appendix E). The effect of CC type on corn YRs further differed between successive and intercropping systems, the former being generally more beneficial (or less detrimental) to corn yield than the latter (Table 2; Fig. 3). LEG in successive CC system resulted in a 31% increase in corn yield, which was nearly two times greater than the increase measured in the intercropping system (Fig. 3). Similarly, MIX significantly increased corn yield in successive systems (by 29%), but had no effect in the intercropping systems (Fig. 3), although there were nearly six less observations available for intercropped than successive MIX. While GRASS decreased corn yield by 13% in intercropping systems, this negative effect was only detected as a trend in successive systems (2% yield decrease; $p = 0.0688$), although eight times more observations were available for successive than intercropped GRASS (Fig. 3). NLB did not influence corn yield in either intercropping ($n = 8$) or successive systems ($n = 97$; Fig. 3).

The effect of CC type on corn yield also differed depending on termination timing (Table 2). While the positive effect of LEG and the negative to neutral effect of GRASS was consistent regardless of when the CCs were terminated (spring or fall), MIX and NLB were found to be more beneficial to corn yield when terminated in spring (promoting a 21% and 17% yield increase, respectively). No significant yield response was indeed observed when MIX or NLB were terminated in the fall (although only four observations corresponded to spring fall terminated NLB given that NLB do generally not

Table 2. Effects of management and environmental variables on cash crop yield ratios for each crop type investigated, obtained by linear mixed models (each line corresponds to a different model).

	Corn		Small grain cereals		Soybean	
	$N_{observations}$	Pr > F	$N_{observations}$	Pr > F	$N_{observations}$	Pr > F
Cover crop management						
CC type	1668	**<0.0001**	430	**<0.0001**	176	0.9925
CC system	1621	0.1106	430	**<0.0001**	176	0.5283
CC duration	1346	**0.0386**	362	0.0818	141	0.7891
CC termination timing	1374	0.6648	328	0.9084	-	-
CC type × CC system	1621	**0.0059**	-	-	-	-
CC type × CC duration	1346	0.4894	-	-	-	-
CC type × CC termination timing	1373	**0.0043**	-	-	-	-
Nitrogen inputs						
N content in CC biomass	1234	**<0.0001**	287	**<0.0001**	107	0.4231
N fertilizer inputs	1641	**<0.0001**	400	0.2330	140	0.8575
Crop rotation, tillage and farm management						
Preceeding crop	1276	0.2176	203	0.1335	154	0.1303
Farming system	1668	0.0914	430	0.5503	176	0.5153
Tillage system	1668	0.4378	430	0.1130	176	0.6571
Soil properties						
SOM	1262	**0.0007**	348	0.6192	144	0.7628
Soil texture	1581	0.3608	388	0.4135	171	0.8568
Weather parameters						
Abundant and well-distributed rainfall (AWDR)	1466	**0.0014**	404	**<0.0001**	174	0.6188
Annual mean air temperature (AMAT, 30-yr normal)	1638	0.4713	411	0.3871	176	0.5310

Note: Significant *p* values are indicated in bold. N, nitrogen; CC, cover crop; SOM, soil organic matter. -, the database did not allow to test the interaction effect (unbalanced factor levels).

overwinter; Appendix F). Corn YRs increased progressively with N content in CC aboveground biomass from a non-significant 2% increase for N content lower than 50 kg N ha^{-1} to significant yield increases of 12% at 50–99 kg N ha^{-1}, 27% at 100–199 kg N ha^{-1} and 52% for N content higher than 200 kg N ha^{-1} (Fig. 2*b*). Conversely, CC benefits on corn yield decreased with N fertilizer inputs: corn yield increased by 31% in the absence of N fertilizer inputs, and by 11% at low N fertilizer inputs (<60 kg N ha^{-1}), but with greater N fertilizer inputs CCs had no effect on corn yield. This general pattern was however modulated by CC type (see Fig. 4 and Environmental controls of cash crop yield response to CCs). Similar results were observed when excluding full-season CCs from analyses (Appendix G).

Small grain cereal crops

In small grain cereals, CC type, CC system and N content in CC aboveground biomass significantly influenced YRs (Table 2). Both LEG and MIX promoted an increase in small grain cereal yield (by 33% and 26%, respectively), while the positive effect of NLB was only detected as a trend (13%; $p = 0.0697$) and GRASS had no significant effect (Appendix H). Intercropping and full-season systems also benefited to the small grain cereal yield, with 29% and 36% yield increases, respectively, while successive CC systems had no effect (Appendix H). Similar to corn, small grain cereal yield increased with N content in CC aboveground biomass from a non-significant effect for CC N content lower than 50 kg N ha^{-1} to significant yield increases of 21% at 50–99 kg N ha^{-1}, 30% at 100–199 kg N ha^{-1} and 100% for N content higher than 200 kg N ha^{-1} (Appendix H). Conversely, the amount of N fertilizer applied to the cash crop did not influence small grain cereal YRs. No difference was observed among these results when excluding full-season CCs from analyses (Appendix G), except for a significant effect of tillage system ($p = 0.0253$) corresponding to a higher small grain cereal yield increase with CCs under reduced tillage (28% ± 7%, $p = 0.0006$) relative to conventional tillage (9% ± 4%, $p = 0.0228$), although these two tillage systems were represented by 30 and 199 observations, respectively.

Environmental controls of cash crop yield response to CCs

Weather factors and soil properties modulated CCs effects on cash crop yield with a significant positive effect of AWDR on both corn and small grain cereal YRs as well as a significant effect of SOM on corn YRs (Table 2). More precisely, small grain cereal yields increased on average by 16% when AWDR increased by 500 mm (regression slope = 3.1×10^{-4} % yield increase mm^{-1}; not shown). In corn, yields increased on average by 4% when AWDR increased by 500 mm (regression slope = 7.9×10^{-5} % yield increase mm^{-1}, not shown), although CC type modulated this general pattern (see multiple regression analysis below). Regarding SOM, the highest corn yield increase provided by CCs (26%) was observed on soils with low

Fig. 2. Effects of (*a*) cover crop duration (i.e., duration of cover crop integration into the cash crop rotation) and (*b*) nitrogen content in cover crop aboveground biomass on corn yield ratios, obtained by linear mixed models (*n*: number of observations). Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; **: $0.0001 < p \leq 0.001$; *: $0.001 < p \leq 0.05$; ns: $p > 0.1$). Letters indicate significantly difference among means based on Fisher's Least Significant Difference.

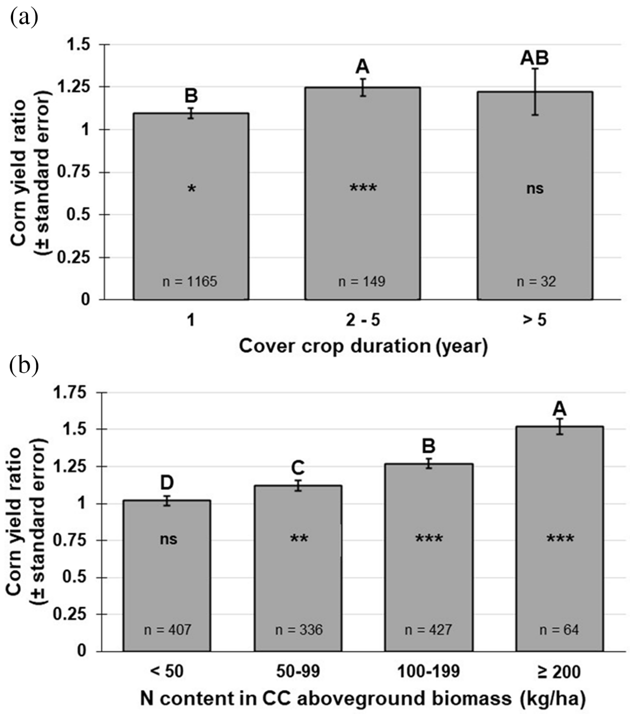
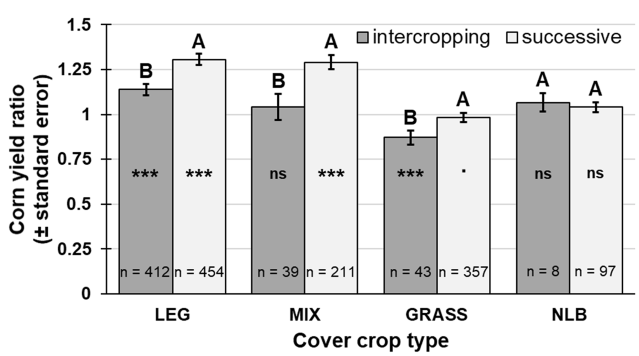


Fig. 3. Effects of cover crop type and system on corn yield ratios, obtained by linear mixed models (*n*: number of observations). Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; ˙: $0.05 < p \leq 0.1$; ns: $p > 0.1$). Different letters indicate significantly different systems within a same cover crop type based on Fisher's Least Significant Difference (LEG: legumes; MIX: mixes with legumes; GRASS: grasses; NLB: non-legume broadleaves). Full-season cover crop systems were excluded from analysis due to low number of observations.



SOM content (≤ 20 g kg^{-1}; $p < 0.0001$). As SOM increased to a $20 < \text{SOM} \leq 50$ g kg^{-1} range, corn YRs increased by 8% ($p = 0.0006$) with CCs, but there was no effect ($p = 0.5125$) when SOM content was between $50 < \text{SOM} \leq 100$ g kg^{-1}; Fig. 5).

The higher number of observations available for corn allowed us to investigate interactive effects between management practices and environmental factors on YRs using a multiple regression. It is important to note that 26% of the observations for corn ($n = 437$) had to be discarded from the model because CC type, N fertilizer inputs, SOM, or precipitation were not reported. This model revealed significant interactions between CC type and N fertilizer inputs, between CC type and AWDR, and between N fertilizer inputs and SOM (Table 3). As N fertilizer inputs increased, CC effects on corn YRs alternatively decreased or increased depending on CC type. The positive effect of LEG on corn yield was maximal in the absence of N fertilizer inputs (32%) and intermediate at 1–60 kg N ha^{-1} (22%; Fig. 4) and when inputs were above 60 kg N ha^{-1}, the positive effect of LEG on corn yield was only 5% to 9%, but still significant. A similar pattern was observed for MIX with a 27% yield increase in the absence of N fertilizer inputs, a 13% increase at 1–60 kg N ha^{-1}, and no significant increase above 60 kg N ha^{-1} (Fig. 4). Conversely, the negative effect of GRASS on corn YRs was reduced as N fertilizer inputs increased: the significant corn yield losses (17%) found in the absence of fertilization were not observed with fertilizer inputs above 60 kg N ha^{-1} (Fig. 4). For NLB, corn yield was generally independent of N fertilizer inputs and similar to those observed without CCs (Fig. 4).

The effect of CCs on corn YRs was also modulated by an interaction between SOM and N fertilizer inputs (Table 3): the positive effect of CCs on corn YRs in low-SOM soils generally decreased when N fertilizer inputs increased. Without fertilization, CCs provided a significant 28% corn yield increase in low-SOM soils ($\text{SOM} \leq 20$ g kg^{-1}), a significant 8% ± 3% corn yield increase in medium-SOM soils ($20 < \text{SOM} \leq 50$ g kg^{-1}), but did not significantly affect yield in high-SOM soils ($50 < \text{SOM} \leq 100$ g kg^{-1}). At low N fertilizer inputs (1–60 kg N ha^{-1}), the significant positive effect of CCs was, however, reduced to 16% compared with unfertilized corn in low-SOM soils, and the effect was not significant in both medium- and high-SOM soils. Above 60 kg N ha^{-1}, CCs effect on corn YRs became non-significant at all SOM contents.

Lastly, precipitation strongly modulated the effects of CC type on corn yield. In dry conditions (AWDR = 500 mm), LEG and MIX were similarly and significantly beneficial to corn yield with an average 18% yield increase, while GRASS significantly decreased corn yield by 14% (Fig. 6). Under moderate precipitation (AWDR = 1000 mm), LEG was more beneficial than MIX, with corn yield increased by 15% and 10%, respectively. The negative effect of GRASS on corn yield was lower

Fig. 4. Interactive effect of cover crop type and nitrogen (N) fertilizer inputs on corn yield ratios, obtained by linear mixed models. Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; **: $0.0001 < p \leq 0.001$; ˙: $0.05 < p \leq 0.1$; ns: $p > 0.1$). In each panel, different letters indicate significantly different levels of N fertilizer inputs for each cover crop type based on Fisher's Least Significant Difference (LEG: legumes; MIX: mixes with legumes; GRASS: grasses; NLB: non-legume broadleaves).

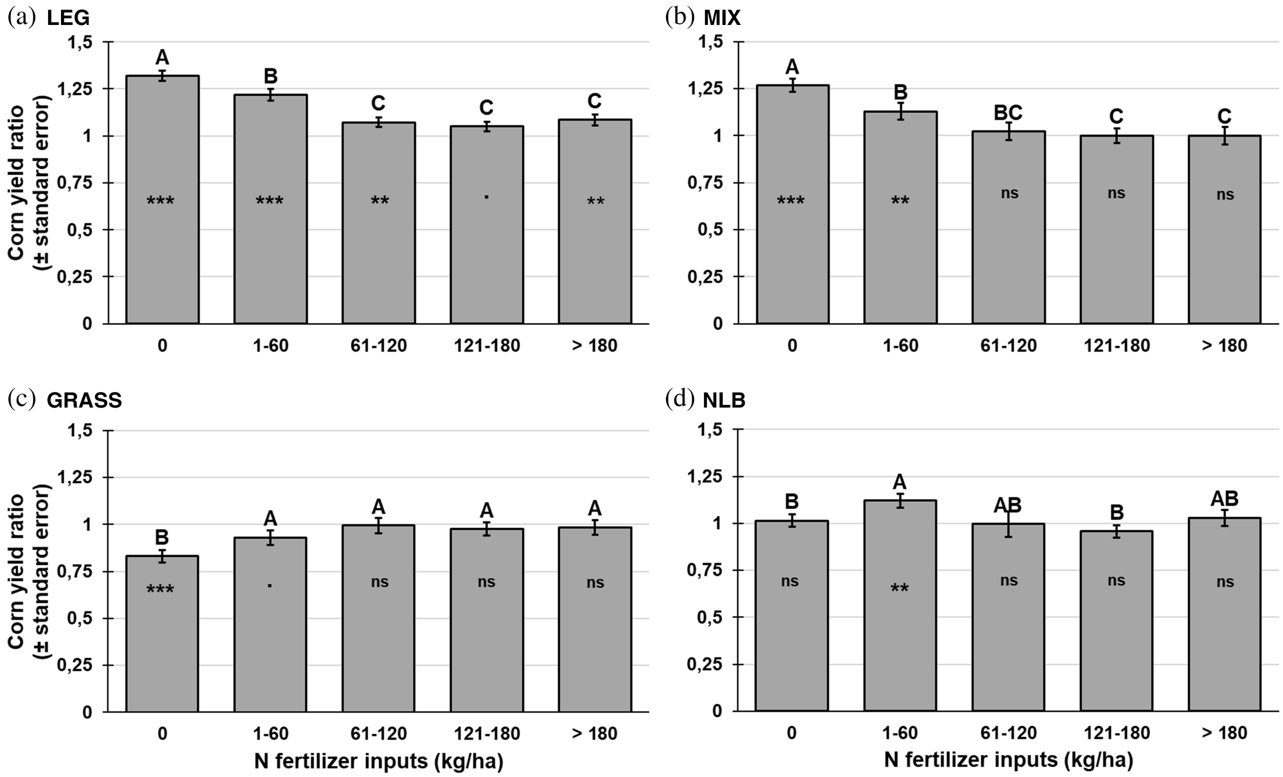


Fig. 5. Effects of soil organic matter content (SOM) on corn yield ratios, obtained by linear mixed models (n: number of observations). Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; ns: $p > 0.1$). Letters indicate significantly different soil organic matter contents based on Fisher's Least Significant Difference. Soils with SOM > 100 g kg^{-1} were excluded from analysis due to low number of observations.

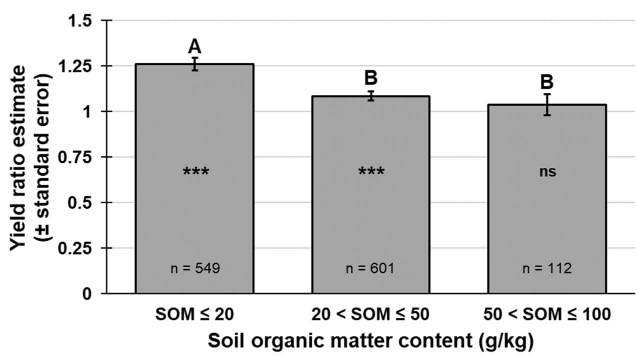


Table 3. Interactive effects of management (CC type, N fertilizer inputs) and environmental variables (AWDR and SOM) on corn yield ratios, obtained by a linear mixed model including 1231 observations.

Variable	DF	F value	Pr > F
CC type	3	9.91	**<0.0001**
N fertilizer inputs	4	5.28	**0.0003**
SOM	2	3.16	**0.0498**
AWDR	1	0.17	0.6810
CC type × N fertilizer inputs	12	13.50	**<0.0001**
CC type × AWDR	3	3.41	**0.0177**
N fertilizer inputs × SOM	8	6.08	**<0.0001**

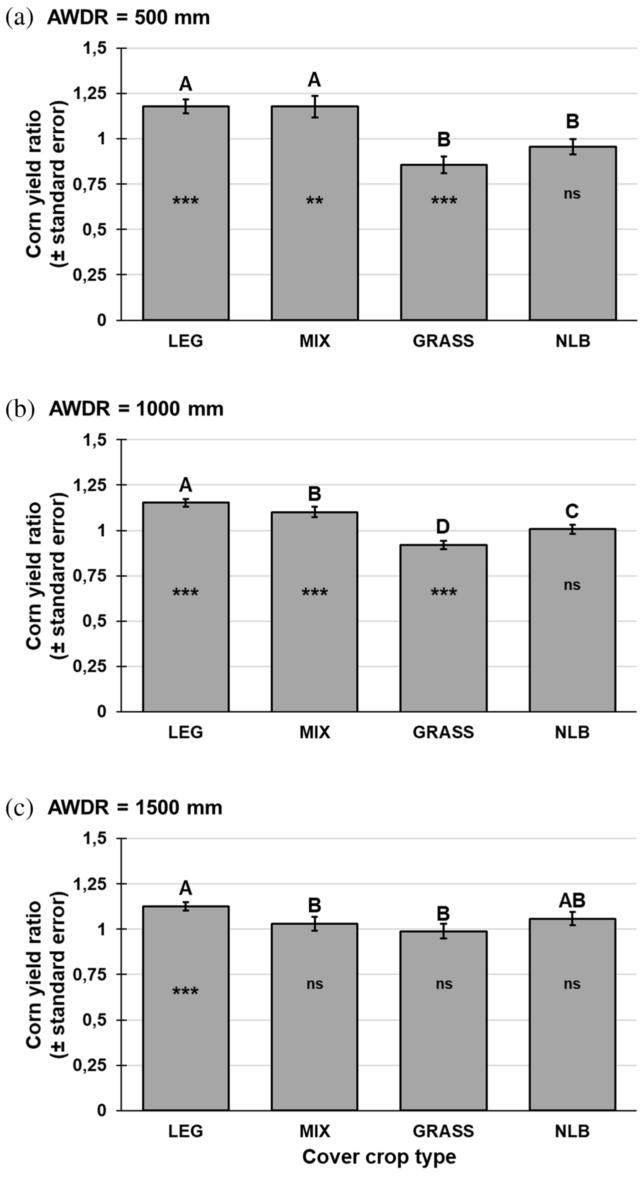
Note: Significant *p* values are indicated in bold. AWDR, abundant and well-distributed rainfall; SOM, soil organic matter; CC, cover crop; N, nitrogen.

under dry (14% reduction) than moderate (8% reduction) precipitation (Fig. 6). In wet conditions (AWDR = 1500 mm), corn yield still significantly increased with LEG by 13%, while the effect of MIX and GRASS were not significant (Fig. 6). NLB effect on corn yield was not significant for all three AWDR categories. Therefore, the positive effects of LEG and MIX and the negative effect of GRASS on corn yield were reduced as AWDR increased. Excluding full-season CCs from analyses led to similar results (Appendix I).

Discussion

This comprehensive meta-analysis sheds a new light on the response of cash crop yield to CCs in humid

Fig. 6. Interactive effect of cover crop type and abundant and well-distributed rainfall (AWDR) on corn yield ratios, obtained by linear mixed models. Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; **: $0.0001 < p \leq 0.001$; ns: $p > 0.1$). Different letters indicate significantly different cover crop types during (*a*) dry (AWDR: 500 mm), (*b*) normal (AWDR: 1000 mm), and (*c*) wet (AWDR: 1500 mm) seasons based on Fisher's Least Significant Difference at the three above-mentioned AWDR values (LEG: legumes; MIX: mixes with legumes; GRASS: grasses; NLB: non-legume broadleaves).



temperate regions. Overall, CCs supported higher cash crop productivity with an average 14% yield increase, which was consistent with the 15% increase reported in a recent meta-analysis encompassing both temperate and tropical areas (Daryanto et al. 2018, 2340 observations). Large differences in CC effects were however observed here among crop types. Small grain cereals displayed the highest yield increase (22%) and corn a lower positive effect (13%), while soybean yield remained similar with and without CCs. Indeed, the lack of soybean yield response to CCs in our meta-analysis (176 observations), was consistent with those previously observed in the Argentine Pampas (Alvarez et al. 2017, 160 observations), and mostly relates the ability of soybean to fix atmospheric N. Yet, positive CCs effect on soybean yield could have been expected in relation to long-term non-N effects (e.g., improved soil structure; see below), but may have been undetected here due to the low number of observations.

The response of small grain cereal and corn yields to CCs strongly varied among CC types. Legume CCs alone or mixed with grasses (such as red clover intercropped with small grain cereals or forage pea succeeding small grain cereals) were more beneficial to small grain cereals and corn than grasses and non-legume broadleaves. The positive effects found with legume CCs in the present meta-analysis were of similar magnitude to those observed in previous quantitative reviews (Miguez and Bollero 2005; Marcillo and Miguez 2017; Daryanto et al. 2018). Regardless of cash crop types, legume CCs both alone or in mixture have been shown to generate higher yields than non-legume CCs (i.e., a 27% and 6% increase, respectively in a meta-analysis of both temperate and tropical climates (Daryanto et al. 2018, 2340 observations)). Yet, a recent meta-analysis reported comparable crop yields with CC mixtures compared to monospecific CCs (Florence and McGuire 2020). In contrast, in corn, pure winter legume CCs and CC mixtures with legumes were found to increase yield by 21%–24% and 13%–22%, respectively, while winter grass CCs had no significant effect (Miguez and Bollero 2005, 160 observations; Marcillo and Miguez 2017, 268 observations). In northern Europe, spring small grain cereal yield was also found to increase with pure legume and legume-grass CC mixtures (both by 6%) and decrease with grass CCs by 3% (Valkama et al. 2015, 34 observations). We attribute the contrasting results among these meta-analysis to the interactive effects of management and environment on crop yield to CCs that our study highlighted.

The increased small grain cereal and corn YRs observed with increasing N content in CC aboveground biomass clearly points to the influence of CCs on N dynamics as a key mechanism promoting crop productivity. In our meta-analysis, corn YRs increased progressively with N content in CC aboveground biomass from a non-significant 2% increase for N content lower than 50 kg N ha^{-1} to significant yield increases (12% to 52 %) as the N content reaches a level of 200 kg N ha^{-1}. The N contribution of a CC is in part determined by the N content of the plant, which is a function of its biomass and N concentration, but also in the case of CC mixtures by both plant taxonomic and functional diversity (Finney et al. 2016; Blesh 2018). The N concentration of a CC is primarily influenced by its phenology and its uptake strategy. Legumes can accumulate high quantity of N in their tissues, making them excellent green manures. Compared with grasses, legume CCs are able to fix atmospheric N and their biomass is characterized by lower C/N ratio, faster N mineralization rate, and reduced competition for N (N'Dayegamiye and Tran 2001; Sarrantonio and Gallandt 2003; Finney et al. 2016; White et al. 2016, 2017; Hunter et al. 2019). It is, however, difficult to estimate the N contribution of CCs to the subsequent crop as several elements will modulate this contribution, such as CC management (type, termination timing, N fertilizer inputs), soil properties (SOM content), and weather parameters as our multiple regression analysis has identified.

A longer growth period of CCs promoted higher cash crop yields. Hence, in corn production, yield increases were generally more pronounced when CCs were terminated in spring rather than fall. In fact, spring termination was generally more beneficial than fall termination for LEG and MIX, while the opposite often characterized GRASS. Under temperate climates, intercropping systems mostly include species such as clovers or alfalfa that are sown with or into the small grain cereals preceding corn, while successive systems in which the CCs are grown between two cash crops mostly rely on species such as hairy vetch or forage pea sown after the harvest of the preceding cash crop. In regions with longer growing seasons, successive CCs can therefore perform better than intercropped CCs. In regions with shorter seasons however, intercropped legumes CCs benefits from a longer growth period compared with successive CCs whose growth is limited by late sowing date as well as temperature, humidity and frost conditions during fall (Langelier et al. 2021). Therefore, environmental conditions during fall seem crucial for CC primary productivity and its related effect on subsequent cash crop yield. In small grain cereals, CC systems favouring a higher CC biomass due to longer growth period (i.e., intercropping and full-season systems) were also more beneficial to yield than successive systems in which the CCs are grown between two cash crops. A longer CC growing season promoting higher CC biomass could therefore be more beneficial to cash crop yield due to greater N accumulation in CC aboveground biomass. The effect of CC belowground biomass on cash crop yield, however, remains to be quantified given CC root biomass is rarely measured.

Our study provides evidence that N input to the cash crop greatly modulates the effects of CCs on corn productivity but it depends on the CC type and SOM levels. More precisely, the positive effects of LEG and MIX CCs were maximized (22% to 32% yield increase) with fertilizer N inputs below 60 kg N ha^{-1}, and above 60 kg N ha^{-1} the positive effect of LEG on corn yield was only 5% to 9%, but still significant. The negative effect of GRASS observed in absence of N fertilizers became negligible at fertilizer rate above 60 kg N ha^{-1}, most probably due to cereal rye which can immobilize N due to a high C/N ratio. Reduced CC effects due to increasing N inputs were previously reported in varied annual cash crops for both temperate and tropical regions (Alam et al. 2018; Daryanto et al. 2018), as well as in corn production in North America (Miguez and Bollero 2005; Tonitto et al. 2006, 635 observations; Marcillo and Miguez 2017). In fact, the effect of CCs on corn YRs was also modulated by SOM. The positive effect of CCs on corn YRs in low-SOM soils and no response in high SOM soils can reflect increasing nutrient availability in this latter soil type for the cash crop (Mullen et al. 1998). But the effect of CCs on corn YRs decreased when N fertilizer inputs increased for all SOM content. Taken together, our research suggests a site-specific approach to CC management depending on SOM content and modifying N inputs to corn based on CC type and biomass.

Climate conditions further modulated CCs effects on corn productivity. The negative effect of GRASS on corn yield lessened with greater precipitation, ranging from a 14% yield decrease under dry conditions to no effect under wetter conditions. Similar to GRASS, the effect of MIX CCs on corn yield decreased with greater precipitation as yields significantly increased under dry to medium conditions (by 18% and 10% at AWDR = 500 mm and AWDR = 1000 mm, respectively), but remained unchanged under wet conditions (AWDR = 1500 mm). On the contrary, the positive effect of legume CCs on corn yield remained relatively constant regardless of the amount of precipitation (ranging from 13 to 18%), suggesting higher resiliency of legume CCs to precipitation regime. Temperatures, on the contrary, did not influence YRs response to CCs.

Although previous studies suggested that CC benefits decrease with rainfall (Roberts et al. 1998; Unger and Vigil 1998; Rusinamhodzi et al. 2011; Blanco-Canqui et al. 2015), we demonstrated here that this pattern is not universal, but rather depends on CC type. The stronger influence of precipitation on YRs with grass CCs could possibly be due the faster root growth, higher root biomass and density (Sainju et al. 1998; Dabney et al. 2001), as well as greater height of standing residues (Blanco-Canqui et al. 2015) that often characterize grasses compared to legumes. This could result in more intense competition for water with the cash crop for grass relative to legume CCs, such as for cereal rye, especially when terminated just before corn seeding. Some grasses such as cereal rye also produce allelopathic compounds that could more strongly affect corn productivity in dry conditions due to a slower degradation or leaching of such compounds. In the case of MIX CCs, higher precipitation could possibly favour higher grass growth, thereby modifying the relative proportion of legumes vs. grasses in the CC mixture and reducing CC-N inputs to the cash crop. Further investigations are required to fully disentangle the processes driving GRASS and MIX CCs effect on cash crop productivity under various water stress conditions.

Long-term benefits of CCs to cash crop yields were also observed in this study. Through time (i.e., with the duration of CCs integration to the cash crop rotation), the positive effects of CCs on corn yield increased from 10% in the first year (n = 1165) to 25% after less than 5 yr (n = 149) and 22% after more than 5 yr (n = 32; $p < 0.05$). Even if several slow processes can explain this cumulative effect, it most likely relies on progressive changes in soil properties, such as increased SOM and soil quality (Chahal et al. 2020; Haruna et al. 2020), and to the storage of CC-derived N in the soil reserve (Langelier et al. 2021), which may be released only after a few years. Many studies have shown that CCs increase SOM content in the long term, largely attributed to belowground biomass inputs (Blanco-Canqui et al. 2013; Olson et al. 2014; Poeplau and Don 2015; Ruis and Blanco-Canqui 2017; Chahal et al. 2020) which promotes microbial biomass and diversity and stimulates microbial activity (Gentsch et al. 2020; Kim et al. 2020), hence eventually increasing nutrient availability for the cash crop (Mullen et al. 1998). Long-term CC integration to crop rotation appears therefore an interesting agroecological strategy to reduce the reliance on fertilizer inputs. Examples of such long-term CC integration to cash crop rotation include among others soybean-corn rotation with cereal rye or oat sown annually right after or just before cash crop harvest (Singer and Kohler 2005; Kaspar et al. 2012), or oat-wheat rotation with successive CCs of ryegrass or red or white clover, alone or mixed (Løes et al. 2011). Most of the studies found in the literature and analyzed here evaluated CC use over only 1 yr (1165 observations), whereas longer-term studies were greatly underrepresented (181 observations). Future research efforts should therefore put more emphasis on longer-term experiments to fully capture cash crop yield trends and soil N supply capacity in response to repeated CC cultivation (Langelier et al. 2021).

Conclusion

This comprehensive meta-analysis provides a greater understanding of cash crop yield response to CCs under humid temperate region conditions, highlighting that CCs are generally beneficial to small grain cereal and corn yields, with an overall 22% and 13% yield increase respectively, but have a neutral effect in soybean. Several factors however modulate these benefits, pointing out the key roles of (1) CC types, as legume and legume/non-legume mixtures were more beneficial than grass-based and non-legume broadleaves CCs, and that CC benefits increased with the N content in CC biomass, but decreased with N fertilizer inputs, (2) environmental parameters, including the (*a*) precipitation regime with a reduced negative effect of grass-based CCs under wet conditions, whereas legume-based CCs showed great resilience to variations in precipitation, and (*b*) SOM as higher corn yield increases with CCs were observed on soils with low SOM content relative to soils with greater SOM content, and (3) duration of CC systems with a 10% increase in the first CC cultivation year compared to a 25% after more than 1 to 5 yr, possibly due to the development of non-N benefits (e.g., better soil structure and greater organic matter content and soil N supply capacity). Therefore, not only agricultural practices and management, but also environmental factors, especially SOM content and precipitation regime, strongly and interactively modulated CC effects, which were highly dependent on CC type. As revealed in this study, such complex interactions highlight the need for a greater understanding of the biophysical determinants modulating CC benefits, and their potential role in explaining discrepancies among studies. More broadly reporting soil and weather factors and testing their effects in future studies would be a first step towards this objective. Systematically providing measures of variability (e.g., standard deviations) in future studies is also strongly encouraged to facilitate weighted meta-analysis to be conducted that may provide more accurate estimates of cash crop yield response to cover cropping. It should also be noted that the general publication bias towards studies presenting positive results (rather than negative ones) could have led to overestimate here CCs benefits to cash crop yield. Nevertheless, as previously pointed out (Blanco-Canqui et al. 2015; Ruis and Blanco-Canqui 2017; Daryanto et al. 2018), long-term experiments are still required to fully comprehend the dynamics of cash crop yields under CC management. Research efforts could also be devoted to the study of non-legume broadleaves CCs and CC mixtures which have, to date, been scarcely investigated as compared to legume and grass CCs. In addition, disentangling the hierarchical order of agricultural practices and environmental factors in terms of importance to cash crop yield is a promising avenue to optimize CC management. Altogether, these perspectives should provide insights to the mechanisms underlying CC effects on cash crop productivity and other ecosystem services and would foster adoption of this beneficial management practice by farmers.

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References

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., et al. 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Glob. Chang. Biol. **25**: 2530–2543. doi:10.1111/gcb.14644. PMID:30955227.

Abdallahi, M.M., and N'Dayegamiye, A. 2000. Effets de deux incorporations d'engrais verts sur le rendement et la nutrition en azote du blé (*Triticum aestivum* L.), ainsi que sur les propriétés physiques et biologiques du sol. Can. J. Soil Sci. **80**: 81–89.

Alam, M.Z., Lynch, D.H., Tremblay, G., Gillis-Maden, R., and Vanasse, A. 2018. Optimizing combining green manures and pelletized manure for organic spring wheat production. Can. J. Soil Sci. **98**: 1–12.

Alvarez, R., Steinbach, H.S., and De Paepe, J.L. 2017. Cover crop effects on soils and subsequent crops in the pampas: a meta-analysis. Soil Till. Res. **170**: 53–65.

Arbuckle, J.G., and Roesch-McNally, G. 2015. Cover crop adoption in Iowa: the role of perceived practice characteristics. J. Soil Water Conserv. **70**: 418–429. doi:10.2489/jswc.70.6.418.

Badararuddin, M., and Meyer, D.W. 1990. Green-manure legume effects on soil nitrogen, grain yield, and nitrogen nutrition of wheat. Crop Sci. **30**: 819–825.

Baggs, E.M., Watson, C.A., and Rees, R.M. 2000. The fate of nitrogen from incorporated cover crop and green manure residues. Nutr. Cycl. Agroecosys. **56**: 153–163. doi:10.1023/A:1009825606341.

Basche, A.D., Archontoulis, S.V., Kaspar, T.C., Jaynes, D.B., Parkin, T.B., and Miguez, F.E. 2016*a*. Simulating long-term impacts of CCs and climate change on crop production and environmental outcomes in the Midwestern United States. Agr. Ecosyst. Environ. **218**: 95–106.

Basche, A.D., Kaspar, T.C., Archontoulis, S.V., Jaynes, D.B., Sauer, T.J., Parkin, T.B., and Miguez, F.E. 2016*b*. Soil water improvements with the long-term use of a winter rye cover crop. Agr. Water Manage. **172**: 40–50. doi:10.1016/j.agwat.2016.04.006.

Blanco-Canqui, H., Holman, J.D., Schlegel, A.J., Tatarko, J., and Shaver, T. 2013. Replacing fallow with cover crops in a semiarid soil: effects on soil properties. Soil Sci. Soc. Am. J. **77**: 1026–1034. doi:10.2136/sssaj2013.01.0006.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A., and Hergert, G.W. 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agron. J. **107**: 2449–2474.

Blesh, J. 2018. Functional traits in cover crop mixtures: biological nitrogen fixation and multifunctionality. J. Appl. Ecol. **55**: 38–48. doi:10.1111/1365-2664.13011.

Bullied, W.J., Entz, M.H., Smith, S.R.J., and Bamford, K.C. 2002. Grain yield and N effects to sequential wheat and barley crops from single-year alfalfa, berseem and red clover, chickling vetch and lentil. Can. J. Plant Sci. **82**: 53–65. doi:10.4141/P01-044.

Chahal, I., Vyn, R.J., Mayers, D., and Van Eerd, L.L. 2020. Cumulative impact of cover crops on soil carbon sequestration and profitability in a temperate humid climate. Sci. Rep. **10**: 13381. doi:10.1038/s41598-020-70224-6. PMID:32770008.

Chen, S., Wyse, D.L., Johnson, G.A., Porter, P.M., Stetina, S.R., Miller, D.R., et al. 2006. Effect of cover crops alfalfa, red clover, and perennial ryegrass on soybean cyst nematode population and soybean and corn yields in Minnesota. Crop Sci. **46**: 1890–1897. doi:10.2135/cropsci2005.09-0296.

Cicek, H., Entz, M.H., Martens, J.R.T., and Bullock, P.R. 2014. Productivity and N effects of late-season legume cover crops in organic wheat production. Can. J. Plant Sci. **94**: 771–783. doi:10.4141/cjps2013-130.

Coombs, C., Lauzon, J.D., Deen, B., and Van Eerd, L.L. 2017. Legume cover crop management on N dynamics and yield in grain corn systems. Field Crop Res. **201**: 75–85. doi:10.1016/j.fcr.2016.11.001.

CRAAQ (Centre de Référence en Agriculture et Agroalimentaire du Québec). 2010. Guide de référence en fertilisation, 2nd ed. CRAAQ, Quebec.

Crews, T.E., and Peoples, M.B. 2005. Can the synchrony of N supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review. Nutr. Cycl. Agroecosys. **72**: 101–120. doi:10.1007/s10705-004-6480-1.

Dabney, S., Delgado, J., and Reeves, D. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plan. **32**: 1221–1250. doi:10.1081/CSS-100104110.

Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., Mitchell, J., and Reeves, W. 2010. Using cover crops and cropping systems for N management. Pages 230–281 in J.A. Delgado and R.F. Follett, eds. Advances in N management for water quality. Soil and Water Conservation Society, Iowa.

Daryanto, S., Fu, B., Wang, L., Jacinthe, P.A., and Zhao, W. 2018. Quantitative synthesis on the ecosystem services of cover crops. Earth-Sci. Rev. **185**: 357–373.

Daryanto, S., Jacinthe, P.A., Fu, B., Zhao, W., and Wang, L. 2019. Valuing the ecosystem services of cover crops: barriers and pathways forward. Agr. Ecosyst. Environ. **270**: 76–78. doi:10.1016/j.agee.2018.10.021.

De Bruin, J.L., Porter, P.M., and Jordan, N.R. 2005. Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. Agron. J. **97**: 587–598. doi:10.2134/agronj2005.0587.

Delgado, J.A., and Gantzer, C.J. 2015. The 4Rs for cover crops and other advances in cover crop management for environmental quality. J. Soil Water Conserv. **70**: 142A–145A. doi:10.2489/jswc.70.6.142A.

De Notaris, C., Rasmussen, J., Sørensen, P., Melander, B., and Olesen, J.E. 2019. Manipulating cover crop growth by adjusting sowing time and cereal inter-row spacing to enhance residual nitrogen effects. Field Crop. Res. **234**: 15–25. doi:10.1016/j.fcr.2019.02.008.

Florence, A.M., and McGuire, A.M. 2020. Do diverse cover crops mixtures perform better than monocultures? A systematic review. Agron. J. **112**: 3513–3534. doi:10.1002/agj2.20340.

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

Gentsch, N., Boy, J., Batalla, J.D.K., Heuermann, D., von Wirén, N., Schweneker, D., et al. 2020. Catch crop diversity increases rhizosphere carbon input and soil microbial biomass. Biol. Fertil. Soils **56**: 943–957.

Halde, C., Gulden, R.H., and Entz, M.H. 2014. Selecting cover crop mulches for organic rotational no-till systems in Manitoba, Canada. Agron. J. **106**: 1193–1204. doi:10.2134/agronj13.0402.

Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S., and Gao, Y. 2020. Improving soil physical properties through the use of cover crops: a review. Agrosyst. Geosci. Environ. **3**: e20105. doi:10.1002/agg2.20105.

Huntington, T.G., Grove, J.H., and Frye, W.W. 1985. Release and recovery of nitrogen from winter annual cover crops in notill corn production. Commun. Soil Sci. Plan. **16**: 193–211.

Hunter, M.C., Schipanski, M.E., Burgess, M.H., LaChance, J.C., Bradley, B.A., et al. 2019. Cover crop mixture effects on Maize, Soybean, and Wheat Yield in rotation. Agric. Environ. Lett. **4**: 180051.

Jian, J., Lester, B.J., Du, X., Reiter, M.S., and Stewart, R.D. 2020. A calculator to quantify cover crop effects on soil health and productivity. Soil Till. Res. **199**: 104575 doi:10.1016/j.still.2020.104575.

Johnson, T.J., Kaspar, T.C., Kohler, K.A., Corak, S.J., and Logsdon, S.D. 1998. Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. J. Soil Water Conserv. **53**: 276–279.

Jokela, W.E., Grabber, J.H., Karlen, D.L., Balser, T.C., and Palmquist, D.E. 2009. Cover crop and liquid manure effects on soil quality indicators in a corn silage system. Agron. J. **101**: 727–737. doi:10.2134/agronj2008.0191.

Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Moorman, T.B., and Singer, J.W. 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agr. Water Manage. **110**: 25–33. doi:10.1016/j.agwat.2012.03.010.

Kaye, J., Finney, D., White, C., Bradley, B., Schipanski, M., Alonso-Ayuso, M., et al. 2019. Managing nitrogen through cover crop species selection in the U.S. mi-Atlantic. PLoS ONE **14**: e0215448. doi:10.1371/journal.pone.0215448. PMID:30978240.

Kim, N., Zabaloy, M.C., Guan, K., and Villamil, M.B. 2020. Do cover crops benefit soil microbiome? A meta-analysis of current research. Soil Biol. Biochem. **142**: 107701. doi:10.1016/j.soilbio.2019.107701.

Lal, R., Delgado, J., Groffman, P., Millar, N., Dell, C., and Rotz, A. 2011. Management to mitigate and adapt to climate change. J. Soil Water Conserv. **66**: 276–285. doi:10.2489/jswc.66.4.276.

Langelier, M., Chantigny, M.H., Pageau, D., and Vanasse, A. 2021. Nitrogen-15 labelling and tracing techniques reveal cover crops transfer more fertilizer N to the soil reserve than to the subsequent crop. Agr. Ecosyst. Environ. **313**: 107359. doi:10.1016/j.agee.2021.107359.

Lavergne, S., Vanasse, A., Thivierge, M.-N., and Halde, C. 2021. Using fall-seeded cover crop mixtures to enhance agroecosystem services: A review. Agrosyst. Geosci. Environ.: e20161.

Løes, A.K., Henriksen, T.M., Eltun, R., and Sjursen, H. 2011. Repeated use of green-manure catch crops in organic cereal production–grain yields and nitrogen supply. Acta Agr. Scand. B.-S. P. **61**: 164–175.

Marcillo, G., and Miguez, F. 2017. Corn yield response to winter cover crops: an updated meta-analysis. J. Soil Water Conserv. **72**: 226–239. doi:10.2489/jswc.72.3.226.

Miguez, F.E., and Bollero, G.A. 2005. Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Sci. **45**: 2318–2329. doi:10.2135/cropsci2005.0014.

Mullen, M.D., Melhorn, C.G., Tyler, D.D., and Duck, B.N. 1998. Biological and biochemical properties in no-till corn with different corn crops. J. Soil Water Conserv. **53**: 219–224.

N'Dayegamiye, A., and Tran, T.S. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. **81**: 371–382. doi:10.4141/S00-034.

N'Dayegamiye, A., Whalen, J.K., Tremblay, G., Nyiraneza, J., Grenier, M., Drapeau, A., and Bipfubusa, M. 2015. The effects of legume crops on corn and wheat yield, N nutrition, and soil properties improvement. Agron. J. **107**: 1653–1665.

Norris, C.N., Bean, M., Cappellazzi, S.B., Cope, M., Greub, K.L.H., Liptzin, D., et al. 2020. Introducing the North American project to evaluate soil health measurements. Agron. J. **112**: 3195–3215. doi:10.1002/agj2.20234.

Olson, K., Ebelhar, S.A., and Lang, J.M. 2014. Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open J. Soil Sci. **4**: 284–292. doi:10.4236/ojss.2014.48030.

Poeplau, C., and Don, A. 2015. Carbon sequestration in agricultural soils via cultivation of cover crops: a meta-analysis. Agr. Ecosyst. Environ. **200**: 33–41. doi:10.1016/j.agee.2014.10.024.

Roberts, R.K., Larson, J.A., Tyler, D.D., Duck, B.N., and Dillivan, K.D. 1998. Economic analysis of the effects of winter cover crops on no-tillage corn yield response to applied nitrogen. J. Soil Water Conserv. **53**: 280–284.

Rosecrance, R.C., McCarty, G.W., Shelton, D.R., and Teasdale, J.R. 2000. Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. Plant Soil **227**: 283–290. doi:10.1023/A:1026582012290.

Ross, S.M., King, J.R., Izaurralde, R.C., and O'Donovan, J.T. 2009. The green manure value of seven clover species grown as annual crops on low and high fertility soils. Can. J. Plant Sci. **89**: 465–476. doi:10.4141/CJPS08173.

Ruis, S.J., and Blanco-Canqui, H. 2017. Cover crops could offset crop residue removal effects on soil carbon and other properties: a review. Agron. J. **109**: 1785–1805 doi:10.2134/agronj2016.12.0735.

Rusinamhodzi, L., Corbeels, M., Van Wijk, M.T., Rufino, M.C., Nyamangara, J., and Giller, K.E. 2011. A meta-analysis of long-term effects of conservation agriculture on maize yield under rain-fed conditions. Agron. Sustain. Dev. **31**: 657. doi:10.1007/s13593-011-0040-2.

Sainju, E.M., Singh, B.P., and Whitehead, W.F. 1998. Cover crop root distribution and its effects on soil nitrogen cycling. Agron. J. **90**: 511–518. doi:10.2134/agronj1998.00021962009000040012x.

Samson, R., Drury, C., and Omielan, J. 1992. Effect of winter rye mulches and fertilizer amendments on nutrient and weed dynamics in no-till soybeans. Agriculture Canada, Ontario.

Sarrantonio, M., and Gallandt, E. 2003. The role of cover crops in North American cropping systems. J. Crop Prod. **8**: 53–74. doi:10.1300/J144v08n01_04.

Schipanski, M.E., Barbercheck, M., Douglas, M.R., Finney, D.M., Haider, K., Kaye, J.P., et al. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agr. Syst. **125**: 12–22. doi:10.1016/j.agsy.2013.11.004.

Seidel, R., Moyer, J., Nichols, K., and Bhosekar, V. 2017. Studies on long-term performance of organic and conventional cropping systems in Pennsylvania. Org. Agric. **7**: 53–61. doi:10.1007/s13165-015-0145-z.

Shirazi, M.A., and Boersma, L. 1984. A unifying quantitative analysis of soil texture. Soil Sci. Soc. Am. J. **48**: 142–147. doi:10.2136/sssaj1984.03615995004800010026x.

Singer, J.W., and Kohler, K.A. 2005. Rye cover crop management affects grain yield in a soybean-corn rotation. Crop Manag. **4**: 1–6. doi:10.1094/CM-2005-0224-02-RS.

Stavi, I., Lal, R., Jones, S., and Reeder, R.C. 2012. Implications of cover crops for soil quality and geodiversity in a humid-temperate region in the Midwestern USA. Land Degrad. Dev. **23**: 322–330.

Thapa, R., Mirsky, S.B., and Tully, K.L. 2018. Cover crops reduce nitrate leaching in agroecosystems: a global meta-analysis. J. Environ. Qual. **47**: 1400–1411. doi:10.2134/jeq2018.03.0107. PMID:30512067.

Thiessen Martens, J.R., Entz, M.H., and Hoeppner, J.W. 2005. Legume cover crops with winter cereals in southern Manitoba: fertilizer replacement values for oat. Can. J. Plant Sci. **85**: 645–648. doi:10.4141/P04-114.

Thilakarathna, M.S., Serran, S., Lauzon, J., Janovicek, K., and Deen, B. 2015. Management of manure N using cover crops. Agron. J. **107**: 1595–1607. doi:10.2134/agronj14.0634.

Tonitto, C., David, M.B., and Drinkwater, L.E. 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**: 58–72. doi:10.1016/j.agee.2005.07.003.

Tremblay, N., Bouroubi, Y.M., Bélec, C., Mullen, R.W., Kitchen, N.R., Thomason, W.E., et al. 2012. Corn response to N is influenced by soil texture and weather. Agron. J. **104**: 1658–1671. doi:10.2134/agronj2012.0184.

Unger, P.W., and Vigil, M.F. 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. **53**: 200–207.

Valkama, E., Lemola, R., Kankanen, H., and Turtola, E. 2015. Meta-analysis of the effects of undersown catch crops on N leaching loss and grain yields in the Nordic countries. Agric. Ecosyst. Environ. **203**: 93–101. doi:10.1016/j.agee.2015.01.023.

Vyn, T.J., Faber, J.G., Janovicek, K.J., and Beauchamp, E.G. 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. **92**: 915–924. doi:10.2134/agronj2000.925915x.
Warnes, D.D., Ford, J.H., Eberlein, C.V, and Lueschen, W.E. 1991. Effects of a winter rye cover crop system and available soil water on weed control and yield in soybeans. Pages 149–151 in W.L. Hargrove ed. Cover crops for clean water. Soil and Water Conservation Society, Iowa.
White, C.M., DuPont, S.T., Hautau, M., Hartman, D., Finney, D.M., Bradley, B., et al. 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., Finney, D.M., Kemanian, A.R., and Kaye, J.P. 2016. A model-data fusion approach for predicting cover cop nitrogen supply to corn. Agron. J. **108**: 2527–2540. doi:10.2134/agronj2016.05.0288.

Appendix A.

Keyword string used for searching the CAB Abstracts database

[**TITLE AND HEADING WORDS =**

(maize *OR* corn *OR* soybean *OR* wheat *OR* barley *OR* oat* *OR* rye *OR* cereal crop* *OR* cereal* grain *OR* small cereal*)

AND

(green manure* *OR* cover crop* *OR* intercrop* *OR* double crop* *OR* overseed* *OR* catch crop* *OR* underseed* *OR* interseed* *OR* companion crop* *OR* relay crop*)

AND

(performance* *OR* yield* *OR* production)]

AND

[**LANGUAGE =** (english *OR* french)]

Appendix B.

List of 86 references included in the database

Abdallahi, M.M., N'Dayegamiye, A. 2000. Effects of two incorporations of green manures on soil physical and biological properties and on wheat (*Triticum aestivum* L.) yields and N uptake. Can. J. Soil Sci. 80: 81–89.

Andraski, T.W., and Bundy, L.G. 2005. Cover crop effects on corn yield response to nitrogen on an irrigated sandy soil. Agron. J. 97: 1239–1244.

Arlauskiene, A., and Maiksteniene, S. 2008. The effect of catch crop nitrogen on soil properties and spring barley yield. Agronomijas Vestis 10: 78–82.

Askegaard, M., and Eriksen, J. 2008. Residual effect and leaching of N and K in cropping systems with clover and ryegrass catch crops on a coarse sand. Agric. Ecosyst. Environ. 123: 99–108.

Badararuddin, M., and Meyer, D.W. 1990. Green-manure legume effects on soil nitrogen, grain yield, and nitrogen nutrition of wheat. Crop Sci. 30: 819–825.

Baggs, E.M., Watson, C.A., and Rees, R.M. 2000. The fate of nitrogen from incorporated cover crop and green manure residues. Nutr. Cycl. Agroecosyst. 56: 153–163.

Belfry, K.D., and Van Eerd, L.L. 2016. Establishment and impact of cover crops intersown into corn. Crop Sci. 56: 1245–1256. [dataset of 2015].

Bérubé, C. 2016. Legumes in successive system preceding corn. St-Stanislas, Quebec. [dataset-research report].

Blackshaw, R.E., Molnar, L.J., and Moyer, J.R. 2010. Sweet clover termination effects on weeds, soil water, soil nitrogen, and succeeding wheat yield. Agron. J. 102: 634–641.

Bourgeois, G. 2010. Essai à la ferme de l'efficacité de cultures d'engrais verts intercalaires sur le rendement du blé biologique. [dataset].

Breland, A. 1996. Green manuring with clover and ryegrass catch crops undersown in small grains: crop development and yields. Acta Agric. Scand. B-S. P. 46: 30–40.

Bullied, W.J., Entz, M.H., Smith, S.R.J., and Bamford, K.C. 2002. Grain yield and N benefits to sequential wheat and barley crops from single-year alfalfa, berseem and red clover, chickling vetch and lentil. Can. J. Plant Sci. 82: 53–65.

Centre d'expertise et de transfert en agriculture biologique et de proximité (CETAB). 2014. Contribution économique et agroenvironnementale des engrais verts en lien avec la problématique d'apport de sédiments dans les tributaires du Lac St-Pierre, Programme Prime-Vert 2013–2018, volet 3.1 – Approche régionale. [dataset-research report].

Centre d'expertise et de transfert en agriculture biologique et de proximité (CETAB). 2014. Contribution économique et agroenvironnementale des engrais verts et de leur apport en azote assimilable calculé à l'aide de l'approche PAN, Programme Prime-Vert 2013-2018, Volet 4 – Appui au développement et au transfert des connaissances en agroenvironnement, Thème: Santé et conservation des sols, # 13-SCS-28. [dataset- research report].

Centre d'expertise et de transfert en agriculture biologique et de proximité (CETAB). 2014. Évaluation de différents trèfles intercalaires comme précédent du maïs grain, Programme Prime-Vert 2013-2018, volet 3.1 – Approche régionale. [dataset-research report].

Centre d'expertise et de transfert en agriculture biologique et de proximité (CETAB). 2014. Fertilisation écologique des cultures grâce à l'utilisation d'engrais verts, CRSNG. [dataset-research report].

Chen, S.Y., Wyse, D.L., Johnson, G.A., Porter, P.M., Stetina, S.R., et al. 2006. Effect of cover crops alfalfa, red clover, and perennial ryegrass on soybean cyst nematode population and soybean and corn yields in Minnesota. Crop Sci. 46: 1890–1897.

Cicek, H., Entz, M.H., Martens, J.R.T., and Bullock, P.R. 2014. Productivity and nitrogen benefits of late-season legume cover crops in organic wheat production. Can. J. Plant Sci. 94: 771–783.

Cicek, H., Martens, J.R.T., Bamford, K.C., and Entz, M.H. 2015. Late-season catch crops reduce nitrate leaching risk after grazed green manures but release N slower than wheat demand. Agric. Ecosyst. Environ. 202: 31–41.

Clark, A.J., Decker, A.M., and Meisinger, J.J. 1994. Seeding rate and kill date effects on hairy vetch-cereal rye cover crop mixtures for corn production. Agron. J. 86: 1065–1070.

Clark, A.J., Decker, A.M., Meisinger, J.J., and McIntosh, M.S. 1997. Kill date of vetch, rye, and a vetch-rye mixture: I. Cover crop and corn nitrogen. Agron. J. 89: 427–434.

Clark, A.J., Meisinger, J.J., Decker, A.M., and Mulford, F.R. 2007. Effects of a grass-selective herbicide in a vetch-rye cover crop system on corn grain yield and soil moisture. Agron. J. 99: 43–48.

CMS Research Services a Division of Ecologistics Limited Waterloo, L., and Ottawa, Ontario, 1991. Cereal cover crop study. p. 49. [dataset-research report].

Corak, S.J., Frye, W.W., and Smith, M.S. 1991. Legume mulch and nitrogen fertilizer effects on soil water and corn production. Soil Sci. Soc. Am. J. 55: 1395–1400.

Dapaah, H.K., and Vyn, T.J. 1998. Nitrogen fertilization and cover crop effects on soil structural stability and corn performance. Commun. Soil Sci. Plan. 29: 2557–2569.

De Bruin, J.L., Porter, P.M., and Jordan, N.R. 2005. Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. Agron. J. 97: 587–598.

Decker, A.M., Clark, A.J., Meisinger, J.J., Mulford, F.R., and McIntosh, M.S. 1994. Legume cover crop contributions to no-tillage corn production. Agron. J. 86: 126–135.

Drury, C.F., Tan, C.S., Reynolds, W.D., Welacky, T.W., Weaver, S.E., Hamill, A.S., and Vyn, T.J. 2003. Impacts of zone tillage and red clover on corn performance and soil physical quality. Soil Sci. Soc. Am. J. 67: 867–877.

Drury, C.F., Tan, C.S., Welacky, T.W., Oloya, T.O., Gregorich, E.G., Weaver, S.E., and Hamill, A.S. 1998. Effects of crop residue in conservation tillage systems on soil quality and crop productivity. [dataset-research report].

Drury, C.F., Tan, C.S., Welacky, T.W., Reynolds, W.D., Zhang, T.Q., Oloya, T.O., and McLaughlin, N.B., Gaynor, J.D., 2014. Reducing nitrate loss in tile drainage water with cover crops and water-table management systems. J. Environ. Qual. 43: 587–598.

Duiker, S.W., and Curran, W.S. 2005. Rye cover crop management for corn production in the Northern Mid-Atlantic Region. Agron. J. 97: 1413–1418.

Eckert, D.J., 1988. Rye cover crops for no-tillage corn and soybean production. J. Prod. Agric. 1: 207–210.

Gailans, S. 2014. Side-dressing Corn following a Winter Rye cover crop — updated 2014. In: Iowa, P.F.o. (Ed.). p. 4. [dataset-research report].

Gaudin, A.C.M.J., Ken, Deen, B., and Hooker, D.C. 2015. Wheat improves nitrogen use efficiency of maize and soybean-based cropping systems. Agric. Ecosyst. Environ. 210: 1–10.

Halde, C., Gulden, R.H., and Entz, M.H. 2014. Selecting cover crop mulches for organic rotational no-till systems in Manitoba, Canada. Agron. J. 106: 1193–1204.

Hesterman, O.B., Griffin, T.S., Williams, P.T., Harris, G.H., and Christenson, D.A. 1992. Forage legume – small grain intercrops: nitrogen production and response of subsequent corn. J. Prod. Agric. 5: 340–348.

Hively, W.D., and Cox, W.J. 2001. Interseeding cover crops into soybean and subsequent corn yields. Agron. J. 93: 308–313.

Holderbaum, J.F., Decker, A.M., Meisinger, J.J., Mulford, F.R., and Vough, L.R. 1990. Fall-seeded legume cover crops for no-tillage corn in the humid east. Agron. J. 82: 117–124.

Holderbaum, J.F., Decker, A.M., Meisinger, J.J., Mulford, F.R., and Vough, L.R. 1990. Harvest management of a crimson clover cover crop for no-tillage corn production. Agron. J. 82: 918–923.

Huntington, T.G., Grove, J.H., and Frye, W.W. 1985. Release and recovery of nitrogen from winter annual cover crops in no-till corn production. Commun. Soil Sci. Plan. 16: 193–211.

Kabir, Z., and Koide, R.T. 2000. The effect of dandelion or a cover crop on mycorrhiza inoculum potential, soil aggregation and yield of maize. Agric. Ecosyst. Environ. 78: 167–174.

Kaspar, T.C., Jaynes, D.B., Parkin, T.B., and Moorman, T.B. 2007. Rye cover crop and gamagrass strip effects on NO3 concentration and load in tile drainage. J. Environ. Qual. 36: 1503–1511.

Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Moorman, T.B., and Singer, J.W. 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agric. Water Manage. 110: 25–33.

Kramberger, B., Gselman, A., Janzekovic, M., Kaligaric, M., and Bracko, B. 2009. Effects of cover crops on soil mineral nitrogen and on the yield and nitrogen content of maize. Eur. J. Agron. 31: 103–109.

Lahti, T., and Kuikman, P.J. 2003. The effect of delaying autumn incorporation of green manure crop on N mineralization and spring wheat (*Triticum aestivum* L.) performance. Nutr. Cycl. Agroecosyst. 65: 265–280.

Leroux, G., Bulher, S., and Proulx, M. 2011. Évaluation des cultures de couverture de vesce velue et de seigle d'automne et du rouleau crêpeur comme méthodes de désherbage dans la production biologique de maïs sucré, soya et blé panifiable. Final report. Project: PSDAB 07-BIO-35. 28 p. [dataset-research report].

Loes, A.K., Henriksen, T.M., Eltun, R., and Sjursen, H. 2011. Repeated use of green-manure catch crops in organic cereal production – grain yields and nitrogen supply. Acta Agric. Scand. B-S. P. 61: 164–175.

Madden, R., 2015. Agronomic evaluation of novel Green manures for organic grain production in Eastern Canada. [dataset-research report].

McCracken, D.V., Corak, S.J., Smith, M.S., Frye, W.W., and Blevins, R.L. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53: 1459–1464.

Mitchell, W.H., and Tell, M.R. 1977. Winter-annual cover crops for no-tillage corn production. Agron. J. 69: 569–573.

Moore, E.B., Wiedenhoeft, M.H., Kaspar, T.C., and Cambardella, C.A. 2014. Rye cover crop effects on soil quality in no-till corn silage–soybean cropping systems. Soil Sci. Soc. Am. J. 78: 968–976.

N'Dayegamiye, A., and Tran, T.S. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. 81: 371–382.

N'Dayegamiye, A., Whalen, J.K., Tremblay, G., Nyiraneza, J., Grenier, M., Drapeau, A., and Bipfubusa, M. 2015. The benefits of legume crops on corn and wheat yield, nitrogen nutrition, and soil properties improvement. Agron. J. 107: 1653–1665.

Parr, M., Grossman, J.M., Reberg-Horton, S.C., Brinton, C., and Crozier, C. 2011. Nitrogen delivery from legume cover crops in no-till organic corn production. Agron. J. 103: 1578–1590.

Power, J.F., Doran, J.W., and Koerner, P.T. 1991. Hairy vetch as a winter cover crop for dryland corn production. J. Prod. Agric. 4: 62–67.

Richards, I.R., Wallace, P.A., and Turner, I.D.S. 1996. A comparison of six cover crop types in terms of nitrogen uptake and effect on response to nitrogen by a subsequent spring barley crop. J. Agric. Sci. 127: 441–449.

Ross, S.M., King, J.R., Izaurralde, R.C., and O'Donovan, J.T. 2009. The green manure value of seven clover species grown as annual crops on low and high fertility temperate soils. Can. J. Plant Sci. 89: 465–476.

Samson, R.A. 1989. On-farm evaluation of cultivation, cover crops and chemical banding for crop and weed management in integrated farming systems. McGill University Libraries. [dataset-research report].

Samson, R.A., Arkinstall, A., and Quinn, J. 1992a. Field testing of cover crops for corn and Soybean production. p. 32. [dataset-research report].

Samson, R.A., Arkinstall, A., and Quinn, J. 1992b. Effect of winter Rye Mulches and fertilizer amendments on nutrient and

weed dynamics in no-Till Soybeans. p. 32. [dataset-research report].
Samson, R., Foulds, C., and Patriquin, D. 1990. Choice and management of cover crop species and varieties for use in row crop dominant rotations. Agric. Can. Res. Stn. [dataset-research report].
Samson, R.A., Weil, A., Arkinstall, A., and Quinn, J. 1992c. Manure management in conservation farming. p. 71. [dataset-research report].
Sarrantonio, M., and Scott, T.W. 1988. Tillage effects on availability of nitrogen to corn following a winter green manure crop. Soil Sci. Soc. Am. J. 52: 1661–1668.
Scott, T.W., Pleasant, J.M., Burt, R.F., and Otis, D.J. 1987. Contributions of ground cover, dry matter, and nitrogen from intercrops and cover crops in a corn polyculture system. Agron. J. 79: 792–798.
Singer, J.W., and Kohler, K.A. 2005. Rye cover crop management affects grain yield in a soybean-corn rotation. Crop Manag. 4: 1–6.
Stopes, C., Millington, S., and Woodward, L. 1996. Dry matter and nitrogen accumulation by three leguminous green manure species and the yield of a following wheat crop in an organic production system. Agric. Ecosyst. Environ. 57: 189–196.
Stute, J.K., and Posner, J.L. 1995. Legume cover crops as a nitrogen source for corn in an oat-corn rotation. J. Prod. Agric. 8: 385–390.
Swanton, C.J., Chandler, K., and Janovicek, K.J. 1996. Integration of cover crops into no-t-ill and ridge-till wheat (*Triticum aestivum* L.)-corn (*Zea mays* L.) cropping sequence. Can. J. Plant Sci. 76: 85–91.
Talgre, L., Lauringson, E., and Makke, A. 2010. Amounts of nitrogen and carbon returned to soil depending on green manure and the effect on winter wheat yield. Agron. Res. 8: 487–492.
Talgre, L., Lauringson, E., Roostalu, H., Astover, A., Eremeev, V., and Selge, A. 2009. The effects of pure and undersowing green manures on yields of succeeding spring cereals. Acta Agric. Scand. B-S. P. 59: 70–76.
Thibaudeau, S., 2013. Développement des systèmes de semis direct sous couverture végétale permanente (SCV) dans les grandes cultures, dans le but d'améliorer la structure du sol et sa productivité. [dataset-research report].
Thiessen Martens, J.R., Entz, M.H., and Hoeppner, J.W. 2005. Legume cover crops with winter cereals in southern Manitoba: fertilizer replacement values for oat. Can. J. Plant Sci. 85: 645–648.
Thilakarathna, M.S., Serran, S., Lauzon, J., Janovicek, K., and Deen, B. 2015. Management of manure nitrogen using cover crops. Agron. J. 107: 1595–1607.
Tiffin, P., and Hesterman, O.B. 1998. Response of corn grain yield to early and late killed red clover green manure and subirrigation. J. Prod. Agric. 11: 112–121.
Utomo, M., Frye, W.W., and Blevins, R.L. 1990. Sustaining soil nitrogen for corn using hairy vetch cover crop. Agron. J. 82: 979–983.
Vanasse, A., Langelier, M., Chantigny, M.H., Angers, D., Pageau, D., Bérubé, C., Thibaudeau, S., 2017. Caractérisation des apports d'azote et de la qualité du sol des systèmes avec cultures de couverture. Rapport final No projet : IA113026. Programme Innov'Action, 46 p. [dataset of 2015-2016-research report].
Verville, F., Vanasse, A., Chantigny, M., Pageau, D., and Tremblay, G. 2014. Effets des engrais verts et de leur période d'enfouissement sur les rendements du blé. CRAAQ – Journée d'information scientifique – Grande Culture 2014, p. 19. [dataset-research report].
Vyn, T.J., Faber, J.G., Janovicek, K.J., and Beauchamp, E.G., 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. 92: 915–924.
Vyn, T.J., Janovicek, K.J., Miller, M.H., and Beauchamp, E.G. 1999. Soil nitrate accumulation and corn response to preceding small-grain fertilization and cover crops. Agron. J. 91: 17–24.
Wagger, M.G. 1989. Cover crop management and nitrogen rate in relation to growth and yield of no-till corn. Agron. J. 81: 533–538.
Wagger, M.G. 1989. Time of dessication effects on plant composition and subsequent nitrogen release from several winter annual cover crops. Agro. J. 81: 236–241.
Warnes, D.D., Ford, J.H., Eberlein, C.V., and Lueschen, W.E. 1991. Effects of a winter rye cover crop system and available soil water on weed control and yield in soybeans. Cover crops for clean water: the proceedings of an international conference, West Tennessee Experiment Station, April.
Wilczewski, E., Piotrowska-Dlugosz, A., and Lemanczyk, G. 2015. Properties of Luvisol and spring barley yield as affected by peas as a catch crop. Zemdirbyste 102: 23–30.
Wivstad, M., Salomonsson, L., and Salomonsson, A.-C. 1996. Effects of green manure, organic fertilizers and urea on yield and grain quality of spring wheat. Acta Agric. Scand. B-S. P. 46: 169–177.

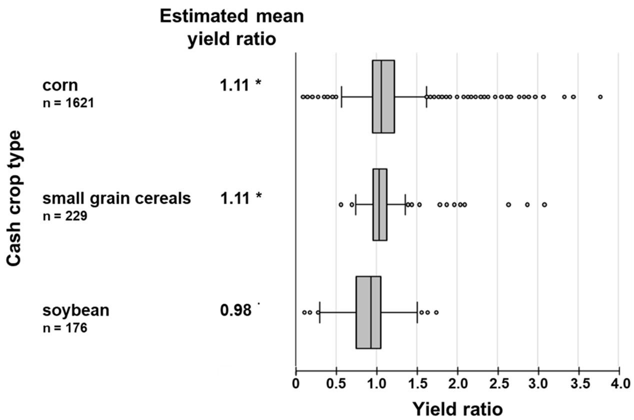
Appendix C.

Table A1. Field experiments analyzed for this study.

Location of the field experiments analyzed			
Country	State	Number of peer-reviewed articles	Number of technical reports
USA	Delaware	1	
	Iowa	5	1
	Kentucky	4	
	Maryland	8	
	Michigan	2	
	Minnesota	3	
	Nebraska	1	
	New York	3	
	North Carolina	3	
	North Dakota	1	
	Ohio	1	
	Pennsylvania	2	
	Wisconsin	2	
Canada	Alberta	2	
	Manitoba	5	
	Ontario	8	8
	Quebec	3	11
Denmark		1	
Estonia		2	
Finland		1	
Lituania		1	
Norway		2	
Poland		1	
Slovenia		1	
Sweden		1	
United Kingdom		3	

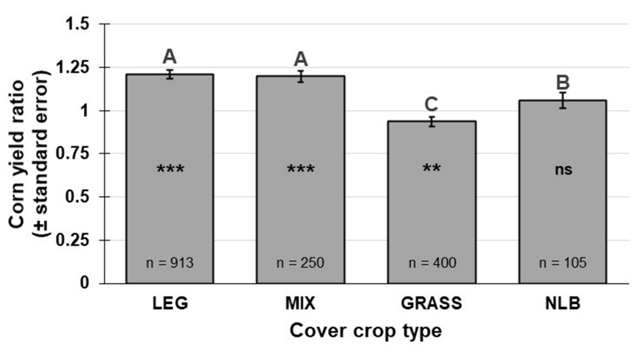
Appendix D.

Fig. A1. Effect of cover crop on distribution of cash crop yield ratios for each crop type studied, excluding full-season cover crops. Boxes represent the 25th percentile (left box side), median (solid interior line) and 75th percentile (right box side). Error bars on the sides of the box indicate the 10th and 90th percentiles. Circles correspond to extreme observations. Asterisks indicate differences of yield ratio estimates from 1 (i.e., no cover crop control) (*: $0.001 < p \leq 0.05$; ˙: $0.05 < p \leq 0.1$).



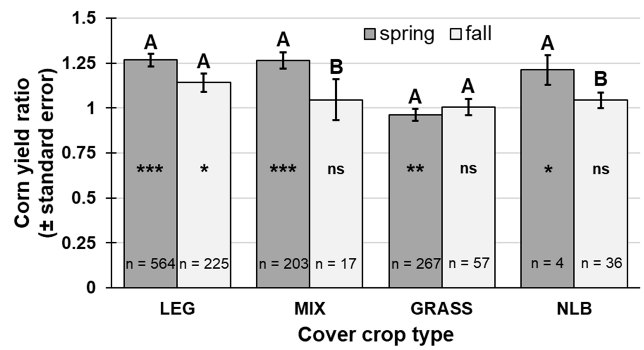
Appendix E.

Fig. A2. Effects of cover crop type on corn yield ratios, obtained by linear mixed models (n: number of observations). Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; **: $0.0001 < p \leq 0.001$; ns: $p > 0.1$). Letters indicate significantly different cover crop types based on Fisher's Least Significant Difference (LEG: legumes; MIX: mixes with legumes; GRASS: grasses; NLB: non-legume broadleaves).



Appendix F.

Fig. A3. Effects of cover crop type and termination timing on corn yield ratios, obtained by linear mixed models (n: number of observations). Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; **: $0.0001 < p \leq 0.001$; *: $0.001 < p \leq 0.05$; ns: $p > 0.1$). Letters indicate significantly different termination timing within a same cover crop type based on Fisher's Least Significant Difference (LEG: legumes; MIX: mixes with legumes; GRASS: grasses; NLB: non-legume broadleaves). Winter and summer termination timing were excluded from analysis due to low number of observations.



Appendix G.

Table A2. Effects of (*a*) management and environmental variables (see Table 1 for variable codes) on corn and small grain cereal yield ratios excluding full-season cover crops, obtained by linear mixed models (each line corresponds to a different model), and associated Fisher's Least Significant Difference in (*b*) corn and (*c*) small grain cereals.

(a)

	Corn		Small grain cereals	
	$N_{observations}$	Pr > F	$N_{observations}$	Pr > F
Cover crop management				
CC type	1621	< **0.0001**	229	< **0.0001**
CC system	1621	0.1106	229	< **0.0001**
CC duration	1331	**0.0404**	197	0.1185
CC termination timing	1327	0.7737	175	0.9189
CC type × CC system	1621	**0.0059**	-	-
CC type × CC duration	-	-	-	-
CC type × CC termination timing	-	-	-	-
Nitrogen inputs				
N content in CC biomass	1199	< **0.0001**	152	< **0.0001**
N fertilizer inputs	1594	< **0.0001**	217	0.7202
Crop rotation, tillage and farm management				
Preceeding crop	1260	0.1323	121	0.6887
Farming system	1621	0.0946	229	0.6369
Tillage system	1621	0.4633	229	**0.0253**
Soil properties				
Soil organic matter	1247	**0.0008**	223	0.4350
Soil texture	1534	0.4751	211	0.2064
Weather parameters				
Abundant and well-distributed rainfall (AWDR)	1419	**0.0337**	228	**0.0014**
Annual mean air temperature (AMAT, 30-yr normal)	1591	0.3897	222	0.6049

Note: Significant *p* values are indicated in bold. N, nitrogen; CC, cover crop; -, the database did not allow to test the interaction effect (unbalanced factor levels).

(*b*)

Variable	Level	$N_{observations}$	Mean yield ratio	Standard error	Pr > t	Group
CC type	LEG	866	1.20	0.03	< 0.0001	A
	MIX	250	1.19	0.03	< 0.0001	A
	GRASS	400	0.93	0.03	0.0010	C
	NLB	105	1.05	0.04	0.3163	B
CC duration	First year with CCs	1150	1.10	0.03	0.0321	B
	Less than 5 yr with CC	149	1.25	0.05	0.0003	A
	More than 5 yr with CC	32	1.22	0.14	0.1537	AB
CC type × CC system	LEG intercropping	412	1.14	0.03	< 0.0001	B
	LEG successive	454	1.31	0.03	< 0.0001	A
	MIX intercropping	39	1.04	0.07	0.6497	B
	MIX successive	211	1.29	0.04	< 0.0001	A
	GRASS intercropping	43	0.87	0.04	< 0.0001	B
	GRASS successive	357	0.98	0.03	0.0688	A
	NLB intercropping	8	1.07	0.05	0.1906	A
	NLB successive	97	1.04	0.03	0.3853	A
N content in CC biomass	<50	403	1.01	0.03	0.2963	D
	50-99	314	1.11	0.03	0.0170	C
	100-199	418	1.26	0.03	< 0.0001	B
	>=200	64	1.51	0.05	< 0.0001	A
N fertilizer inputs	Null	559	1.29	0.03	< 0.0001	A
	Low	317	1.10	0.04	0.0081	B
	Medium	258	0.99	0.03	0.8705	C
	High	262	1.03	0.03	0.5897	C
	Very high	198	1.07	0.03	0.1371	BC
Soil organic matter	0 to 2	549	1.26	0.03	< 0.0001	A
	2 to 5	601	1.08	0.03	0.0006	B
	5 to 10	97	1.04	0.06	0.4414	B

Note: CC, cover crop; LEG, legumes; MIX, mixes with legumes; GRASS, grasses; NLB, non-legume broadleaves; N, nitrogen.

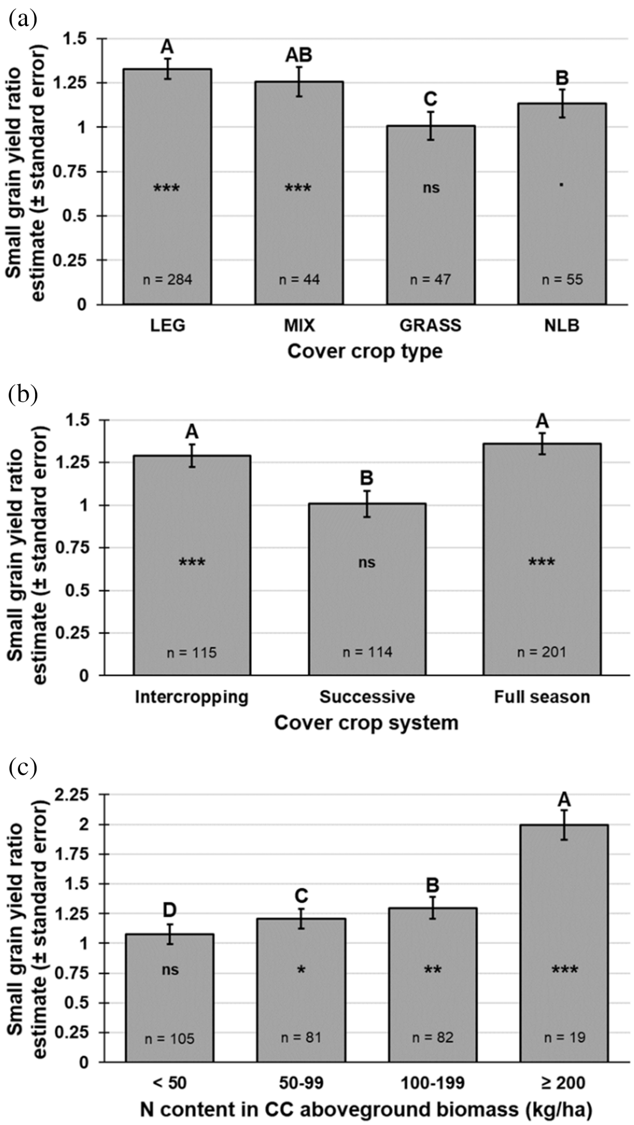
(*c*)

Variable	Level	$N_{observations}$	Mean yield ratio	Standard error	Pr > t	Group
CC type	LEG	122	1.20	0.04	< 0.0001	A
	MIX	21	1.13	0.07	0.0469	AB
	GRASS	40	0.97	0.05	0.1533	C
	NLB	46	1.04	0.05	0.257	B
CC system	Intercropping	115	1.25	0.04	< 0.0001	A
	Successive	114	0.94	0.05	0.2411	B
N content in CC biomass	<50	99	1.06	0.06	0.3922	B
	50-99	37	1.11	0.06	0.0818	B
	100-199	16	1.34	0.07	< 0.0001	A
Tillage system	Conventional	199	1.09	0.04	0.0228	B
	Reduced tillage	30	1.28	0.07	0.0006	A

Note: CC, cover crop; LEG, legumes; MIX, mixes with legumes; GRASS, grasses; NLB, non-legume broadleaves; N, nitrogen.

Appendix H.

Fig. A4. Effects of (a) cover crop type, (b) cover crop system, (c) nitrogen content in cover crop aboveground biomass on small grain cereal yield ratios, obtained by linear mixed models (n: number of observations). Asterisks indicate differences of yield ratio estimates from 1 (***: $p \leq 0.0001$; **: $0.0001 < p \leq 0.001$; *: $0.001 < p \leq 0.05$; ˙: $0.05 < p \leq 0.1$; ns: $p > 0.1$). Letters indicate significantly different cover crop types based on Fisher's Least Significant Difference (LEG: legumes; MIX: mixes with legumes; GRASS: grasses; NLB: non-legume broadleaves).



Appendix I.

Table A3. Interactive effects of (*a*) management (cover crop (CC) type, nitrogen (N) fertilizer inputs) and environmental variables (AWDR: abundant and well-distributed rainfall; SOM: initial soil organic matter for the site) on corn yield ratios excluding full season CCs (obtained by a linear mixed model including 1216 observations), and (*b*) associated Fisher's Least Significant Difference. LEG: legumes; MIX: mixes with legumes; GRASS: grasses; NLB: non-legume broadleaves.

(*a*)

Variable	DF	F-value	Pr > F
CC type	3	10.10	< **0.0001**
N fertilizer inputs	4	4.93	**0.0006**
SOM	2	2.85	0.0654
AWDR	1	0.06	0.8116
CC type × N fertilizer inputs	12	13.54	< **0.0001**
CC type × AWDR	3	3.77	**0.0108**
N fertilizer inputs × SOM	8	5.88	< **0.0001**

Note: Significant *p* values are indicated in bold. DF, degrees of freedom.

(*b*)

Level of CC type	Level of N fertilizer inputs	Mean yield ratio	Standard error	Pr > t	Group
LEG	Null	1.32	0.03	< 0.0001	A
LEG	Low	1.23	0.03	< 0.0001	B
LEG	Medium	1.07	0.03	0.0050	C
LEG	High	1.05	0.03	0.0510	C
LEG	Very high	1.10	0.03	0.0016	C
MIX	Null	1.27	0.04	< 0.0001	A
MIX	Low	1.13	0.05	0.0077	B
MIX	Medium	1.02	0.05	0.7207	BC
MIX	High	1.00	0.04	0.9934	C
MIX	Very high	1.00	0.05	0.9884	C
GRASS	Null	0.83	0.03	< 0.0001	B
GRASS	Low	0.94	0.04	0.0885	A
GRASS	Medium	0.99	0.04	0.8679	A
GRASS	High	0.98	0.03	0.4857	A
GRASS	Very high	0.99	0.04	0.8882	A
NLB	Null	1.02	0.03	0.6347	B
NLB	Low	1.13	0.04	0.0017	A
NLB	Medium	1.00	0.07	0.9521	AB
NLB	High	0.96	0.03	0.2282	B
NLB	Very high	1.04	0.04	0.3306	AB

Level of N fertilizer inputs	Level of SOM	Mean yield ratio	Standard error	Pr > t	Group
Null	0 to 2	1.28	0.03	< 0.0001	A
Null	2 to 5	1.08	0.03	0.0060	B
Null	5 to 10	0.94	0.07	0.3516	B
Low	inf 2	1.16	0.04	0.0001	A
Low	2 to 5	1.05	0.04	0.1553	A
Low	5 to 10	1.09	0.07	0.2333	A
Medium	inf 2	1.02	0.04	0.5742	A
Medium	2 to 5	1.05	0.04	0.2048	A
Medium	5 to 10	0.99	0.05	0.7849	A
High	inf 2	1.01	0.04	0.8353	A
High	2 to 5	1.02	0.03	0.4560	A
High	5 to 10	0.96	0.06	0.4815	A
Very high	inf 2	1.11	0.03	0.0023	A
Very high	2 to 5	0.96	0.03	0.2257	B
Very high	5 to 10	1.03	0.07	0.6470	AB

Level of AWDR	Level of CC type	Mean yield ratio	Standard error	Pr > t	Group
500	LEG	1.182	0.038	< 0.0001	A
500	MIX	1.198	0.059	0.0024	A
500	GRASS	0.861	0.046	0.0013	C
500	NLB	0.962	0.042	0.3561	B
1000	LEG	1.158	0.022	< 0.0001	A
1000	MIX	1.104	0.027	0.0004	B
1000	GRASS	0.924	0.023	0.0007	D
1000	NLB	1.012	0.026	0.6580	C
1500	LEG	1.134	0.023	< 0.0001	A
1500	MIX	1.018	0.040	0.6604	B
1500	GRASS	0.992	0.041	0.8526	B
1500	NLB	1.064	0.035	0.0788	B