Field Crops Research 183 (2015) 204–210

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Nitrogen fertilization reduces yield declines following no-till adoption

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ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form 17 July 2015
Accepted 19 July 2015

Keywords:
Tillage
Nitrogen fertilizer
No-till duration
Residue
Rotation
Tropical/subtropical
Temperate
Meta-analysis

ABSTRACT

Conservation agriculture (CA) has been promoted as a method of sustainable intensification and climate change mitigation and is being widely practiced and implemented globally. However, no-till (NT), a fundamental component of CA, has been shown to reduce yields in many cases. In order to maintain yields following adoption of CA, it has been recently suggested that fertilizer application should be an integral component of CA. To determine the contribution of nitrogen (N) fertilizer in minimizing yield declines following NT implementation, we assessed 2759 paired comparisons of NT and conventional tillage (CT) systems from 325 studies reported in the peer-reviewed literature between 1980 and 2013. Overall, we found that NT yields decreased −10.7% (−14.8% to −6.5%) and −3.7% (−5.3% to −2.2%) relative to CT in tropical/subtropical and temperate regions, respectively. Among management and environmental variables that included: the rate of N fertilization; the duration of the NT/CT comparison; residue, rotation, and irrigation practices; the crop type; and the site aridity, N rate was the most important explanatory variable for NT yield declines in tropical/subtropical regions. In temperate regions, N fertilization rates were relatively less important. NT yield declines were most consistently observed at low rates of N fertilization during the first 2 years of NT adoption in tropical/subtropical regions. Applications of N fertilizer at rates of up to 85 ± 12 kg N ha^{-1} yr^{-1} significantly reduced NT yield declines in these scenarios. While this result should not be viewed as a rate recommendation, it does suggest that farmers applying rates of N fertilizer that are low for their specific system will, on average, see higher NT yields if they increase application rates. In addition, when crop rotation was not practiced or residues were removed from the field, NT yield declines were magnified by low rates of N fertilization in tropical/subtropical regions. These results, based on a global data set and across a broad range of crops, highlight the importance of N fertilization in counteracting yield declines in NT systems, particularly in tropical/subtropical regions.

1. Introduction

Conservation agriculture (CA) is a suite of management practices designed to sustainably intensify the productivity of farming systems (FAO, 2008). Currently, an estimated 125 M ha (9% of all global cropland) are under some form of CA management (Friedrich et al., 2012; Kassam et al., 2012), and CA is being actively promoted in sub-Saharan Africa (SSA) as part of "Climate Smart" agricultural efforts (FAO, 2013). Conservation agriculture is based on three key principles: (1) limited or zero soil disturbance (i.e. minimum tillage or no-till (NT)), (2) crop residue retention to ensure maximum soil cover, and (3) crop rotation (FAO, 2013; Hobbs et al., 2008). Multiple biophysical benefits from CA have been reported in a wide array of cropping systems across the globe. Among the most widely documented of these benefits are erosion control (Lal, 1998; Scopel et al., 2005), soil water conservation (Hobbs et al., 2008; Thierfelder and Wall, 2009, 2010), and improved crop water use efficiency

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http://dx.doi.org/10.1016/j.fcr.2015.07.023

(Hobbs et al., 2008; Thierfelder and Wall, 2009, 2010). In addition, some authors have reported sustained or increased crop productivity resulting from the implementation of CA (Hansen et al., 2012; Rusinamhodzi et al., 2011; Ngwira et al., 2012).

Yet, recent work by Pittelkow et al. (2015a) suggests that yield changes due to the implementation of CA principles are usually negative, and depend upon the duration and extent to which all three CA principles are enacted as well as on the climate where CA is practiced. Indeed, despite the documented benefits of CA, its adoption has been more widespread in developed countries and temperate regions (Friedrich et al., 2012), and its broad applicability to the diverse cropping systems around the globe continues to be a topic of debate. For example, Giller et al. (2009) argued that the ecological and socio-economic conditions within SSA are often unsuitable to justify the implementation of CA. Among the concerns raised were the potential for yield reductions following CA implementation and the limited availability of crop residues in SSA cropping systems. Vanlauwe et al. (2014) echoed parts of this argument in a recent call for the application of fertilizer to be considered a “fourth principle” for CA in SSA. They argued that: (1) a primary reason for limited CA adoption by SSA smallholders is the lack of organic resources (e.g. crop residues) required to achieve sufficient soil cover; (2) application of adequate fertility can remedy this lack of soil cover; and (3) promoting a supply chain of fertilizer available at affordable prices should go hand-in-hand with promoting CA. Sommer et al. (2014) agreed that fertilizer inputs are crucial to the successful implementation of CA, but disagreed that this was grounds for articulating it as a fourth principle. These authors argued that insufficient fertilizer use is not unique to CA systems in SSA and that nutrient management is no more serious of a problem than lack of crop rotation or residue retention in CA systems. Meanwhile, Lal (2015) included “improving soil fertility by integrated nutrient management” as one of four CA principles in a recent overview of CA research.

To shed light on the discussion regarding the relative importance of nitrogen (N) fertilizer in the successful implementation of CA systems, we supplemented the data reported by Pittelkow et al. (2015a) with N management information and measured the proportional contribution of N fertilizer rates to NT/CT yield differences following NT implementation in both tropical/subtropical and temperate regions. Further, we evaluated mixed-effects models to determine whether and how the rate of N fertilization interacts with other management variables and affects the relationship between NT and CT yields in these regions.

2. Materials and methods

2.1. Data collection

As detailed in Pittelkow et al. (2015a), we searched the peer-reviewed literature for publications investigating the effects of NT on crop yields from January 1980 to May 2013 using Scopus (Elsevier, Amsterdam, Netherlands). Search terms included ‘tillage’, ‘no till’, ‘zero till’, ‘direct drill*’, or ‘conservation ag*’ in the article title and ‘yield’ in the article title, abstract, or keywords. The publications that resulted from this search were screened to ensure that only studies with side-by-side comparisons of NT and CT yields without confounding effects were included. Studies reporting differences in management between NT and CT treatments such as variations in residue management, crop rotation, N fertilization, or irrigation were not included (e.g. a study comparing yields from a NT treatment with residues retained to a CT treatment with residues removed would have been excluded). The lone exception was that NT and CT treatments were not required to have the same weed management because the different tillage approaches tend to result in distinct weed recruitment patterns (Farooq et al., 2011). Site characteristics including crop type, location, aridity index, duration of the NT/CT comparison, rotation history, and residue management were recorded. As reported by Pittelkow et al. (2015a), information for continuous and categorical variables was extracted from the Materials and Methods section of publications, and to a lesser extent was inferred from discussions of crop management details found in the Introduction or Discussion sections.

For the purposes of the present study, N fertilizer management information was recorded from each study when available. Observations from studies that reported a range of N rates across sites, crops, or years, were only included in the database if exact rates were provided or if the range of values was smaller than 15 kg N ha^{-1} (for these studies, the midpoint was chosen). When the main effects of tillage were presented across a range of N rates applied in sub-plots, N rates were not entered into the database. In addition, only observations where inorganic forms of fertilizer were used or where no fertilizer was applied were included.

The database was further confined to: (1) observations for which crop rotation information was available (observations with a preceding cover crop were categorized as having a crop rotation); (2) observations for which the duration of the NT/CT yield comparison was reported; (3) observations from plots where residues were not reported to have been burned (4) observations on non-legume crops. Finally, the data was partitioned into tropical/subtropical (latitude zones: $\leq 30°$N or $\geq -30°$S) or temperate (latitude zones: $>30°$N or $<-30°$S) regions. A total of 2777 observations from 325 studies were initially included. Following the removal of extreme values (described below) a total of 2759 observations from 325 studies were analyzed; the included studies can be found in Supplementary Table S1. Summary statistics regarding N fertilizer rates, climate regime, duration of the NT/CT comparison, residue management (retained/removed/not stated), crop rotation prevalence, and irrigation prevalence in the evaluated studies are displayed in Table 1.

Supplementary Table S1 related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2015.07.023

2.2. Data analysis

To determine the effect of tillage practices on yield, response ratios were calculated as the natural log of the ratio of paired NT to CT yields, $\ln[\text{yield}_{NT/}\text{yield}_{CT}]$ (Hedges et al., 1999). Individual observations were assigned weights based on the number of replications associated with the observation, with weights = $(n_{CT} \times n_{NT})/(n_{CT} + n_{NT})$, where n_{CT} and n_{NT} are the number of replicates for CT and NT treatments, respectively (Adams et al., 1997). Where more than one observation from a study was included, weights were divided by the total number of observations from that study. Extreme values were identified as those ±5 standard deviations (SD) from the weighted mean and removed from the data set, which totaled 0.9% and 0.4% of the observations in the tropical/subtropical and temperate data sets, respectively. Bootstrapping procedures were used to generate 95% confidence intervals (CI) for weighted mean effect sizes using the “boot” package in R (version 3.0.2) with 4999 iterations (R Core Team, 2013). Weighted mean effect sizes were considered significantly different from zero and from other values if the CI(s) did not overlap. For ease of interpretation, results were back-transformed and reported as percentage change in yield for NT relative to CT practices.

Using the yield response ratio as the dependent variable and with observation weights included in the fitting process, the relative importance of the independent variables was determined via

Table 1
For both tropical/subtropical and temperate regions: the number of observations and studies, and the weighted means for the continuous variables analyzed (i.e. N rate, duration of NT/CT comparison, and aridity index), as well as the percentage of observations where irrigation was reported, crop rotation was reported, and residue management was either specified or not stated.

	Observations	Studies	N rate ($kg\,ha^{-1}$); % fertilized	Duration (yr)	Aridity index	Irrigated	Rotation	Residue: Retained	Residue: Removed	Residue: Not stated	Residue retained and rotation
	N	*n*	Mean ± standard deviation			% of studies					
Tropical/subtropical	529	83	106 ± 58; 91%	2.8 ± 3.3	0.75 ± 0.37	47	62	49	15	36	32
Temperate	2230	242	118 ± 76; 87%	4.6 ± 4.9	0.75 ± 0.32	19	55	65	13	22	37

conditional random forest classification and regression approaches using the “cforest” procedure in the “party” package in R (Hothorn et al., 2006; Strobl et al., 2009). The independent variables included in the “cforest” procedure were: N fertilizer rate; the duration of the NT/CT yield comparison; residue retention (yes/no/not stated); crop rotation (yes/no); irrigation (yes/no/not stated); the aridity index (mean annual precipitation divided by potential annual evapotranspiration); and crop type. Variable importance was expressed as a proportion of the most important variable as determined by percent change in mean square error following random permutation of input variables. The overall variance explained by the procedure was calculated as a pseudo-R2 using the observed vs. the predicted values from the model. For further discussion of the application of these procedures to agronomic meta-analysis see Pittelkow et al. (2015b).

To examine interactive effects between tillage, the rate of N fertilization, and the other independent variables, exploratory linear mixed-effects models were developed using the “lme” procedure in the “nlme” package in R (version 3.0.2). For both tropical/subtropical and temperate data subsets, paired, natural log-transformed yields were regressed against possible 3-way interactions of the effects of tillage, N rate and the other management and environmental variables mentioned previously. The study from which an observation was derived was designated as a random effect and a weighting factor was included in the model to account for within-group heteroscedasticity. Assumptions of normality and homoscedasticity were assessed visually using plots of the residual values.

Previous work has shown that NT yield declines are more prevalent at low rates of N fertilization (Alvarez and Steinbach, 2009; Corbeels et al., 2014; Ogle et al., 2012; Rusinamhodzi et al., 2011). These findings, combined with heteroscedastic and/or non-normal residuals that resulted from the mixed linear modeling approach, indicated that a non-linear model might more precisely characterize the relationship between tillage and N rate for subsets where their interaction significantly affected yield, in addition to helping avoid type I errors. Therefore, subsets of the data for which a significant 3-way interaction was reported by the mixed linear model were analyzed further via mixed non-linear regression using the “nlme” procedure in the “nlme” package in R (version 3.0.2). To explore the three-way interaction between tillage, N rate, and NT duration via the nonlinear procedure, subsets with durations ≤ 2 years were analyzed because duration was a continuous integer variable and this separation represented the most equitable distribution of the observations ($n = 299$ for NT durations ≤ 2 years and $n = 230$ for NT durations >2 years in studies from tropical/subtropical regions).

Specifically, to determine the N rate at which NT yield declines were no longer observed when moving from low to high N rates, yield response ratios were fit to a plateau model. The plateau model was Makowski et al. (1999):

$$\begin{array}{ll} Y = Y_{\max} + b(N - N_{max}) & \text{if} \quad N < N_{\max} \\ Y = Y_{\max} & \text{if} \quad N > N_{\max} \end{array}$$

where Y = yield response ratio; b = slope; N = N rate ($kg\,ha^{-1}\,yr^{-1}$); $Y_{\max}$ = yield response ratio that is not responsive to higher N rates; and $N_{\max}$ = N rate at which the yield response ratio is not responsive to higher N rates. The study from which an observation was derived was designated as a random effect and a study-specific weighting factor was included to account for heteroscedasticity of variance. The plateau coefficient ($N_{\max}$) represents the N rate at which the slope of the yield decline no longer changed as N rate increased, accounting for between-study differences. For ease of interpretation, yield response ratios and modeled parameters were back-transformed and reported as percentage change in yield

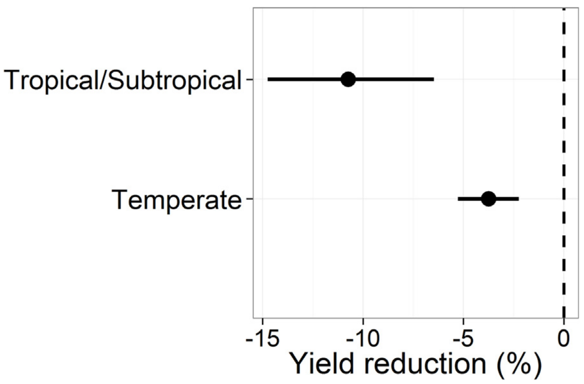

Fig. 1. Weighted mean reduction in yield ±95% bootstrapped confidence intervals based on paired comparisons of no tillage (NT) versus conventional tillage (CT) in tropical/subtropical ($n = 529$) or temperate ($n = 2230$) regions from 83 and 242 studies of non-legume crops, respectively.

for NT relative to CT practices. All analyses were performed in R (version 3.0.2) (R Core Team, 2013).

3. Results

The implementation of NT led to a significant decline in yield that was more extreme in tropical/subtropical regions (mean = −10.7%; 95% CI: −14.8% to −6.5%) than in temperate regions (mean = −3.7%; CI: −5.3% to −2.2%) (Fig. 1). In addition to these yield differences, the relative importance of the variables in explaining the NT yield change differed between tropical/subtropical and temperate regions (Fig. 2). In tropical/subtropical regions the rate of N fertilization was the most important variable for explaining yield changes due to NT (Fig. 2a). In contrast, site aridity, the least important variable for explaining yield declines in the tropical/subtropical regions, was the most important explanatory variable in temperate regions (Fig. 2b). Additionally, although in temperate regions N rate accounted for similar proportions of the variance as crop rotation, it was approximately half as important as residue management and two-thirds as important as NT duration in explaining the yield changes (Fig. 2b). Altogether, the independent variables explained approximately 37% and 14% of the overall variability in tropical/subtropical and temperate regions, respectively, according to the “cforest” procedure. As such, N rate explained approximately 11% of the overall yield decline in tropical/subtropical regions compared to less than 2% in temperate regions.

According to linear mixed-effects models, yields in tropical/subtropical regions were significantly affected by 3-way interactions between: tillage, N rate, and NT duration ($P = 0.001$); tillage, N rate, and residue management when residues were removed ($P = 0.008$); and tillage, N rate, and crop rotation when crop rotation was not practiced ($P = 0.001$). In contrast, three-way interactions among tillage, N rate, and aridity, and tillage, N rate, and irrigation did not significantly affect yields in tropical/subtropical regions. Likewise, there were no significant interactions between tillage, N rate and the other independent variables in studies from temperate regions. However, in general, the residuals resulting from the linear mixed-effects models were inconsistently homoscedastic and/or normally distributed.

Therefore, in order to avoid type I errors, for those subsets of data where significant 3-way interactions had been detected with the linear mixed-effects models between the paired yields, we examined the yield response ratios using nonlinear mixed-effects models (Fig. 3a, c, e). During the first 2 years of NT adoption, NT yield declines decreased by 0.22% per unit of N applied up to 85 ± 12 standard error (SE) kg N ha^{-1} yr^{-1} in tropical/subtropical regions (Fig. 3a). Whereas, for NT durations >2 years there was not a significant interactive effect of tillage and N rate on yield (Fig. 3b) according to the linear mixed-effects model ($P = 0.66$). Data subsets from tropical/subtropical regions where residues were removed (Fig. 3c) and where crop rotation was not practiced (Fig. 3e) either failed to converge, produced inconsistently significant parameter estimates and/or did not meet assumptions of normality and homoscedasticity using the nonlinear mixed-effects model. For data subsets where residues were retained (Fig. 3d) or where crop rotation was practiced (Fig. 3f) in tropical/subtropical regions, the interaction between tillage and N rate did not significantly affect yields according to the linear mixed-effects procedure ($P = 0.42$ and $P = 0.22$, respectively). Therefore, based on both the linear and nonlinear mixed modeling approaches, the most unambiguous interactive effects of tillage and N rate on crop yields apply to NT durations ≤2 years and N rates ≤85 ± 12 SE kg N ha^{-1} yr^{-1} in tropical/subtropical regions (Fig. 3a).

For the subsets where a significant 3-way interaction had been detected using the linear mixed-effects model, we also summarized the effects of N fertilizer addition using a categorical rather than continuous variable approach as in Corbeels et al. (2014) and Rusinamhodzi et al. (2011). Weighted mean effect sizes and associated confidence intervals were determined via bootstrapping from

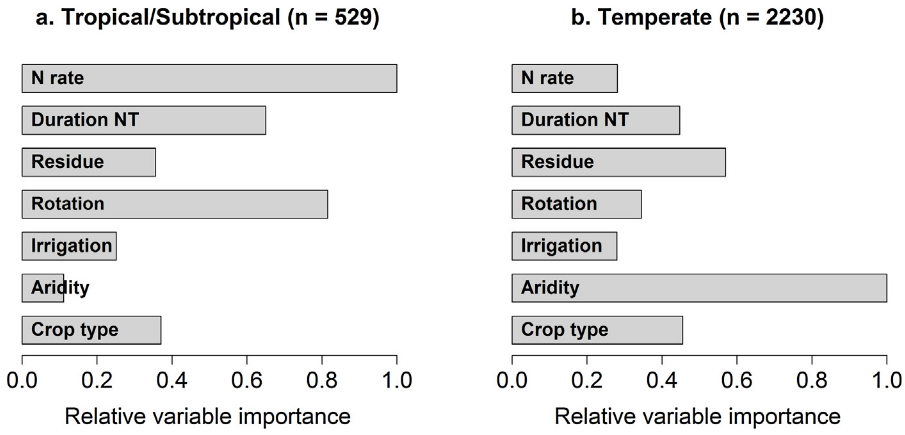

Fig. 2. Relative variable importance for predicting no-till (NT) yield reductions based on paired comparisons of NT versus conventional tillage (CT) in tropical/subtropical ($n = 529$) or temperate ($n = 2230$) regions from 83 and 242 studies of non-legume crops, respectively. Variable importance is depicted as a proportion of the most important variable as determined by percent change in mean square error via conditional random forest classification and regression procedures.

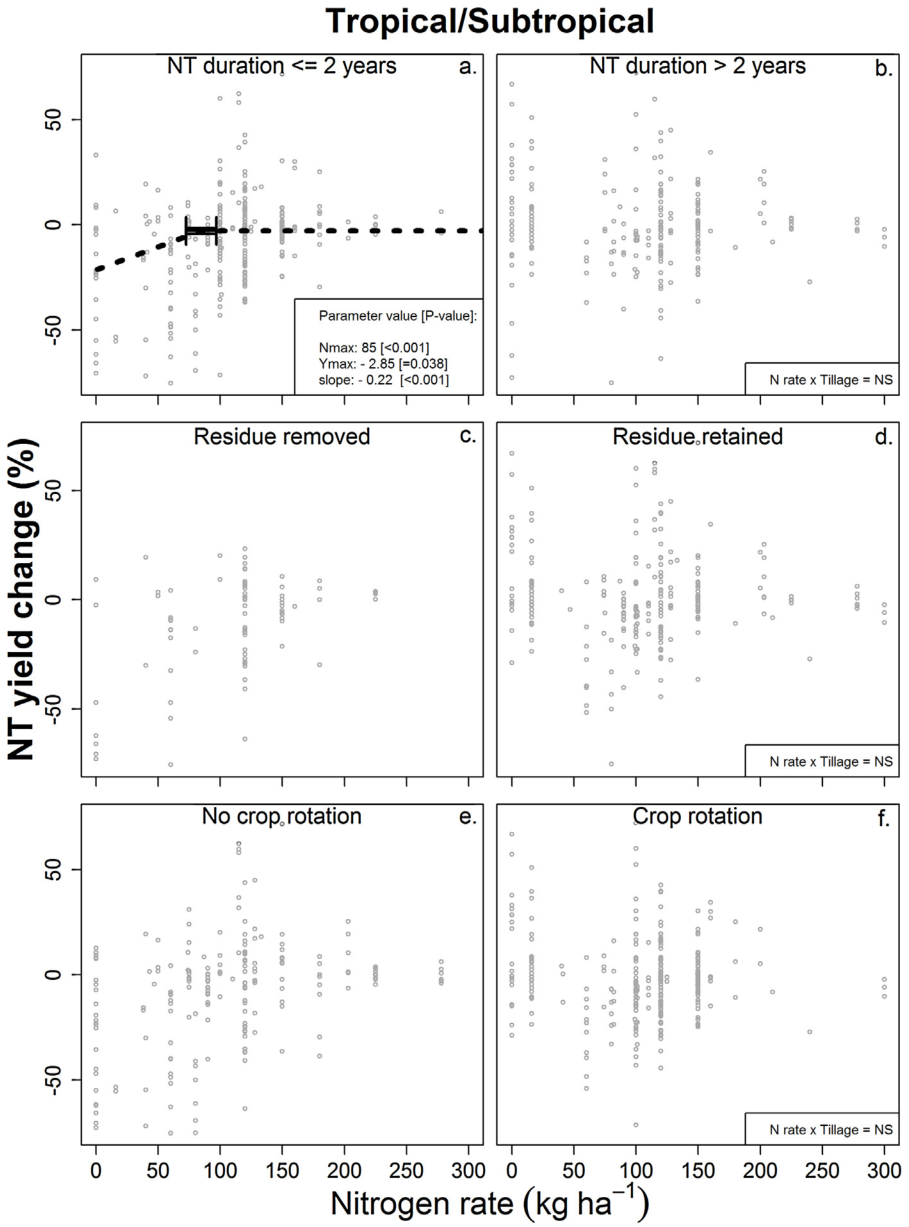

Fig. 3. Changes in the NT yield decline by nitrogen (N) fertilization based on paired comparisons of NT versus conventional tillage (CT) in tropical/subtropical regions for: NT durations ≤2 years (a, $n = 299$); NT durations > 2 years (b, $n = 230$); observations where residues were removed (c, $n = 80$) or retained (d, $n = 259$); and observations where crops were not (e, $n = 201$) or were (f, $n = 328$) rotated. N_{max} = N rate at which the yield response ratio is not responsive to higher N rates; Y_{max} = yield response ratio that is not responsive to higher N rates. For ease of interpretation, yield response ratios were back-transformed and reported as percentage change in yield for NT relative to CT practices. Error bars depict the standard error of the modeled parameters.

tropical/subtropical studies where: (1) the rate of N fertilization was either ≤100 kg ha^{-1} yr^{-1} or > 100 kg ha^{-1} yr^{-1} and (2) NT durations were ≤2 years, residues were removed, or no crop rotation was practiced (Fig. 3a, c, e). For observations where rates of N fertilization were ≤100 kg ha^{-1} yr^{-1}, NT yields were -27% (CI: −34% to −17%) lower than CT yields for NT durations ≤2 years, −34% (CI: −45% to −19%) lower for observations where residues had been removed, and −31% (CI: −37% to −23%) lower for observations where no crop rotation had been practiced. In contrast, for observations where rates of N fertilization were >100 kg ha^{-1} yr^{-1}, NT yields were equal to CT yields in 2 of the 3 subsets. In these subsets NT yield changes were −0.3% (CI: −3% to 4%) for NT durations ≤2 years, −8% (CI: −13% to −3%) for observations with residues removed, and 5% (CI: −3% to 13%) for observations where crop rotation was not practiced. However, unlike the mixed-effects models, which directly accounted for between-study differences as random effects, confounding effects, such as different distributions of crop types among the subsets, are not accounted for in the weighted mean effects approach.

4. Discussion

These results suggest that yield declines related to the implementation of NT (Fig. 1) are more sensitive to the rate of N fertilization in tropical/subtropical than in temperate regions (Fig. 2). Additionally, lower rates of N fertilization are, on average, more likely to result in larger NT yield declines than higher rates of N fertilization where the other components of CA are not practiced in tropical/subtropical regions (Fig. 3). Furthermore, NT yield declines are particularly magnified under low rates of N fertilization during the early years of NT adoption (Fig. 3a). Although the potential shortcomings of the various statistical models employed should not be overlooked (i.e.: a relatively small proportion of the overall variance explained by the "cforest" procedure; heteroscedastic and/or non-normal residuals in the mixed modeling as described above), their agreement regarding the overall conclusions suggests that they are robust.

These results also agree with the findings of Rusinamhodzi et al. (2011), who reported that maize yields for CA systems tended to be lower than in CT systems if less than 100 kg N ha^{-1} yr^{-1} was applied but higher than CT systems if more than 100 kg N ha^{-1} yr^{-1} was applied. Likewise, Corbeels et al. (2014) reported higher relative yields for CA versus CT systems in SSA when at least 100 kg N ha^{-1} yr^{-1} were applied. In addition, Ogle et al. (2012) conducted a meta-analysis on variables that contribute to yield changes after conversion from CT to NT in North America and found that the rate of N fertilization reduced the yield difference between CT and NT for maize and wheat. Also, Six et al. (2004) attributed a tendency for a yield decline in recently established NT systems to N deficiency, and Alvarez and Steinbach (2009) concluded that a decline of cereal grain yields under NT could be overcome by increasing N fertilizer rates.

Our work confirms these prior results but also indicates that, overall, this interaction is more consistently observed in studies conducted in tropical/subtropical than in temperate regions. In addition, by modeling the rate of N fertilization as a continuous variable while accounting for confounding factors to the extent possible, the results reported here in Figs. 2 and 3 more directly quantify the interaction between tillage and N fertilization than previous work. Another distinguishing feature is that these conclusions are drawn from a global data set and across a wide array of crops (11 and 21 crops, from tropical/subtropical and temperate regions, respectively). It should also be noted that the observations reported here were strictly from non-leguminous crops. In a broader analysis by Pittelkow et al. (2015b) using a less restricted subset of the same original meta-data (including observations from leguminous crops, a larger overall number of crop types, no requirement that specific N rates were reported, and no differentiation between temperate and tropical/subtropical regions) the relative importance of N rate as well as other variables included in the 'cforest' procedure differed to some extent from the results reported here. This might be expected due to variations in the level of management information reported in the original publications. For the present analysis, a more restricted subset of data was considered to be the most rigorous approach for addressing the proportional contribution of N rate relative to the other independent variables in tropical/subtropical and temperate regions.

Other investigators have offered several hypotheses to explain yield declines following a conversion to NT. These include delayed or uneven germination and seedling emergence (Powlson et al., 2014; Giller et al., 2009; Huggins and Reganold, 2008), slower rates of crop development due to lower soil temperatures (Halvorson et al., 2006; Iragavarapu and Randall, 1995), waterlogging in poorly-drained soils (Rusinamhodzi et al., 2011; Giller et al., 2009; Thierfelder and Wall, 2009), increased weed competition (Giller et al., 2009; Huggins and Reganold, 2008), soil N immobilization from residues (Giller et al., 2009; Erenstein, 2002; Rice and Smith, 1984), increased occurrence of crop diseases (Fernandez et al., 2009; Giller et al., 2009; Huggins and Reganold, 2008), and a 'learning-curve' effect (Pittelkow et al., 2015a,b; Huggins and Reganold, 2008). Some of the aforementioned causes may be more prominently observed in tropical/subtropical than temperate regions, which, on their own and/or in interaction with rates of N fertilization, may explain the more dramatic yield declines for NT systems in those regions.

For example, because farmers in tropical/subtropical regions are, on average, poorer than those in temperate regions (Sachs et al., 2001), there may be reduced access to the specialized equipment and external inputs that often accompany successful NT farming (Powlson et al., 2014; Ngwira et al., 2012). This might result in NT crops that are less responsive to N fertilization than those managed under CT. Indeed, of the 24 studies comprising the subset of data in tropical/subtropical regions where ≤85 kg N ha^{-1} yr^{-1} were applied with NT durations ≤2 years (Fig. 3a), more than half of the crops were sown by hand and/or relied on manual weeding. If the NT plant population, stand establishment and/or early plant vigor were negatively affected by planting/weeding technology and/or efficacy relative to CT, compensatory growth in the NT crops would have been less likely to occur under N-limited conditions than conditions where N was non-limiting. Also, that the plateau shape only significantly converged for observations where NT management had been enacted for ≤2 years (Fig. 3a) might suggest that a 'learning curve' effect (Pittelkow et al., 2015a,b; Huggins and Reganold, 2008) could have contributed to the reduced N responsiveness of the NT crops. In addition to these possible explanations, the greater prevalence of pests and diseases in tropical/subtropical regions (Gallup and Sachs, 2000) might have magnified interactions between tillage, non-N yield-limiting factors, and the rate of N fertilization. That is, under low N rates there might be less likelihood for compensatory growth if NT crops were disproportionately affected by a pest/disease relative to CT crops. Yet, the different conclusions between the tropical/subtropical and temperate regions may also be partly due to the smaller set of data derived from tropical/subtropical regions ($n = 529$ from 83 studies versus $n = 2230$ from 242 studies in temperate regions).

It should also be noted that a greater proportion of the observations analyzed for tropical/subtropical regions received irrigation (47%) than in the temperate regions (19%) (Table 1), which could have multiplied negative, water-related effects of NT on yield (e.g., waterlogging, disease occurrence), complicating the potential response to N fertilization. However, it could also be argued that more control over the application of water would decrease the probability of these interactions. Overall, the availability of soil moisture appears to be a primary limitation in observations from temperature regions but less important in tropical/subtropical regions, according to the relative importance of the aridity index and residue management practices between the two regions (Fig. 2). This may help to explain why the higher irrigation prevalence in tropical/subtropical studies would not account for the overall differences in NT yield declines between the two regions (Fig. 1). Further, because irrigation was included as an explanatory variable in the 'cforest' procedure and no significant interactions between tillage, N rate and irrigation were detected in the linear mixed-effects model, the relative importance of N fertilization in determining NT yield declines appears to hold independent of irrigation effects.

Where crops were rotated (Fig. 3f), differential rooting patterns between crop types might have resulted in more soil N availability for NT crops and less of a yield penalty relative to CT crops when application rates of N fertilizer were low (Fig. 3e). In addition, although leguminous crops were not included in the analysis, they could have been present in the crop rotation, potentially contributing N to the system for subsequent crops and reducing the probability of N-related NT/CT yield interactions for the subset of observations where crops were rotated (Fig. 3f). Similarly, if the yields of NT crops were relatively more sensitive than CT crops to low rates of N fertilization for any of the aforementioned reasons, relative to observations where residues were removed (Fig. 3c), observations where residues were retained (Fig. 3d) might have resulted in a larger pool of soil N, reducing such sensitivity. However, the fact that the nonlinear mixed-effects plateau model was not significant for those tropical/subtropical subsets where residues were removed (Fig. 3c) and no crop rotation was practiced (Fig. 3e) reduces our confidence in the significance of the interactions detected by the linear mixed-effects model.

Speculation on mechanisms aside, our analysis indicates that, among the variables accounted for in this study, N rate is of foremost importance for determining relative NT yields in tropical/subtropical regions (Fig. 2a). In addition, the modeled N rates necessary to offset NT yield reductions in tropical/subtropical regions during the first 2 years after NT implementation (Fig. 3a) are far greater than average rates used in SSA (Morris et al., 2007). While the modeled plateau should not be viewed as a rate recommendation, the results do suggest that farmers applying rates of N fertilizer that are low for their specific system will, on average, see higher NT yields if they increase their rates of N application.

In general, these results support the call by Vanlauwe et al. (2014) for sustainable, affordable fertilizer supply chains in SSA regions where CA is promoted. Of course, yields are only one of a suite of factors that may influence a farmer's decision to adopt NT and other CA principles (Nebraska Declaration, 2013). In addition, the analyses here only examined systems where zero tillage was practiced, so the conclusions may not apply to systems where minimum or reduced tillage are practiced. Furthermore, readers are encouraged to consider the limitations of the meta-analytical approach reported here, which is discussed in more depth by Pittelkow et al. (2015b). Nevertheless, given our findings across a broad range of crops and growing conditions, whether or not N fertilization is articulated as a fourth CA principle (Vanlauwe et al., 2014; Sommer et al., 2014) appears to be less important than whether the global agronomic community recognizes its importance in sustaining NT crop productivity.

Acknowledgements

We are grateful to the National Key Science and Technology Project of China for supporting X.Q.L. with grant No. 2014ZX07101-012. Additionally, K.J.v.G. received financial support from U.S. Department of Energy, Office of Science, Biological and Environmental Research Program, under Award Number DE-SC-008260.

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