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When does no-till yield more? A global meta-analysis

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ABSTRACT

No-till agriculture represents a relatively widely adopted management system that aims to reduce soil erosion, decrease input costs, and sustain long-term crop productivity. However, its impacts on crop yields are variable, and an improved understanding of the factors limiting productivity is needed to support evidence-based management decisions. We conducted a global meta-analysis to evaluate the influence of various crop and environmental variables on no-till relative to conventional tillage yields using data obtained from peer-reviewed publications (678 studies with 6005 paired observations, representing 50 crops and 63 countries). Side-by-side yield comparisons were restricted to studies comparing conventional tillage to no-till practices in the absence of other cropping system modifications. Crop category was the most important factor influencing the overall yield response to no-till followed by aridity index, residue management, no-till duration, and N rate. No-till yields matched conventional tillage yields for oilseed, cotton, and legume crop categories. Among cereals, the negative impacts of no-till were smallest for wheat (−2.6%) and largest for rice (−7.5%) and maize (−7.6%). No-till performed best under rainfed conditions in dry climates, with yields often being equal to or higher than conventional tillage practices. Yields in the first 1–2 years following no-till implementation declined for all crops except oilseeds and cotton, but matched conventional tillage yields after 3–10 years except for maize and wheat in humid climates. Overall, no-till yields were reduced by 12% without N fertilizer addition and 4% with inorganic N addition. Our study highlights factors contributing to and/or decreasing no-till yield gaps and suggests that improved targeting and adaptation, possibly including additional system modifications, are necessary to optimize no-till performance and contribute to food production goals. In addition, our results provide a basis for conducting trade-off analyses to support the development of no-till crop management and international development strategies based on available scientific evidence.

1. Introduction

Feeding a growing world population with increasing dietary preferences for resource-intensive food products is a major challenge facing humanity (Foley et al., 2011). It has been suggested that maintaining the increases in yields achieved over the past half-century, itself a challenge, will be insufficient to meet future global food demand (Grassini et al., 2013). Meanwhile, increased crop productivity is only one aspect of meeting future food security goals, and concerns over agricultural sustainability are greater than ever, with evidence that intensive conventional production practices can have severe negative environmental consequences (Foley et al., 2011; Godfray and Garnett, 2014; Tilman et al., 2011). High-yielding, conventional agricultural systems are often characterized by high rates of fossil fuel energy consumption, excessive nutrient use, soil degradation, and water pollution (Foley et al., 2011). Thus a global imperative has been set forth – to produce more with less – and various strategies are being promoted to achieve these goals.

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No-till[1] agriculture represents a relatively widely adopted soil management practice. The origins of no-till agriculture lie in the dustbowl of the 1930s in USA, where severe erosion of degraded soils occurred over large areas of agricultural land, prompting a shift toward reduced tillage practices (Six et al., 2002; Derpsch et al., 2010). However, the majority of no-till expansion worldwide has occurred since the mid- to late-1990s, facilitated by the use of herbicides and improved no-till technologies (Derpsch et al., 2010). From both an agricultural research and development standpoint, no-till has received much attention as a potential solution to the large challenges described above.

Research on no-till has often occurred within the context of conservation agriculture (CA). Conservation agriculture represents a set of three crop management principles: minimum soil disturbance (including no-till), crop rotation, and residue retention/permanent soil cover (FAO, 2011). For a thorough discussion of how CA farming systems are implemented in different parts of the world including site-specific benefits, factors enabling adoption, and key challenges, the reader is directed to several recent special journal issues and books (Serraj and Siddique, 2012; Stevenson et al., 2014; Jat et al., 2014a).

The environmental and economic benefits of no-till implemented as the core principle of CA are well-documented (Hobbs et al., 2008). One of the key factors underlying the success of no-till in combination with the other CA principles is that it conserves soil resources by reducing wind and water erosion (Verhulst et al., 2010). No-till in the context of CA can also lead to improvements in soil quality by improving soil structure and enhancing soil biological activity, nutrient cycling, soil water holding capacity, water infiltration and water use efficiency (Six et al., 2002; Hobbs et al., 2008; Verhulst et al., 2010; FAO, 2011). Importantly, no-till in combination with the other two CA principles can reduce production costs and increase profitability, often attributed to decreases in energy and labor consumption compared to conventional systems (Erenstein et al., 2012). Economic benefits coupled with reduced soil erosion are likely the main reasons for no-till adoption (Derpsch et al., 2010). Although there is the potential for no-till to contribute to soil C sequestration among other ecosystem services such as reduced soil greenhouse gas emissions in specific circumstances (Six et al., 2004; van Kessel et al., 2013), recent reports indicate that these benefits may not be as widely observed as previously thought (Powlson et al., 2014; Palm et al., 2014).

In terms of how no-till influences crop productivity, there is little consensus as to whether yields are maintained or yield increases or decreases can be expected despite these practices being widely investigated (Brouder and Gomez-Macpherson, 2014; FAO, 2011; Giller et al., 2009). Several previous analyses have summarized the yield impacts of various forms of no-till (including no-till implemented as the core principle of CA) on a crop-specific or regional basis, concluding that yields often increase under water-limited conditions (Farooq et al., 2011; Rusinamhodzi et al., 2011). In contrast, a number of reviews have shown that no-till practices can reduce crop productivity due to the potential for soil waterlogging and/or cooler soil temperatures which can inhibit crop establishment, compaction which can affect root growth, or altered soil fertility requirements which may lead to nutrient deficiencies (Alvarez and Steinbach, 2009; Ogle et al., 2012; Van den Putte et al., 2010). While recent work has synthesized data across large numbers of cropping systems and wide geographical areas (Brouder and Gomez-Macpherson, 2014; Toliver et al., 2012; Ogle et al., 2012; Van den Putte et al., 2010; Scopel et al., 2013; Pittelkow et al., 2015), no-till yield outcomes have not been quantified at a global scale across a range of important agronomic and environmental factors.

In light of increasing support for no-till as a tool to address global food security and sustainability goals, we used meta-analyses to summarize previous studies investigating the effects of no-till on crop yields. At a global scale, our objectives were to (i) evaluate the influence of crop and environmental variables on no-till productivity and (ii) identify factors contributing to no-till yield gaps to provide the scientific support for evidence-based crop management and international development strategies.

2. Materials and methods

2.1. Data collection

Following the approach reported by Pittelkow et al. (2015), we conducted a literature search to collect yield data from publications reporting side-by-side comparisons of conventional and no-till practices. Unlike in the data analyzed in Pittelkow et al. (2015), individual studies were not required to report residue management or crop rotation practices to be included in the database. Thus, the present analysis contained 68 additional studies (542 observations) compared to Pittelkow et al. (2015). A thorough description of no-till definitions used in this study and the specific paired yield comparisons extracted from publications are provided in Pittelkow et al. (2015). In brief, no-till treatments consisted of zero tillage immediately before crop establishment for a given growing season (that is, reduced tillage treatments such as strip-tillage were not considered). A reference list for publications included in the present analysis is provided as Supplementary Material.

Crops were grouped into the following categories: maize, wheat, miscellaneous cereals (barley, millet, oat, rye, sorghum, tef, triticale), legumes (alfalfa, bean, chickpea, clover, groundnut, lentil, lupin, pea, peanut, pigeonpea, soybean, vetch), oilseeds and cotton (canola, cotton, flax, linseed, mustard, safflower, sunflower, yellow sarson), rice, miscellaneous (broccoli, coffee, cucumber, lettuce, mustard leaf, pepper, squash, tobacco, tomato, watermelon), and root crops (cassava, cocoyam, potato, sugar beet, sweet potato, taro, yam). Cotton was grouped with oilseeds as it is also a dicot that can be used for oil production and there were not sufficient observations available for it to represent its own category ($n = 188$). Sugarcane, ryegrass, and canary seed (representing only 12, 4, and 1 observation(s), respectively) were not included in these crop categories.

When assessing yield responses by latitude, categories for tropical, subtropical, and temperate latitudes were defined as 0–20, 20–30, and 30–66 degrees, respectively. For studies that reported N management information, the source of N fertilizer was recorded as organic, inorganic, or integrated (i.e. both organic and inorganic N). Inorganic N rates were determined by summing individual preseason and within-season N applications. In a small number of cases where organic or inorganic N was applied to a previous cover crop or crop other than the no-till vs. conventional tillage yield comparison, these N sources were not included. If a range of N rates was reported in a study across sites, crops, or years, values were only included in the database if exact N rates were provided or if the range of values was smaller than 15 kg N ha^{-1} in which case the average N rate was used. When a range of N rates were applied in sub-plot N trials, but only the main effects of tillage were presented, N rates for those observations were not entered into the database. When analyzing the overall effects of N source and inorganic N rate across crops, legumes were not included.

[1] Despite an increasing focus on no-till globally, it needs to be acknowledged that the term 'no-till' is not always used consistently. In order to appropriately define the context for this study, a brief discussion of no-till terminology has been supplied as Supplementary Material. In addition, a discussion of specific study considerations and limitations is provided in Section 4.4. Our analysis aimed to quantify the effects of no-till rather than systems-level modifications to a cropping system as outlined by Derpsch et al. (2014).

2.2. Overview of the database

Data used in the meta-analysis are summarized in Table 1. In total, the overall crop category included 678 studies and 6005 observations following removal of outliers, representing 50 crops and 63 countries. Due to the large number of input variable combinations analyzed, figures with more than two levels of sub-categorization are provided as Supplementary Material (Supplementary Figs. 7–9). The number of observations in each crop category followed the order of wheat (29%), maize (27%), and legumes (18%), while the categories of rice, miscellaneous (mostly horticultural), and root crops had relatively few observations (Table 1). The dataset was dominated by studies from North America, followed by Asia and then Europe, while South America, Africa, and Australia and New Zealand contributed the least number of observations (Supplementary Fig. 10).

2.3. Data analysis

A meta-analysis was performed following the procedures reported in Pittelkow et al. (2015). To quantify impacts of each input variable in relation to each other, we applied nonparametric recursive partitioning techniques to the dataset using the “party” package in R (Hothorn et al., 2006; Strobl et al., 2009). Recently, machine learning recursive partitioning techniques are increasingly used in agronomic and ecological studies because they do not rely on parametric assumptions, they can handle missing data, and they are designed to detect interactions and nonlinear patterns in complex datasets with many predictor variables (Philibert et al., 2012; Strobl et al., 2009). Using these procedures, conditional inference trees can be created in a two-step recursive process where response variables are first partitioned into groups containing similar values and, secondly, the input variable with the strongest association to the response (as measured by a p-value based on permutation tests) is selected and a binary split is implemented. Importantly, conditional inference trees are unbiased (i.e. do not favor continuous input variables with many possible splits) and do not overfit the data (Hothorn et al., 2006).

Random forest procedures represent an ensemble of trees and results are considered to be more robust and stable than individual decision trees (Strobl et al., 2009). Hence, unbiased variable importance rankings were determined using the conditional random forest (cforest) function (Hothorn et al., 2006). To maintain consistency with the meta-analysis subcategories, the dataset was restricted to observations with duration and N fertilizer addition (zero or inorganic N fertilizer addition) information available. Overall, maize, wheat, miscellaneous cereals, legumes, and oilseed and cotton crop categories contained 4347, 1208, 1372, 542, 680, and 338 observations, respectively. Variable importance was determined as the percentage increase in mean square error (MSE) following random permutation of input variables (with increasing MSE representing a decrease in accuracy). To normalize across crop groups, relative variable importance was determined by setting the variable with the highest importance to 1 and calculating individual values as a percentage of the most important variable.

As recommended by Philibert et al. (2013), the potential for publication bias was investigated and sensitivity analyses were conducted to examine how individual observations influenced weighted mean effect sizes. Because sampling variances were not available for individual observations, funnel plots were created for each crop category using approximated standard errors using the “metafor” package in R (Viechtbauer, 2010). Standard deviation values between 10% and 20% of the sample mean were randomly assigned to individual observations and estimated sampling variances were calculated following Hedges et al. (1999). Regression tests for data asymmetries in funnel plots revealed no significant

Table 1
Summary of data used in the meta-analysis.[a] Values for no-till yield, conventional tillage yield, duration, inorganic N rate, and aridity index are presented as weighted mean ± weighted standard deviation.

Category	Observations	Studies	Crops	Countries	Temperate obs.	Subtropical obs.	Tropical obs.	No-till yield ($kg\,ha^{-1}$)	Conv. tillage yield ($kg\,ha^{-1}$)	No-till duration (yrs)	Inorganic N rate ($kg\,N\,ha^{-1}$)	Aridity index
Overall	6005	678	50	63	4842	559	520	5323 ± 8462	5672+/9071	4.4 ± 5.2	100 ± 92	0.74 ± 0.33
Maize	1624	224	1	38	1337	65	203	7596 ± 5791	8074 ± 6125	5.4 ± 6.3	150 ± 113	0.83 ± 0.28
Wheat	1736	260	1	39	1384	268	66	3550 ± 1854	3655 ± 1865	4.2 ± 4.8	102 ± 68	0.59 ± 0.30
Misc. cereals	846	120	7	28	735	37	56	3471 ± 1973	3586 ± 1974	4.2 ± 3.8	79 ± 52	0.71 ± 0.33
Legumes	1063	166	12	28	867	101	69	2355 ± 1397	2345 ± 1488	5.7 ± 5.7	17 ± 35	0.79 ± 0.28
Oilseeds and cotton	447	74	8	18	427	18	1	2342 ± 4625	2325 ± 4370	4.9 ± 4.9	85 ± 70	0.70 ± 0.31
Rice	154	31	1	9	32	65	57	5286 ± 2670	5529 ± 2597	2.3 ± 1.8	119 ± 54	0.94 ± 0.37
Misc.	50	17	10	9	44	0	6	29,100 ± 35,026	33,614 ± 37,611	2.0 ± 1.6	147 ± 98	0.80 ± 0.39
Root crops	69	19	7	5	6	0	63	15,676 ± 17,694	18,255 ± 17,608	1.7 ± 1.1	47 ± 65	1.05 ± 0.39

[a] Sugarcane, ryegrass, and canary seed (representing only 12, 4, and 1 observation(s), respectively) were included in the overall crop category only.

evidence of publication bias (Supplementary Figs. 1–6). Sensitivity analyses were conducted using the jackknife procedure in the "boot" package (Canty and Ripley, 2014). With this procedure, centered bootstrap values for the 0.05, 0.5, and 0.95 quantiles are depicted as hatched horizontal lines and the effects of omitting individual observations from bootstrap calculations are displayed as changes in the distribution of the quantiles. Standardized jackknife values are on the x-axis, with larger values indicating a particular observation more strongly influences the bootstrapped mean. Individual observations are labeled at the bottom of each figure. As would be expected given the large size of the database, there was little influence of individual observations on the weighted mean effect size within each crop category, suggesting the bootstrapped estimates are relatively insensitive to the inclusion of specific data points (Supplementary Figs. 1–6). In a few instances, omission of individual observations shifted the 0.5 and 0.95 quantiles by several percent but this did not alter the conclusions of the study.

3. Results

3.1. Yield impacts by crop, region, and variable importance

Across all observations (all crop categories and locations), no-till reduced yields by 5.1% (Fig. 1). Yields were not reduced for oilseeds and cotton or legume crop categories, but yields significantly declined by 20.4 and 21.4% for miscellaneous and root crop categories, respectively. Yields for cereals were moderately impacted by no-till practices (−5.0%). The negative impacts of no-till for cereals were smallest for wheat (−2.6%) and miscellaneous cereals (−3.0%) and largest for rice (−7.5%) and maize (−7.6%) (Fig. 2).

When results were analyzed by latitude, no-till reduced yields the most in tropical latitudes (−15.1%) and the least in temperate latitudes (−3.4%) (Fig. 3). Crop group was the most important factor influencing the overall yield response to no-till, followed by aridity index, residue management, duration, and N rate (Fig. 4a). Duration, residue management, and aridity were the three most important variables for maize (Fig. 4b), whereas aridity, irrigation, and N rate stood out as the most important three variables for wheat (Fig. 4c). For miscellaneous cereals (Fig. 4d), the presence of crop rotation, duration, and aridity were most influential. For legumes, N rate and aridity had the largest impact (Fig. 4e), whereas aridity and irrigation stood out as the most important factors for oilseeds and cotton (Fig. 4f).

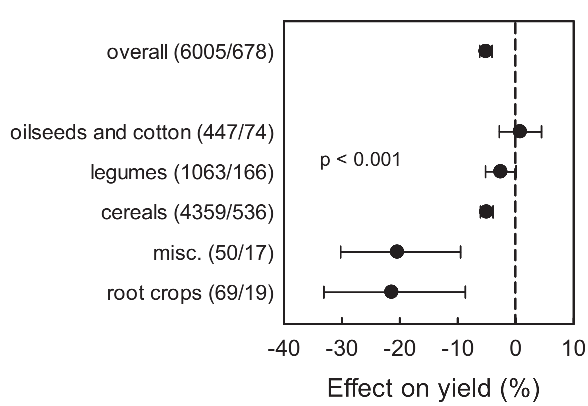

Fig. 1. Yield impacts of no-till relative to conventional tillage for different crop categories. The misc. category included broccoli, coffee, cucumber, lettuce, mustard leaf, pepper, squash, tobacco, tomato, and watermelon. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by crop category are indicated by p-values based on randomization tests.

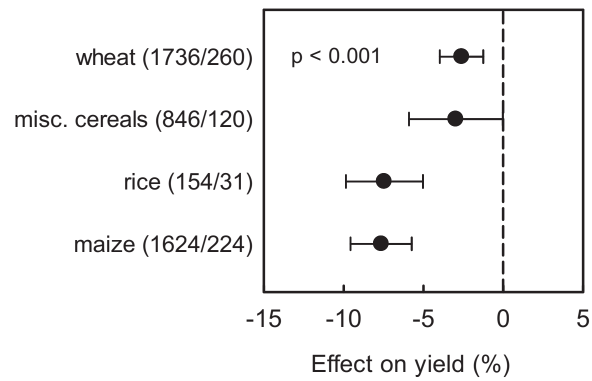

Fig. 2. Yield impacts of no-till relative to conventional tillage for different cereal crop categories. Misc. cereals include barley, millet, oat, rye, sorghum, tef, and triticale. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by grain crop category are indicated by p-values based on randomization tests.

3.2. Impacts of aridity, irrigation, and no-till duration

No-till performed best under rainfed conditions in dry climates, matching conventional tillage yields overall (Fig. 5a) and matching or exceeding conventional tillage yields for each crop category (Fig. 5b–f). However, for the other three combinations of water management practices and climate (i.e. irrigated and dry, rainfed and humid, and irrigated and humid), consistent yield declines were observed for each crop category except for oilseeds and cotton, irrigated legumes in humid climates, irrigated miscellaneous cereals in dry climates, and rainfed miscellaneous cereals in humid climates.

Yield responses in the first 1–2 years following no-till implementation were negative for all crop categories except oilseeds and cotton (Fig. 6). In all cases except maize, the negative effects of no-till, where present, decreased with time (Fig. 6b–f). No-till yields started to match conventional tillage yields after 3–4 years for miscellaneous cereals and legumes and 5–10 years for other crops. Although there was a trend of increasing yield response over time for a number of crop categories, no-till yields did not exceed conventional tillage yields for any crop in any experiment duration category. Results for no-till duration depended on climate, with negative yield effects in early years generally being more consistent across crop categories in humid climates while only the maize crop category showed significant yield declines in early years in

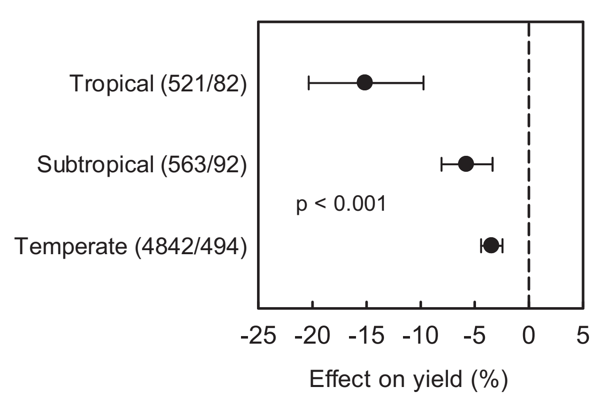

Fig. 3. Yield impacts of no-till relative to conventional tillage in tropical, subtropical, and temperate latitudes. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by latitude categories are indicated by p-values based on randomization tests.

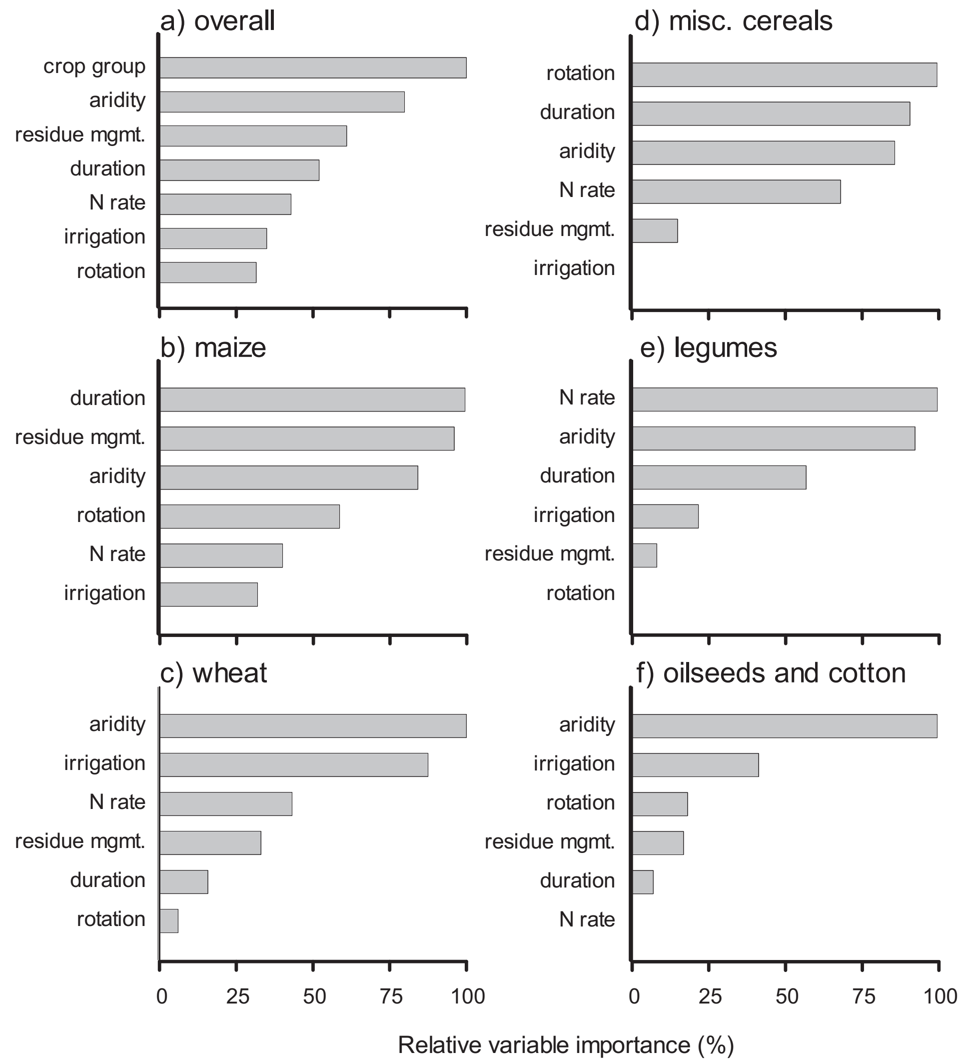

Fig. 4. Relative variable importance ranking for the yield impacts of no-till relative to conventional tillage for different crop categories based on conditional random forests. Continuous variables in the analysis included aridity index, duration of no-till practices, and N rate (kg N ha^{-1}). Categorical variables included rotation (yes/no), residue management (retained/removed), and irrigation (yes/no). Misc. cereals include barley, millet, oat, rye, sorghum, tef, and triticale.

dry climates (Supplementary Fig. 7). In contrast, yield reductions for the wheat and legume crop categories were more pronounced in early years in humid climates and yields generally took longer to match conventional tillage yields. The overall crop category showed significant yield declines in early years, regardless of climate.

3.3. *Impacts of N fertilizer, residue management, and rotation*

Across all observations, yields under no-till were reduced by 12% without N fertilizer addition and 4% with inorganic N fertilizer addition (Fig. 7). Although relatively few studies assessed organic N sources, the results suggest that large yields declines (−20%) are possible with large variability. Yield reductions under no-till were smallest (−4%) at inorganic N rates between 80 and 120 kg N ha^{-1} (Fig. 8a). Moderate to high N inputs did not significantly reduce the negative effects of no-till compared to zero N inputs for any crop category, although this trend was present for maize and wheat (Fig. 8b–f). Yields for legumes under no-till were similar to conventional tillage without N addition or at low N rates, but decreased at N rates >15 kg N ha^{-1}. In general, the response to N rate for each crop category differed depending on climate (Supplementary Fig. 8). In dry climates, yield declines without N addition or at low N rates were either not present or were much smaller compared to data pooled across climates. In humid climates, yield reductions were more severe with a 22% yield reduction occurring in the overall crop category without N addition.

The negative impacts of no-till decreased when crop rotation and residue retention practices were implemented for the overall category (Fig. 9a). Yet, this relationship varied for individual crop categories (Fig. 9b–f). For example, when crop rotations were not implemented, residue removal led to significantly stronger yield reductions for maize but not wheat or miscellaneous cereals compared to when residues were retained. Regardless of crop category, positive responses to residue retention and crop rotation (i.e. a reduction in yield decline with no-till) were observed only in dry climates (Supplementary Fig. 9). In contrast, yield declines remained similar regardless of these practices in humid climates.

4. Discussion

4.1. *Impacts by crop and region*

Yield responses varied widely depending on crop category (Fig. 1). For the oilseeds and cotton and legume crop categories, we observed no negative impact of no-till on yields. Toliver et al. (2012) and Ogle et al. (2012) found similar results in their quantitative

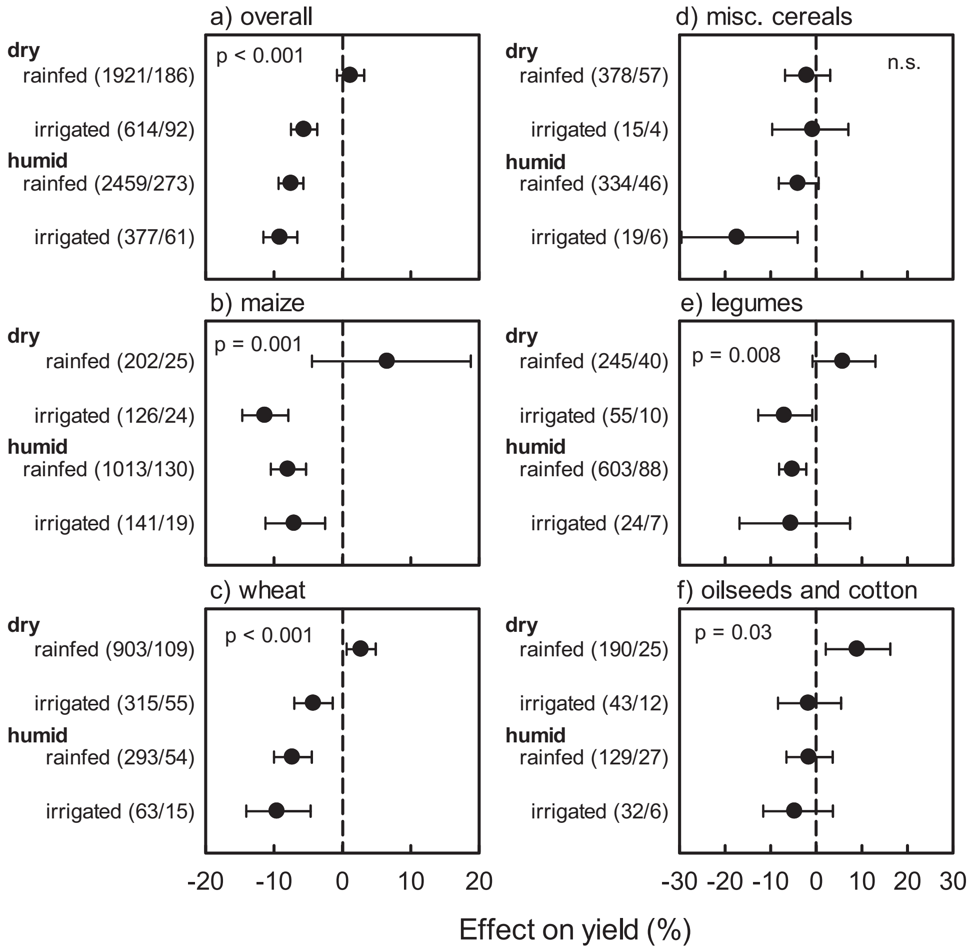

Fig. 5. The influence of climate and irrigation on the yield impacts of no-till relative to conventional tillage for different crop categories. Misc. cereals include barley, millet, oat, rye, sorghum, tef, and triticale. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by climate and irrigation are indicated by *p*-values based on randomization tests. n.s. = non-significant.

analyses of soybean yields in the USA. Alvarez and Steinbach (2009) also reported no differences in yield in their review of soybean production in the Argentine Pampas. Although fewer analyses have been performed for oilseeds and cotton crops, our results are in agreement with the findings of Ogle et al. (2012) and Toliver et al. (2012) who concluded that mean yields remained similar for cotton produced under no-till relative to conventional tillage practices in the USA. The fact that yields are maintained under no-till for legumes, oilseeds, and cotton is an important finding given the prominence of these crops globally.

Large yield declines for miscellaneous (primarily horticultural) and root crop categories suggest that these crops are more susceptible to losses in productivity due to no-till than other crop categories. Surface soil compaction can increase with no-till, which may inhibit root growth as well as prevent adequate drainage and soil aeration which can reduce root crops yields under no-till compared to conventional tillage practices (Howeler et al., 1993). Across the world, it is likely that little no-till production of these crops occurs. To avoid large yield reductions, our results suggest that conventional or reduced tillage practices may be more applicable for root and horticultural crops.

Importantly, as the most extensive no-till adoption has occurred in countries focusing on grain crop production (Derpsch et al., 2010), our results show that yields for wheat along with the miscellaneous cereal category were only moderately impacted (−3%). Similar findings have been reported in several review studies where yield declines for these crops, if observed, were relatively minor, and at times, higher yields were achieved (Buschiazzo et al., 1998; Rasmussen, 1999; Van den Putte et al., 2012). In some long-term experiments, it has also been observed that average wheat yields under no-till relative to conventional tillage in Mediterranean climates tended to be higher in years when water stress occurred but lower in years when there was little water stress (Amato et al., 2014). When assessing no-till practices in the USA, Toliver et al. (2012) determined that wheat yields significantly increased compared to conventional tillage. Yield gains with no-till for wheat are likely because this crop is often grown in semi-arid regions (Table 1) where no-till practices tend to perform better due to the effects of water conservation and increased water use efficiency as discussed below.

Compared to the other cereals, maize and rice were the most negatively impacted by no-till practices. In many areas in South and Southeast Asia, rice is grown under puddled conditions, which typically entails intensive tillage operations to help maintain flooded conditions during the growing season. No-till in rice systems represents a large shift in management and yield declines following no-till implementation have frequently been reported (e.g. Gathala et al., 2011; Singh et al., 2011). In a longer-term study, Jat et al. (2014b) found that no-till plus residue retention initially resulted in lower yields compared to conventional tillage with residue removed in a rice-wheat rotation in India. However, after 4–5 years yields were equivalent, and after 6 years yields were higher in the

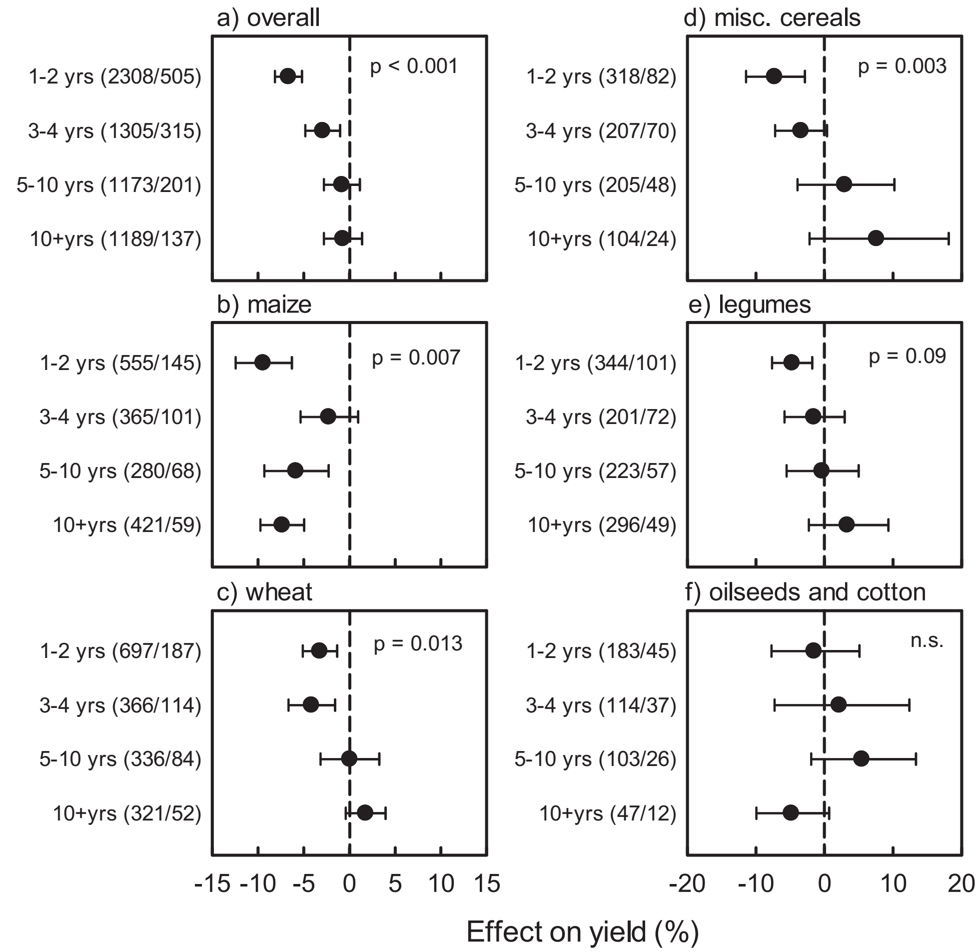

Fig. 6. The influence of no-till duration on the yield impacts of no-till relative to conventional tillage for different crop categories. Misc. cereals include barley, millet, oat, rye, sorghum, tef, and triticale. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by no-till duration are indicated by *p*-values based on randomization tests. n.s. = non-significant.

no-till system. Our results may partially be explained by the fact that there were a relatively small number of rice observations in our database and most studies were short-term in length (Table 1).

Previous reviews on the yield impacts of no-till have also concluded that maize yields decrease more than other crops, particularly in cooler climates and/or areas with high precipitation (Van den Putte et al., 2012; Toliver et al., 2012; Rusinamhodzi et al., 2011; Ogle et al., 2012). Yield declines for maize under

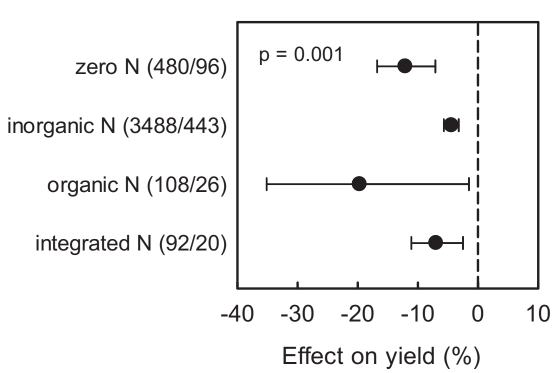

Fig. 7. The influence of inorganic, organic, or integrated N addition on the yield impacts of no-till relative to conventional tillage. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by N source are indicated by *p*-values based on randomization tests.

no-till have been attributed to waterlogging and poor crop establishment (Halvorson et al., 2006; Iragavarapu and Randall, 1995), restricted root growth due to compaction (Cid et al., 2014) and nutrient deficiencies (Rusinamhodzi et al., 2011; Ogle et al., 2012). Derpsch et al. (2014) also argue that a certain level of experience is needed to establish no-till crops properly and that poor crop establishment can arise from both biophysical factors as well as a lack of knowledge by researchers on appropriate equipment, soil conditions, seeding techniques, etc. Our findings reinforce previous quantitative assessments primarily focusing on maize (Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014; Rusinamhodzi et al., 2011), but at a global scale.

Considering that a number of current international efforts focused on improving cropping system sustainability and profitability target no-till practices for maize, our results highlight the need for strategies to achieve at least similar and preferably greater maize yields with no-till. One strategy is to comprehensively adjust crop management practices at a systems-level so that multiple aspects of the no-till system are optimized to improve productivity and environmental outcomes rather than simply switching from conventional tillage to no-till in isolation. There is growing evidence that no-till needs to be managed differently in order to optimize yields (e.g. modifications to N management and/or planting earlier). However, large-scale analyses are hindered at present by the limited number of publications that have investigated no-till effects using an optimized systems approach (Derpsch et al., 2014).

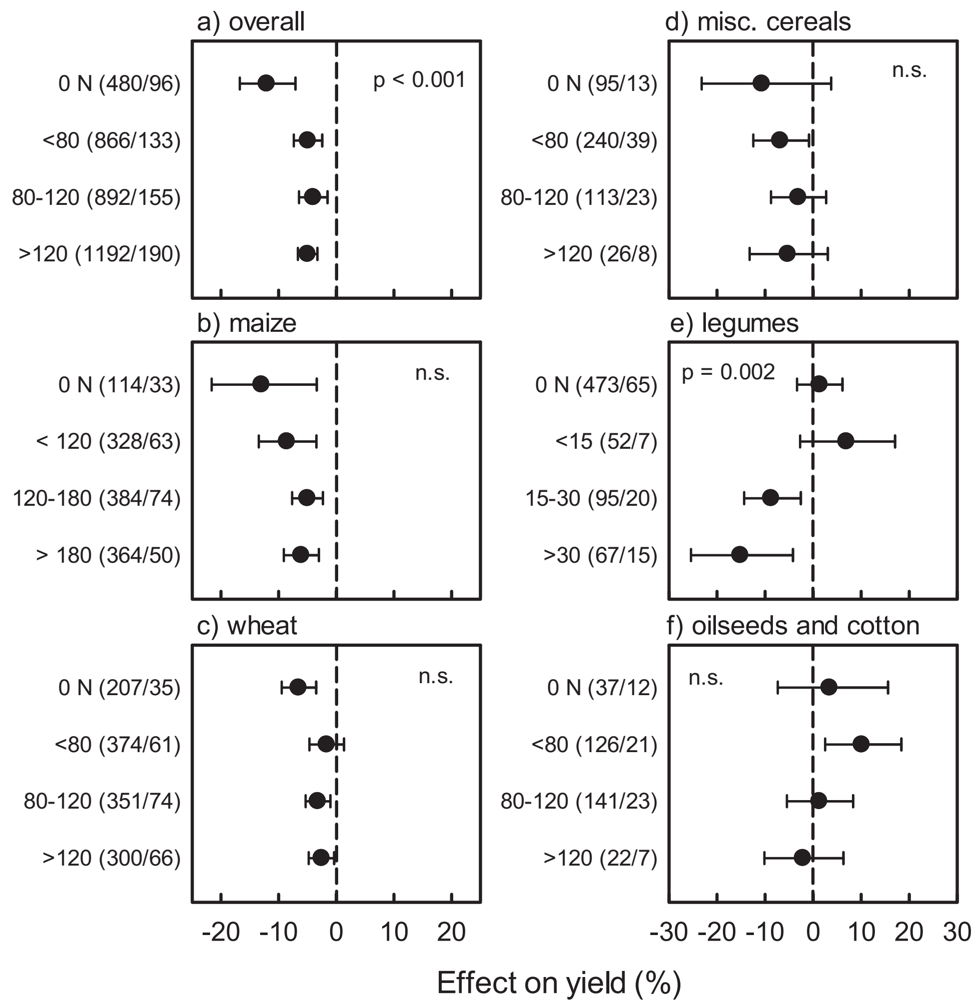

Fig. 8. The influence of inorganic N fertilize rate (kg N ha^{-1}) on the yield impacts of no-till relative to conventional tillage for different crop categories. Misc. cereals include barley, millet, oat, rye, sorghum, tef, and triticale. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by N rate are indicated by *p*-values based on randomization tests. n.s. = non-significant.

When analyzing the effects of no-till by latitude, two conclusions can be drawn. First, barriers limiting the productivity of no-till systems appear to be greatest and/or hardest to overcome in the tropics, as yields were most negatively impacted in these regions. These results are concerning because no-till practices form an important part of many agricultural development strategies to improve the productivity of smallholder cropping systems in the tropics, with a number of programs focused specifically on maize and wheat (Erenstein et al., 2012). Second, compared to the large amount of research that has occurred in temperate climates, fewer studies have been conducted in the tropics and subtropics which may be hampering the development of improved no-till cropping systems adapted to local conditions and needs.

The unequal distribution of studies as well as the significant yield declines observed in tropical regions strengthen the conclusions of recent reports evaluating the impacts and applicability of no-till globally: more targeted research and extension efforts are needed to develop locally based systems and solutions for raising productivity (Giller et al., 2009; Brouder and Gomez-Macpherson, 2014; Rosenstock et al., 2014; Rusinamhodzi et al., 2011). Moreover, to prevent smallholder farmers from experiencing the negative impacts of yield losses, which may lead to a general avoidance of no-till and other sustainable crop management practices, it is advisable that current efforts to promote no-till ensure that these risks are adequately addressed. Adopting no-till alone may not produce the expected cropping systems benefits, hence simultaneous crop management changes, such as fertilization and integrated pest management, are often required to address these risks and optimize no-till yields.

4.2. *Influence of environmental and crop management factors*

Our results show that in general, no-till performs best relative to conventional tillage under water-limited conditions, supporting the common claim that one of the primary benefits of no-till practices is enhanced water use efficiency when residues are retained (Hobbs et al., 2008; Serraj and Siddique, 2012; Farooq et al., 2011; Rusinamhodzi et al., 2011; Pittelkow et al., 2015). According to the variable importance ranking, aridity index was the most important factor influencing the overall yield response to no-till following crop group (Fig. 4). Approximately 45% of our dataset represented dry climates and yields for each crop category were either similar to conventional tillage or increased (wheat and oilseeds and cotton) under rainfed conditions in dry climates (Fig. 5). These findings have important global development implications, as dry climates cover more than 40% of the world's land area and support more than 35% of the global population, primarily in developing countries in Asia and Africa (UN Environment Management Group, 2011). For irrigated studies in humid climates where water was (presumably) non-limiting, no-till yields tended to decline relative

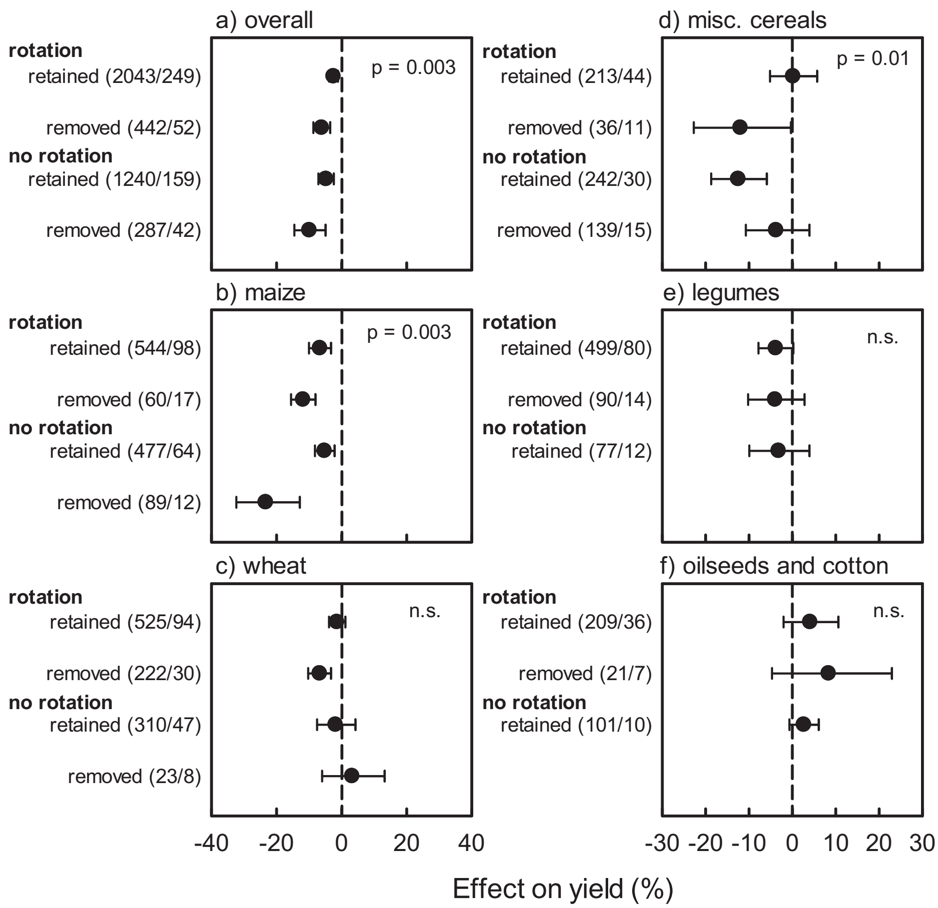

Fig. 9. The influence of crop rotation and residue management practices on the yield impacts of no-till relative to conventional tillage for different crop categories. Misc. cereals include barley, millet, oat, rye, sorghum, tef, and triticale. The number of observations and total number of studies included in each category are displayed in parentheses. Error bars represent 95% confidence intervals. Significant differences by crop rotation and residue management are indicated by *p*-values based on randomization tests. Note, several categories did not contain sufficient observations and were excluded from further analyses. n.s. = non-significant.

to conventional tillage yields, yet this was not observed for legumes and oilseeds and cotton crop categories. Based on these results we hypothesize that these crops are less susceptible to other potential yield limiting factors associated with no-till including increased fertility requirements, soil compaction, among other factors.

The importance of residue retention and crop rotation practices in minimizing no-till yield declines in the context of CA has been quantified previously (Pittelkow et al., 2015; Rusinamhodzi et al., 2011). It should be noted that for many crop categories in our analysis, there were relatively few observations from experiments where residues were removed. It has been argued that soil surface cover by residues is an essential part of the definition of no-till because residues help prevent erosion and increase water use efficiency – some of the main benefits of no-till systems – meaning that, in principle, residue retention and no-till cannot be separated (Derpsch et al., 2014). Consistent with Corbeels et al. (2014) and Rusinamhodzi et al. (2011), our results show that residue retention along with crop rotation are particularly important practices for overall, maize, and miscellaneous cereal categories in dry climates where no-till yields matched or exceeded conventional tillage yields when these practices were employed (Supplementary Fig. 9). In contrast, in humid climates no-till yield declines were prevalent across categories, regardless of residue retention and crop rotation practices. Despite the importance of residue retention in dry climates, residues are not always retained in no-till systems (Erenstein et al., 2012; Giller et al., 2009), which likely represents a major barrier to successful no-till implementation.

No-till duration was identified as the fourth most influential variable overall, with a lag period of several years occurring before no-till yields matched conventional tillage yields (Fig. 6a). Following the transition from conventional tillage to no-till, yield reductions in early years are often attributed to soils taking time to stabilize and beneficial soil properties such as increases in soil C, aggregate stability, and available water capacity taking time to develop (Kumar et al., 2012; Six et al., 2002; Lal, 1997). In addition, although it is not always acknowledged in individual studies, no-till often requires a number of changes to a system and initial yield reductions may result from sub-optimal management by farmers or researchers (Derpsch et al., 2014). It should also be considered that the length of an experiment does not always translate into improved management, as equipment operators and researchers may change during the course of an experiment and sub-optimal management may reoccur. Despite this possibility, no-till yields for all crop categories were similar to conventional tillage yields after 5+ years, with the exception of maize for which yields generally did not improve with time. Similarly, Toliver et al. (2012) found that no-till maize yields significantly decreased with respect to conventional tillage yields over time in the USA.

When considering the long-term impacts of no-till, we anticipated that yields would increase relative to conventional tillage in the 10+ year category as indicated elsewhere (Dick et al., 1991; Sa et al., 2014). However, significant yield differences were not observed for any crop after 10+ years, despite trends in yield improvements for wheat, miscellaneous cereals, and legume crop categories. Importantly, both short and long-term yield responses differed by climate. None of the crop categories (with the exception of maize) experienced yield declines in initial years in dry climates. In contrast, most of the initial yield declines for each crop category occurred in humid climates. In dry climates, water is likely the primary limitation to crop growth (e.g. wheat and miscellaneous cereals in arid climates). Thus, it can be expected that the longer that no-till is in place, the more positive its effects will be, assuming a positive feedback cycle develops where greater soil moisture conservation increases biomass production, in turn increasing residue cover and improving soil quality over the long-term. However, in humid climates water is likely less of a primary limitation to growth and other factors such as weeds, pests, or disease become a proportionately larger contributor to yield declines. A longer no-till duration may not result in yield benefits as these constraints will likely be exacerbated over time (e.g. maize in humid climates).

Nitrogen fertilizer rate was the fifth most important variable influencing overall yields (Fig. 4a). Utilizing yield responses from our database, the issue of N rate is discussed elsewhere (Lundy et al., 2015), but in general our results support the concept that sufficient N additions are a critical strategy for reducing no-till yield declines (Corbeels et al., 2014; Rusinamhodzi et al., 2011; Vanlauwe et al., 2014). In terms of N fertilizer source, inorganic N additions resulted in yields closest to conventional tillage, although confidence intervals overlapped for inorganic, organic, or integrated N sources (Fig. 7). The large variability in yield response with organic N fertilizers suggests that when placed on the soil surface in no-till systems, organic N may either remain unavailable or it is more susceptible to losses as compared to incorporation with conventional tillage. In addition, the large variability in yield response to organic N may also be caused by the differences in the quality of the applied organic N. As combining organic and inorganic N sources is thought to be a more balanced approach to meeting N fertility needs (Palm et al., 1997; Vanlauwe et al., 2010), additional work is needed to further decrease the observed yield reductions with integrated N management in no-till systems.

Our analysis shows that the response to inorganic N rate depends on crop category and climate (Fig. 8, Supplementary Fig. 8). In semi-arid climates, where water is likely a more limiting factor to crop growth than soil N availability for both no-till and conventional tillage systems, there is no negative yield impact of zero N addition with the exception of wheat. On the contrary, in humid climates yield reductions are much more severe without N addition in initial years following no-till implementation, indicating that application of sufficient inorganic N fertilizer is an important factor in minimizing yield penalties associated with no-till practices. As discussed elsewhere (Vanlauwe et al., 2014; Sommer et al., 2014), N fertilizer is an important practice to be incorporated with no-till systems, but its role is likely more pronounced when water is not the most limiting factor to crop growth. Although not considered in our analysis, the timing and placement of N fertilizer also likely need to be adjusted in order to optimize N management in no-till systems by placing N below residues to overcome N immobilization issues (Derpsch et al., 2014).

4.3. Global yield response

Across the globe, no-till is being promoted in agroecosystems to reduce erosion, sequester additional soil C, and reduce production costs. Our meta-analysis shows that, when averaged across all observations, the implementation of no-till leads to a significant decrease in yield (5.1%). This global average yield decrease under no-till practices does not account for obvious differences in climate, soils, and crop management practices occurring throughout the world and should not be interpreted as a predictor of yield outcomes at the field-scale. We recognize that no-till has been successfully implemented in various crop production regions (e.g. Llewellyn et al., 2012; Scopel et al., 2013) and has allowed the expansion of agriculture in places which could not support conventional tillage practices due to the high potential for water or wind induced soil erosion. Moreover, the average yield decrease reported here refers to the effects of no-till in the absence of other crop management modifications relative to conventional tillage, which limits our interpretation of the results.

A reductionist approach was employed in this study to isolate the effects of a single management practice (no-till) rather than evaluating the effects of a fully optimized system. This decision was based on several important factors. An initial step in all quantitative reviews is to develop a set of standardized and transparent literature search procedures and formulate criteria with which studies are evaluated against for inclusion in the database. These criteria need to be as objective as possible to ensure that the literature search and study selection process are repeatable and unbiased. Moreover, these criteria need to be consistent with the objectives of the study. In order to meet our objectives and draw conclusions about the effects of no-till, we required that no-till represented the only change to a cropping system aside from herbicide management as detailed in Pittelkow et al. (2015).

If one were to decide to evaluate the effects of an optimized no-till system with a number of additional changes in management, a high degree of subjectivity would be required to establish search criteria (e.g. what specific practices constitute an optimal as compared to sub-optimal system?). Moreover, conclusions would be limited to interpreting the effects of system-level changes in crop management that might include no-till as only one factor of possibly many. Importantly, a number of management practices associated with optimized no-till systems may contribute to increased yields regardless of the implementation of no-till (e.g. additional N inputs). Hence, changes in yield in systems-level studies could not be attributed to no-till itself. While we encourage others to carry out additional analyses consistent with their objectives, we would argue that any such studies should explicitly discuss the implications and resulting limitations of their approach.

We also recognize that our analysis did not account for the fact that no-till may represent a more profitable management system due to the potential for reduced costs such as fuel savings. No-till is commonly adopted to help achieve other agronomic and environmental goals, aside from increased yields, in a larger cropping systems context. For example, no-till can reduce erosion, which is important for sustaining long-term crop productivity (Verhulst et al., 2010). Additionally, in some areas, the possibility of earlier planting with no-till due to lower time requirements for land preparation and tillage prior to seeding may raise yield potential within a season (e.g. rice-wheat systems in India (Hobbs et al., 2008)) or allow for two crops to be produced within a year instead of one (e.g. areas of Brazil (Calegari et al., 2014)).

Nonetheless, the yield declines reported here on a global scale call into question whether no-till represents as promising a practice to significantly increase or double food production as suggested by some international agricultural organizations. For example, no-till serves as the basis for FAO's sustainable crop production intensification strategy when practiced as a CA package (i.e. combined with residue cover and crop rotation practices) (FAO, 2011). Other international organizations predict that no-till practices have the potential to increase global maize and wheat production levels by approximately 30% by 2050 (Rosegrant et al., 2014). In general, international agricultural organizations researching or promoting no-till are not recommending that farmers simply switch to no-till without also modifying other additional system-level management factors. Indeed, yield increases may be possible if no-till is implemented as part of a comprehensive systems approach where fertilizer rate and placement, planting depth, planting date, etc. are all optimized (Derpsch et al., 2014).

However, to the best of our knowledge the extent to which no-till is implemented globally by farmers as the absence of tillage vs. an optimized no-till systems approach remains unknown. Systematic changes to a cropping system are not easily implemented, as noted by a number of assessments on CA showing that the principles of crop rotation and residue management are not always adopted alongside no-till (Erenstein et al., 2012; Giller et al., 2009). That the adoption of two additional CA principles has proven to be a challenge casts doubt on whether the list of specific (and often equipment-related) factors proposed by Derpsch et al. (2014) is routinely implemented as part of a standard no-till package under real-world farming conditions. As such, our results remain relevant to global agricultural development.

To meet the anticipated increases in global food demand, it is likely that many technologies and approaches will be necessary depending on the specific requirements and limitations of individual cropping systems and agricultural contexts. Considering our results, a more balanced approach to no-till might consist of promoting it in contexts where yields match or exceed conventional tillage practices at present, while continuing to focus research efforts in areas where yield declines are prevalent. In theory, this would allow no-till practices to be better tailored to meet local conditions and needs from an economic, social, and biophysical standpoint (Giller et al., 2009; Richards et al., 2014; Rosenstock et al., 2014).

4.4. Limitations

There are several limitations of this meta-analysis that should be considered. Despite no-till often being practiced on sloping lands, agronomic experiments are typically placed on level sections of a field where there is minimal variability in factors affecting crop growth. With this type of experimental design, conventional tillage treatments may not always be subject to the same level of soil degradation (e.g. soil erosion, nutrient mining, etc.) that occurs under real world conditions. Over the long-term, yields of no-till may therefore be more likely to be maintained or increased under real world conditions relative to conventional tillage, depending on how degraded conventional soils become. On a related note, the majority of experiments in this analysis were conducted at agricultural experiment stations rather than under on-farm conditions. Research stations are often situated on better soils and this may have resulted in a smaller yield response to no-till in some experiments. Similarly, more timely and optimal crop management is often possible in research station experiments, thus our results may not always extend to sub-optimal conditions.

Meta-analyses are also inherently limited by data availability. Although factors not considered here may influence the yield response to no-till, our study was limited by the information reported in original studies. For example, the majority of studies did not contain soil texture data, particularly those studies conducted in countries outside of North America and Europe. We chose to not extract soil type information from the studies in which it was reported as this would represent a biased subset of the database that did not fit within our global objectives. Similarly, cumulative precipitation values for each growing season, and particularly the distribution of precipitation within a growing season, were not reported in the majority of individual studies. As a result, aridity index values were assigned to locations to assess the impacts of climate on no-till yield responses. We acknowledge that aridity index represents an average of annual precipitation values and does not capture inter-annual precipitation variability. Moreover, within an individual year in climates that are categorized as humid on an annual basis, crops could also be produced under dry conditions in the dry season. Assuming that no-till yield increases might occur under dry conditions in the dry season of humid climates – similar to the dry climate category as reported above – results from this study for humid climates are likely on the conservative side (i.e. actual yield responses in humid climates would likely be more negative than currently reported).

As above, whether an experiment was conducted on a level field may influence the results, but individual studies often did not report slope and it was therefore not possible to quantify the effects of slope. Even for several critical factors that we considered in our analysis, such as N rate and residue management practices, sufficient experimental details were not provided in many studies which prevented extraction of this information. Therefore, we support the conclusions of Derpsch et al. (2014) and Brouder and Gomez-Macpherson (2014) that a minimum dataset of experimental details, crop management practices, and study site conditions should be required for all published studies to better support systematic and standardized reviews and analyses and help prioritize no-till research needs.

Finally, there was a strong geographical bias in the dataset that likely has implications for the results of this analysis. North America, Asia, Africa, and Europe were overrepresented in the database, accounting for 47, 9, 23, and 13% of studies. However, according to FAO estimates (2014), these continents only account for 36, <1, 3, and 4% of global land under CA, respectively (note, we only use land under CA as a proxy here to reflect the global distribution of no-till practices, recognizing that the total amount of land dedicated to CA is likely less than that dedicated to no-till production globally). Conversely, South America and Australia and New Zealand, which account for 43 and 12% of global CA area (FAO, 2014), were under-represented in the database, each contributing 4% of the studies. In order to inform future decisions regarding the performance and applicability of no-till in different contexts, it is advisable that field research is undertaken in under-represented areas to minimize data biases.

5. Conclusions

This global meta-analysis allowed us to evaluate a range of agronomic and environmental factors affecting no-till yields. Whereas no-till is being widely promoted around the world, our results show that no-till performance is highly context dependent. Therefore, site- and region-specific targeting is necessary and the promotion of no-till in regions with large food security challenges and relatively poor farmers that are risk averse, such as Sub-Saharan Africa, should not be taken lightly. No-till resulted in yield declines in tropical latitudes and when maize was grown, highlighting the need for increased no-till research and extension efforts before no-till is promoted broadly in these regions and/or for this crop. Our results also demonstrate that there are clearly some contexts in which no-till increases yields relative to conventional tillage systems; these are typically in arid regions – particularly where water is limiting to crop growth. Yields are only one of a suite of factors influencing the decision to practice no-till and must be weighed appropriately alongside economic and environmental considerations. This meta-analysis quantified the yield impacts of no-till based on available scientific evidence, providing a basis for conducting trade-off analyses to support the development and improvement of no-till crop management under various conditions across the globe.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2015.07.020

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