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RESEARCH ARTICLE

No tillage outperforms conventional tillage under arid conditions and following fertilization

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HIGHLIGHTS

- On average conventional tillage outperformed no tillage.
- Across fertilized trials, however, no tillage performed best.
- Aridity increases yield benefits of no tillage over conventional tillage.
- Fertile settings favor conventional tillage over no tillage.

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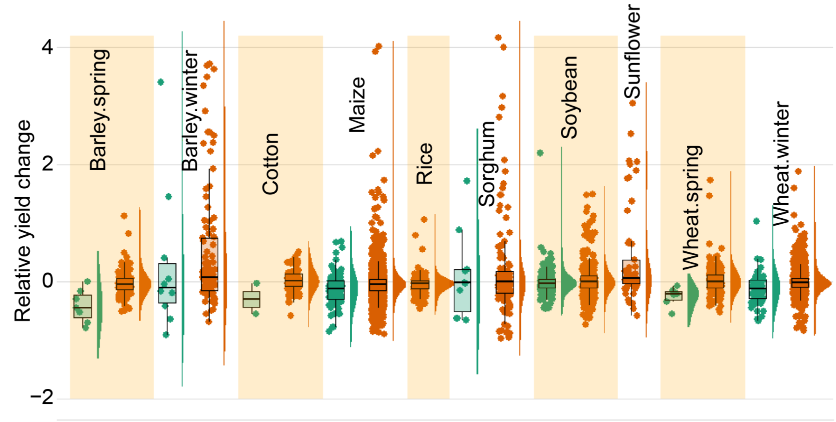
GRAPHICAL ABSTRACT



ABSTRACT

Reduced tillage practices present a tool that could sustainably intensify agriculture. The existing literature, however, lacks a consensus on how and when reduced tillage practices should get implemented. We reanalyzed here an extensive dataset comparing how regular tillage practices (i.e., conventional tillage) impacted yield of eight crops compared to stopping tillage altogether (i.e., no-tillage practice). We observed that aridity and fertilization favored no tillage over conventional tillage whereas conventional tillage performed better under high fertility settings. We further show that the responses are consistent across the crops. Our reanalysis complements the original and fills a gap in the literature questioning the conditions under which reducing tillage presents a viable alternative to common tillage practices.

1 Introduction

A major challenge that agriculture nowadays faces is to preserve the quality of soil while sustaining global produce (Montgomery et al., 2007; Tilman et al., 2014). A practice that aims at improving soil quality is lowering the frequency and intensity of tillage practices (Powlson et al., 2014). Reducing tillage, however, has apparent setbacks such as favoring the growth of unwanted weeds which can compromise crop yield (Lamour and Lotz, 2007). Practices that reduce or stop (i.e., no tillage) tillage have been introduced in agriculture relatively recently (Scopei et al., 2013; Tripplet Jr and Dick, 2008) and there is thereby no

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consensus on whether they are a viable alternative to conventional agricultural practices (e.g., Powlson et al., 2014; Dang et al., 2018). Much of our understanding comes from existing quantitative syntheses (i.e., meta-analyses) of field trials (e.g., Pittellkow et al., 2015; Peixoto et al., 2020; Shakoor et al., 2021). Stopping tillage (i.e., no tillage practice) can be less detrimental to crop yield under specific conditions such as relatively high aridity, fertilization with nitrogen and irrigated settings (Pittellkow et al., 2015). Simply reducing the intensity of tillage (conservational tillage; Adekalu and Okunade, 2006; Javadi et al., 2009) or using tillage less frequently (i.e., occasional tillage; e.g., Peixoto et al., 2020) could be more sustainable than stopping tillage all together. At the same time there are apparent benefits of reduced tillage in lowering soil erosion and promoting a more active microbial community in soil dominated by symbiotic microbes (Mathew et al., 2012; Schmidt et al., 2019; Zuber and Villamil, 2016). Because the magnitude of potential benefits and the exact environmental conditions that favor no tillage and conservational tillage practices over conventional tillage remain uncertain, there have been several calls for larger syntheses in the field (Scopei et al.,2013; Derpsch et al., 2014).

Recently Su et al. (2021a) compiled a large dataset of 413 studies which addressed the implications that conservational tillage and no-tillage practices have on crop yield compared to traditional tillage management practices. Those implications were captured in the dataset by the effect size of the trials per study describing the ratio of the yield difference (nominator) between no tillage and conventional tillage over (denominator) the yield under no tillage to which the authors referred to as a *relative yield change* (higher values manifest a better performance of no tillage over conventional tillage and *vice versa*). Su et al. (2021b) analyzed this dataset using machine learning techniques to gauge the relative importance of different environmental parameters in determining produce under those management regimes of no tillage and conservational tillage. Their analysis yielded as a take home message that conservational tillage outperforms no tillage (i.e., there was a below zero average relative yield importance), particularly when residues are retained and performs exceptional well at drier climatic conditions (Su et al., 2021b). While such findings can foster immense progress in the field we believe that we could provide complementary insights by re-analyzing the data with the help of linear models. As a rule of thump linear models tend to be more parsimonious that machine learning approaches and can reveal underlying mechanisms (e.g., Zhou et al., 2021), meaning that we can be confident about the sign of the generated coefficients. More specifically we wanted to explore the interaction of climatic conditions and fertilization management practices with the relative benefits or costs that using either no tillage or conventional tillage. We accepted the overall conclusion from Su et al. (2021b) that (at least in the specific dataset) conservational tillage on average outperforms no-tillage and formulated two hypotheses in relation to two specific conditions where no tillage practices might be preferable to conventional tillage. We specifically hypothesized that in agreement with Pittellkow et al. (2015) we would observe highest yield benefits of no tillage as compared to conventional (or forms of reduced tillage such as conservational) tillage in sites receiving a low precipitation (*Hypothesis One*). We additionally anticipated (i.e., based on Pittellkow et al., 2015) that fertilization increases the yield benefits of no-tillage compared to conventional tillage (*Hypothesis Two*).

2 Materials and methods

We carried out a re-analysis of the data from Su et al. (2021) using general linear models. For the purposes of our study we only used the entries which contained information on whether fertilization had been added or not (this was the case for 930 out of 1041 entries which meant the resolution that we subsequently lost in our analysis was little). The re-analysis was a two step procedure. First, we screened potentially collinear variables (i.e., multiple linear regression does not handle well collinearity) using a machine learning approach (i.e. Random Forests; Breiman, 2001). We preserved the *relative yield ratio* as a response variable (to maximize compatibility to the original studies) and used as predictors the parameters maximum temperature, aridity, yield and fertilization. We calculated aridity as the difference between the value 1 and the ratio between precipitation and evapotranspiration. We further truncated negative values (i.e., cases where precipitation exceeded evapotranspiration) to zero. An important consideration in our analyses is that relative yield change could scale differently with environmental parameters across different crops (but we also wanted to use productivity as a predictor which would not have been possible otherwise). We thus fitted the model separately for each crop and averaged relative importance (Output One in Supplementary material-Appendix One). Second, we used the subset of non-collinear variables that we found to have the highest relative importance in our preliminary (Random Forest) models to build our mixed effects linear model. Because fertilization and crop yield explain comparable fractions of variance but at the same time describe very different mechanisms, we included both of them in the linear model.

The mixed effects linear model that we used had *relative yield change* as a response variable, crop type as a random effects factor and the subset of non-colinear parameters as predictors. We engaged into a manual stepwise backwards selection procedure to simplify the structure of this model. Because the model violated the assumptions of homoscedasticity and normality, we log transformed yield and integrated variance structures which in this particular case was a *varExp* variance structure scaling with yield (Pinheiro and Bates, 2001). We refer to the final version of the model as *simplified model* (output TWO in Supplementary material-Appendix One). In a form of a sensitivity test we further refitted the *simplified model* into observations irrespective of whether they contained information on fertilization and suppressed the specific predictor (output TWOb in Supplementary material-Appendix One).

We used the simplified form of the model as the basis for a variation partitioning exercise based on the adjective R^2 values of nested versions of the simplified model. We used a series of nested models to assess the relative importance of the three fixed effects predictors of our simplified model, aridity, fertilization and yield. To calculate R^2 values for each model we used the command *r2_nakagawa* from the R package *performance* (Nakagawa and Schielzeth, 2013).

To assess whether our observations were consistent across crops (i.e., sensitivity analyses) we carried out the following supplementary analyses: in relation to fertilization (output Three in Supplementary material-Appendix One) we carried out Mann-Whitney tests between the subset of trials which received fertilization and those that did not, separately for each individual crop with *relative yield chance* as response variable. In relation to yield and aridity we replicated the analyses using 0.5 quantile regression, presenting a non-parametric alternative to our simplified linear model (function *rq* in the r library *quantreg*; Koenger, 2021).

3 Results

3.1 Overall patterns

Fertilization, consistently across crops (in four out of the eight crops which contained both fertilized and unfertilized trials there were larger effect sizes in fertilized that in unfertilized cases; Fig. 1), increased the *relative yield change* meaning that it favored no tillage over conventional tillage (Fig. 1). When we analyzed all trials were fertilization had been applied together with a one sample *t*-test we found an above zero mean relative yield change (0.098) which different significantly from zero (t=2.77, P=0.006), meaning that no tillage outperformed conventional tillage following fertilization. This was different from the unfertilized trials where the original publication reported negative effect sizes and where a respective one sample *t*-test showed a trend for negative values (t=−1.31, P=0.19). For six out of the ten crops the median *relative yield change* decreased with increased yield (Table S1). The median *relative yield change* also increased with aridity for six out of the ten crops (Table S1).

3.2 Random Forests

The variables with the highest mean importance (Supplementary material-Appendix One) were yield (943.6), maximum temperature (154.2), aridity (92.3) and P availability (85.3). Fertilization was of lower importance (0.64) but we included it in the subsequent models. We rationalized earlier for that decision.

3.3 Simplified linear model

The best fit model contained the variables yield (log-transformed; F=71.6, P<0.001), fertilization (F=7.35, P=0.007) and aridity (F=232.2, P<0.001; Fig. S1) as fixed effect factors (Fig. 2). The coefficients for fertilization and aridity were positive (0.12 and 0.23 respectively) whereas that for yield was negative (-5.4×10^{-6}) (Supplementary material-Appendix One).

3.4 Variation partitioning

Yield explained the largest fraction of variance (7.84×10^{-3}%; Fig. 3). The specific variance fraction showed little overlap with aridity and only a 0.99×10^{-3}% was shared

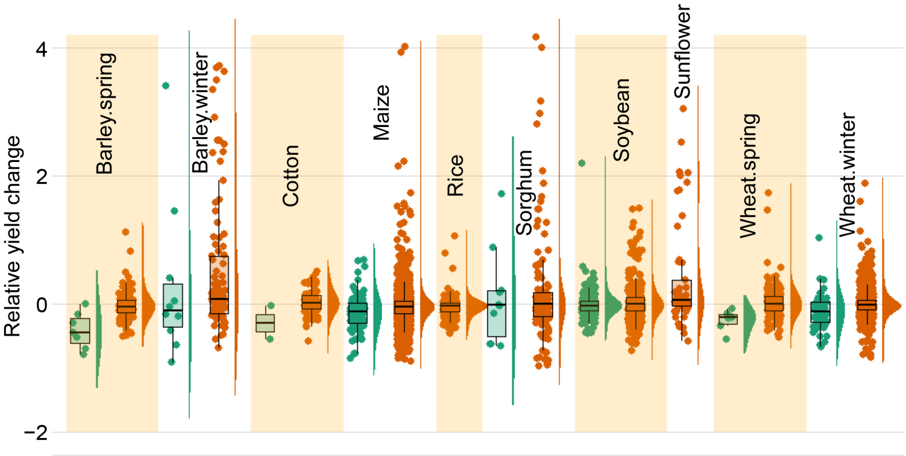

Fig. 1 Relative yield change (*y* axis) differences across crops that received no fertilization (in green on the left) or got fertilized (in orange on the right). Each effect is summarized as a boxplot and a vertical histogram. Note the consistency with which relative yield change increases with fertilization. The mean relative yield change for fertilized crops is above zero (one sample *t*-test: t=2.77, P=0.006).

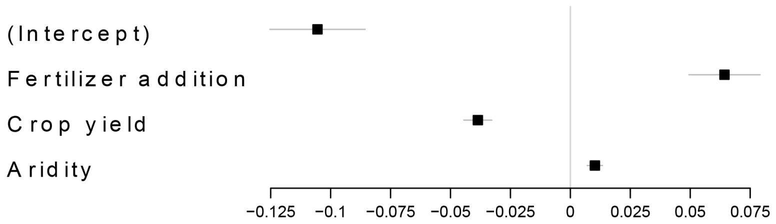

Fig. 2 Standardized coefficients (mean ± 95% CIs depicted as a rectangle and a grey horizontal line, respectively) for the linear model which we used for predictions in this paper. The simplified model consisted of three predictors, fertilizater addition (categorical: yes/no), crop yield (continuous) and aridity (continuous). We additionally present statistics for the intercept of the model which was fitted with the *lme* command in the package *nlme* and had crop as a random effects factor as well as a variance structure.

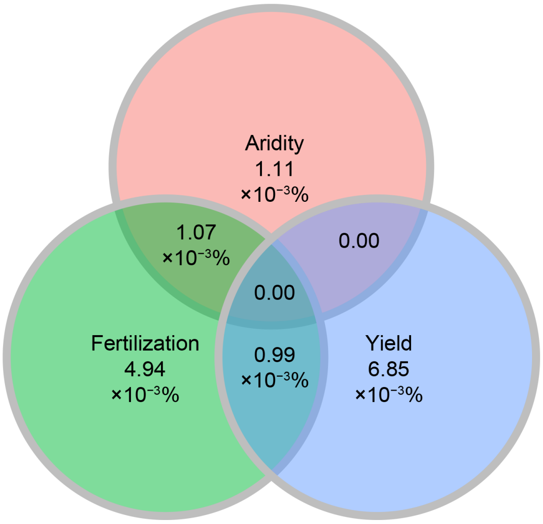

Fig. 3 Partitioning of the variation in the relative yield change which is explained by the predictors yield, fertilization and aridity in the mixed effects model which we used. Even though the fraction of variation that is explained by the parameters is really small, the effects are significant.

with fertilization. The variance fraction of fertilization (2.55×10^{-3}%) was shared with yield (0.99×10^{-3}%) and aridity (1.11×10^{-3}%). Aridity explained a 2.18×10^{-3}% variance.

4 Discussion

We re-analyzed here the dataset from Su et al. (2021a) and arrived in a considerably more compact model than the original study with fewer parameters. Our model only explains a small fraction of the total variance but at the same times results are consistent across crops. Su et al. (2021b) reported as their main findings that conservational tillage practices outperform no-tillage and that they benefit most from drier climatic conditions. Here we addressed the relative performance of no tillage against conventional tillage practices. We found that following fertilization no tillage outperformed conventional tillage and that this was mostly the case under less productive environmental settings. We also found that aridity favored no tillage over conventional tillage.

A major advantage of our re-analysis is that we control for the different responses that crops may show to tillage. We do so through either though analyzing crops separately to each other (e.g., Fig. 1) or by integrating the parameter "crop" as a random effects parameter in our simplified model. The possibility to control for some grouping factors that cause significant heterogeneity in a dataset presents one of the major advantages of general linear models over machine learning approaches. Unsurprisingly our results differ considerably from, and thus complement, those from Su et al. (2021b). Notwithstanding the differences in the results the assumptions of the approach of Su et al. (2021b) and of our analysis are quite different (but it is beyond the scope of this article to detail why) and each of the two studies presents unique insights on the system.

The findings in our reanalysis that fertilization practices and aridity favor no-tillage are in agreement with Pittellkow et al. (2015). By contrast we believe that this is the first report observing that a high fertility (i.e., captured here as a high yield) can favor conventional tillage practices over no-tillage practices. We also observed that yield explains a fraction of variance that is unrelated to the other two predictors (i.e., fertilization and aridity) of our simplified model. It may thus present a descriptor of the state of a field site that should be given more attention in future studies.

5 Conclusions

In the introduction we formulated two hypotheses. We found evidence in support of *Hypothesis One* that aridity favors no tillage practices over conventional tillage. We also found support for *Hypothesis Two* stating that fertilization benefits disproportionably no tillage practices over conventional tillage ones. Fertilization however can make sites on the longer term more productive implying that on the longer term it could favor conventional tillage as well. Over the last few decades a large body of experimental studies on tillage has accrued. We are now experiencing the revolutionizing power of data synthesis. A bird's eye view for agronomists!

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Electronic supplementary material

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