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Productivity limits and potentials of the principles of conservation agriculture

Cameron M. Pittelkow[1]*†, Xinqiang Liang[2]*, Bruce A. Linquist[1], Kees Jan van Groenigen[3], Juhwan Lee[4], Mark E. Lundy[1], Natasja van Gestel[3], Johan Six[4], Rodney T. Venterea[5,6] & Chris van Kessel[1]

One of the primary challenges of our time is to feed a growing and more demanding world population with reduced external inputs and minimal environmental impacts, all under more variable and extreme climate conditions in the future[1–4]. Conservation agriculture represents a set of three crop management principles that has received strong international support to help address this challenge[5,6], with recent conservation agriculture efforts focusing on smallholder farming systems in sub-Saharan Africa and South Asia[7]. However, conservation agriculture is highly debated, with respect to both its effects on crop yields[8–10] and its applicability in different farming contexts[7,11–13]. Here we conduct a global meta-analysis using 5,463 paired yield observations from 610 studies to compare no-till, the original and central concept of conservation agriculture, with conventional tillage practices across 48 crops and 63 countries. Overall, our results show that no-till reduces yields, yet this response is variable and under certain conditions no-till can produce equivalent or greater yields than conventional tillage. Importantly, when no-till is combined with the other two conservation agriculture principles of residue retention and crop rotation, its negative impacts are minimized. Moreover, no-till in combination with the other two principles significantly increases rainfed crop productivity in dry climates, suggesting that it may become an important climate-change adaptation strategy for ever-drier regions of the world. However, any expansion of conservation agriculture should be done with caution in these areas, as implementation of the other two principles is often challenging in resource-poor and vulnerable smallholder farming systems, thereby increasing the likelihood of yield losses rather than gains. Although farming systems are multifunctional, and environmental and socio-economic factors need to be considered[14–16], our analysis indicates that the potential contribution of no-till to the sustainable intensification of agriculture is more limited than often assumed.

To help address global food security challenges, conservation agriculture holds much promise as ‘an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment’[13]. Conservation agriculture represents a set of three crop management principles: (1) direct planting of crops with minimum soil disturbance (that is, no-till), (2) permanent soil cover by crop residues or cover crops, and (3) crop rotation[5,6]. In recent decades, widespread adoption of no-till has occurred over approximately 125 million hectares, equivalent to 9% of global arable land, with varying degrees of application of the other two conservation agriculture principles[5,13]. However, the impacts of no-till by itself and conservation agriculture on crop productivity remain contested[5–13]. Here, we synthesized current scientific evidence at a global scale to assess crop yields under no-till in relation to implementation of the other two conservation agriculture principles, residue retention and crop rotation.

A comprehensive meta-analysis was performed on data from peer-reviewed publications, representing the largest assessment so far on this topic. Because not all three principles of conservation agriculture are adopted by all farmers[8,17], studies at a minimum had to include no-till, the original and central concept of conservation agriculture, and conventional tillage treatments (note: minimum-tillage practices were not included). Only field experiments containing side-by-side yield comparisons were included in the database (see Methods for study selection details). Since conservation agriculture is not necessarily a low-input form of agriculture and in fact has been adopted to the greatest extent[13] in countries characterized by highly mechanized, high-input agricultural systems, all comparisons were included regardless of input intensity. To examine how the effects of no-till changed across the other two principles of conservation agriculture, yield comparisons were grouped into categories based on the presence or absence of residue management and crop rotation practices as determined by information reported in the original studies. For each paired yield comparison, no-till and conventional tillage treatments received the same residue management and rotation practices. In total, the database consisted of 5,463 observations from 610 studies.

Overall, we found that no-till negatively impacts crop yields by 5.7% (Fig. 1), although under certain conditions it produces yields equivalent to or even greater than conventional tillage systems (Figs 2 and 3). To limit global agricultural expansion and thereby reduce net environmental degradation, enhancing production per unit area through agricultural intensification efforts has been identified as a promising approach[3,4,14,18]. However, our meta-analysis indicates that no-till is limiting rather than enhancing global crop production and sustainable intensification efforts. Certainly, yield is only one component of agricultural systems, and there is an urgent need to optimize farming practices across other environmental and socio-economic performance indicators[1,15]. We recognize that in many, but definitely not all situations, continuous no-till along with the other two conservation agriculture principles may represent a more profitable management system (often because of reduced energy/diesel costs related to tillage), with the potential to improve soil quality and provide greater ecosystem services[16,17,19]. In addition, as agricultural crop yields are variable in time and space, yield outcomes can be difficult to predict at the individual farm-scale.

Importantly, the negative impacts of no-till are minimized when both of the other conservation agriculture principles are also applied (−2.5%) (Fig. 1). The largest yield declines occur when no-till is implemented alone (−9.9%) or with only one other conservation agriculture principle (−5.2 and −6.2% for residue retention and crop rotation, respectively). To help close the yield gap with conventional tillage, these findings suggest that instead of implementing no-till as the first step towards conservation agriculture in cropping systems where residue retention and crop rotation are absent (and anticipating that these two principles will follow in

[1]Department of Plant Sciences, University of California, Davis, California 95616, USA. [2]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310058, China. [3]Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, Arizona 86011, USA. [4]Department of Environmental Systems Science, Swiss Federal Institute of Technology, ETH-Zurich, Zurich 8092, Switzerland. [5]United States Department of Agriculture, Agricultural Research Service, Soil and Water Management Unit, St Paul, Minnesota 55108, USA. [6]Department of Soil, Water, and Climate, University of Minnesota, St Paul, Minnesota 55108, USA. †Present address: Department of Crop Sciences, University of Illinois, Urbana, Illinois 61801, USA.
*These authors contributed equally to this work.

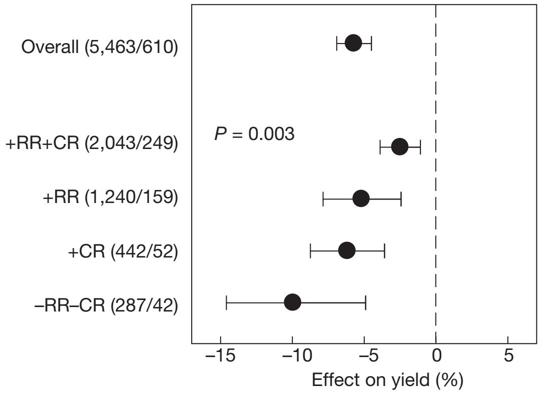

Figure 1 | Comparison of yield in no-till versus conventional tillage systems in relation to the other two principles of conservation agriculture. Results are shown for the entire data set (overall) and for subcategories of studies which indicated the presence or absence of residue retention and crop rotation for both no-till and conventional tillage systems: +RR+CR (residue retention + crop rotation), +RR (residue retention), +CR (crop rotation), or –RR–CR (without residue retention or crop rotation). 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 between categories are indicated by *P* values based on randomization tests.

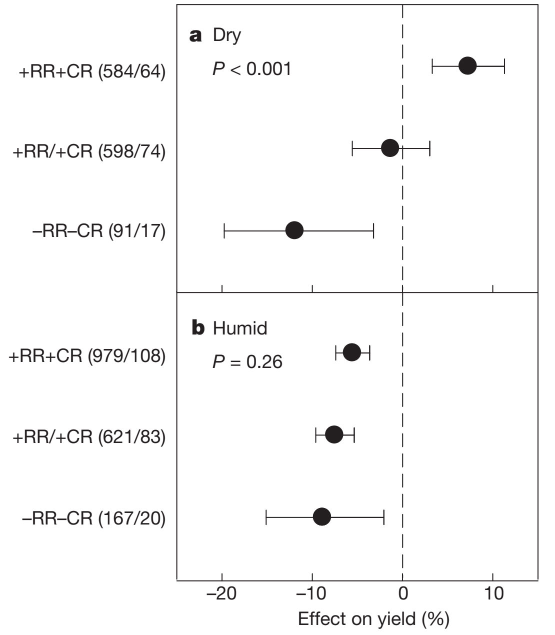

Figure 2 | Comparison of rainfed crop yield in no-till versus conventional tillage systems in relation to the other two principles of conservation agriculture as a function of climate. The influence of (**a**) 'Dry' and (**b**) 'Humid' climates, defined by aridity index values (mean annual precipitation divided by potential evapotranspiration) less or more than 0.65, respectively. Categories represent studies that indicated the presence or absence of residue retention and crop rotation for both no-till and conventional tillage systems: +RR+CR (residue retention + crop rotation), +RR/+CR (either residue retention or crop rotation), or –RR–CR (without residue retention or crop rotation). 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 between categories are indicated by *P* values based on randomization tests.

time), the primary focus should be on implementing no-till systems that already employ the other two principles. This conclusion has important implications for the promotion of conservation agriculture as an agricultural development strategy in areas where the former is common, including areas of sub-Saharan Africa or South Asia[7,17,19]. Because residue retention and crop rotation are generally considered good agronomic practices, a reconsideration of the order in which conservation agriculture principles are introduced in these regions (that is, better targeting of no-till to systems already based on the other two conservation agriculture principles) is not in conflict with general recommendations for sustainable crop production.

Our analysis, synthesizing information from hundreds of field trials across 48 crops and 63 countries (Extended Data Fig. 1), shows that no-till significantly enhances yields (7.3%) under rainfed agriculture in dry climates when the other two conservation agriculture principles are also implemented (Fig. 2a). Yet, the reverse is true when no-till is applied alone (−11.9%). Furthermore, yields decrease with no-till regardless of whether the other principles are applied in humid climates (Fig. 2b). These results are consistent with smaller data sets (for example, 26 studies on no-till rainfed maize) in which residue retention in semiarid environments and crop rotation positively impacted yields[9]. A yield benefit with no-till in combination with the other two conservation agriculture principles in dry climates is probably because of improved water infiltration and greater soil moisture conservation[6,20]. We found that when water is non-limiting owing to irrigation, no-till in dry climates maintains yields similar to conventional systems (residue retention + crop rotation mean effect size for 34 studies and 213 observations: −3.0%; 95% confidence interval: −6.2 to 0.4%), providing further support for this conclusion.

To help meet current and future crop production challenges, our results suggest that this set of integrated management practices can provide agronomic benefits in water-limited and/or water-stressed regions. This is an important finding given that millions of hectares in dry climates of sub-Saharan Africa and South Asia have recently been identified as suitable for sustainable intensification efforts[21]. Still, if conservation agriculture is to be successful at increasing crop productivity in these areas, it must be adjusted to local conditions through an innovative, multi-stakeholder driven approach that is sensitive to market opportunities, equipment availability, and farmers' production objectives and needs[8,17,19]. Our findings further suggest that no-till in combination with the other two conservation agriculture principles, when targeted appropriately, may become an increasingly important strategy to deal with soil moisture stress due to climate change. Projected changes in precipitation and temperature are expected to cause increased drying and drought in important agricultural production areas of the world[22,23]. Depending on the severity of these changes, a number of adaptations will be required to maintain global agricultural production levels; the attributes of soil moisture conservation and water use efficiency with the three principles of conservation agriculture could play an important role.

It is often suggested that the risk for short-term decreases in crop productivity represents a major barrier for farmers considering conservation agriculture[8–10]. Our results confirm this; regardless of whether the other two conservation agriculture principles are implemented, no-till reduces yields in the first few years following adoption (Fig. 3a). However, the yield decline in initial years is minimized when all three principles are applied compared with one principle (−3.0% versus −11.4%, respectively). Moreover, despite no-till yields in all categories becoming comparable with conventional tillage in the medium term (Fig. 3b), after 10+ years yields begin to decline when only no-till is implemented (Fig. 3c). Hence, to mitigate the negative impacts of no-till, our findings emphasize the importance of implementing all three principles and the overall need for strategies to overcome yield reductions in early and later (10+) years. Although the economic benefits of conservation agriculture may be more strongly driven by cost reductions rather than increased yields[17], negative yield outcomes can discourage poorer farmers who tend to focus on short-term gains, probably making it an overriding factor limiting the adoption of conservation agriculture[7,19].

It cannot be determined from our database whether initial yield reductions are caused by biophysical conditions (for example, soil structure, decomposition of residues on the soil surface) or sub-optimal management (that is, a learning curve effect). The transition to no-till integrated with the other two conservation agriculture principles is challenging

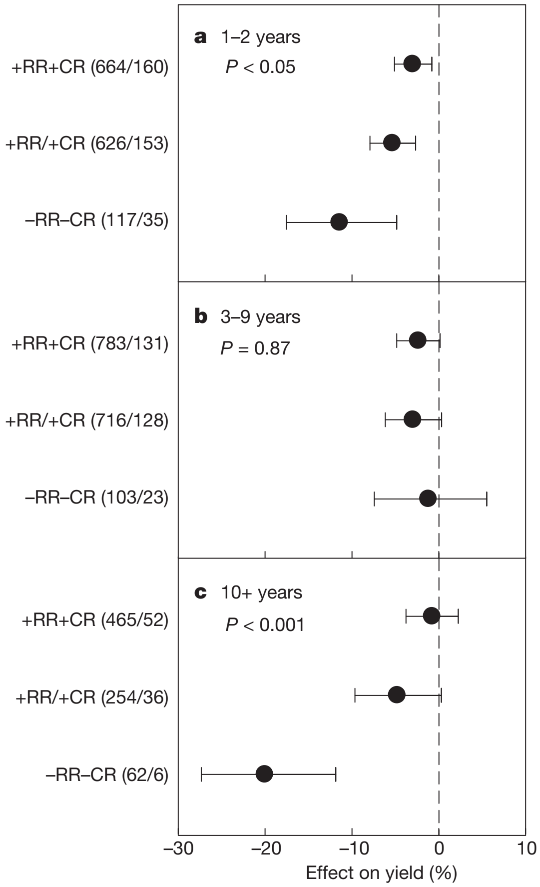

Figure 3 | Comparison of yield in no-till versus conventional tillage systems in relation to the other two principles of conservation agriculture over time. The influence of (**a**) 1–2, (**b**) 3–9, and (**c**) 10+ years following no-till implementation. Categories represent studies that indicated the presence or absence of residue retention and crop rotation for both no-till and conventional tillage systems: +RR+CR (residue retention + crop rotation), +RR/+CR (either residue retention or crop rotation), or –RR–CR (without residue retention or crop rotation). 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 between categories are indicated by *P* values based on randomization tests.

as it represents a holistic change in management requiring adaptation at the individual farm-level. A targeted review of no-till studies in sub-Saharan Africa and South Asia reported a high risk of short-term yield declines for major annual crops[10]. Similar to previous work[9], these authors also noted that implementation of the other two conservation agriculture principles can minimize this risk and that no-till yield losses tend to diminish with time[10]. Interestingly, regardless of initial impacts on yield, our results do not indicate that no-till outperforms conventional tillage in the 10+ year category. One possible explanation for these results is that weed, pest, and disease pressures may increase with continuous no-till systems over time depending on how the other conservation agriculture principles are implemented[24], possibly offsetting improvements in soil quality. Further research is needed to identify initial and long-term yield constraints of no-till systems.

When considering the relative importance of crop rotation versus residue management practices in enhancing yield of no-till systems, our meta-analysis does not provide evidence that one principle regulates productivity more than the other. Across all observations, the individual effects of residue retention and crop rotation reduce the negative impacts of no-till by 4.8 and 3.8%, respectively, although differences between categories are insignificant (Fig. 1). However, in dry climates these principles each have a much stronger effect on rainfed crop yields, reducing yield losses by 10.1 and 11.0%, respectively. Indeed, previous work has stressed the importance of residue retention to enhance soil and cropping system benefits of reduced tillage systems[25,26], with our study being the first to quantify impacts on crop productivity at a global scale. Our results illustrate the need to implement at least one, and preferably both, principles in addition to no-till in rainfed cropping systems in dry climates, while also suggesting that consistent yield declines with no-till in humid environments may be primarily caused by factors unrelated to these principles.

Clearly, there are important environmental (for example, reduced erosion and improved soil quality) and economic outcomes of continuous no-till[5,16,17] beyond the scope of the present analysis that might justify adoption at the farm scale and should be considered in a trade-off analysis against yield reductions. Nevertheless, agricultural regions containing a disproportionate number of the world's poor, including sub-Saharan Africa and South Asia, currently struggle with food security issues and have a high probability of experiencing yield reductions due to climate change in the future[2]. Despite the promising effects of no-till in certain contexts (that is, rainfed agroecosystems in dry climates), we stress that benefits in yield are only seen when the other two conservation agriculture principles are also implemented. Of far greater concern is that no-till alone tends to have the opposite of the intended goal, thereby placing farmers at increased risk of yield losses. It is precisely resource-poor and vulnerable smallholder farming systems that will have the greatest challenges adopting the other two principles, most notably the retention of crop residues due to strong competition for residues by livestock and other uses[8,17]. Hence, efforts to expand conservation agriculture further must remain conscious of the potential for no-till to 'backfire' in these contexts.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to C.M.P. (cmpitt@illinois.edu).

METHODS

Data collection. We comprehensively searched the peer-reviewed literature for publications investigating the effects of no-till in relation to the other two conservation agriculture principles on crop yields from Jan 1980 to May 2013 using Scopus (Elsevier). 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. Conference proceedings and non-English language publications were excluded. This search produced a total of 2,471 publications, which were screened on the basis of the following criteria: (1) studies had to represent field experiments containing side-by-side comparisons of no-till and conventional tillage practices; (2) 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 rejected); (3) crop yields were reported; (4) location of the experiment was stated; (5) management information regarding at least one other conservation agriculture principle was available (that is, residue management or crop rotation); and (6) confounding effects between treatments were absent (that is, differences in residue management, seeding rates, fertilizer rates, etc. were determined to be negligible). When more than one form of tillage was assessed in a study, we selected the treatment representing the greatest soil disturbance (generally mouldboard plow). Although it only represented a small portion of the data, no-till treatments were not always required to represent continuous zero-tillage (for example, if two crops were grown per year and the first crop required tillage but the second was planted using no-till practices, yield comparisons for the second crop were included).

Studies were rejected if it was unclear from reading the experimental methods whether factors other than tillage differed between treatments with the exception of herbicides (the absence of tillage as a weed control strategy generally requires changes in herbicide management under no-till[24]). Owing to the large size of the database, particular attention was given to avoiding data duplication (for example, when different studies reported the same data). Thus, if it was unclear whether a publication contained duplicate data, it was rejected. A number of publications from the conservation agriculture literature were rejected because of the lack of a control treatment that satisfied our criteria (that is, conservation agriculture treatments representing all three principles were compared with conventional tillage treatments with residues removed and no rotation).

Means for no-till and conventional tillage yields were extracted from each study in addition to study and site characteristics including crop type, study location, study duration, irrigation, residue management, and crop rotation practices. In cases where yield data were only presented in figures, values were extracted using Plot Digitizer (http://plotdigitizer.sourceforge.net/). In a few instances where yield data were only reported as a percentage change relative to the other treatment, we assumed absolute yield values for the reference treatment and calculated the natural log of the response ratio normally as described below (because this metric only quantifies the relative difference between means, the same value is produced regardless of the absolute magnitude of means). To investigate changes in yield over time, the number of years since the initiation of no-till was recorded for each observation. Observations were excluded from the analysis of no-till duration when only mean yields over a number of years were presented. For the small number of studies in which tillage occurred periodically in no-till systems, the duration of no-till was reset to time zero with each tillage event. For example, if tillage occurred during the rice phase of a rice–wheat rotation during five consecutive years, each wheat yield observation was recorded as the first year under no-till.

The effect of climate was assessed for yields under rainfed conditions by determining the aridity index (mean annual precipitation divided by potential evapotranspiration) for each study using latitude and longitude coordinates and the WorldClim database[27]. Following the generalized climate classification scheme[28], aridity index values less and more than 0.65 were categorized as 'dry' and 'humid', respectively. If latitude and longitude coordinates were not stated, an attempt was made to contact study authors. Otherwise, coordinates were estimated using the location of the nearest city or the experiment station at which the study took place. In a few cases where only large geographical areas were stated in publications, coordinates and aridity index values were not estimated.

Crop rotation, residue management, and irrigation practices were recorded for each study as categorical variables where possible. Crop rotation was treated as a binary variable (yes/no), where 'yes' indicated that two or more crops were grown in sequence in the same field over time (including the use of a cover crop), and 'no' indicated continuous cultivation of a single crop. Residue management was also treated as a binary variable (retained/removed), where 'retained' indicated that crop residues were retained in the field following harvest each growing season (or in a minority of cases, residues were supplied from elsewhere or by growing a cover crop between seasons), and 'removed' indicated that residues were physically removed from the field or burned following harvest. Information for 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. Irrigation practices (yes/no) were recorded when available, with cells left blank when irrigation practices were unclear.

Before data analysis, observations were grouped into categories depending on the presence of residue management and crop rotation practices as determined by information reported in the original studies. For each paired yield observation, we required that no-till and conventional tillage treatments received the same residue management and rotation practices. Thus, categories represented the following comparisons: three principles (no-till versus conventional tillage, both with residues retained + crop rotation), two principles (no-till versus conventional tillage, both with either residues retained or crop rotation), and one principle (no-till versus conventional tillage, both without residue retention or crop rotation).

Data analysis. Following previous work[29], we calculated the natural log of the response ratio (the ratio of no-till to conventional tillage yields) as the effect size in our meta-analysis. Because within-study variance measures for mean yields were available for less than a few percent of studies, individual observations were weighted by replication, with weights $= (n_{\mathrm{conv.}} \times n_{\mathrm{no\text{-}till}})/(n_{\mathrm{conv.}} + n_{\mathrm{no\text{-}till}})$, where $n_{\mathrm{conv.}}$ and $n_{\mathrm{no\text{-}till}}$ are the number of replicates for conventional tillage and no-till treatments, respectively[30]. In situations where more than one observation from a study was included in a category, weights were divided by the total number of observations from that study. When yield values for a treatment equalled zero and thereby indicated crop failure or experimental error, observations were excluded. Moreover, observations more than five standard deviations from the weighted mean effect size within each category were excluded (this represented $<0.5\%$ of data on average). All statistical analyses were conducted with R (version 3.0.2)[31]. Bootstrapping procedures within the 'boot' package[32] were used to generate 95% confidence intervals for weighted mean effect sizes using 4,999 iterations[30]. Between-group heterogeneity was assessed using randomization procedures based on 4,999 replications[30]. Results were considered significant if confidence intervals did not overlap with zero and randomization tests yielded P values <0.05. For ease of interpretation, all results were back-transformed and reported as percentage change in yield for no-till relative to conventional tillage practices.

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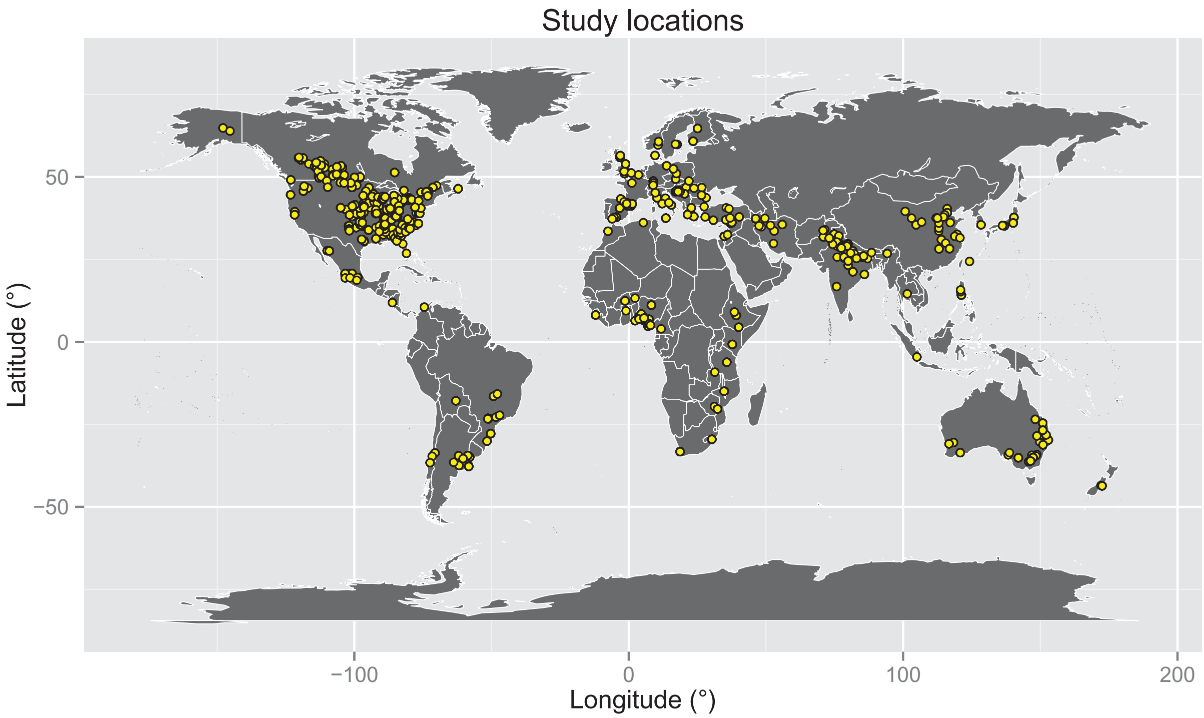

Extended Data Figure 1 | The location of studies containing yield comparisons between no-till and conventional tillage systems used in the meta-analysis.