ANALYSIS
https://doi.org/10.1038/s41893-020-0500-2

nature sustainability

Conservation agriculture for sustainable intensification in South Asia

Mangi Lal Jat[1]✉, Debashis Chakraborty[2], Jagdish Kumar Ladha[3], Dharamvir Singh Rana[4], Mahesh Kumar Gathala[5], Andrew McDonald[6] and Bruno Gerard[7]

Agriculture's contribution to the Sustainable Development Goals requires climate-smart and profitable farm innovations. In the past decade, attention has been given to conservation agriculture as a 'sustainable intensification' strategy, although a lack of evidence-based consensus on the merits of conservation agriculture prevails in the context of intensive smallholder farming in South Asia. A meta-analysis using 9,686 paired site–year comparisons representing different indicators of cropping-system performance suggest significant ($P < 0.05$) benefits when conservation-agriculture component practices are implemented either separately or in tandem. For example, zero tillage with residue retention had a mean yield advantage of 5.8%, a water use efficiency increase of 12.6%, an increase in net economic return of 25.9% and a reduction of 12–33% in global warming potential, with more-favourable responses on loamy soils and in maize–wheat systems. Results suggest that there are opportunities to maximize expected benefits, and policymakers and development practitioners should continue to be appraised of the potential of CA for contributing to the Sustainable Development Goals in South Asia.

South Asian agriculture is a global 'hotspot' for contemporary and future climate vulnerability. Further, 1.7 billion people live in South Asia, and by 2050, that number is expected to rise to 2.4 billion. Although the region enjoys high economic growth, it suffers from extreme poverty, undernourishment and the deterioration of natural resources[1]. South Asia has more than 42% of the world's poor (earning less than US$1.90 per day), about 21% of the population is undernourished, and more than 41% of children are underweight[2]. Rapid population growth will increase the demand for cereals by about 43% between 2010 and 2050. Meeting this projected need is doubly challenging considering 94% of the land suitable for farming is already in production and 58% of agricultural areas face multiple climatic hazards such as water shortage and extreme heat stress[3]. The present situation is anticipated to worsen with climate change, with rising temperatures and changing monsoon rainfall patterns projected to cost India 2.8% of gross domestic product[4]. Although global crop productivity has more than doubled during the past decades, negative impacts on environment, biodiversity, soil quality and air quality are common[5,6].

Future food production in South Asia requires new management approaches that are efficient and climate smart to make tangible contributions to the United Nations' Sustainable Development Goals (SDGs). Conservation agriculture (CA) has emerged as an alternative to an inefficient tillage-based conventional agriculture. CA is an ecosystem approach to regenerative sustainable agriculture and land management based on three interlinked principles: (1) continuous no or minimum mechanical soil disturbance, (2) permanent maintenance of soil mulch (crop biomass and cover crops) and (3) diversification of cropping system (economically, environmentally and socially adapted rotations including legumes and cover crops), along with other complementary good agricultural production and land management practices[7]. CA helps in managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. It is estimated that a partial CA-based system (at least one crop has no till, with or without residue retention) is spread to over 2.5 million ha in South Asia (M.L. Jat, personal communication). Numerous favourable impacts have been reported in the global literature on CA, including for crop yields, resource (labour, water, energy) use efficiencies, timeliness of cropping practices, soil quality and ecosystem services[8–13]. Nevertheless, a meta-analysis of global yield data from 48 crops across 63 countries reported limited yield gains with full CA or with some components of CA[14], a result that has drawn into question the wisdom of making CA a sustainable intensification priority for agricultural development programs.

Although the benefits derived from CA have been broadly questioned, there has been gradual increase in adoption of CA over time. Zero-tillage (ZT) wheat has been adopted on a significant area in the rice–wheat system of the northwestern Indo-Gangetic Plains[15] and in the Eastern Gangetic Plain[16] with positive impacts on wheat yield, profitability and resource-use efficiencies[17,18]. The national governments in South Asia are actively promoting CA to address sustainability problems.

Although numerous on-station and on-farm studies have been carried out during the past two decades to evaluate CA in South Asia, a systematic synthesis of evidence is lacking. To clarify the regional potential of CA as a full package or combination of its components in South Asia, this study presents a comprehensive meta-analysis on data from on-station (1996–2016) and on-farm (2010–2014) studies in South Asia's dominant cereal-based cropping systems. Performance parameters considered in the analyses included (1) grain yield, (2) protein-equivalent yield (PEY), (3) water use efficiency, (4) cost of cultivation and net economic return, and (5) emission of GHGs (methane and nitrous oxide) and global warming potential (GWP). Results are contrasted with conventional best practices and contextualized with respect to

---

[1]International Maize and Wheat Improvement Center (CIMMYT), New Delhi, India. [2]ICAR-Indian Agricultural Research Institute, New Delhi, India. [3]Department of Plant Sciences, University of California, Davis, CA, USA. [4]International Rice Research Institute (IRRI), New Delhi, India. [5]International Maize and Wheat Improvement Center (CIMMYT), Dhaka, Bangladesh. [6]Soil and Crop Sciences Section, School of Integrative Plant Science, Cornell University, Ithaca, NY, USA. [7]International Maize and Wheat Improvement Center (CIMMYT), El Batan, Texcoco, Mexico. ✉e-mail: M.Jat@cgiar.org

Table 1 | Treatment details

Treatment	Tillage and CE	Residue management	Annual crop system
Control	CT and CE in all crops in a system	Residue removed, burnt, or incorporated in all crops	Double to triple crops
CA 1	ZT direct seeding in either crop in a system	Residue removed/ retained in one crop or both	Double crops
CA 2	ZT direct seeding in both crops in a system	Residue retained in one or both the crops	Double crops
CA 3	ZT direct seeding in all crops in a system	Residues retained in at least both main (cereal) crops	Triple crops

potential contributions to the SDGs related to poverty, hunger, health, climate action and clean water.

Results

Meta-analysis was done in two stages. At the first stage, the conventional practices ('control') and CA practices were compared on the basis of tillage, crop establishment (CE) and residue management. At the second stage, CA was further classified into three sublevels (CA1, CA2 and CA3) and compared with the control (see Table 1 for details).

Conventional versus conservation agriculture. The first-stage analysis showed improvements in all the measured performance indicators (crop yield, protein yield, water use efficiency and net economic return). Compared with conventional practice, CA had 4.6% higher grain yield, which was very similar to PEY. A 14.6% increase in water use efficiency was observed with CA. The net economic return increased by 25.6% (Fig. 1).

Segregating on-station and on-farm studies revealed higher CA responses in the former than in the latter. On-station crop yields increased by 11.1% and on-farm by 4.7%, while water use efficiency was 29.3% and 9.3% higher in the on-station and on-farm studies, respectively. However, the changes in the economic return in on-station and on-farm studies were similar.

Analysis based on cropping system revealed that the maize–wheat system had the highest grain yield increase with CA (18.6%), followed by rice–wheat (5.1%) and rice–maize (3.6%) (Fig. 2a). The 'others' category also demonstrated improvement in grain yields (4.3%). Similar trends were obtained in on-farm studies. In on-station studies, however, all cropping systems showed no change except maize–wheat, which had a 5.8% higher yield with CA (Supplementary Table 1). The PEY followed a similar trend as in grain yield (Supplementary Table 2). Water use efficiency with CA improved by 28.5% in the maize–wheat system, which was higher than in rice–wheat (13.2%), rice–maize (7.4%) and other crop systems (5.4%) (Fig. 2b). Water use efficiency in rice–wheat was higher in the on-station studies compared with the on-farm trials, while the rest of the cropping systems could not be compared between on-station studies and on-farm trials due to non-availability of data in one or the other (Supplementary Table 3). Rice–wheat generated the maximum economic return with CA, which was 29.0% higher than with the conventional practice (Fig. 2c). Increase in economic return was similar among the maize–wheat, rice–maize and other systems.

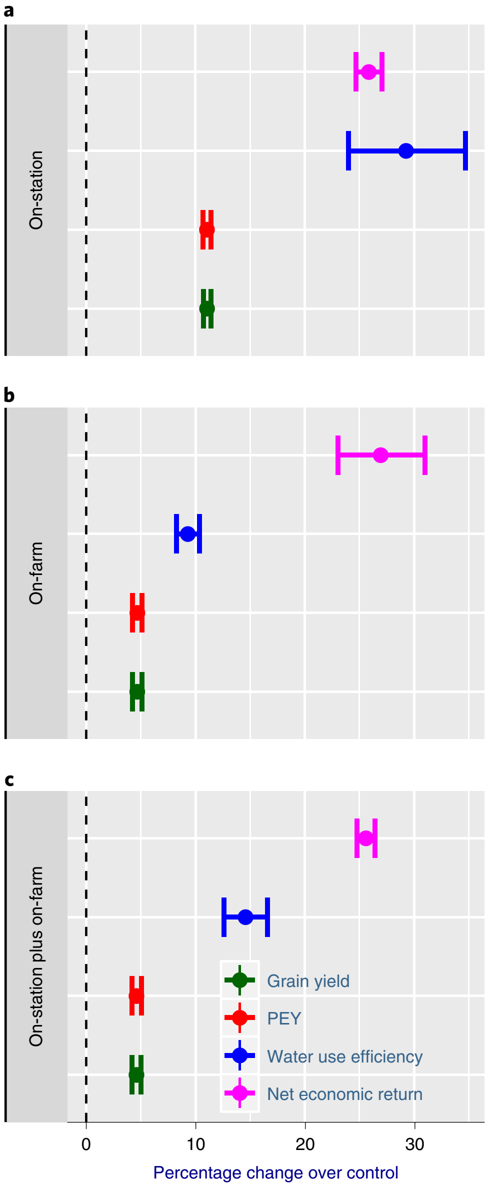

Fig. 1 | Comparison of CA with conventional agricultural practice. **a**–**c**, The percentage change over control in terms of grain yield, PEY, water use efficiency and net economic return using the on-station dataset (**a**), the on-farm dataset (**b**) and the whole (on-farm plus on-station) dataset (**c**). Error bars indicate 95% CIs; all differences are significant ($P < 0.05$).

Crop-based analyses showed higher yields for wheat and maize (6.8 and 6.2%, respectively) than for rice (1.7%) under CA practices (Supplementary Fig. 1a). Crops in the 'others' category exhibited a 3.8% increase in yield. The trend was similar in on-station and on-farm data for maize and wheat crops (Supplementary Table 1). However, yield in rice was higher in on-farm studies, but there was no change in on-station studies. Wheat and maize had much higher water use efficiency (20.7% and 16.4%, respectively) compared with rice (2.0%) (Supplementary Fig. 1b). Other crop systems had 12.7% higher water use efficiency. CA-based practices increased the economic return for all crops, with the highest (33.8%) in wheat and lowest (15.7%) in rice (Supplementary Fig. 1c).

Conventional agriculture versus sublevels of CA. Meta-analyses of key parameters (crop yield, water use efficiency and economics) of on-station and on-farm studies, including all crops and

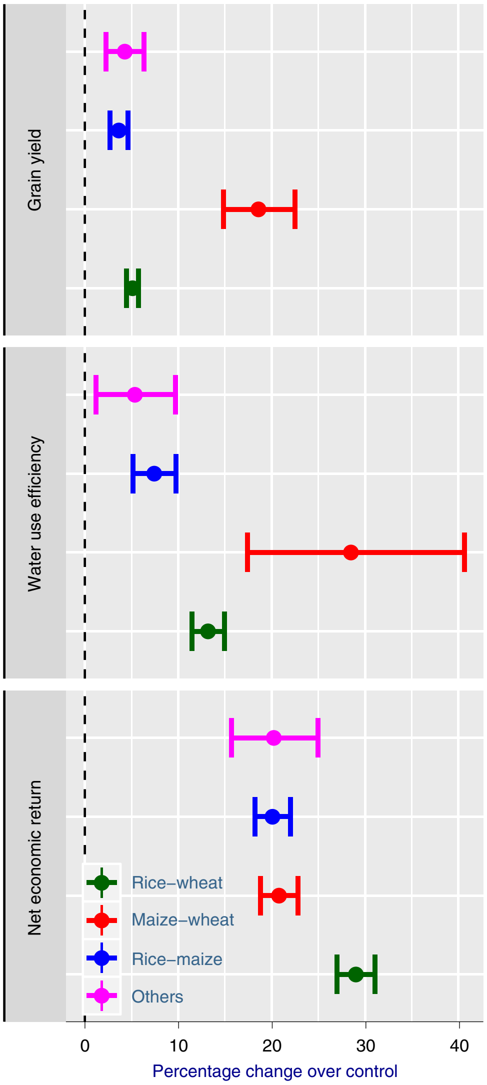

Fig. 2 | Performance of CA across the cropping systems. a–c, The percentage change over control in terms of grain yield (**a**), water use efficiency (**b**) and net economic return (**c**). Error bars indicate 95% CIs. Effect is significant at $P < 0.05$ if CI does not overlap zero.

systems in response to the sublevels of CA (CA1, CA2 and CA3), are shown in Table 2. The beneficial effects tend to increase from CA1 to CA2, while the differences between CA2 and CA3 are negligible. Compared with conventional practice, grain yield increased 3.0% in CA1, 5.8% in CA2 and 5.5% in CA3. The increase in PEY followed a similar trend. Likewise, water use efficiency increased 8.3% in CA1, 12.6% in CA2 and 11.6% in CA3. The increase in net economic return was, however, the largest in CA3 (40.5%) compared with conventional practices. The increase in net return was higher in CA2 (25.9%) compared with CA1 (20.3%). In on-station studies, grain yield increase was similar in CA2 and CA3 with no change in CA1; in on-farm studies, all the CA sublevels had similar yield gains (Supplementary Table 2). The PEY showed a similar response as in grain yield (Supplementary Table 3).

Cropping-system analyses showed the highest yield increase in the maize–wheat system, ranging from 13.7% to 24.2%, which did not differ among three sublevels of CA. The rice–wheat system had the highest increases in grain yield in CA2 (6.1%), which was similar to CA3 (4.6%) but higher than CA1 (2.6%) (Table 2). The rice–maize system, for which data of only CA1 and CA2 were available, showed similar increases of 2.2% in CA1 and 4.5% in CA2. The PEY had comparable increases in the CA categories under the cropping systems. In the rice–wheat and rice–maize systems, the water use efficiencies were similar among CA1, CA2 and CA3. In the maize–wheat system, CA2 and CA3 had comparable increases in water use efficiency of 25.1% and 26.0% (no data were available in the CA1 category). CA3 had the highest increase in economic return (36.7%) in rice–wheat, but in the maize–wheat system, all three CA practices brought similar economic return. In the rice–maize system, greater increase in economic return was achieved in CA2 (24.3%) compared with CA1 (11.9%). Crop-based analyses showed higher wheat and maize yields in all the CA sublevels, and water use efficiencies were significantly higher in all three CA sublevels (see Supplementary Results and Supplementary Table 4 for full details).

Response of CA as affected by soil texture. As a function of soil texture, yield responses were nominal on sandy soil (0.3%) with increasing responses for fine clayey (2.4%), medium loamy (4.2%) and moderately coarse loamy (5.6%) soils (Fig. 3a). The PEY had a trend similar to grain yield. The moderately fine loam had the highest increase in grain yield (7.4%) and water use efficiency (13.2%) (Fig. 3a,b). In maize–wheat, the highest yield gain was obtained from medium loamy soils (34.0%), which is comparable to the yield increase in moderately fine loamy soils, but moderately fine loamy soils resulted in the highest increase in water use efficiency (46.8%) (Supplementary Table 5). In rice–wheat, moderately fine loamy soils contributed to the highest yield gain, but increases in water use efficiency were similar for all the textures. In the rice–maize system, both moderately fine and medium loamy soils showed the largest gains in yield and water use efficiency. Moderately coarse loamy soil appears to be better suited for the 'others' category, improving both the yield and water use efficiency compared with conventional practice. The net return was higher in all soil textures except the coarse sandy soils and closely followed the trend in yield gains.

Crop-based analysis showed the most significant performance gains in the loamy soils for all the crops while the sandy soils had the poorest response, with marginally positive to negative effect (Supplementary Table 6). Clay also did not seem to be favourable under CA. Among the subclasses of loam, fine loam was the most favourable for all three cereals, with the maximum yield advantage of 16.0% in wheat. Maize performed similarly in all three subclasses of loam, with grain yield increases ranging from 6.1% to 8.9%. Rice had the maximum yield advantage of 3.6% in fine loam and relatively poor or no responses in other soil texture classes. Increase in water use efficiency in wheat was similar in all textures, except in coarse sandy soil, which was significantly lower. Maize had comparable increases in water use efficiency in moderately fine and moderately coarse loamy textured soils. In rice, water use efficiency was higher only in medium loamy soils, with no change in other soil texture classes.

Effect of CA on GHG emissions. The on-station data revealed methane reductions of 12.8% in CA1 and 75.2% in CA2. Crop-wise analysis showed no difference in methane reduction in rice and wheat, whereas the moderately fine loamy soil had a greater methane reduction (69.5%) than medium loamy soil (41.9%) (Table 3). By contrast, there were no changes in nitrous oxide emissions.

The GWP reduced by 33.5% in CA2, which was higher compared with CA1 (12.4%). A larger reduction in GWP was associated with rice (35.1%) compared with the wheat (9.8%) crop.

In the on-farm data, CA2 and CA3 sublevels resulted in comparable reductions in CO_2-equivalent (CO_2e) emissions of 12.6% and 11.0%, respectively, which was higher than the reduction in CA1 (Supplementary Table 7). A significant reduction in CO_2e emissions was obtained under all cropping systems, with the largest reductions observed in rice–wheat (13.6%). For individual crops,

Table 2 | Comparison (percentage change over control) of grain yield, PEY, water use efficiency and net economic return among different CA practices under the rice–wheat, maize–wheat and rice–maize cropping systems

Parameters	Overall			Rice–wheat			Maize–wheat			Rice–maize		
	CA1	CA2	CA3	CA1	CA2	CA3	CA1	CA2	CA3	CA1	CA2	CA3
Grain yield	3.0 (2.2 to 3.8)	5.8 (5.2 to 6.4)	5.5 (3.2 to 7.9)	2.6 (1.5 to 3.7)	6.1 (5.3 to 6.8)	4.6 (2.3 to 7.0)	24.2 (15.2 to 34.0)	16.5 (10.7 to 22.7)	13.7 (3.0 to 25.6)	2.2 (0.9 to 3.5)	4.5 (3.4 to 5.6)	–
PEY	3.0 (2.1 to 3.8)	5.8 (5.0 to 6.4)	5.5 (3.2 to 7.8)	2.5 (1.5 to 3.6)	6.1 (5.4 to 7.0)	4.5 (2.1 to 7.3)	24.2 (15.2 to 34.0)	16.6 (10.7 to 22.7)	13.7 (3.1 to 25.6)	3.2 (0.9 to 3.4)	4.5 (3.4 to 5.6)	–
Water use efficiency	8.3 (6.1 to 10.5)	12.6 (10.6 to 14.7)	11.6 (9.2 to 14.0)	11.0 (7.8 to 14.2)	14.7 (12.0 to 17.5)	14.0 (10.7 to 17.3)	–	25.1 (10.8 to 41.1)	26.0 (10.9 to 43.2)	5.4 (2.7 to 8.1)	7.8 (5.1 to 10.6)	11.5 (6.7 to 16.5)
Net economic return	20.3 (17.5 to 23.2)	25.9 (25.0 to 26.8)	40.5 (36.8 to 44.3)	30.7 (28.6 to 32.9)	26.9 (24.8 to 29.0)	36.7 (34.5 to 39.0)	35.6 (29.8 to 41.8)	26.7 (21.2 to 32.4)	27.8 (22.3 to 33.5)	11.9 (8.5 to 15.5)	24.3 (21.4 to 27.3)	–

Confidence intervals are given in parentheses.

emission reductions for wheat were estimated as 15.1%, which was higher than the reduction in rice (12.2%) but was comparable with maize (14.1%). Reductions in emissions were similar across the evaluated soil textures (sandy soil had no data points), with fine clay soil exhibiting a marginally larger reduction of 16.0%.

Discussion

Our meta-analysis of 1,353 field studies with major cereal-based cropping systems conducted on research stations and farmers' fields closes a data gap for South Asia that has limited the regional inferences that can be drawn from earlier meta-analyses[14,19,20]. Our analysis reveals the positive average effects of full and partially implemented CA (CA1, CA2 and CA3; see Table 1) on crop yield (actual and PEY), water use efficiency and economic return in the cereal-based cropping systems of South Asia. Although all three combinations of CA sublevels had significant positive effects, the impacts tended to be more positive when both the cereals had ZT with residues retained in one or both the crops across the cropping system. However, the net economic return was 40.5% higher in CA3 compared with around 20% in CA1 and 26% in CA2, suggesting that a full or close to full extent of CA would maximize the economic benefits, which is an important consideration in the farmers' decision making. Superiority of CA2 and CA3 over CA1 may also indicate cumulative effects of ZT and residue retention resulting from a carryover effect in a system. However, since there were only a limited number of published studies examining long-term effects of CA in South Asia[21,22], it was not possible to evaluate the carryover effects in multiple years in the present study. The ZT with surface residue retention has been reported to produce higher crop yield than without residue[21,23]. In a global meta-analysis[14], average yield loss of 9.9% was documented with ZT, a decline that was reduced to 5.2% when residue was retained. By contrast, our results show more positive effects on crop yield and other parameters. This could be because South Asia was not well represented in earlier meta-analyses published in 2015. The literature search in the present study revealed 48 new studies after the meta-analysis published in 2015. In addition, our study included data from 1,197 on-farm trials. Earlier meta-analyses had no on-farm data.

Our results demonstrate that CA benefits vary among crops, cropping systems and soil textures. The CA practices tend to perform best for upland crops (for example, maize, wheat) and non-rice cropping systems, a result consistent with earlier findings in South Asia[24,25]. Higher yield (grain as well as protein) gains with CA in maize–wheat than in the rice-based system provide ample opportunity for much-needed diversification. Diversification is a key to address not only the issues of a faster-declining water table but also the perceived challenges of food and nutrition security.

While all the studies included in the meta-analysis had grain yield data, most did not have all the performance parameters, namely, grain and PEYs, water use efficiency and net economic return; hence, analyses may not have captured the relative performance of CA. Research on CA in South Asia is largely focused on rice-based and maize-based systems, resulting in fewer studies in other cropping systems. Nevertheless, it is notable that rice-based and maize-based are the most dominant cropping systems in South Asia. Published data on GHG emissions under CA were limited, and only emissions from on-station studies in the rice–wheat system were available. Most studies also lacked soil information (texture). Another notable limitation was that there were not many long-term studies to assess the residual effects of CA on succeeding crops.

All the crops, including rice, had higher average yields in loam than in clay or sand. These results may explain the variable performance of CA reported by those that did not consider soil texture as a factor[26]. These findings highlight the need for a better environmental characterization for targeting CA by appropriately defining recommendation domains. Greater benefits in the field studies carried out by the researchers compared with those implemented by farmers are probably attributable to knowledge gaps that influence appropriate implementation of CA practices.

The use of CA not only provides significant private benefits but can contribute to several ecosystem services[13]. In our data, GWP was reduced by 12.4% in CA1 and 33.5% in CA2 in rice–wheat systems, values that are consistent with others[19]. Moreover, public benefits are not limited to GHG emissions. Residue burning is a serious public health threat in South Asia, and approximately 23 million tons of rice residues are burned every year in Northwest India[27]. The CA-based practices provide an economically feasible alternative to burning, which has been made possible with the development of 'next generation' seeders that permit ZT into heavy residues[28,29].

Beyond the potential benefits that our study directly assessed, CA is largely mechanized and hence provides opportunity for (1) timeliness of operations, reducing risks[21,30,31], (2) increasing use efficiency of fertilizers through precise placement[23,32,33] and (3) reducing drudgery and hence attracting youth and women to remain engaged in agriculture[34].

Our extensive literature examination of published studies on CA and a large number of on-farm trials revealed the need for a pragmatic approach to scaling CA practices. Few farmers in South Asia are able

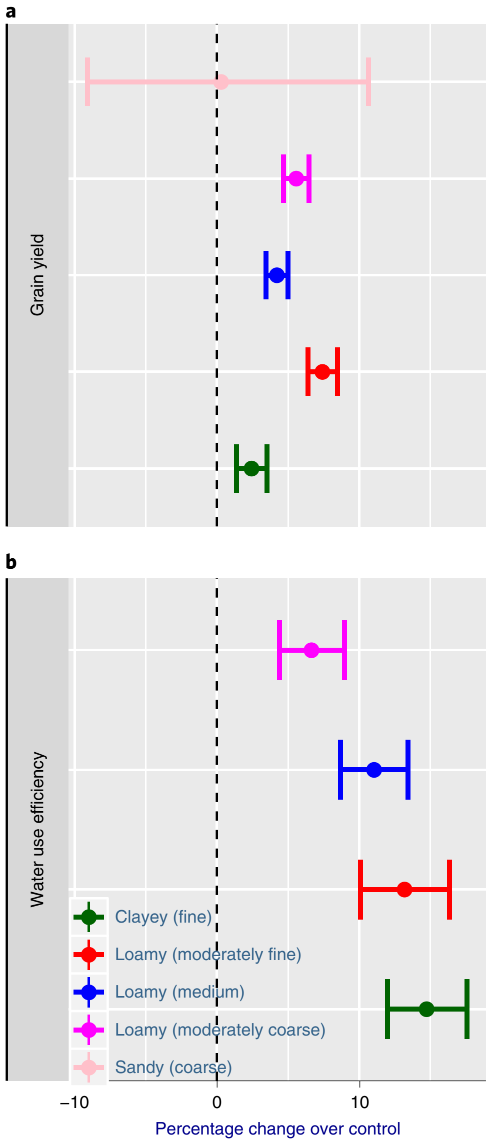

Fig. 3 | Effect of soil texture on the performance of CA. a,**b**, The percentage change over control in terms of grain yield (**a**) and water use efficiency (**b**). Error bars indicate 95% CIs; effect is significant at $P < 0.05$ if the CI does not overlap zero.

Table 3 | GHG emissions (methane and nitrous oxide) and GWP (on-station studies) under CA compared with conventional agricultural practice

	Methane	Nitrous oxide	GWP
CA category			
CA1	−12.8 (−21.4 to −4.5)	0.9 (−45.1 to 85.6)	−12.4 (−20.1 to −4.1)
CA2	−75.2 (−79.6 to −69.8)	12.2 (−26.2 to 70.8)	−33.5 (−39.1 to −27.5)
Cropping system			
Rice-wheat	−49.0 (−55.5 to 41.5)	8.6 (−23.1 to 53.3)	−24.1 (−28.1 to 19.8)
Crop			
Rice	−51.5 (−58.8 to −42.9)	−1.5 (−18.6 to 19.1)	−35.1 (−40.0 to −29.9)
Wheat	−42.8 (−58.5 to −21.1)	−5.5 (−18.3 to 9.2)	−9.8 (−16.7 to −2.2)
Soil texture			
Loamy (moderately fine)	−69.5 (−78.0 to −57.7)	22.2 (−28.0 to 107.3)	−29.5 (−34.6 to 24.1)
Loamy (medium)	−41.9 (−50.3 to −32.2)	−1.8 (−42.1 to 66.4)	−16.5 (−20.3 to −12.5)

to adopt all three elements of CA at once, but benefits of partial adoption are clear. Some of the impediments to full adoption include the conflicting edaphic requirements of crops in a system; for example, rice grown in a rainy or wet season gets flooded before planting, which makes residue retention difficult[35]. However, our analysis suggests that the classical definition of CA should not limit the smallholder farmers from adopting CA elements (CA1, CA2 or CA3) as their application separately or in tandem has potential benefits. Most farmers in South Asia follow ZT in only one crop, and few farmers retain complete residue cover at the soil surface throughout the annual cropping cycle. This situation has been observed and discussed by others but has not been resolved in terms of characterizing CA[36,37].

According to our findings, if 50% of the area under the dominant cereal-based cropping systems (rice–wheat, rice–maize, maize–wheat, cotton–wheat and pigeon pea–wheat) of South Asia is brought under CA by 2030, there will be additional outputs of 3.6 million metric tons of grain and 0.5 million metric tons of grain protein on an annual basis (Supplementary Table 8). In addition, water used for irrigation will be reduced by 14,100 million m^3, GWP (CO$_2$e) will be reduced by 2.9 million tons and farmer income will increase by US$1,771 million. A concerted effort involving public and private stakeholders supported by an effective enabling environment for technology scaling is required. A renewed eco-regional initiative like the Rice–Wheat Consortium for the Indo-Gangetic Plains[38,39] is perhaps part of the answer, with the provision that market-led approaches must be at the centre of the approach[16]. It is noteworthy that the Rice–Wheat Consortium pioneered and led much of the strategic and adaptive research on CA in South Asia, resulting in an accumulation of knowledge[15,40], which largely made this meta-analysis possible.

Our results clearly show that while adoption of full CA is often superior on the basis of multi-criteria assessment, it is not always necessary to achieve meaningful benefits in the South Asian context. Since the benefits of partial adoption of CA practices are consistently observed in the cereal-based cropping systems in South Asia, rigid adherence to an 'all or nothing' approach to scaling CA does not seem warranted. More fundamentally, our results suggest that conclusions regarding the potential of CA derived from global meta-analyses[14] or those reported from Africa[41,42] do not hold true for the cereal-based cropping systems of South Asia. It is important to note that agriculture in South Asia is different from that in the rest of the world. The cropping system in South Asia is predominantly under irrigated management and is very intensive, with two or more crops in a year. It is likely that these situations respond differently to CA compared with other regions where CA has been evaluated in less-intensive systems and under rain-fed situations. The benefits of CA can be best achieved through proper use of machinery. One unique aspect of South Asia is the small size of farms, and many farmers cannot afford to own equipment. More service providers and promotion through policies, loans and training are needed to accelerate the adoption of CA. Sensible approaches to agricultural development in the South Asia region will embrace the evidence-based potential of the practices while being realistic about the magnitude of achievable gains and deploying more targeted approaches to scaling that prioritize crops and soil types where expected benefits are the highest.

Methods

Data mining. Extensive literature review revealed that most published and unpublished on-station/on-farm studies had not followed the three defined CA principles[43]. This is not surprising because it is often not practical in the context of diverse cropping/farming systems comprising crops with conflicting requirements and farmers' preferences and circumstances[8,44]. Our literature search therefore led us to formulate three key sublevels of CA (Table 1). We compared the three CA-based tillage and CE practices (treatments) with those of the control (conventional tillage (CT) along with conventional CE with residue removed or burnt or incorporated) in double- to triple-crop annual systems: (1) ZT direct seeding in either crop and residue removed or retained in one or both the crops in double-crop systems (CA1), (2) ZT direct seeding in both crops and residue retained in one or both the crops in double-crop systems (CA2) and (3) ZT direct seeding in all crops and residue retention on the soil surface in at least both main (cereal) crops in a system of three crops (CA3). A control in the on-station studies is referred to as the best management practices or recommended package of practices (nutrient, varieties, seed rate, plant spacing and so on) for conventional tillage-based systems that is often mentioned in the publications. Similarly, a control in on-farm studies, which are also researcher managed, is referred to as best management practices for CT. The full details regarding range of tillage and CE options are given in Supplementary Table 9.

In this paper, we have referred to all three CA-based tillage and CE sublevels as CA, irrespective of their magnitude.

The data used in this paper were obtained from on-station studies conducted by the researchers (a total of 2,741 paired data points from 155 on-station studies carried out from 2000 to 2018) and from on-farm studies conducted by the researchers in participation with farmers (a total of 1,197 paired data points from 1,097 on-farm studies carried out during 2003–2018) in South Asia (Supplementary Table 10). These made 9,686 paired comparisons representing different numbers of performance indicators under different CA categories, cropping systems, crops and soil textures. The on-station data were archived from 143 original peer-reviewed publications and 13 proceedings/book chapters/reports through the Web of Science and Google Scholar search, libraries and personal communications (Supplementary Note). The on-farm original data (published/unpublished) were obtained from researchers on a personal contact basis as well as using open access data. In on-farm data, trials conducted in a given year in a specific location and soil type under a single cropping system with similar management practices (CA sublevels) were identified (or referred to) as a single study.

The peer-reviewed publications dealing with the effects of zero tillage in relation to the CT practice were searched, using the Web of Science (Elsevier) indexing service, with keywords 'tillage', 'conservation', 'zero tillage', 'no-tillage', 'cropping system', 'crop', 'residue', 'yield', 'water use', 'cost', 'economics', 'methane', 'carbon dioxide', 'nitrous oxide' and 'global warming potential' in different combinations in the article abstract. Proceedings/book chapters/reports were included, and non-English language publications were excluded.

Studies were selected on the basis of the following criteria exclusively:

1. Field experiments with side-by-side comparisons of CA and CT practices
2. CA practices falling within the three options described in Table 1
3. Studies conducted in the same location and same soil type with the same crop management practices in CA and CT options
4. Studies that used the same methods of measurements in CT and CA options
5. Studies that reported yield data

Performance parameters and the methods of measurement. The following performance parameters were considered in the analysis: (1) grain yield (Mg ha^{-1}), (2) water use efficiency (ratio of yield (Mg ha^{-1}) and water (irrigation plus rain) input (mm ha^{-1}) to the crop/cropping system from sowing to harvest), (3) GHG (CH_4 and N_2O; CH_4-C kg ha^{-1}and N_2O-N kg ha^{-1}) emissions, CO_2e emission (Mg ha^{-1}) and GWP, (4) cost of cultivation and net economic return (US$ ha^{-1}) during a cropping season and (5) PEY. On-farm studies had GHG estimation in terms of CO_2e emissions (Mg ha^{-1}). In addition, other basic parameters such as location, key soil characteristics, fertilizer inputs, sowing and harvest time, seed rate and weed control were recorded.

Crops were manually or mechanically harvested and allowed to dry in the sun before threshing. Grain yields were recorded at harvest or at physiological maturity from the net plot area ranging from 5 to 200 m^2, with moisture adjustment at 12–14% (rice and wheat) and 14–15% (maize and other crops).

The PEY was calculated on the basis of the percentage protein content in crops following the formula:

$$\text{PEY of the crop} = [\text{Yield of the crop (kg ha}^{-1}) \times \text{average crude protein content in grains of the crop }(\%)]/100 \quad (1)$$

Details of the average crude protein content are available in the Supplementary Methods.

Total water input was computed as the sum of water applied through irrigation and effective rainfall during the crop growing period. Irrigation water input was computed by multiplying the discharge (measured through v-notch/Parshall flume/digital velocity metre/water metre) and the time required for the irrigation. Otherwise, depth of irrigation was used to calculate the total amount of water applied to a plot. Irrigation water depth was calculated on the basis of soil moisture deficit (using a soil moisture sensor, for example, tensiometer, time domain reflectrometer, gravimetric) at the root zone. Irrigation was mostly given at critical/recommended growth stages of the crops or when the soil moisture deficit reached a threshold limit. Rainfall data were measured in situ (by using a rain gauge) or collected from a nearby weather station. Effective rainfall was calculated using standard methods given by the Food and Agriculture Organization of the United Nations (FAO)[45] or, in some studies, by using CropWat or from soil–water balance wherein the change in soil water content was monitored periodically. Water use efficiency was computed as the ratio of yield and water input.

Total variable cost of cultivation included cost of human labour (person days ha^{-1} or 8 h equivalent; minimum wage rate by the government; time (h) required to complete a particular field operation in a given treatment), tractor (time required by a tractor-drawn machine to complete field operations of tillage, seeding, fertilizer application and harvesting; h ha^{-1}), inputs (tillage, seeds, planting, irrigation, fertilizer, pesticide, weeding and so on) and cost of electricity. In cases where crop residue was retained, the cost of residues (as an alternative source of feed or fuel) was accounted for. The cost of irrigation was calculated by multiplying time (h) required to irrigate a plot, consumption of diesel by the pump (l h^{-1}) and cost of diesel. All costs were estimated on the basis of approved market rates for inputs as fixed by the respective governments. Gross return was calculated as follows:

$$\begin{aligned}\text{Gross return} &= \text{grain yield} \times \text{minimum support price or the standard local price} \\ &\quad + \text{straw yield} \times \text{current market price}\end{aligned} \quad (2)$$

Government's guaranteed minimum support prices (per 100 kg) were rice (US$20.70), wheat (US$22.50), maize (US$19.50), soybean (US$38.80), cotton (US$55.80), pigeon pea (US$68.60), pulses (US$71.70) and ground nut (US$59.90). All prices were the average of the minimum support prices for years 2014–2015, 2015–2016 and 2016–2017.

Net economic return was the gross return minus the cost of cultivation. All these were expressed in US$ ha^{-1} (where currency other than US$ was mentioned, it was converted to US$ with the average exchange rates of 2014–2017).

In on-station studies, the GHG measurements were based on closed static chamber techniques with gas samples analysed using a gas chromatograph equipped with a flame ionization detector (for CH_4) and an electron capture detector (for N_2O). Emissions between two adjacent measurement days were interpolated, and total gas emissions over the season were cumulated. In on-farm data, GHG emissions were estimated by taking the CO_2e emission (Mg ha^{-1}). The GWP was estimated from CH_4 and NO_2 emissions, multiplying with the respective GWP coefficients and summing these (Supplementary Methods).

Categorical variables (moderators). The performance parameters were further categorized on the basis of cropping system, crop and soil texture. A total of 26 crop systems appeared in our on-station search, but only major systems were considered in the database. Key cropping systems included were rice–wheat, maize–wheat, rice–maize, cotton–wheat, soybean–wheat and pigeon pea–wheat. An additional category referred to as 'others' was created to include less-predominant cropping systems (ground nut–mustard, cluster bean–wheat, mung bean–wheat and pearl millet–mustard). The on-farm data comprised five cropping systems: rice–wheat, maize–wheat, rice–maize, rice–lentil and rice–mung bean. In the combined (on-station + on-farm) analysis, rice–wheat, maize–wheat and rice–maize were included along with a fourth category 'others' where all others cropping systems were collectively taken. Analysis was also done for individual crops (maize, rice and wheat) of only dominant cropping systems (rice–wheat, maize–wheat, rice–maize). Soil textural classes of the study areas were categorized into five major texture groups: clayey (fine), loamy (moderately fine, medium and moderately coarse) and sandy (coarse). To investigate the combined effect of CA, the data points of three sublevels (CA1, CA2 and CA3) were combined for a comparison with the control and referred to as CA. For all the parameters, pair-wise data were used for calculation of effect size, and in none of the cases was cumulative or system yield considered for either of the CA groups.

Statistical analysis. The effect size was calculated for each study as the natural logarithm of the response ratio (LRR) using the following equation[46]:

$$\text{Effect size} = \text{LRR} = \ln\left[\frac{\text{Mean}_{\text{CA}}}{\text{Mean}_{\text{CS}}}\right] \quad (3)$$

where Mean_{CA} and Mean_{CS} are means of parameters under CA and conventional system (CS, control), respectively.

Since within-study variance of means of parameters was not available for most of the on-station studies, individual observations were weighted by the experimental replications[47] (equation (4)). However, in on-farm studies, replicated observations were available, and therefore the variance could be calculated. 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. The LRR was finally back-transformed to generate the percentage change of parameters (equation (5)).

$$\text{Weight} = \frac{N_{\text{CA}} \times N_{\text{CS}}}{N_{\text{CA}} + N_{\text{CS}}} \qquad (4)$$

$$\text{Percentage change} = [\exp(\text{LRR}) - 1] \times 100 \qquad (5)$$

where N_{CA} and N_{CS} are number of replicates for the CA and CS, respectively.

The 'metafor'[48] package in R was used for generating the LRR and the corresponding variance from individual studies, which were subjected to meta-regression (mixed-effect) models with or without moderators to generate the main effect and the interactions between two moderators. Effects were considered significant if the 95% confidence intervals (CIs) did not overlap with zero ($P = 0.05$). Effects for different moderators varied significantly when their CIs did not overlap. The between-study variability (heterogeneity) and the publication bias were also evaluated before analysis (Supplementary Methods and Supplementary Fig. 2).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available on request from the corresponding author on a case-by-case basis. The on-station data sources have been listed in the Supplementary Information. Source Data for Figs. 1–3 are provided as Source Data files.

Code availability

The reproducible code for the analyses is available at https://github.com/wviechtb/metafor; common code for generating figures is available at https://ggplot2.tidyverse.org/.

Received: 15 July 2019; Accepted: 25 February 2020;
Published online: 16 April 2020

References

1. Hattleback, M. *Malnutrition in South-Asia. Poverty, Diet or Lack of Female Empowerment?* CMI Working Pap. Wp. 4, 14 (CMI, 2012).
2. *The Future of Food and Agriculture: Trends and Challenges* (FAO, 2017).
3. Amarnath, G., Alahacoon, N., Smakhtin, V. & Aggarwal, P. *Mapping Multiple Climate-Related Hazards in South Asia* Research Report 170 (IWMI, 2017).
4. Muthukumara, M., Bandyopadhyay, S., Chonabayashi, S., Markandya, A. & Mosier, T. *South Asia's Hotspots: Impacts of Temperature and Precipitation Changes on Living Standards* (World Bank, 2018).
5. Tilman, D., Balzer, C., Hill, J. & Befort, B. L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* **108**, 20260–20264 (2011).
6. Godfray, H. C. J. & Garnett, T. Food security and sustainable intensification. *Phil. Trans. R. Soc. B* **369**, 20120273 (2014).
7. *What Is Conservation Agriculture?* (FAO, 2014).
8. Giller, K., Witter, E., Corbeels, M. & Tittinell, P. A. Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Res.* **114**, 23–24 (2009).
9. Rusinamhodzi, L. et al. A meta-analysis of long-term effects of maize grain yield under rain-fed conditions. *Agron. Sust. Dev.* **31**, 657–673 (2011).
10. Friedrich, T., Derpsch, R. & Kassam, A. Overview of the global spread of conservation agriculture. *Field Actions Sci. Rep.* **6** (Special issue), 1–7 (2012).
11. Jat, M. L. et al. (eds) *Proc. Regional Dialogue on Conservation Agriculture in South Asia* (CIMMYT; APAARI; ICAR, 2012).
12. Brouder, S. M. & Gomez-Macpherson, H. The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. *Agric. Ecosyst. Environ.* **187**, 11–32 (2014).
13. Palm, C., Bnalco-Canqui, H., Declerck, F., Gatere, L. & Grace, P. Conservation agriculture and ecosystem services: an overview. *Agric. Ecosyst. Environ.* **187**, 87–105 (2014).
14. Pittelkow, C. M. et al. Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**, 365–368 (2015).
15. Harrington, L. W. & Hobbs, P. H. in *Integrated Crop and Resource Management in the Rice–Wheat System of South Asia* (eds Ladha, J. K. et al.) 3–67 (ADB, 2009).
16. Kiel, A., D'Souza, A. & McDonald, A. Growing the service economy for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: lessons from custom hiring services for zero-tillage. *Food Secur.* **8**, 1011–1028 (2016).
17. Erenstein, O. & Laxmi, V. Zero tillage impacts in India's rice–wheat systems: a review. *Soil Tillage Res.* **100**, 1–14 (2008).
18. Ladha, J. K. et al. in *Integrated Crop and Resource Management in the Rice–Wheat System of South Asia* (eds Ladha, J. K. et al.) 69–108 (ADB, 2009).
19. Huang, Y. et al. Greenhouse gas emissions and crop yield in no-tillage systems: a meta-analysis. *Agric. Ecosyst. Environ.* **268**, 144–153 (2018).
20. Van den Putte, A., Govers, G., Diels, J., Gillijns, K. & Demuzere, M. Assessing the effect of soil tillage on crop growth: a meta-regression analysis on European crop yields under conservation agriculture. *Eur. J. Agron.* **33**, 231–241 (2010).
21. Jat, R. K. et al. Ten years of conservation agriculture in a rice–maize rotation of Eastern Gangetic Plains of India: yield trends, water productivity and economic profitability. *Field Crop. Res.* **232**, 1–10 (2019).
22. Gathala, M. K. et al. Effect of tillage and crop establishment methods on soil physical properties of a medium-textured soil under a seven-year rice–wheat rotation. *Soil Sci. Soc. Am. J.* **75**, 1851–1862 (2011).
23. Jat, R. D. et al. Conservation agriculture and precision nutrient management practices in maize–wheat system in North-West IGP: effects on crop and water productivity and economic profitability. *Field Crops Res.* **218**, 33–50 (2018).
24. Kumar, V. & Ladha, J. K. Direct seeding of rice. Recent developments and future research needs. *Adv. Agron.* **111**, 297–413 (2011).
25. Chakraborty, D. et al. A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. *Sci. Rep.* **7**, 9342 (2017).
26. Pittelkow, K. M. et al. When does no-till yield more? A global meta-analysis. *Field Crops Res.* **183**, 156–168 (2015).
27. Shyamsundar, P. et al. Fields on fire: alternatives to crop residue burning in India. *Science* **365**, 536–538 (2019).
28. Sidhu, H. S. et al. Development and evaluation of Turbo Happy Seeder to enable efficient sowing of wheat into heavy crop rice residue in rice–wheat rotation in the IGP of NW India. *Field Crops Res.* **184**, 201–212 (2015).
29. Shyamsundar, P. Can India's farmers deliver clean air along with good food? *Cool Green Science* https://go.nature.com/3aJkWUT (2017).
30. Aryal, J. P. et al. Conservation agriculture-based wheat production better copes with extreme climate events than conventional tillage-based systems: a case of untimely excess rainfall in Haryana, India. *Agric. Ecosyst. Environ.* **233**, 325–335 (2016).
31. Jat, M. L. in *Agriculture under Climate Change: Threats, Strategies and Policies* (eds Belavadi, V. V., Nataraja Karaba, N. & Gangadharappa, N. R.) 147–154 (Allied Publishers Pvt. Ltd., 2017).
32. Singh, Yadvinder et al. Nitrogen management for zero till wheat with surface retention of rice residues in north-west India. *Field Crops Res.* **184**, 183–191 (2015).
33. Sidhu, H. S. et al. Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: a breakthrough for addressing water and nitrogen use efficiency. *Agric. Water Manag.* **216**, 273–283 (2019).
34. Groot, A. E. et al. Business models of SMEs as a mechanism for scaling climate smart technologies: the case of Punjab, India. *J. Clean. Prod.* **210**, 1109–1119 (2019).
35. Alam, M. M. et al. Improvement of cereal-based cropping systems following the principles of conservation agriculture under changing agricultural scenarios in Bangladesh. *Field Crop Res.* **175**, 1–15 (2015).
36. Kirkegaard, J. A. et al. Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. *Agric. Ecosyst. Environ.* **187**, 133–145 (2014).
37. Ladha, J. K. et al. Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. *Glob. Change Biol.* **22**, 1054–1074 (2016).
38. Seth, A., Fischer, K., Anderson, J. & Jha, D. *The Rice-Wheat Consortium: An Institutional Innovation in International Agricultural Research on the Rice–Wheat Cropping Systems of the Indo-Gangetic Plains (IGP)* The Review Panel Report (Rice-Wheat Consortium, 2003).
39. Gupta, R. & Seth, A. A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic Plains (IGP). *Crop Prot.* **26**, 436–447 (2007).
40. Ladha, J. K., Pathak, H., Tirol-Padre, A., Dawe, D. & Gupta, R. K. in *Improving the Productivity and Sustainability of Rice–wheat Systems: Issues and Impacts* (eds Ladha et al.) 45–76 (ASA, CSA and SSSA, 2003).
41. Giller, K., Witter, E., Corbeels, M. & Tittinell, P. A. Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Res.* **114**, 23–24 (2009).
42. Giller, K. E. et al. Beyond conservation agriculture. *Front. Plant Sci.* **6**, 870 (2015).
43. Kassam, A., Friedrich, T. & Derpsch, R. Global spread of conservation agriculture. *Int. J. Environ. Stud.* **76**, 29–51 (2018).
44. Ridaura, S. L. et al. Climate smart agriculture, farm household typologies and food security: an ex-ante assessment from Eastern India. *Agric. Sys.* **159**, 57–68 (2018).

45. Dastane, N. G. *Effective Rainfall in Irrigated Agriculture* Irrigation and Drainage Paper 25 (FAO, 1974).
46. Hedges, L. V., Gurevitch, J. & Curtis, P. S. The meta-analysis of response ratios in experimental ecology. *Ecology* **80**, 1150–1156 (1999).
47. Adams, D. C., Gurevitch, J. & Rosenberg, M. S. Resampling tests for meta-analysis of ecological data. *Ecology* **78**, 1277–1283 (1997).
48. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **36**, 1–48 (2010).

Acknowledgements

We thank the Indian Council of Agricultural Research (ICAR), Government of India for Window 3 grant to CIMMYT, the CGIAR Research Programs on Wheat Agri-Food Systems (CRP WHEAT) and Climate Change, Agriculture and Food Security (CCAFS) for funding this research. CCAFS's work is supported by CGIAR Fund Donors and through bilateral funding agreements. For details, please visit https://ccafs.cgiar.org/donors. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the associated and/or supporting institutions/funders. The usual disclaimer applies.

Author contributions

M.L.J. conceptualized, designed and coordinated the work. M.L.J., D.C., M.K.G. and D.S.R. acquired the data. D.C. and D.S.R. analysed the data and interpreted results. J.K.L. supervised and drafted the work, interpreted results and revised the manuscript. A.M. and B.G. interpreted results and revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-020-0500-2.

Correspondence and requests for materials should be addressed to M.L.J.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

nature research

Corresponding author(s): Mangi Jat

Last updated by author(s): Feb 18, 2020

Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see Authors & Referees and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☐	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	The data used in this study were obtained from on-station trials conducted by the researchers (a total of 2741 paired data points from 156 on-station studies carried out from 2000-2018) and from those conducted on-farm by the researchers in participation with farmers (a total of 1197 paired data from 1097 on-farm studies carried out during 2003-2018) in South Asia. The on-station data were archived from 143 original peer-reviewed publications and 13 proceedings/book chapters/reports through the Web of Science and Google Scholar search, libraries, and personal communications. The on-farm original data (published/unpublished) were obtained from researchers on a personal contact basis as well as using open access data. Details are given in Supplementary Information.
Data analysis	All the variables were subjected to the meta-analysis by using 'R' in two stages: 1) the effect size was calculated for each study as the natural log of the response ratio (LRR) and 2) effect sizes from individual studies were combined using a random-effects model and was considered significant if the 95% confidence intervals [Mean ± 1.96 * SD/Sqrt (number of observations); 1.96 is the ‘z’-value at 95%] did not overlap with zero. Since within-study variance of means of parameters was not available for most of the OS studies, individual observations were weighted by the experimental replications. However, in on-farm studies, replicated observations were available, and therefore the variances were calculated. 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. The log response ratio (LRR) was finally back-transformed to generate the percent change of parameters. Meta-analysis was also performed for the groups (cropping system, individual crop and soil texture). The between-study variability (heterogeneity) and the publication bias were also evaluated before analysis. Supplementary Information includes details of data analysis methods.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

A list of on-station studies, which were used in meta-analysis has been provided in the Supplementary Information file. The on-farm data (in MS Excel format) is available with the lead author, and will be provided upon request.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This is a meta-analysis to assess performance of three core elements of conservation agriculture (CA) against the conventional best management practice. The performance parameters were grain and protein equivalent yields, water input, cost of cultivation and net return and green-house gases emission. The categorical variable were selected as crop rotation, crop and soil texture.
Research sample	Data from on-station trials (2741 paired data points from 156 studies between year 2000-18; collected and compiled from 143 original peer-reviewed publications and 13 proceedings/book chapters/reports through the Web of Science and Google Scholar search, libraries, and personal communications) and on-farm experimentations (published/unpublshed) was used in the analysis.
Sampling strategy	No sampling strategy is applicable here. All data (Explained above) were used in the meta-analysis.
Data collection	On-station data were collected from peer-reviewed publications (published between 2000 and 2018) by searching through Web of Science (Elsevier) indexing service and Google Scholars with relevant keywords. Proceedings/book chapters/reports were included, and non-English language publications were excluded. On-farm data were collected from researchers on personal communication basis.
Timing and spatial scale	All data (On-station) pertains to the period between 2000 and 2018. Period of on-farm data was 2003 and 2008-18.
Data exclusions	No data were excluded from the compilation.
Reproducibility	There was no experiment involved in this study. On-station and on-farm Data (explained above) were analyzed by using open source 'R' software by following set procedure. The software performs 999 iterations during computation of cumulative effect size.
Randomization	Radomization is not relevant to this study
Blinding	Not relevant to the study.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology
☒	☐	Animals and other organisms
☒	☐	Human research participants
☒	☐	Clinical data

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging