



**HAL**  
open science

**Carbon sequestration potential through conservation agriculture in Africa has been largely overestimated. Comment on: “Meta-analysis on carbon sequestration through conservation agriculture in Africa”**

Marc Corbeels, Rémi Cardinael, David S. Powlson, Regis Chikowo, Bruno Gérard

► **To cite this version:**

Marc Corbeels, Rémi Cardinael, David S. Powlson, Regis Chikowo, Bruno Gérard. Carbon sequestration potential through conservation agriculture in Africa has been largely overestimated. Comment on: “Meta-analysis on carbon sequestration through conservation agriculture in Africa”. *Soil and Tillage Research*, 2020, 196, pp.104300. 10.1016/j.still.2019.104300 . hal-02454023

**HAL Id: hal-02454023**

**<https://hal.science/hal-02454023>**

Submitted on 24 Jan 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Carbon sequestration potential through conservation agriculture in Africa has been**  
2 **largely overestimated**

3 *Comment on: “Meta-analysis on carbon sequestration through conservation agriculture in*  
4 *Africa”*

5 Marc Corbeels<sup>1,2,\*</sup>, Rémi Cardinael<sup>1,3</sup>, David Powlson<sup>4</sup>, Regis Chikowo<sup>3</sup> and Bruno Gerard<sup>5</sup>

6 <sup>1</sup> Agroecology and Sustainable Intensification of Annual Crops - AIDA, University of  
7 Montpellier, French Agricultural Research Centre for International Development - CIRAD,  
8 Montpellier, France

9 <sup>2</sup> Sustainable Intensification Program, International Maize and Wheat Improvement Centre -  
10 CIMMYT, Nairobi, Kenya

11 <sup>3</sup> Crop Science Department, University of Zimbabwe, Harare, Zimbabwe

12 <sup>4</sup> Department of Sustainable Agriculture Sciences, Rothamsted Research, Harpenden, United  
13 Kingdom

14 <sup>5</sup> Sustainable Intensification Program, International Maize and Wheat Improvement Centre -  
15 CIMMYT, El Batán, Mexico

16

17 \*Corresponding author: [corbeels@cirad.fr](mailto:corbeels@cirad.fr)

18 CIMMYT

19 United Nations Avenue

20 Gigiri

21 Nairobi, Kenya

22

23 Soil organic carbon (SOC) sequestration depends on several factors, including land use, pedo-  
24 climatic conditions, topographic position and the initial SOC stock (Post and Kwon, 2000;  
25 Minasny et al., 2017). At the plot scale, a positive SOC balance is created by increasing the  
26 input of organic matter to the soil to exceed the carbon (C) losses by mineralization, leaching  
27 and erosion or by decreasing the rate of SOC decomposition. In Africa, agricultural soils are  
28 generally known to have potential as a C sink due to previous SOC depletion (Vågen et al.,  
29 2005; Swanepoel et al., 2016). Two widely promoted crop management practices to store C in  
30 agricultural soils are conservation agriculture (CA) and agroforestry. Both practices can  
31 increase SOC through increased C inputs from higher biomass productivity and reduced C  
32 losses (through soil cover), leading to a net transfer of C from the atmosphere to the soil, thus  
33 contributing to the mitigation of climate change (Smith et al., 2005, Powlson et al., 2011;  
34 Griscom et al., 2017).

35 In their recent study published in *Soil and Tillage Research*: “Meta-analysis on carbon  
36 sequestration through conservation agriculture in Africa”, Gonzalez-Sanchez et al. (2019)  
37 conclude that the practice of CA in Africa can effectively contribute to mitigating global  
38 warming through SOC sequestration. Gonzalez-Sanchez et al. (2019) claim that the SOC  
39 sequestration potential through CA for the African continent is  $143 \text{ Tg C yr}^{-1}$  on 160 Mha  
40 cropland (including perennial woody crops) which corresponds to about  $0.90 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ .

41 Good estimates of the SOC sequestration potential with CA are certainly of great interest to  
42 policymakers at various levels of government in Africa regarding the nations’ commitments to  
43 reduce greenhouse gas emissions by 2020. As a result, greater investments in research and  
44 innovations for the development and scaling of CA practices may be decided. However, we  
45 argue that the mitigation calculations and interpretations by Gonzalez-Sanchez et al. (2019) are  
46 flawed and biased.

47 Gonzalez-Sanchez et al. (2019) evaluated datasets from a number of studies in Africa for their  
48 estimations of annual per-area SOC sequestration rates with CA practiced in annual or woody  
49 perennial cropping systems for four climatic zones (i.e. Mediterranean, Sahelian, Tropical and  
50 Equatorial, see Figure 1 and Table 1 in their study). In their analysis, the total SOC  
51 sequestration potential for Africa was then calculated from the climate-specific rates and from  
52 estimated total land areas cultivated with annual and woody perennial crops in the different  
53 countries (from FAOSTAT, <http://fao.org/faostat/en/#data> ), considering the major climate(s)  
54 in each country. Finally, they compared their estimate of sequestration potential with an  
55 estimated current annual SOC sequestration based on present areas of cropland under CA. They  
56 conclude that the total annual SOC sequestration potential through CA in Africa is about 93  
57 times the current estimated figure.

58

59 Here, we challenge the excessively optimistic results of their study.

60

61 First, in contrast with their claims, the reported annual per-area SOC sequestration rates under  
62 CA in their study (see Table 1 in their paper) are high, ranging from 0.44 Mg C ha<sup>-1</sup> yr<sup>-1</sup>  
63 (Mediterranean climatic zone) to 1.56 Mg C ha<sup>-1</sup> yr<sup>-1</sup> (Equatorial climatic zone) for annual  
64 crops, and from 0.12 Mg C ha<sup>-1</sup> yr<sup>-1</sup> (Sahelian climatic zone) to 1.29 Mg C ha<sup>-1</sup> yr<sup>-1</sup>  
65 (Mediterranean climatic zone) for woody perennial crops. The resulting average rates for the  
66 whole of Africa are 0.92 and 0.70 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for CA with annual and woody perennial  
67 crops, respectively (recalculated from Table 3 and 4 in their study). Even though Gonzalez-  
68 Sanchez et al. (2019) refer to their analysis as a meta-analysis, their reported figures do not  
69 reveal any use of statistical tests, lacking any indicator of data variability and uncertainty of  
70 their estimates. In fact, from their paper it is not clear which, and how many studies were used

71 for their estimates of annual per-area SOC sequestration rates. They simply list the publications  
72 they referred to but do not cite any “supplementary information” that presents the data used to  
73 derive their mean values.

74

75 We estimated average SOC sequestration rates for CA on croplands per climatic zone from  
76 published studies used in a recent literature review (Corbeels et al., 2019). Our results for the  
77 Tropical and Equatorial climate zones show rates that are 20-60% of those reported by  
78 Gonzalez-Sanchez et al. (2019) and show high variability (Table 1). Since the review by  
79 Corbeels et al. (2019) only referred to sub-Saharan Africa (excluding South Africa), the  
80 Mediterranean region was not considered. No studies were found in Corbeels et al. (2019) for  
81 the Sahelian climatic zone. The sequestration rate of 0.5 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for annual crops in the  
82 Sahelian region given by Gonzales-Sanchez et al (2029) seems extraordinarily high given the  
83 strong water limitations to crop growth in this region. Average cereal yields in this region are  
84 1000 kg ha<sup>-1</sup> or less (<http://fao.org/faostat/en/#data>). Assuming a harvest index of 0.35 and a  
85 root:shoot ratio of 0.3 (corresponding to the 0–30 cm soil layer), this represents a potential  
86 annual input of about 2700 kg dry matter ha<sup>-1</sup>, corresponding to about 1200 kg C ha<sup>-1</sup>. A  
87 sequestration rate of 0.5 Mg C ha<sup>-1</sup> yr<sup>-1</sup> would mean that 42% of the C input is converted into  
88 SOC, which is clearly not plausible. A recent study on SOC sequestration in tropical croplands  
89 found that the conversion rate of C inputs to SOC was 8.2 ± 0.8% (Fujisaki et al., 2018). Smith  
90 et al. (2008) estimated that the annual per-area sequestration rate for no-tillage and residue  
91 management practices in warm-dry regions was about 0.10 Mg C ha<sup>-1</sup> yr<sup>-1</sup> with high uncertainty  
92 (range between -0.21 and 0.40 Mg C ha<sup>-1</sup> yr<sup>-1</sup>). Similar results were found for sub-Saharan  
93 Africa in the meta-analysis of Powlson et al. (2016).

94

95 Table 1. Soil carbon sequestration rates ( $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ , average and standard deviation) in  
 96 annual cropping systems under CA per climate zone (data from Corbeels et al., 2019, values  
 97 larger than  $4 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  or smaller than  $-4 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  were considered as outliers and  
 98 excluded).

Climatic Zone	Soil carbon sequestration rate ( $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ )
Sahel	No data
Tropical	$0.58 \pm 1.06$ (n = 17)
Equatorial	$0.32 \pm 1.53$ (n = 8)

99 n denotes the number of studies

100 Soil depth considered varies between 5 and 60 cm

101

102

103 Second, Gonzalez-Sanchez et al. (2019) estimated the cropland area in 2016 based on  
 104 FAOSTAT. This area include land that has recently been converted from native forest or  
 105 savannah. Given the relatively high original SOC stocks under forest or savannah land,  
 106 converting this land into agriculture will induce SOC losses irrespective of the type of  
 107 agricultural management practices employed (Sommer et al., 2018). For example, negative  
 108 SOC sequestration rates ( $-0.17$  to  $-0.55 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ) were reported in experiments in Nigeria  
 109 where CA was installed following recent clearing of native vegetation (Lal, 1998; Agbede,  
 110 2008). Thus, new croplands should have been excluded from the calculations of the SOC  
 111 sequestration potential. Based on data provided by FAOSTAT, the increase of cropland area  
 112 over the last ten years in Africa is estimated at about 15 to 20%.

113 Besides, Gonzalez-Sanchez et al. (2019) included in their calculations the land area on which  
 114 (most type of) woody perennial crops were cultivated in 2016. This land was considered as  
 115 land where CA could be practiced, labelled in their study as “CA in woody crops due to ground  
 116 cover”. However, it seems that the annual per-area SOC sequestration rates (Table 1 in their  
 117 study) were estimated from studies on agroforestry systems. In these studies, the control plot

118 is a treeless agricultural plot having the same tillage practice as the agroforestry plot. Therefore,  
119 the SOC sequestration rates are due to the presence of trees and are not linked to CA practices.  
120 In agroforestry systems, the soil can be tilled and is not necessarily covered by a mulch of crop  
121 residues, and tree crops can be grown in crop monoculture, as this was the case in many of the  
122 cited papers. Therefore, these rates cannot be used for woody perennial cropping systems  
123 practiced under CA. To have an estimation of the effect of CA in woody perennial cropping  
124 systems, we would need treatments in agroforestry with CA and with conventional tillage,  
125 which was not the case in the publications cited by the authors. Moreover, we found that the  
126 SOC sequestration rates were highly dependent on the type of agroforestry system (Cardinael  
127 et al., 2018, Corbeels et al., 2019). It is therefore not correct to group them in a single category  
128 as proposed by Gonzalez-Sanchez et al. (2019).

129

130 Third, Gonzalez-Sanchez et al. (2019) did not address the adoption rate of CA by farmers,  
131 supposing that all estimated cropland area (including woody perennial crops) in 2016 is easily  
132 and immediately converted to CA. This is misleading. As stated in their study, adoption of CA  
133 in 2016 covered an estimated 1.5 Mha of land, or 1.1 % of the total land area of annual crops.  
134 A realistically achievable mitigation potential must also consider the socio-economic realities  
135 of farmers (Smith et al., 2005). This consideration is crucial; it has been extensively discussed  
136 elsewhere (e.g. Giller et al., 2011) but was totally ignored by Gonzalez-Sanchez et al. (2019).  
137 Smallholder farmers in Africa often face significant technical, infrastructural or socio-  
138 economic barriers to the adoption of CA (Andersson and D'Souza, 2014; Corbeels et al., 2014).  
139 Therefore, it is not realistic to rely on immediate adoption of CA over millions of hectares as a  
140 major strategy to mitigate climate change (Powlson et al., 2016).

141 Fourth, we argue that the extrapolation of the per-area SOC sequestration rates over the whole  
142 of Africa using climatic zones is simplistic, ignoring important factors of SOC sequestration.  
143 Although a similarly simple approach is employed in the Tier 1 method of the  
144 Intergovernmental Panel on Climate Change (IPCC, 2006), it has clearly been shown in the  
145 broader literature that SOC sequestration depends to a large extent on soil properties (Feller  
146 and Beare, 1997; Torn et al., 1997). Countries in West Africa such as Mali, Burkina Faso or  
147 Niger are mainly characterized by sandy Arenosols and Lixisols, compared to e.g. Kenya,  
148 Tanzania or Ethiopia where largely Nitisols and Vertisols are present, that have a much more  
149 clayey texture. It is generally known that the SOC sequestration potential is considerably lower  
150 in sandy soils than in clayey soils (Chivenge et al., 2007). Yet in their analysis, the basic SOC  
151 sequestration rates used for e.g. Burkina Faso are the same (or higher) than of those for Ethiopia  
152 (Table 3 and 4). Digital soil maps for Africa are now available (<http://soilgrids.org>), which  
153 enables to include soil factors, such as soil texture, in SOC sequestration estimates, and could  
154 have been used by Gonzalez-Sanchez et al. (2019).

155

156 Finally, Gonzalez-Sanchez et al. (2019) compared their estimated SOC sequestration potential  
157 (i.e. 143 Tg C yr<sup>-1</sup>) with an estimated (current) SOC sequestration based on the present cropland  
158 area under CA (i.e. 1.5 Tg C yr<sup>-1</sup>). This is not correct. A baseline including other best crop  
159 management practices that increase C input to the soil, such as fertilization, irrigation,  
160 improved crop rotations, and agroforestry, should be used. It has been estimated that 7 to 15  
161 Tg C yr<sup>-1</sup> can be sequestered on croplands in Africa, assuming 20% of the croplands are  
162 subjected to improved management (Batjes, 2004).

163 For the reasons given in our analysis, we believe that Gonzalez-Sanchez et al. (2019) grossly  
164 overestimated the total SOC sequestration potential through the practice of CA in Africa.

165 Roughly, as a first approximation we estimate the potential at 10.8 Tg C yr<sup>-1</sup> assuming an  
166 average per-area rate of 0.45 Mg C ha<sup>-1</sup> yr<sup>-1</sup> and that 20% of the current soil C-depleted (annual)  
167 croplands (estimated at 120 Mha) are cultivated with CA. It is, however, important to note that  
168 SOC stocks do not increase forever, and that annual sequestration rates decline as the soil  
169 approaches a new equilibrium, which can take from 20 to +50 years depending on climate and  
170 soil type. Hence, rates cannot be extrapolated indefinitely (Paustian et al., 1997; Powlson et al.,  
171 2011, 2014). Lastly, it should also be mentioned that nitrous oxide (N<sub>2</sub>O) emissions could be  
172 enhanced in CA and, more generally, in practices with addition of organic amendments  
173 (Charles et al., 2017; Lugato et al., 2018; Mei et al., 2018), partially offsetting the climate  
174 benefits due to increased SOC storage.

175 It remains critical that we determine rates of SOC sequestration through improved agricultural  
176 practices, and the role they can play in helping to meet short- to medium-term reduction targets  
177 of greenhouse gas emission. It would, however, be appropriate for Gonzalez-Sanchez et al.  
178 (2019) to reflect on a more conservative assessment of the mitigation potential through CA in  
179 Africa. The presentation of implausible potentials leads to unrealistic expectations of climate  
180 change mitigation with improved agricultural management. There is a danger that presenting  
181 unrealistically high numbers of climate change mitigation potential through agricultural  
182 practices could have a negative impact on the necessary actions to reduce CO<sub>2</sub> emissions from  
183 fossil fuel combustion.

184 On the other hand, even if CA has limited value for climate change mitigation, the practice of  
185 CA – through crop residue mulching and crop diversification- is expected to enhance the  
186 resilience of cropping systems to climate change (Rusinamhodzi et al., 2011; Steward et al.,  
187 2018). This may bring livelihood benefits to farmers, especially in regions with increased risk  
188 of drought stress. Thus, it is more reasonable for policymakers and investors to plan promotion  
189 of CA for reasons of climate resilience benefits than for climate change mitigation.

190 **References**

- 191 Agbede, T.M., 2008. Nutrient availability and cocoyam yield under different tillage practices.  
192 Soil Tillage Res. 99, 49–57.
- 193 Andersson, J.A., D’Souza, S., 2014. From adoption claims to understanding farmers and  
194 contexts: A literature review of Conservation Agriculture (CA) adoption among  
195 smallholder farmers in southern Africa. Agric. Ecosyst. Environ. 187, 116–132.
- 196 Batjes, N. H. ,2004. Estimation of soil carbon gains upon improved management within  
197 croplands and grasslands of Africa. Environ. Dev. Sustain. 6, 133-143.
- 198 Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L., Bernoux, M., 2018. Revisiting  
199 IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry  
200 systems. Environ. Res. Lett. 13, 1–20.
- 201 Charles, A., Rochette, P., Whalen, J.K., Angers, D.A., Chantigny, M.H., Bertrand, N., 2017.  
202 Global nitrous oxide emission factors from agricultural soils after addition of organic  
203 amendments: A meta-analysis. Agric. Ecosyst. Environ. 236, 88–98.
- 204 Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of  
205 reduced tillage and residue management on soil carbon stabilization: Implications for  
206 conservation agriculture on contrasting soils. Soil Tillage Res. 94, 328–337.
- 207 Corbeels, M., Cardinael, R., Naudin, K., Guibert, H. Torquebiau, E., 2019. The 4 per 1000 goal  
208 and soil carbon storage under agroforestry and conservation agriculture systems in sub-  
209 Saharan Africa. Soil Tillage Res. 188,16-26.
- 210 Corbeels, M., de Graaff, J., Ndah, T.H., Penot, E., Baudron, F., Naudin, K., Andrieu, N., Chirat,  
211 G., Schuler, J., Nyagumbo, I., Rusinamhodzi, L., Traore, K., Mzoba, H.D., Adolwa, I.S.,

212 2014. Understanding the impact and adoption of conservation agriculture in Africa: A  
213 multi-scale analysis. *Agric. Ecosyst. Environ.* 187, 155–170.

214 Feller, C., Beare, M. H., 1997. Physical control of soil organic matter dynamics in the tropics.  
215 *Geoderma* 79, 69-116.

216 Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D.,  
217 Ndour, Y.B., Chotte, J.-L., 2018. Soil carbon stock changes in tropical croplands are  
218 mainly driven by carbon inputs: A synthesis. *Agric. Ecosyst. Environ.* 259, 147–158.

219 Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., Titttonell,  
220 P., 2011. A research agenda to explore the role of conservation agriculture in African  
221 smallholder farming systems. *Field Crops Res.* 124, 468-472.

222 Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Conway, G., Moreno-Garcia, M., Kassam, A.,  
223 Mkomwa, S., Ordoñez-Fernandez, R., Triviño-Tarradas, P., Carbonell-Bojollo, R., 2019.  
224 Meta-analysis on carbon sequestration through conservation agriculture in Africa. *Soil*  
225 *Tillage Res.* 190, 22–30.

226 Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger,  
227 W.H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A.,  
228 Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R.,  
229 Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S.,  
230 Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., Fargione,  
231 J., 2017. Natural climate solutions. *Proc. Natl. Acad. Sci.* 114, 11645–11650.

232 IPCC, 2006. Volume 4: Agriculture, forestry and other land use (AFOLU), in: *IPCC Guidelines*  
233 *for National Greenhouse Gas Inventories*, 673 pp.

234 Lal, R., 1998. Soil quality changes under continuous cropping for seventeen seasons of an  
235 Alfisol in western Nigeria. *Land Degrad. Dev.* 9, 259–274.

236 Lugato, E., Leip, A., Jones, A., 2018. Mitigation potential of soil carbon management  
237 overestimated by neglecting N<sub>2</sub>O emissions. *Nat. Clim. Chang.* 8, 219–223.

238 Mei, K., Wang, Z., Huang, H., Zhang, C., Shang, X., Dahlgren, R.A., Zhang, M., Xia, F., 2018.  
239 Stimulation of N<sub>2</sub>O emission by conservation tillage management in agricultural lands:  
240 A meta-analysis. *Soil Tillage Res.* 182, 86–93.

241 Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A.,  
242 Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B.,  
243 Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L.,  
244 O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G.,  
245 Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.C., Vågen,  
246 T.G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. *Geoderma* 292,  
247 59–86.

248 Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van  
249 Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO<sub>2</sub>  
250 emissions. *Soil Use Manag.* 13, 230–244.

251 Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and  
252 potential. *Glob. Chang. Biol.* 6, 317–328.

253 Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman,  
254 K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. *Nat.*  
255 *Clim. Chang.* 4, 678–683.

256 Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation  
257 agriculture deliver climate change mitigation through soil carbon sequestration in  
258 tropical agro-ecosystems? *Agric. Ecosyst. Environ.* 220, 164-174.

259 Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate  
260 climate change: a critical re-examination to identify the true and the false. *Eur. J. Soil*  
261 *Sci.* 62, 42–55.

262 Rusinamhodzi, L., Corbeels, M., van Wijk, M., Rufino, M., Nyamangara, J., Giller, K., 2011.  
263 A meta-analysis of long-term effects of conservation agriculture on maize grain yield  
264 under rain-fed conditions. *Agron. Sustain. Dev.* 31, 657–673.

265 Smith, P., Andrén, O., Karlsson, T., Perälä, P., Regina, K., Rounsevell, M., Van Wesemael, B.,  
266 2005. Carbon sequestration potential in European croplands has been overestimated.  
267 *Glob. Chang. Biol.* 11, 2153-2163.

268 Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S.,  
269 O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G.,  
270 Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008.  
271 Greenhouse gas mitigation in agriculture. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* 363,  
272 789–813.

273 Sommer, R., Paul, B. K., Mukalama, J., Kihara, J., 2018. Reducing losses but failing to  
274 sequester carbon in soils – the case of conservation agriculture and integrated soil fertility  
275 management in the humid tropical agro-ecosystem of western Kenya. *Agric. Ecosyst.*  
276 *Environ.* 254, 82-91.

277 Steward, P.R., Dougill, A.J., Thierfelder, C., Pittelkow, C.M., Stringer, L.C., Kudzala, M.,  
278 Shackelford, G.E., 2018. The adaptive capacity of maize-based conservation agriculture

279 systems to climate stress in tropical and subtropical environments: a meta-regression of  
280 yields. *Agric. Ecosyst. Environ.* 251, 194–202.

281 Swanepoel, C.M., van der Laan, M., Weepener, H.L., du Preez, C.C., Annandale, J.G., 2016.  
282 Review and meta-analysis of organic matter in cultivated soils in southern Africa. *Nutr.*  
283 *Cycl. Agroecosystems* 104, 107–123.

284 Torn, M.S., Trumbore, S.E., Chadwick, O.A., Vitousek, P.M., Hendricks, D.M., 1997. Mineral  
285 control of soil organic carbon storage and turnover. *Nature* 389, 170–173.

286 Vågen, T.-G., Lal, R., Singh, A.B.R., 2005. Soil carbon sequestration in sub-Saharan Africa: a  
287 review. *Land Degrad. Dev.* 16, 53–71.