1 **Global meta-analysis of the relationship between soil organic matter and crop yields**

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Abstract

16 Resilient, productive soils are necessary to sustainably intensify agriculture to increase

17 yields while minimizing environmental harm. To conserve and regenerate productive

18 soils, the need to maintain and build soil organic matter (SOM) has received considerable

19 attention. Although SOM is considered key to soil health, its relationship with yield is

20 contested because of local-scale differences in soils, climate, and farming systems. There

21 is a need to quantify this relationship to set a general framework for how soil

22 management could potentially contribute to the goals of sustainable intensification. We

23 developed a quantitative model exploring how SOM relates to crop yield potential of

24 maize and wheat in light of co-varying factors of management, soil type, and climate. We

25 found that yields of these two crops are on average greater with higher concentrations of

26 SOC. However, yield increases level off at ~2% SOC. Nevertheless, approximately two

27 thirds of the world's cultivated maize and wheat lands currently have SOC contents of

28 less than 2%. Using this regression relationship developed from published empirical data,

29 we then estimated how an increase in SOC concentrations up to regionally-specific

30 targets could potentially help reduce reliance on nitrogen (N) fertilizer and help close

31 global yield gaps. Potential N fertilizer reductions associated with increasing SOC

32 amount to 7% and 5% of global N fertilizer inputs across maize and wheat fields,

33 respectively. Potential yield increases of 10±11% (mean±SD) for maize and 23±37% for

34 wheat amount to 32% of the projected yield gap for maize and 60% of that for wheat. Our

35 analysis provides a global-level prediction for relating SOC to crop yields. Further work

36 employing similar approaches to regional and local data, coupled with experimental work

37   to disentangle causative effects of SOC on yield and vice-versa, are needed to provide

38   practical prescriptions to incentivize soil management for sustainable intensification.

1 Introduction

The pressure to increase crop production has resulted in the expansion of land area dedicated to agriculture and the intensification of cropland management through practices such as irrigation and fertilization. These practices have led to degradation of land and waters prompting "sustainable intensification" initiatives to increase yields on existing farmland while decreasing the environmental impact of agriculture (Foley et al., 2011; Godfray et al., 2010; Mueller et al., 2012). One sign of land degradation is the loss of soil organic matter (SOM) (Reeves, 1997). Re-building SOM in agricultural lands holds the promise of improving soil fertility, as SOM affects many properties of soils, including their ability to retain water and nutrients, to provide structure promoting efficient drainage and aeration, and to minimize loss of top-soil via erosion (Reeves et al., 1997; Robertson et al., 2014). As such, managing SOM to ensure stable and long-lasting crop productivity and to decrease reliance on external inputs such as mineral fertilizers and irrigation has been identified as a critical component of sustainable intensification (Foley et al., 2011). Yet the emphasis on soil management has remained qualitative, meaning that the potential contribution of building SOM as a means to increase crop production and minimize the environmental impact of agriculture has not yet been broadly quantified (Adhikari and Hartemink, 2016; Chabbi et al., 2017; Hatfield et al., 2017).

A primary hurdle to managing SOM for sustainable intensification is the lack of predictive, quantitative targets of SOM for specific agricultural and environmental objectives (Herrick, 2000; NRC, 2010). While several studies show correlations between SOM and yield (Culman et al., 2013; de Moraes Sa et al., 2014; Lucas and Weil, 2012; Stine and Weil, 2002), it remains unclear how much yield could be expected to increase per unit change in organic matter (Herrick, 2000; NRC, 2010). Establishing these

63   quantitative metrics is challenging because research shows increases (Bauer and Black,

64   1992), decreases (Bhardwaj et al., 2011), and no change (Hijbeek et al., 2017) in yields

65   with increased SOM. This lack of a general relationship is likely the result of a number of

66   interacting factors related to management, climate, and soil type that can confound the

67   SOM-yield relationship. This confusion has led some to claim that the amount of SOM is

68   unnecessary for crop yields, so long as there is sufficient N fertilizer (Hijbeek et al.,

69   2017; Loveland and Webb, 2003; Oelofse et al., 2015); whereas others highlight the need

70   to build SOM to increase crop yields while minimizing environmental harm (Lal, 2004).

71   The growing momentum to launch global scale initiatives to manage SOM (Banwart et

72   al., 2014; Lal, 2004; Minasny et al., 2017; Zomer et al., 2017) suggests the need to test

73   competing claims about the effects of SOM on these agricultural and environmental

74   outcomes.

75   One could critique the effort to establish a global-level understanding of the

76   SOM-yield relationship on the grounds that farm-level responses are necessarily

77   heterogeneous and poorly predicted by global assessments. Yet, global initiatives for

78   managing SOM could create policy environments that stimulate regional- and local-

79   prescriptions for SOM levels that inform practice (Chabbi et al., 2017; Minasny et al.,

80   2017; Zomer et al., 2017). Whereas it is difficult to disentangle the extent to which SOM-

81   yield relationships are driven by SOM effects on yield, as opposed to yield (i.e. higher

82   plant carbon inputs) effects on SOM, there is nevertheless experimental evidence

83   showing that building SOM positively affects yield (Bauer and Black, 1994; Majumder et

84   al., 2008; Oldfield et al., 2017). In addition, numerous soil properties that relate to soil

85   fertility, such as water holding capacity, respond positively to increasing SOM and in

86   turn are expected to increase yields (Williams et al., 2016). As such, correlative SOM-

87   yield relationships suggest the potential – but likely not the true – effect of SOM on yield.

88   We developed a quantitative model exploring how SOM relates to crop yield

89   potential in light of co-varying factors of management, soil type, and climate. The aim is

90   that this model can then be used to establish relationships at broad scales between SOM

91   and yield to provide better quantification of this relationship for policy initiatives. We

92   quantified the relationship between SOM (measured as SOC, a common proxy for SOM)

93   and yield at a global level using data from published studies. We focused our analyses on

94   wheat and maize, two common staple crops that (along with rice) constitute two-thirds of

95   the energy in human diets (Cassman, 1999). Along with SOC, we modeled the effects on

96   crop yields of several factors widely reported in yield studies: N input rate, irrigation, pH,

97   soil texture (% clay), aridity, crop type (i.e. wheat or maize), and latitude (as a proxy for

98   growing-season day length). The data informing our model came from empirical studies

99   that capture local scale variation in these variables, and hence we interpret our results in

100 light of the correlative nature of the database we assembled. Using the resulting multiple-

101 regression relationship, we then estimated how an increase in SOC concentrations up to

102 regionally-specific target thresholds might affect global yields. Our overarching aim was

103 to estimate the potential extent to which restoring SOC in global agricultural lands could

104 help close global yield gaps and potentially help reduce reliance on – and the negative

105 effects of – N fertilizer.

106

107 **2 Results and Discussion**

108 **2.1 The relationship between SOC and yield**

109 At the global level and focusing specifically on the potential effect size of SOC on yield,

110 we found that the largest gains in yield occur between SOC concentrations of 0.1 to

111 2.0%. For instance, yields are 1.2 times higher at 1.0% SOC than 0.5% SOC (Fig. 1).

112 Gains in yield leveled off at a concentration of approximately 2% SOC (Fig. 1). Two

113 percent SOC has previously been suggested as a critical threshold, with values below this

114 concentration threatening the structure, and ultimately, the ability of a soil to function

115 (Kemper and Koch, 1966). Importantly, the asymptotic relationship between SOC and

116 yield lends support to the idea that building SOC will increase yields – at least to a

117 certain extent – as opposed to simply being an outcome of higher yields. That is, if yield

118 was an explanatory variable for SOC, we would expect greater yields to keep driving

119 greater levels of SOC (i.e. the relationship would appear more linear) since we know that

120 soils can accumulate concentrations much greater than 2% (Castellano et al., 2015).

121 However, our data do not display a linear pattern, suggesting that higher yields are not

122 driving higher levels of SOC.

123   It has been suggested that there is no evidence for 2% SOC being a critical

124 threshold for productivity, as long as there is sufficient mineral fertilizer to support crop

125 production (Edmeades, 2003; Loveland and Webb, 2003; Oelofse et al., 2015). Such

126 conclusions deem the amount of SOM as substitutable by mineral fertilizers (at least for

127 crop growth), but are inconsistent with the motivation for sustainable intensification to

128 minimize environmental harm caused by mineral fertilizers in relation to emissions of

129 greenhouse gases and eutrophication of waters (Vitousek et al., 2009). The same logic

130 about substitutability also does not account for the other co-benefits associated with

131 building SOM in agricultural lands, such as reductions in nutrient run-off, drought

132 resistance, and yield stability (Robertson et al., 2014). Field- and regional-scale studies

133   have shown a similar pattern as that observed from our global analysis: there exists a

134   positive relationship between SOC and yield that starts to level off at ~2% SOC

135   (Kravchenko and Bullock, 2000; Pan et al., 2009; Zvomuya et al., 2008). Our analysis

136   suggests that this relationship holds on average at the global scale and when N

137   fertilization is controlled for.

138   Ninety-one percent of the published studies used for our analysis were carried out

139   in fields with less than 2% SOC, with a mean of 1.1%. To see whether these observations

140   in SOC distribution reflected global patterns, we used globally gridded data on crop yield

141   and SOC (to a depth of 15 cm) (Hengl et al., 2014; Monfreda et al., 2008). We found that,

142   by both area and production, two thirds of maize and wheat cultivation takes place on

143   soils with less than 2% SOC (Fig. 2). Indeed, a recent analysis estimates that agricultural

144   land uses (including cropland and grazing) have resulted in a loss of 133 Pg of carbon

145   over the past 12,000 years of human land use (Sanderman et al., 2017). There appears to

146   be, therefore, significant opportunity to increase SOC on maize and wheat lands to

147   improve crop yields.

148

149   **2.2 The interaction between SOC and N fertilizer on yield**

150   One of the key goals of sustainable intensification is to reduce the environmental impacts

151   of agriculture (Foley et al., 2011; Mueller et al., 2012). Nitrogen fertilization, while a

152   boon to yields, can cause environmental damages, such as eutrophication of waters and

153   increased soil emissions of nitrous oxide, a potent greenhouse gas (Vitousek et al., 2009).

154   Using our regression model, we asked whether there might be target N fertilizer addition

155   rates that suggest the possibility of maximizing yield per unit N applied by building SOC

156   and reducing inorganic N inputs. We wanted to see if yields converge at higher levels of

157 SOC, suggesting that crops are obtaining sufficient nutrients through SOM and excess

158 mineral N is not necessary. Our analysis suggests that SOC is not directly substitutable

159 for mineral fertilizer (Fig. 1); however, at lower rates of N input ($\leq$50 kg N ha^{-1}), we

160 found that increasing SOC from 0.5 to 1.0% could potentially maintain current yields and

161 reduce fertilizer inputs by approximately half (50%). At higher rates of N input ($\geq$200 kg

162 N ha^{-1}), an increase from 0.5 to 2.0% SOC could potentially reduce synthetic N inputs by

163 up to 70% per hectare (Fig. 3). Building SOC from 0.5 to 2.0% represents a very large

164 increase, which would require a significant amount of inputs that may not be feasible due

165 to inherent and logistical difficulties related to soil properties, climate, and farmer access

166 to inputs. Furthermore, such an increase could take several years or decades to

167 accomplish. For example, results from long-term field trials show a range of annual

168 increases in SOC for temperate agricultural soils, which were as low as 0.3% and as high

169 as 18% (Poulton et al., 2018). At the low end of this range, and starting at 0.5% SOC, it

170 would take ~47 years to build to 2% SOC if the annual relative rate of increase was

171 constant, and ~9 years at the high end of the range. Admittedly, the range emerged as a

172 result of a number of different inputs ranging from farmyard manure to sewage sludge to

173 mineral fertilization, some of which may not be available to farmers given cost and/or

174 access (Poulton et al., 2018). Feasibility aside, however, our results suggest that building

175 SOM in agricultural lands may supply enough plant available nutrients to sustain crop

176 yields while drastically cutting back on N fertilizer inputs.

177   There was an interaction between SOC and N input, where at higher SOC

178 concentrations N input had a greater impact on yield (Fig. 1, Table 1). This may be

179 because higher SOC improves soil structure and water holding properties, resulting in

180 improved crop growth at a given level of N input (Powlson et al., 2011). Higher levels of

181   SOM could also provide more essential macro- and micro-nutrients that are limiting in

182   soils with lower SOC concentrations. Additionally, soils receiving more N may have

183   greater SOC because N increases crop yields, which can increase the return of plant

184   residues into the soil and potentially build SOC (Powlson et al., 2011). However, if the

185   relationship was simply an effect of greater inputs building SOC, we should not have

186   seen an interaction between SOC and N on yields (because SOC should then just have

187   been additively related to yield). Whatever the specific explanation, the SOC by N

188   interaction we detect suggests that a combination of both building SOM and using

189   targeted N applications could lead to potential increases in yield (Fig. 3). Practices such

190   as cover-cropping represent a strategy that can both increase N supply and build SOM

191   through biological N fixation and the return of high quality residues (narrow C:N ratios)

192   to the soil (Drinkwater et al., 1998). Building SOM and reducing fertilizer N input would

193   require a balance where SOM-N mineralization accounts for any limitations in N supply

194   that arise from reducing mineral fertilizer applications. The balance required will depend

195   on the amount and C:N ratios of inputs used in specific agricultural systems, and could

196   prove challenging to achieve in some small-holder systems where low SOC

197   concentrations might be compounded by a lack of access to and insufficient quality of

198   organic inputs (Giller et al., 2009; Palm et al., 2001). As such, the combination of both

199   SOM improvement and targeted fertilizer input will likely be especially important for

200   degraded soils, which require a suite of organic and inorganic nutrients to help build

201   SOM and improve crop yields (Palm et al., 1997).

202   Gains in yield from fertilizer input leveled off at about 200 kg N ha^{-1} y^{-1} (Fig. 3),

203   meaning that optimum yields appear achievable, at least on average, with this fertilizer

204   input level and an SOC target concentration of 2%. Using this target N input rate, we

205   explored potential fertilizer reductions on agricultural lands using more than 200 kg N ha^{-}

206   ^{1} y^{-1}. We found that for lands receiving more than 200 kg N ha^{-1} y^{-1}, current yields could

207   be maintained, while decreasing global N fertilizer inputs by 7% for maize and 5% for

208   wheat. It is estimated that 25 to 30% of fertilizer N is exported to streams and rivers,

209   resulting in eutrophication (Raymond et al., 2012). Targeted reductions in the application

210   of fertilizer N on the order of magnitude our analysis suggests could then prevent the

211   annual export of as much as 3.73 million tonnes of N into inland waters, which amounts

212   to 10% of mineral fertilizer applied to maize and wheat lands (see Methods for an

213   explanation of how this percentage was obtained).

214

215   **2.3 Exploring potential reductions in global yield gaps of maize and wheat**

216   With a majority of cultivated lands containing less than 2% SOC and a growing

217   imperative to build, restore, and protect SOC in agricultural soils (NSTC, 2016; FAO,

218   2008; NRCS, 2012), we used global gridded datasets coupled with our regression model

219   (Table 1) to examine the potential gains in yield and production if opportunities to

220   increase SOC are realized (Table 2). We then calculated how these gains in production

221   would impact global yield gaps of maize and wheat, the difference between observed and

222   attainable yields (Mueller et al., 2012). Although our model identified 2% as a global

223   target for SOC, we created regionally-specific SOC targets given the fact that achieving

224   2% SOC in some soils (e.g. those of drylands) may be unachievable due to inherent

225   constraints of physical soil properties and climate (see Methods). We found that

226   increasing SOC concentrations to the defined targets has the potential capacity to increase

227   average yields on a per hectare basis by 10±11% (mean±SD) for maize and 23±37% for

228   wheat. These gains in yield translate to a 5% and 10% increase in the global annual

229   tonnes produced of maize and wheat, respectively (Table 2). These increases in

230   production would close 32% of the global yield gap for maize and 60% of the gap for

231   wheat (Fig 4a,b).

232   These yield gap results represent an exploration of potential "best case" impacts

233   of increasing SOC concentrations. We recognize there are inherent and logistical

234   challenges to building SOM in agricultural soils; and when managing for and building

235   SOM, it is important to account for its dynamic nature. For instance, to derive some of

236   the nutrient benefits of SOM, it must be mineralized and used (Janzen, 2006), and so

237   frequent additions of organic inputs may be necessary to sustain SOM levels.

238   Furthermore, soil characteristics such as texture can have a large effect on SOC content

239   because sandier (rather than more clay rich) soils have less surface area to stabilize SOC

240   (Rasmussen et al., 2018), and so hold much less water and nutrients than clay-rich soils

241   (Johnston et al., 2009). Maintaining SOC contents in sandy soils may require more

242   frequent additions of organic amendments because these soils do not have the surface

243   area to retain nutrients, moisture, and to stabilize SOC (Lehmann and Kleber, 2015).

244   Different regions and climate types also face different imperatives for building

245   SOM. In the mid-western United States, for instance, building SOM may be a good

246   strategy to reduce fertilizer inputs and irrigation needs; whereas in sub-Saharan Africa,

247   building SOM may be critical for drought protection and nutrient provision. Notably,

248   high SOM values are not common in dryland environments (for our dataset, mean SOC =

249   0.9% for dryland climates versus 1.4% SOC for mesic soils), and building and

250   maintaining SOM in arid zones is typically hindered by the lack of organic matter to

251   return to soils (Rasmussen et al., 1980). On a positive note, however, our analysis

252   suggests that increases in SOC in drylands, for example, from 0.5 to 0.8%, could

253   potentially increase yields by 10%, likely due to impacts on water retention as well as

254   improved nutrient supply.

255   The goal of our analysis was to establish a global, average relationship between

256   SOC and yield. Whereas we did use lower SOC targets (ranging from 1.0 to 1.5%) for the

257   arid AEZs in our analysis, the majority of data used for our analysis is from the more

258   temperate and tropical humid zones (Fig. S2) and a large proportion of our data comes

259   from China (Fig. 1). We recognize that the distribution of our data could potentially bias

260   our results. As such, we explored the SOM-yield relationship in the absence of data from

261   China and also for Chinese observations only. While the effect size of SOC changes

262   depending on the subset of data analyzed (Table S2), the qualitative patterns of this

263   relationship remain the same. That is, SOC leads to gains in yield that are most

264   pronounced at lower SOC concentrations and decline in their magnitude as ~2% SOC is

265   reached (Fig. S3). Notably, when exploring the subset of data from China, the effect size

266   of SOC was higher than that from the entire dataset (Table S2). However, China only had

267   10 observations above 2% SOC, and so the modeled relationship for China captures the

268   part of the SOM-yield relationship where an increase in SOC leads to the largest gains in

269   yield (i.e. where the modeled slope is the steepest). Our analysis then highlights both the

270   need for studies to come evenly from systems where maize and wheat are grown and also

271   the importance of analyzing regional datasets that capture the observed range of SOC

272   values in order to quantify a regionally-specific relationship between SOC and yield to

273   more directly inform practice.

274   Moving from the global relationship presented in our paper to bolstering and/or

275   refining SOC targets, our correlative analysis needs to be supplemented with well-

276   replicated experimental studies incorporating different management strategies across

277   multiple soil and climate types to develop SOC-yield relationships that can be applied to

278   the specific set of local farm conditions. Further, these studies should ideally report data

279   related to soil texture and mineralogy, nutrient management, and paired SOC-yield

280   observations with SOC taken to meaningful depths, such as those that represent plant-

281   rooting depth. These experimental studies will help generate information that

282   practitioners can use to inform management by taking into account the potential benefits

283   of SOC, compared against the inherent and logistical challenges to building SOC to target

284   levels.

285

286   **3 Conclusions**

287   Despite uncertainties and calls for further research into how SOM affects agricultural

288   performance (Cassman, 1999; Herrick, 2000; Oldfield et al., 2015), policy for sustainable

289   intensification already widely supports the merits of increasing SOM in agricultural lands

290   (FAO, 2008; NRCS, 2012). The purported benefits include improved yields, increased

291   resilience, and decreased inputs of fertilizer and irrigation water. However, although

292   consensus exists around the importance of SOM to soil health, translating SOM policy to

293   practice is hindered by the lack of a predictive capacity for SOM target setting to inform

294   management efforts focused on yield and reducing fertilizer and irrigation (Chabbi et al.,

295   2017; Herrick, 2000; NRC, 2010). Our analysis helps establish a quantitative framework

296   for SOC targets that achieve measurable agricultural outcomes as part of sustainable

297   intensification efforts. It quantifies the potential effect size of SOC on yield while also

298   accounting for climate, soil, and management variables that influence crop yield. We find

299   that greater concentrations of SOC are associated with greater yields up to an SOC

300   concentration of 2%. With two thirds of global maize and wheat lands having SOC

301   concentrations of less than 2%, there seems significant opportunity to increase SOC to

302   reduce N inputs and potentially help close global yield gaps.

303

304   **4 Methods**

305   Our approach consisted of a two-stage process. In the first stage, we assembled published

306   empirical data from studies that reported both SOC and yield data for maize and wheat.

307   From this meta-dataset, we then quantified how both SOC concentrations and N input

308   rates are related to yields, in the context of spatial variation in climatic, management, and

309   soil co-variables. In the second stage, we used globally-gridded datasets to extract values

310   for the factors we investigated in the first stage for global lands where maize and wheat is

311   produced. Using the regression relationship developed from the published empirical data

312   compiled under the first stage, we then estimated how an increase in SOC concentrations

313   up to target thresholds we identified (ranging from 1 to 2% depending on agro-ecological

314   zoning) affected global yield potentials. Finally, we used an N input threshold identified

315   through our regression analysis (200 kg N ha^{-1} yr^{-1}) to calculate potential N reductions on

316   global maize and wheat lands.

317

318   **4.1 Data collection**

319   In the first stage of our approach, we searched the database Web of Science (Thomson

320   Reuters) in January 2016 and again in October 2016 using the following topic search

321   terms: "soil organic matter" OR "soil organic carbon" OR "soil carbon" OR "soil c"

322   AND "yield" OR "crop yield" OR "productivity" AND "agricult*." We restricted the

323   initial search to articles published in English between 1980 through December 2015, and

324   excluded conference proceedings; the second search captured articles published in 2016.

325   The initial search resulted in 1,384 articles and the second 169 articles (Fig. S1). For each

326   citation, we reviewed titles and abstracts to select articles that met the following criteria:

327   experimental field studies whose abstract included information on yield and SOC for

328   systems growing wheat and/or maize. This initial screening resulted in 523 records for

329   which we assessed the full text. We assessed these records for eligibility based on

330   inclusion of data on crop yield, SOC, and N fertilizer rates for each observation. For

331   inclusion within our analysis, it was essential that studies reported paired SOC and yield

332   data. Furthermore, we required SOC concentrations (as opposed to stocks). Studies did

333   not meet our criteria for inclusion if they reported SOC stocks with no corresponding data

334   on bulk density to convert into concentrations; and also if they reported baseline SOC

335   concentrations as opposed to experimental SOC concentrations that we could pair with

336   yield data. In addition to our literature search, we also contacted authors to see if they

337   were willing to include raw data within our database. This resulted in three datasets

338   (Adiku et al., 2009; Birkhofer et al., 2008; Kautz et al., 2010). Finally, we consulted the

339   recently published database by the Swedish Board of Agriculture that is a key repository

340   of peer reviewed literature focusing specifically on studies (735 in total) related to the

341   effects of agricultural management on soil organic carbon (Haddaway et al., 2015). We

342   explored this database to find studies from regions that were under-represented within our

343   literature search (e.g. the southern hemisphere). This resulted in a search of 55 studies to

344   see if they met our criteria for inclusion. We scanned each paper to see if they included

345   SOC data paired with matching yield data. From these papers, we extracted data from 12

346   studies, which resulted in an additional 52 data points. We encountered limitations

347   similar to our initial search: Namely, SOC and yield data were not paired, studies

348   included only baseline SOC concentrations, or SOC stocks were reported without any

349 corresponding bulk density data to convert into concentrations. Overall, our dataset

350 included 840 individual observations from 90 articles covering sites across the globe

351 (Adiku et al., 2009; Agegnehu et al., 2016; Albizua et al., 2015; Alijani et al., 2012;

352 Araya et al., 2012; Atreya et al., 2006; Bai et al., 2009; Bedada et al., 2014; Bhardwaj et

353 al., 2011; Bhattacharyya et al., 2015; Birkhofer et al., 2008; Boddey et al., 2010; Boulal

354 et al., 2012; Bremer et al., 1994; Calegari et al., 2008; Campbell et al., 2007; Castellanos-

355 Navarrete et al., 2012; Celik et al., 2010; Chen et al., 2015; Chirinda et al., 2010; Cid et

356 al., 2014; Costa et al., 2010; D'Hose et al., 2014; Datta et al., 2010; DeMaria et al., 1999;

357 Diacono et al., 2012; Grandy et al., 2006; Guo et al., 2012; 2009; He et al., 2011; Hossain

358 et al., 2016; Hu et al., 2015; 2014; Kaihura et al., 1999; Karbozova Saljnikov et al., 2004;

359 Kautz et al., 2010; Kazemeini et al., 2014; Kucharik et al., 2001; Larsen et al., 2014;

360 Lebbink et al., 1994; Leogrande et al., 2016; Li et al., 2015; Liu et al., 2014a; 2016;

361 2014b; 2014c; López-Garrido et al., 2014; Lu et al., 2016; Ma et al., 2012; 2016;

362 Madejón et al., 2001; Mandal et al., 2013; Masto et al., 2007; Mikanová et al., 2012;

363 Mishra et al., 2015; Mupangwa et al., 2013; N'Dayegamiye, 2006; Niu et al., 2011; Njoku

364 and Mbah, 2012; Paul et al., 2013; Qin et al., 2015; Quiroga et al., 2009; Sadeghi and

365 Bahrani, 2009; Saikia et al., 2015; Scalise et al., 2015; Seremesic et al., 2011; Singh and

366 Dwivedi, 2006; Singh et al., 2016; Sisti et al., 2004; Soldevilla-Martinez et al., 2013;

367 Spargo et al., 2011; Šimon et al., 2015; Tejada et al., 2016; Tiecher et al., 2012; van

368 Groenigen et al., 2011; Vieira et al., 2007; 2009; Wang et al., 2015; 2014a; 2014b;

369 Wortman et al., 2012; Wu et al., 2015; Yang et al., 2013; 2015a; 2015b; Yeboah et al.,

370 2016; Zhang et al., 2015; 2009; 2016; Zhao et al., 2016). Where necessary, we extracted

371 data from manuscript figures using GraphClick Software (v. 3.0.3, http://www.arizona-

372 software.ch/graphclick/).

373   Studies that presented individual data points recorded over multiple years were

374   included as well as studies that averaged both yield and SOC data over multiple years. To

375   avoid over-representation of studies that included data points recorded for both yield and

376   SOC over multiple years (>10 y), we took observations from the beginning, middle, and

377   last year of the study.

378

379   **4.2 Data compilation**

380   For each extracted observation, we compiled the following information: latitude,

381   longitude, year of data collection, crop type, yield, SOC or SOM, depth of SOC or SOM

382   measurement, N fertilization rate, P fertilization rate, soil pH, texture, and whether or not

383   crops were irrigated. We used SOC (as opposed to SOM) for our analysis given that SOC

384   is a common proxy for SOM. Carbon, as an element that is easily identified and

385   measured within soil, is thought to comprise ~50-60% of SOM and is commonly reported

386   in the literature (Pribyl, 2010). When SOM was reported, we converted it to SOC by

387   dividing the value by 1.724 (Cambardella et al., 2001). Different studies reported SOC

388   concentrations to different depths, which ranged from 0-5 cm to 0-30 cm, with the

389   majority of studies reporting SOC to 0-20 cm. When studies reported SOC to multiple

390   depths, we averaged SOC values across depths to 30 cm. If no information on irrigation

391   was provided, we scored the observation as rain-fed. Soil texture and pH were not

392   reported for every study; 79% of included studies reported pH, and so we used the

393   study's latitude and longitude to extract these data using ISRIC SoilGrids (Hengl et al.,

394   2014) to fill in the missing pH values. Texture was reported for about half (49%) of

395   included studies, and so we used coordinates to pull these data from SoilGrids as well

396   (Hengl et al., 2014). We also used latitude and longitude to obtain an "aridity index"

397 through the CGIAR-CSI database (Zomer et al., 2008). We chose to use aridity as our

398 primary climatic variable since it is expressed as a function of precipitation, temperature,

399 and potential evapo-transpiration (Trabucco 2009).

400

401 **4.3 Data analysis**

402 We used a linear mixed model (LMM) to analyze the observations we extracted from the

403 literature. Our model included SOC, N fertilizer rate, crop type (maize or wheat, coded as

404 a binary variable), irrigation (coded as a binary variable), aridity index, latitude, pH, and

405 texture (% clay) as fixed effects. The differences in soil carbon observed in our dataset

406 are from experimental plots capturing long-term differences in SOC within a given site.

407 Specifically, our data capture differences within SOC largely driven by management

408 interventions related to inputs (e.g. compost, fertilizer, manure, crop residues) and tillage

409 (e.g. no-till versus till). Site-specific differences in management as well as spatial and

410 temporal correlation among the studies were accounted for by nesting year within study

411 as random effects (Bolker et al., 2009). The LMMs were fit with a Gaussian error

412 distribution in the "lme4" package for the "R" statistical program (version 3.3.1), using

413 the "lmer" function. The first stage of our data analysis was to test the data distributions.

414 We removed data points with N fertilization rates >600 kg N ha^{-1} (4 data points) and

415 yields >18 t ha^{-1} (2 data points) since these represented outliers for our dataset (being

416 beyond 3 times the inter-quartile range of the meta-dataset) and are not representative of

417 on-farm management practices or outcomes. Our final model was based on 834

418 observations across 90 studies. We added quadratic terms for both SOC and N input rate

419 since these variables exhibited a nonlinear relationship with yield. The square-root of the

420 variance inflation factors (vif) was <2 for all factors when included as main effects,

421   indicating that collinearity was low among all variables. As would be expected, there was

422   a correlation between SOC and its quadratic term and N input rate and its quadratic term.

423   We re-ran our regression after removing four seemingly influential data points (those that

424   had high SOC concentrations with low yields, see Fig. 2) and model coefficients

425   remained essentially the same. We calculated the r^2 values for our model following

426   Nakagawa and Schielzeth (Nakagawa and Schielzeth, 2013) to retain the random effects

427   structure. The r^2 of our model was 83% for the full model, with the fixed effects

428   explaining 42% of observed variance within our dataset.

429   We based the choice of factors for inclusion in our model on the approach of

430   Hobbs et al. (Hobbs and Hilborn, 2006), by only investigating factors where biological

431   mechanism as to their influence on yield is firmly established and where we were

432   interested in their effect sizes relative to one another. Also following Hobbs et al. (Hobbs

433   and Hilborn, 2006), we did not carry out model selection. Operationally, there is

434   substantial subjectivity and lack of agreement in model selection approaches, with

435   different decisions leading to markedly different conclusions as to the influence of

436   different factors. Instead, coefficients are generally most robust when all terms are

437   retained in a model, assuming that inclusion of each is biologically justified. We decided

438   to include an SOC by N interaction to explore potential reductions in N fertilizer with

439   increased SOC concentrations. This was an effort to see if there is a level of SOC that can

440   compensate for N input. We acknowledge that there are a number of interactions we

441   could have included within our statistical model, and we did run our regression model

442   with additional interactions to include SOC by irrigation, SOC by clay, and SOC by

443   aridity. Including these interactions, however, did not offer any additional explanatory

444   power and our main results between SOC, N inputs, and yield were essentially

445   unchanged with these additional interactions (Table S3). As such, we chose to present our

446   analysis including only the SOC x N interaction.

447   To examine the effects sizes of the factors on yield, we took two approaches.

448   First, we compared the size of the standardized coefficients, where standardizing

449   involved subtracting the mean of the factor from each observed value and dividing by

450   two standard deviations (Gelman, 2008). Dividing by two standard deviations is useful

451   when binary predictors are included within regression models (in our case, crop type and

452   irrigation are coded as a binary predictors). This way, continuous and binary variables all

453   have a mean of 0 and a standard deviation of 0.5 (Gelman, 2008). This accounts for the

454   fact that the factors were measured on different unit scales (Table 1). Second, we

455   examined the influence of changing SOC concentration or N fertilization rates on yield.

456   To do this, we used the regression relationship derived from our statistical model, held all

457   other factors at a constant value (e.g. the mean of all observations for that factor), and

458   systematically varied SOC or N fertilization across the range of values we extracted from

459   the literature. For SOC, this meant varying SOC values from 0.1 to 3.5% to estimate

460   changing yield of rain-fed maize or wheat as SOC concentrations were increased (Fig. 1).

461   For N fertilization, we varied N input rates from 0 to 300 kg N ha^{-1} for rain-fed maize or

462   wheat at different SOC concentrations (Fig. 3). When these factor-yield relationships

463   were plotted, we identified threshold values where yield became minimally responsive to

464   SOC or N fertilization as the point where the slope of the relationship became <0.25 (for

465   SOC) and < 0.002 (for N fertilization).

466

467   **4.4 Global extrapolations**

468   We used the regression relationship developed in the first stage of our approach to predict

469   how building SOC concentrations would potentially affect global crop yield averages. To

470   obtain values for each of the factors in our regression model at a global scale, we used

471   globally gridded data products. Global SOC, pH, and texture data were taken from ISRIC

472   SoilGrids (Hengl et al., 2014) at a 10-km grid cell resolution to match the spatial grain for

473   maize and wheat yields and N fertilization data, which we obtained from the EarthStat

474   product (Monfreda et al., 2008; Mueller et al., 2012). SoilGrids has multiple layers for

475   SOC concentrations, and we used the 0-15 cm layer as the average depth to which SOC

476   was reported for our dataset was 0-20 cm. The aridity index was obtained from the

477   CGIAR-CSI database (Zomer et al., 2008). We used the resulting global dataset to

478   explore the potential impact of increasing SOC (up to regionally identified threshold

479   levels ranging from 1 to 2%) on yield for lands across the globe where maize and wheat

480   are produced.

481   To establish regionally appropriate SOC targets, we classified maize and wheat

482   producing areas by their agro-ecological zones (AEZ). The Food and Agricultural

483   Organization have 18 zones defined on the basis of combinations of soil, landform, and

484   climatic characteristics (Ramankutty et al., 2007). For each AEZ, we examined the

485   distribution of SOC in areas classified as naturally vegetated (e.g. not in urban or

486   agricultural land uses). We did this by stacking two GIS raster layers of SOC (SoilGrids)

487   and land use (Friedl et al., 2010), excluding agricultural and urban land use

488   classifications. We then extracted SOC data for each AEZ using a shape file outlining the

489   geographical extent of each AEZ (Ramankutty et al., 2007). Examining the distribution

490   of SOC across each AEZ, we identified targets based on the mean SOC value within each

491   zone. All but four zones had means greater than 2% SOC, so we set target values for

492   those zones at 2%. Mean SOC concentrations were lower for the more arid zones and so

493   we set those targets to 1% for AEZ 1 and 1.5% for AEZ zones 2, 3, and 7. These targets

494   were in line with recent quantitative assessments based on similar climatic classifications.

495   For instance, recent analysis of global SOC concentrations across globally defined

496   Ecoregions shows mean values of SOC at or greater than 2% for all regions except land

497   classified as desert and xeric shrubland (Stockmann et al., 2015).

498   Prior to our global extrapolations, we performed a suite of data checks. We

499   wanted to ensure that global yields predicted using our regression model were

500   comparable to those from EarthStat. These checks helped validate the strength of our

501   extrapolations. Firstly, we explored the range of variation in variables from experimental

502   data used to generate our model as well as the range of global variation in variables we

503   project across. The range of our regressors encompasses the range of global variation,

504   except for aridity, in which case 4.6% percent of our projections fall in grids that have

505   axis conditions outside of our range of measurements. These values fall in extremely arid

506   systems, with aridity values of less than 0.1. In these extremely arid zones, we do make a

507   point to use lower target SOC values, recognizing that achieving 2% SOC in these very

508   arid areas is not very likely. Secondly, using our regression model to predict global yields

509   for both maize and wheat (separately), we first removed all values from the analysis that

510   had predicted yields of less than 0 because negative yields are not possible. This

511   amounted to 0.004% of the total predictions for maize and 0.15% for wheat. For

512   clarification, we refer to predictions from our regression model as "predicted" or "model-

513   predicted." We then calculated the proportional difference between model-predicted and

514   globally gridded yield data from EarthStat. We dropped all cells for which the

515   proportional difference between predicted and gridded data was >3-times. This threshold

516   represents the mean ± half of the standard deviation for the distribution of the

517   proportional difference between predicted and EarthStat yield data. This amounted to

518   14% of cells for maize and 7% for wheat. The mean proportional difference between

519   predicted and gridded data was 0.85±0.91 for maize (Fig. S4b) and 0.45±0.87 for wheat

520   (Fig. S5b). The correlation between predicted and gridded data was r=0.73 for maize

521   (Fig. S4c) and r=0.38 for wheat (Fig. S5c). We also visualized overlap in the distribution

522   of model-predicted and gridded data. Model-predicted maize yield had a global mean of

523   4.66±1.84 t ha^{-1} and EarthStat had a global mean of 3.34±2.62 t ha^{-1} (Fig. S4a). Model-

524   predicted wheat yield had a global mean of 3.18±1.66 t ha^{-1} and EarthStat had a global

525   mean of 2.43±1.58 t ha^{-1} (Fig. S5a).

526   We also compared the distribution of EarthStat yield data with observed yield

527   data from the studies included in our analysis. We found that correlation (r values)

528   between the gridded and collected data was 0.56 for maize and 0.39 for wheat. Average

529   observed maize yield was 5.61±3.32 t ha^{-1} and wheat yield was 4.02±2.11 t ha^{-1}

530   (mean±SD). EarthStat maize yield, again, was 3.34±2.62 t ha^{-1} and wheat yield was

531   2.43±1.58 t ha^{-1}. These differences between predicted and EarthStat yield averages are

532   likely due to the fact that EarthStat data is based on regional census data, incorporating

533   much more variability in terms of management practices and skill than experimental field

534   studies.

535   After the data checks, we then used our model to extrapolate global yield

536   potentials of maize and wheat given increases in SOC. We masked EarthStat production

537   and cultivated area data layers for maize and wheat for cells that had SoilGrids SOC

538   concentrations of >2%. We compared the subsetted data (i.e. cultivated lands with < 2%

539   SOC) with the original data layers to determine the fraction of global maize and wheat

540   production and cropland that is on soils with less than 2% SOC. We used this subsetted

541   data along with our regression model to predict yields at current SOC levels. As stated

542   above, we used EarthStat, ISRIC SoilGrids, and CGIAR-CSI data layers to fill in the

543   values for each of the factors in our regression model. This new data layer was used as a

544   baseline with which to compare to potential gains in yield with an increase to SOC target

545   values. This created a second data layer with model-predicted yields given an increase in

546   SOC. We calculated the percentage increase in yield between these two layers (the

547   baseline and the improved-SOC layer) and multiplied this by EarthStat yield and

548   production data to determine potential gains in maize and wheat yields and production

549   (Table 2). We then used EarthStat yield gap data to see how such an increase in SOC

550   would reduce projected yields gaps. Using the new yield data layer (with yields at SOC

551   target values), we calculated the proportion of EarthStat yield gaps that was reduced for

552   both maize and wheat.

553   Finally, we used data on global N use (EarthStat) to explore potential reductions

554   in fertilizer use for both maize and wheat, separately. We used a value of 200 kg N ha^{-1}

555   yr^{-1} as our N input threshold, as this is the value from our regression model at which gains

556   in yields level off. We created a new data layer for those areas that have N input rates

557   greater than 200 kg N ha^{-1} y^{-1}. We then calculated the potential N reductions, in tonnes,

558   by multiplying this new data layer by EarthStat cultivated maize and wheat lands,

559   separately. Finally, we divided the potential reduction in N input (in tonnes) by total N

560   input (in tonnes) as provided through the EarthStat data product.

561

562   **Data availability**

563   The dataset generated and analyzed during the current study is available through the

564   KNB repository: https://doi.org/10.5063/F19W0CQ5

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566

567   **Author contributions**

568   EEO, MAB, and SAW conceived of the study. EEO and SAW performed data analysis.

569   EEO wrote the first draft of the manuscript. All authors contributed to data interpretation

570   and paper writing.

571

572   **Competing Interests**

573   The authors declare that they have no conflict of interest.

574

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1147 **Table 1. Modeled regression coefficients with standard errors, standardized**
1148 **coefficients, and *P* values for our regression model.**

Variable	Unstandardized Coefficients	Standardized Coefficients	*P* value
Intercept	-1.61 ± 1.71	5.59 ± 0.18	0.35
SOC	1.79 ± 0.59	1.44 ± 0.30	0.003
SOC^2	-0.46 ± 0.18	-0.66 ± 0.27	0.012
N input	0.018 ± 0.0014	2.71 ± 0.15	< 0.00001
N input^2	-0.000039 ± 0.0000036	-1.64 ± 0.15	< 0.00001
Irrigation	0.75 ± 0.35	0.77 ± 0.34	0.032
pH	0.053 ± 0.18	0.12 ± 0.42	0.76
Aridity	0.16 ± 0.51	0.12 ± 0.41	0.76
Crop Type	1.54 ± 0.15	1.54 ± 0.15	< 0.00001
Clay (%)	0.013 ± 0.014	0.29 ± 0.31	0.37
Latitude	0.054 ± 0.016	1.40 ± 0.41	0.001
SOC*N input	0.0039 ± 0.00099	0.96 ± 0.25	0.00010

1149 The output of our linear mixed effect model (n=834). The full model explained 83% of

1150 observed variability within the dataset with fixed effects (included in the table)

1151 accounting for 42% of the variability. Standardized coefficients allow for direct

1152 comparison of the relative effect size of each modeled variable despite different scales on

1153 which the variables are measured. For example, crop type's effect on yield is two-times

1154 greater than that of irrigation. Crop type was coded as a binary variable with 0 for wheat

1155 and 1 for maize. Irrigation was also coded as a binary variable with 0 for no irrigation and

1156 1 for irrigation.

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1163 **Table 2. Scenarios for increases in yield and reductions in N input with an increase**

1164 **in SOC concentration to target values.**

Scenario	Crop	Global Yield Average (t ha^{-1})	Increase in production (Mt)	Nitrogen input (Mt N ha^{-1})
Current condition	Maize	3.34 ± 2.62	NA	17.24
	Wheat	2.43 ± 1.58	NA	33.07
Increase SOC to target concentrations	Maize	3.93 ± 3.08	29.96 (5%)	15.96
	Wheat	3.17 ± 2.06	55.41 (10%)	32.04

1165 Values (mean±SD) represent current EarthStat yields and projected gains in yield and

1166 production (with % increase in parentheses) resulting from an increase in SOC

1167 concentration to target values for each agro-ecological zone (targets ranged from 1.0 to

1168 2.0%). We used our regression model to determine potential gains in EarthStat yield and

1169 reductions in EarthStat N input. Global yield averages represent tonnes produced per unit

1170 land area, whereas production represents tonnes of maize and wheat produced globally.

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Distribution by country

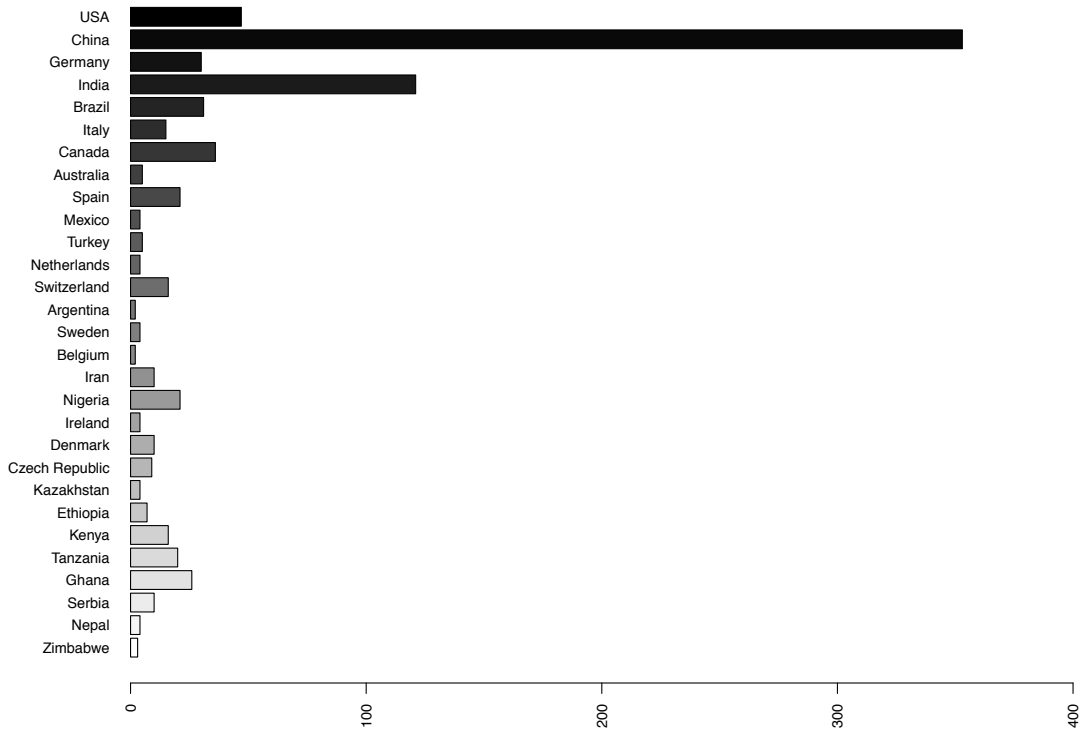



Figure 1: Distribution of data points by country. Countries are ordered by Gross

Domestic Product (GDP) in order from largest (top) to smallest (bottom). The dataset

used for this study contains a total of 840 individual observations from 29 different

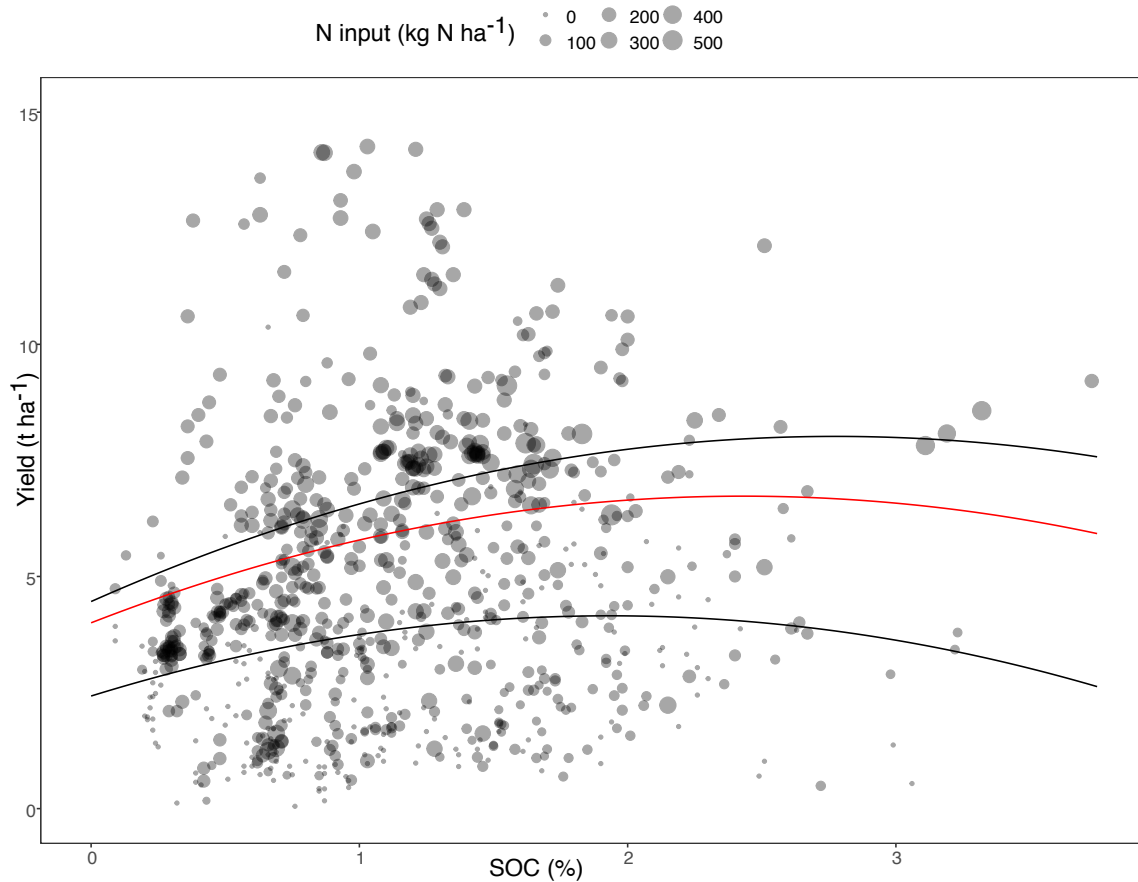
countries.

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Figure 2: Relationship between SOC and yield of maize for published studies. The

regression lines are modeled yields (i.e. effect sizes) for rain-fed (i.e. non-irrigated) maize

using observed means of our meta-dataset for aridity, pH, texture, and latitude at different

N input rates. We varied SOC (x-axis) across the range of values extracted from the

literature. The red line represents the mean N input rate (118 kg N ha^{-1} y^{-1}) across all

studies, with the bottom line representing 0 inputs of N and the top line representing 200

kg N ha^{-1} y^{-1}. For the raw data points, N input is mapped as a continuous variable across

its range from 0 (smallest circles) to 500 kg N ha^{-1} y^{-1} (largest circles). Note that the

observed scatter of the individual observations is an outcome of the fact yield is

controlled by multiple factors (Table 1), and therefore the regression lines isolate just the

potential effect of SOC with all other factors held constant.

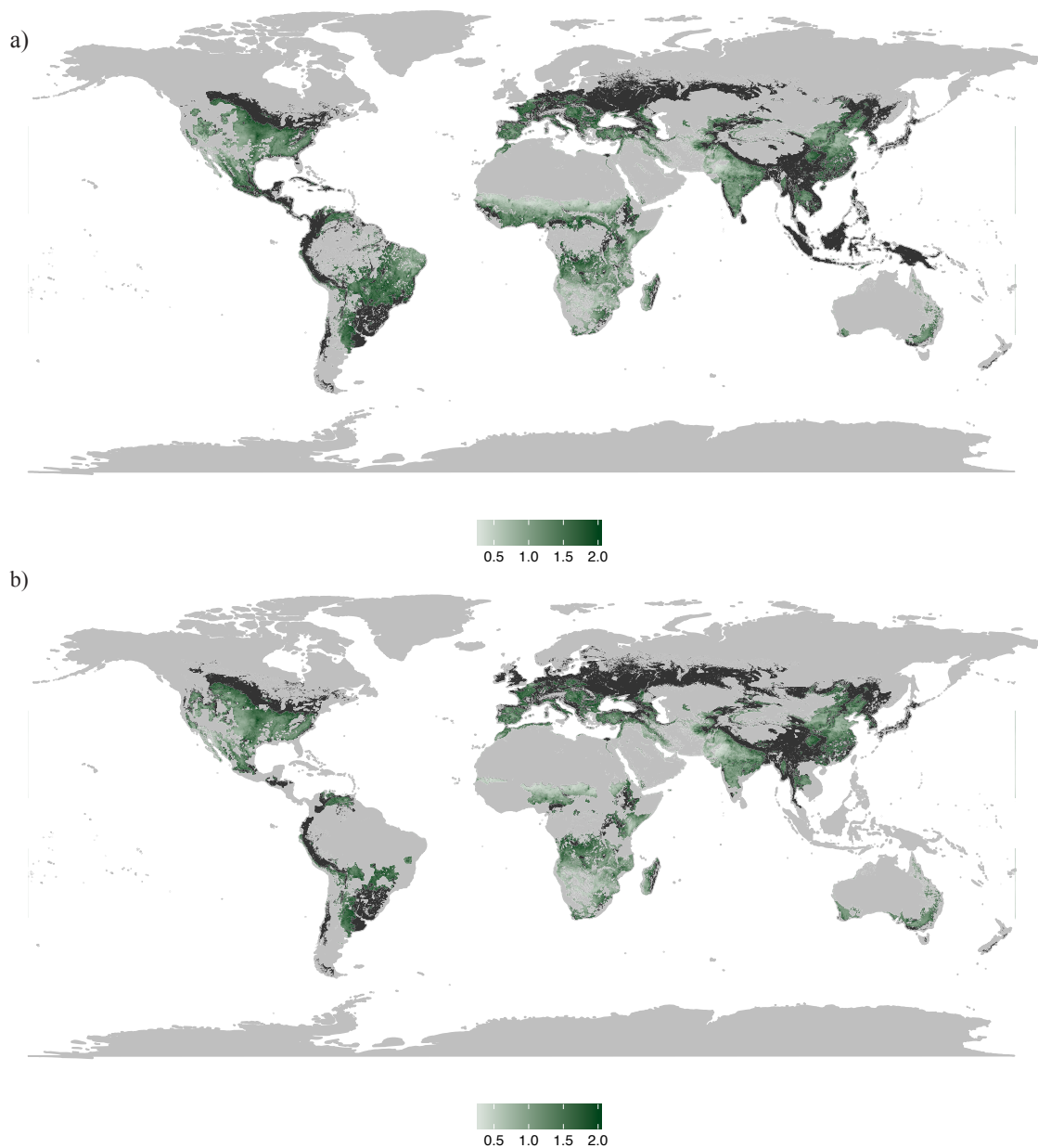



Figure 3: Global maize and wheat lands with less than 2% SOC. Cultivated (a) maize

lands and (b) wheat lands on soils with SOC contents less than 2%. Approximately two

thirds of all maize (61%) and of all wheat (64%) producing areas are on soils with less

than 2% SOC. Black areas on the maps are cultivated maize and wheat lands that have

concentrations over 2% SOC. Yield data is taken from EarthStat and SOC data is taken

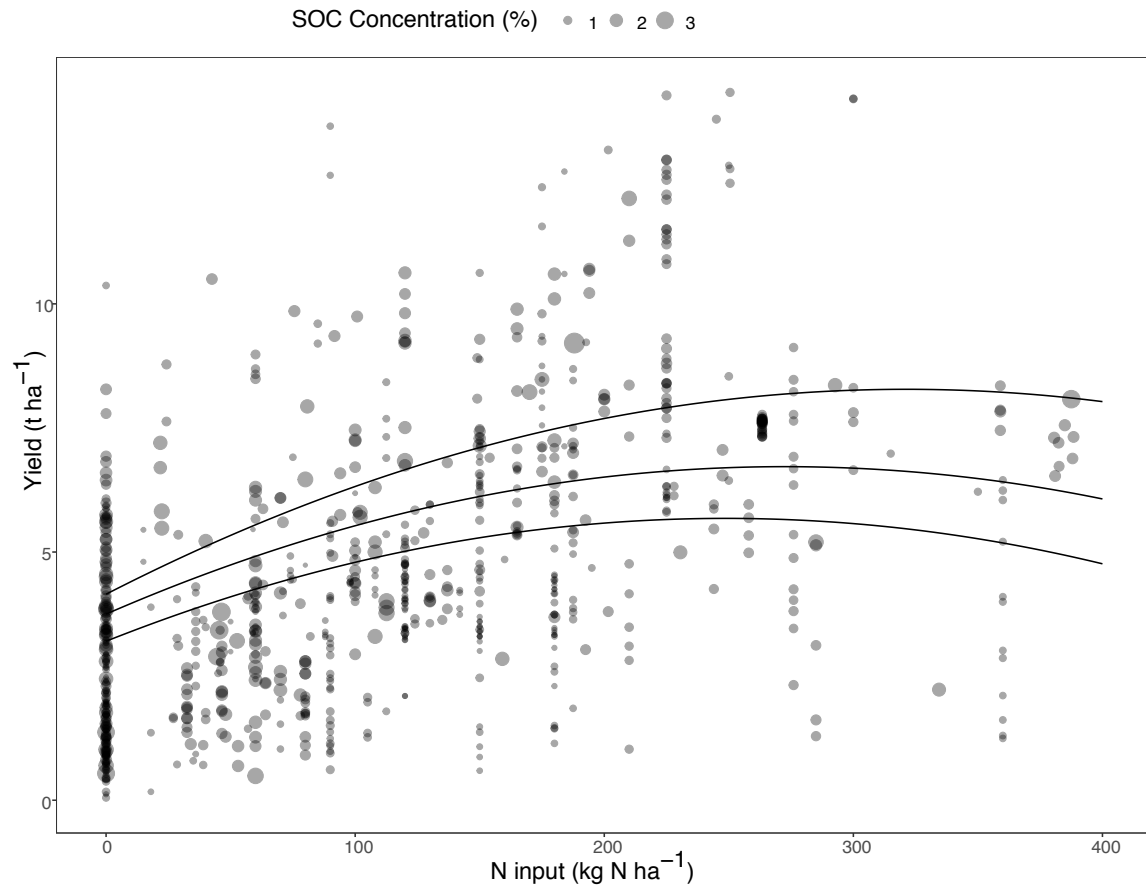
from ISRIC-SoilGrids.

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Figure 4: Potential reductions in nitrogen fertilizer with an increase in SOC

concentration. The lines on the graph represent varying SOC concentrations, 2.0%,

1.0%, and 0.5% SOC from top to bottom for rain-fed maize. These lines are plotted on

top of the observations from our dataset with SOC mapped as a continuous variable

across its range from 0.1% (smallest circles) to 3.0% (largest circles). Our model shows

that keeping yield constant by increasing SOC contents allows for potentially significant

reductions in N input (e.g. the same yield is achievable with 0 N input and 2% SOC, as

with 50 kg N ha^{-1} y^{-1} and 0.5% SOC). Recognizing that the 0 N input values may

influence the modeled relationship, we analyzed data excluding these values. The

qualitative patterns remain the same if the 0 N input values are excluded from the

analysis; and while the absolute quantitative patterns shift slightly, the general trends

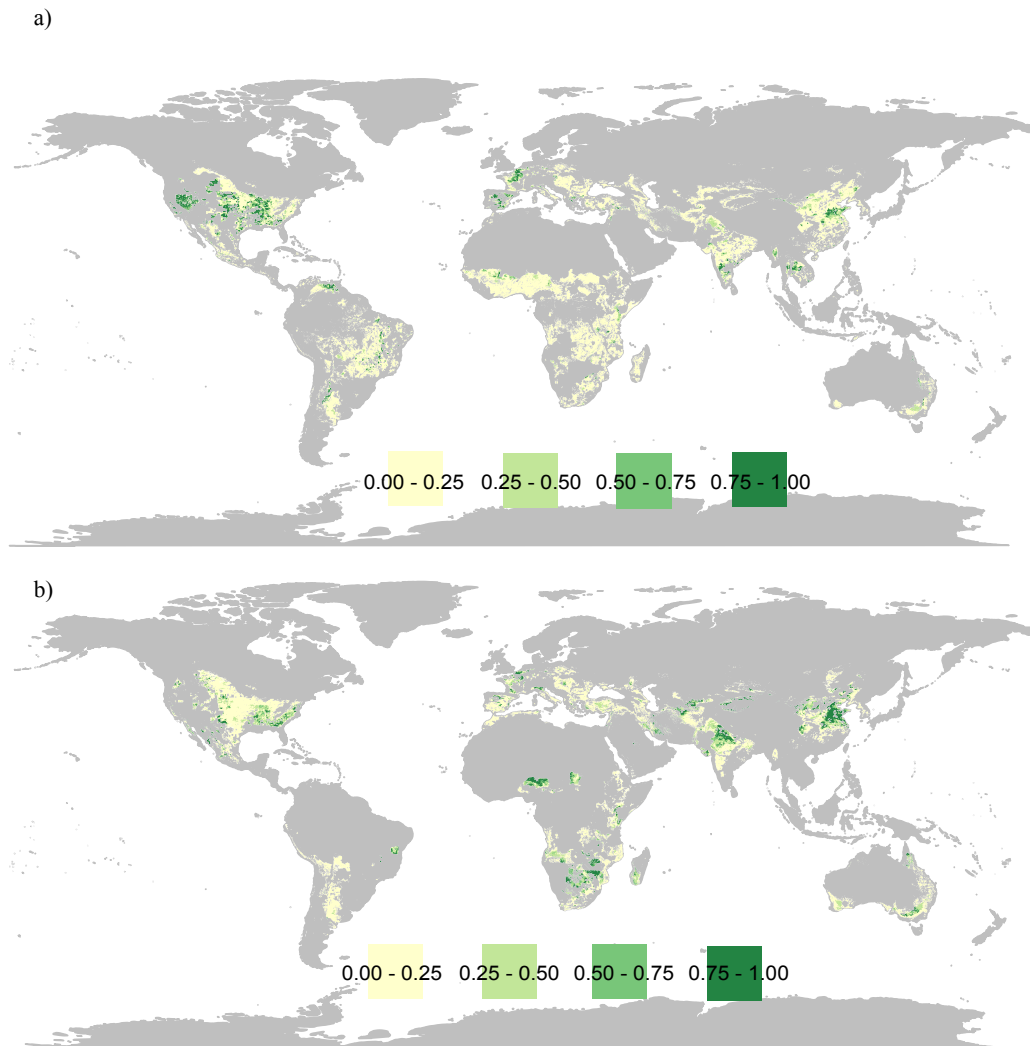
1224 remain intact.

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Figure 5: Proportion closure of yield gap for (a) maize and (b) wheat given an increase in SOC concentration to target values for each AEZ (ranging from 1-2%).
1228 Modeled gains come from our regression relationship between SOC and yield and
1229 applying it to EarthStat yield gap data. Doing so determines the potential increase in yield
1230 and therefore projected reductions in yield gaps for maize and wheat.

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