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## Carbon opportunity cost increases carbon footprint advantage of grain-finished beef

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<b>Abstract:</b>	<p>Beef production accounts for the largest share of global livestock greenhouse gas emissions and is an important target for climate mitigation efforts. Most life-cycle assessments comparing the carbon footprint of beef production systems have been limited to production emissions. None also consider potential carbon sequestration due to grazing and alternate uses of land used for production. We assess the total carbon footprint of 100 beef production systems in 16 countries, including production emissions, soil carbon sequestration from grazing, and carbon opportunity cost—the potential carbon sequestration that could occur on land if it were not used for production. We conduct a pairwise comparison of pasture-finished operations in which cattle almost exclusively consume grasses and forage, and grain-finished operations in which cattle are first grazed and then fed a grain-based diet. We find that pasture-finished operations have 20% higher production emissions and 42% higher total carbon footprint than grain-finished systems. We also find that more land-intensive operations generally have higher carbon footprints. Regression analysis indicates that a 10% increase in land-use intensity is associated with a 4.8% increase in production emissions, but a 9.0% increase in the total carbon footprint, including production emissions, soil carbon sequestration and carbon opportunity cost. The carbon opportunity cost of operations was, on average, 130% larger than production emissions. These results point to the importance of accounting for carbon opportunity cost in assessing the sustainability of beef production systems and developing climate mitigation strategies.</p>
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Additional data availability information:	

1 Carbon opportunity cost increases carbon footprint advantage of grain-finished beef

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## 13 **Abstract**

14 Beef production accounts for the largest share of global livestock greenhouse gas emissions and  
15 is an important target for climate mitigation efforts. Most life-cycle assessments comparing the  
16 carbon footprint of beef production systems have been limited to production emissions. None  
17 also consider potential carbon sequestration due to grazing and alternate uses of land used for  
18 production. We assess the total carbon footprint of 100 beef production systems in 16 countries,  
19 including production emissions, soil carbon sequestration from grazing, and carbon opportunity  
20 cost—the potential carbon sequestration that could occur on land if it were not used for  
21 production. We conduct a pairwise comparison of pasture-finished operations in which cattle  
22 almost exclusively consume grasses and forage, and grain-finished operations in which cattle are  
23 first grazed and then fed a grain-based diet. We find that pasture-finished operations have 20%  
24 higher production emissions and 42% higher total carbon footprint than grain-finished systems.  
25 We also find that more land-intensive operations generally have higher carbon footprints.  
26 Regression analysis indicates that a 10% increase in land-use intensity is associated with a 4.8%  
27 increase in production emissions, but a 9.0% increase in the total carbon footprint, including  
28 production emissions, soil carbon sequestration and carbon opportunity cost. The carbon  
29 opportunity cost of operations was, on average, 130% larger than production emissions. These  
30 results point to the importance of accounting for carbon opportunity cost in assessing the  
31 sustainability of beef production systems and developing climate mitigation strategies.

## 32 **Introduction**

33 Beef production accounts for about 6% of all anthropogenic ~~greenhouse gas emissions~~ [1].  
34 Given rising demand in developing countries, reducing the greenhouse-gas (or carbon) footprint



35 of production, measured as kilograms carbon dioxide-equivalent (CO<sub>2</sub>e) per kilogram of beef, is  
36 an important climate mitigation strategy [2-3].

37 Whether beef is produced in pasture-finished or grain-finished systems affects its carbon  
38 footprint. In both pasture-finished and grain-finished systems, cattle are raised initially on  
39 pasture or rangeland. The primary difference lies in the finishing stage—in grain-finished  
40 systems, cattle are fed a grain-based diet and often kept in feedlots, whereas cattle in pasture-  
41 finished systems continue to eat fresh and stored grasses and hay until they reach slaughter  
42 weight [4]. The finishing stage therefore accounts for any potential difference in the carbon  
43 footprint of these systems. Pasture-finished systems are common in many parts of the world and  
44 account for approximately 33% of global beef production. Grain-finished systems account for  
45 15%, and other systems, such as mixed crop-livestock production, account for the remainder [5].

46 Most life-cycle assessments of the carbon footprint of grain-finished and pasture-finished  
47 systems have been limited to emissions directly attributable to cradle-to-farmgate activities (here  
48 referred to as production emissions) [6]. Reviews and meta-analyses of these studies conclude  
49 that pasture-finished systems have a higher average carbon footprint [4,6,7]. Grain finishing  
50 typically leads to much higher growth rates. As a result, proportionally less energy is expended  
51 on maintenance rather than growth, such that inputs and emissions per unit of beef is lower [8].

52 In addition to emissions associated with production, beef's carbon footprint is also  
53 influenced by land use. Recent meta-analyses show that pasture-finished systems have higher  
54 land-use intensity (measured as area per unit production) on average, since the amount of pasture  
55 needed in the finishing stage of pasture-finished cattle is much larger than the amount of  
56 cropland needed to provide grain for the finishing stage of grain-finished cattle [46].

57 Greater land requirements influence the carbon footprint in two ways. First, pasture and crop  
58 management can increase soil carbon sequestration [9-10]. Use of improved grazing practices in  
59 some pasture-finished systems has sequestered enough carbon to offset production emissions  
60 from finishing [11]. Yet large soil carbon sequestration rates are only possible under particular  
61 agro-ecological conditions and for a limited time period [9,12].

62 Second, greater land use for beef production can displace native ecosystems and reduce land  
63 available for restoration. The amount of CO<sub>2</sub> that could be removed on land used for production  
64 through reforestation or other restoration has been referred to as the “carbon opportunity cost”  
65 [13].

66 Existing global comparisons of pasture-finished and grain-finished systems are incomplete  
67 as they do not account for both carbon opportunity cost and soil carbon sequestration. For  
68 instance, Poore and Nemecek (2018) [6], in a global meta-analysis of life-cycle assessments, do  
69 not account for potential soil carbon sequestration from production or the carbon opportunity  
70 cost of land use. The authors do account for emissions from land-use change, but only from  
71 recent changes in which total area for the crop or livestock product increased in the country of  
72 production. This approach, unlike the carbon opportunity cost approach, can result in zero carbon  
73 costs associated with many types of land use (see Searchinger *et al.* 2018 [14] Supplementary  
74 Discussion for a detailed treatment). Balmford *et al.* (2018) [15] estimate the relationship  
75 between the carbon footprint and land-use intensity of beef production including foregone carbon  
76 sequestration from land use—finding that there is a strong positive correlation—but their  
77 analysis is limited to Latin America and does not estimate soil carbon sequestration from  
78 grazing. Schmidinger and Stehfest (2012) [16], Searchinger *et al.* (2018) [14], and Hayek *et al.*  
79 (2020) [13] estimate the carbon opportunity cost of beef production at different geographic

80 scales, but do not compare grain-finished and pasture-finished systems or estimate soil carbon  
81 sequestration from grazing.

82 Here, for the first time, we assess the total carbon footprint – defined as the sum of carbon  
83 emissions from production, soil carbon sequestration, and carbon opportunity cost – of pasture-  
84 finished and grain-finished systems from across the world. We compare the total carbon footprint  
85 of pasture-finished and grain-finished systems that exist in the same region and that have been  
86 studied using the same methodology. To assess the relationship between land-use intensity and  
87 carbon footprint, regardless of the system, we also regress several carbon footprint measures on  
88 land-use intensity.

89 Beef production systems are changing rapidly across the world, and decisions about the  
90 future direction of this change will have important implications for climate mitigation as well as  
91 other environmental impacts. Accounting for the total carbon footprint, including the carbon  
92 opportunity cost, as we do in this paper, should help guide these decisions.

## 93 **Materials and methods**

94 We calculate the total carbon footprint (the sum of production emissions, soil carbon  
95 sequestration, and carbon opportunity costs in kilograms CO<sub>2</sub>e per kilogram of retail weight  
96 beef) of 100 beef production operations across 16 countries, including those from beef and dairy  
97 herds, drawn from a dataset of food and beverage life-cycle assessments [9] and from Stanley *et*  
98 *al.* (2018) [11]. Poore and Nemecek (2018) [9] includes production emissions and land-use  
99 intensity data. Stanley *et al.* (2018) [11] reports production emissions, carbon sequestration,  
100 emissions from soil erosion, and land-use intensity for the finishing stage of a pasture-finished  
101 and grain-finished operation in the Midwestern USA; we derive values from earlier stages from

102 Pelletier *et al.* (2010) [17] which also studied operations in the Midwest. We conduct a pair-wise  
103 comparison of carbon footprints between pasture-finished and grain-finished beef production  
104 systems, and a regression analysis of the relationship between land-use intensity and carbon  
105 footprint.

## 106 **Production emissions and land-use intensity**

107 Production emissions represent cradle-to-farmgate life-cycle greenhouse gas emissions. This  
108 includes emissions associated with enteric fermentation, animal housing, manure management,  
109 and inputs associated with feed production such as fertilizers, pesticides, and machinery.

110 Land-use intensity represents land required for grazing and crop production, in hectare per  
111 kilogram of retail weight beef. Land use for pasture is calculated as the sum of temporary and  
112 permanent pasture, and land use for cropland is calculated as the sum of seed, arable and  
113 fallowed crop land. We use and standardize production emissions and land-use intensity values  
114 from Poore and Nemecek (2018) [9] and Stanley *et al.* (2018) [11].

## 115 **Soil carbon sequestration**

116 Soil carbon sequestration (SCS) in kg CO<sub>2</sub> per kg of retail weight beef is calculated as the  
117 product of land-use intensity of grazing (LUI) and carbon sequestration due to grazing (CSG) in  
118 kg C ha<sup>-1</sup> yr<sup>-1</sup> (Equation 1).

$$119 \quad SCS = LUI \cdot CSG \cdot \frac{44 \text{ CO}_2}{12 \text{ C}} \quad (1)$$

120 There is insufficient data to calculate a specific carbon sequestration rate for each life-cycle  
121 assessment location. This is in part because sequestration rates depend on environmental and  
122 management factors, such as soil texture and grazing intensity, not consistently described in the  
123 life-cycle assessments. Instead, for all life-cycle assessments we use the mean carbon

124 sequestration rate of 0.28 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for “improved grazing management” estimated in a  
125 synthesis of the grassland management literature [18]. This estimate, drawn from studies with an  
126 average soil depth of 23 cm, is within the range of peer reviewed estimates: 0.03 and 1.04 Mg C  
127 ha<sup>-1</sup>yr<sup>-1</sup>, with the lowest values corresponding to dry climates and the highest to specific  
128 grassland management practices and regions [19]. Given that not all the life-cycle assessments  
129 included are of operations with improved grazing practices, the true carbon sequestration rates  
130 across operations may be lower. To be conservative in our carbon footprint for grain-finished  
131 operations, we assume that no carbon sequestration occurs on cropland used for feed production,  
132 consistent with research that shows that CO<sub>2</sub> emissions from agricultural land are generally  
133 balanced by removals [20].

## 134 **Carbon opportunity cost**

135 Our measure of carbon opportunity cost calculates how much carbon sequestration would  
136 have occurred had land been occupied with native ecosystems instead of pasture or cropland.  
137 This assumes that reducing land-use intensity results in proportionately less agricultural land area  
138 locally.

139 We calculate carbon opportunity cost (COC) as the sum of the carbon opportunity cost of  
140 pasture (*p*) and cropland (*c*) used in production. For each of these two land uses, the carbon  
141 opportunity cost is calculated as the product of land-use intensity (LUI) and potential carbon  
142 sequestration (PCS) of the land in the area where the life-cycle assessments was conducted, in kg  
143 C ha<sup>-1</sup> yr<sup>-1</sup> (Equations 2 and 3).

$$144 \quad COC = \sum_i LUI_i \cdot PCS_i \cdot \frac{44 CO_2}{12 C} \text{ for } i = c, p \quad (2)$$

145 where

146 
$$PCS_i = \frac{NPP_i \cdot k_i \cdot r - s_i}{r} \text{ for } i = c, p \quad (3)$$

147  $NPP_i$  denotes the potential net primary productivity of native vegetation ( $\text{kg C ha}^{-1} \text{ yr}^{-1}$ ) that  
 148 could be restored on agricultural land within a given radius of where the life-cycle assessment  
 149 was conducted. We report results using a radius of 2 degrees ( $\sim 223 \text{ km}$  at equator).  $k_i$  is the  
 150 conversion factor from net primary productivity to carbon sequestration in vegetation and soils  
 151 or, put differently, the average level of carbon sequestration generated by devoting one kilogram  
 152 of NPP to restoring native vegetation. This value is  $0.42 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$  for every kg of NPP for  
 153 cropland and 0.44 for pasture, as calculated by Searchinger *et al.* (2018) [14].  $r$  denotes the time  
 154 period over which carbon sequestration is averaged, in this case 100 years; and  $s_i$  denotes  
 155 existing vegetation carbon stocks ( $\text{kg C ha}^{-1}$ ), 1100 for cropland and 3100 for pasture, based on  
 156 global averages for cereals and pasture, respectively, from Searchinger *et al.* (2018) [14].  
 157 Although spatially explicit estimates of cropland carbon stocks exist [21], we are not aware of  
 158 any for pasture carbon stocks.

159 The logic behind Equation 3 is as follows. The numerator represents the difference in  
 160 potential carbon stocks between current land use and native vegetation.  $NPP_i \cdot k_i$  is a flux  
 161 measure, in kilograms of carbon per hectare per year, which we multiply by 100 to turn into a  
 162 stock measure. In effect, this assumes that the equilibrium carbon stock in native ecosystem is  
 163 reached after 100 years. The numerator, the difference in potential carbon stocks, is then divided  
 164 by 100 to arrive at an annual (flux) rate. We select a time period of 100 years based on previous  
 165 studies such as Searchinger *et al.* (2018) [14] and Schmidinger and Stehfest (2012) [16], which  
 166 use it as a time period over which to calculate average carbon sequestration rates in regenerating  
 167 forests.

168 Data on potential net primary productivity under native vegetation is generated by the Lund–  
169 Potsdam–Jena managed Land (LPJmL) model, a dynamic global vegetation model that simulates  
170 vegetation composition, distribution, and carbon stocks and flows at 0.5x0.5° spatial resolution.  
171 We use LPJmL results from Searchinger *et al.* (2018) [14].

172 We assume life-cycle assessment sites located in climate categorized as “dry” in Poore &  
173 Nemecek (2018) [9] have zero potential carbon sequestration because they either cannot support  
174 substantial additional biomass or are native grasslands or savannas for which restoration does not  
175 typically involve reforestation [22].

## 176 **Pairwise comparison between pasture-finished and grain-finished** 177 **production systems**

178 We compare the carbon footprint of 20 pairs of pasture-finished and grain-finished  
179 production systems, across 12 countries, in the Poore and Nemecek (2018) [9] database and one  
180 recent comparative life-cycle assessment [11] with and without soil carbon sequestration and  
181 carbon opportunity cost included. Systems were selected for inclusion if they were in the same  
182 subnational region or country, if the study was national in scope, and reported in the same study  
183 or within two studies by the same primary author. Details of the pairs are listed in S8 Table.  
184 Fourteen of the pairs were reported for the same geographic region, but lacked coordinates. For  
185 those, we estimated carbon opportunity cost by calculating mean potential net primary  
186 productivity on cropland and grazing land within the subnational region or country the life-cycle  
187 assessment was located (Supplementary Methods). We used a paired t-test to test if the mean  
188 difference between the pasture-finished and grain-finished system was significantly different  
189 from zero.

## 190 **Regression analysis**

191 We also assess the relationship between carbon footprint and land-use intensity using cross-  
192 section regression analysis of beef production operations. We include 72 operations from life-  
193 cycle assessments that report geographic coordinates, including a total of 24 studies in 12  
194 countries (S1 Fig, S7 Table). We log-transform the carbon footprint and land-use intensity  
195 because the input data is heavily right-skewed and because this enables us to present results as  
196 elasticities—the expected percent change in the carbon footprint with a percentage change in  
197 land-use intensity.

198 We run three different regressions, starting with production emissions as the only regressor,  
199 adding carbon opportunity cost in the second regression, and then also including soil carbon  
200 sequestration in the third regression. We use a linear model to facilitate comparison of the  
201 relationship across the regressions. Since there may be variables operating at the country level  
202 that influence the carbon footprint (e.g. climate, national policy), we use a multilevel model with  
203 country-level random effects, particularly varying intercepts and constant slopes (Gelman and  
204 Hill, 2007). This yields the following regression equation:

$$205 \quad \log(\text{carbon footprint}_{i,j}) = \beta_0 + \beta_1 \log(LUI_{i,j}) + u_j + \epsilon_{i,j} \quad (4)$$

206 where  $j$  indexes countries,  $i$  indexes operations within countries,  $\beta_0 + u_j$  is the intercept for  
207 each country,  $\beta_1$  represents the elasticity between land-use intensity and the carbon footprint, and  
208  $\epsilon_{ij}$  is an error term.

209 We choose this specification over a fixed effect model as there is substantial variation in the  
210 independent variable within units (i.e. countries), the level of correlation between unit effects and  
211 the independent variable is not extremely high, and we are interested in accounting for the  
212 variability between units but not in estimating specific unit effects, in which case a random



213 effects model can be appropriate to use and result in superior estimates (Clark and Linzer 2015).  
214 Regressions with fixed effects produced results very similar to those with random effects (S5  
215 Table S5). Our analysis examines differences in total carbon footprint across operations with  
216 different land-use intensity and does not attempt causal inference per se.

## 217 **Robustness checks**

218 We vary four parameters to assess the robustness of the results. First, we run the analysis  
219 with 0.25, 0.5, 1.0 and 4 degree radius. We do this to confirm our results cannot be explained by  
220 the choice of radius as NPP values can vary widely over a small area.

221 Second, we run the analysis with alternative calculations for carbon opportunity cost at the  
222 national and global levels. The national and global carbon opportunity costs assume that if the  
223 amount of land needed to support a given level of food production declines by one unit as a  
224 result of lower land-use intensity, then one unit of land will be restored to native vegetation  
225 somewhere in the country or world, respectively. These are relevant comparisons in cases where  
226 domestic and international trade allow land-use intensity reductions to be spatially disconnected  
227 from pasture and cropland expansion/contraction. We calculate national carbon opportunity cost  
228 using the average NPP values over all crop and pasture land across the country each production  
229 system is located in. This method could be improved by using crop-specific values; however, not  
230 all life-cycle assessments in our dataset describe which crops are used in production. We also  
231 calculate global carbon opportunity cost using average global net primary production values.

232 Third, we run the analysis using a carbon sequestration rate of  $0.47 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ , the  
233 average value reported across all studies of improved grassland management included in Conant  
234 *et al.* (2017). This reduces the total carbon footprint of more land-intensive operations such as

235 pasture-finished systems more than it reduces the carbon footprint of less land-intensive  
236 operations.

237 Fourth, we run the analysis with and without the potential carbon sequestration, and thus the  
238 carbon opportunity cost, set to 0 for operations in dry climates.

## 239 **Results**

240 In this study we calculated the total carbon footprint of beef production systems as the sum  
241 of production emissions, carbon opportunity cost, and soil carbon sequestration, and assessed the  
242 relationship of total carbon footprint and land-use intensity. After presenting summary statistics,  
243 we show the results of the pair-wise comparison of the carbon footprints of pasture-finished and  
244 grain-finished beef production systems. We then present results from regression analysis of  
245 carbon footprints on land-use intensity, with separate regressions for the different approaches for  
246 calculating carbon footprint.

247 The total carbon footprint across the 72 beef production operations with reported latitude  
248 and longitude, and the 28 operations without latitude/longitude included in the pasture-  
249 finished/grain-finished comparison ranged from -68.3 to 2169.3 kg CO<sub>2</sub>e kg<sup>-1</sup>retail weight, with  
250 mean 177.37 and median 107.14 (Table 1). Four pasture-finished and one grain-finished  
251 production systems in Queensland, Australia are estimated to have negative carbon footprints, in  
252 part because we assume that the dry climate results in zero carbon opportunity cost. If soil  
253 carbon sequestration rates are lower in dry climates than other climates, as some studies such as  
254 Smith *et al.* (2008) suggest, these operations would be more likely to also have positive carbon  
255 footprints. The total carbon footprint was similar in robustness checks, with the mean value

256 ranging from 141.6 to 210.0 kg CO<sub>2</sub>e kg<sup>-1</sup> retail weight when different radii are used and when  
 257 we do not assume zero carbon opportunity cost for arid climates (S1 Table).

258

259 **Table 1: Summary statistics for beef operations**

Variable	Mean	Median	Range	95% CI	Units
Production emissions	52.64	41.42	4.9, 182	45.48, 59.8	kg CO <sub>2</sub> e kg <sup>-1</sup>
Soil carbon sequestration	-15.11	-7.41	-164.8, 0	-19.96, -10.26	kg CO <sub>2</sub> e kg <sup>-1</sup>
Carbon opportunity cost	139.85	68.46	0, 2243	87.1, 192.59	kg CO <sub>2</sub> e kg <sup>-1</sup>
Total carbon footprint	177.37	107.14	-68.3, 2169.3	124.79, 229.96	kg CO <sub>2</sub> e kg <sup>-1</sup>
Land-use intensity	0.02	0.01	0, 0.2	0.01, 0.02	ha kg <sup>-1</sup>

260 All units are per kilogram retail weight.  $n = 100$ .

261

262 In individual systems, carbon opportunity cost was, on average, 130% larger than production  
 263 emissions. Soil carbon sequestration offset 31.5% of production emissions and 18.9% of the  
 264 production emissions and carbon opportunity cost, on average. Across all robustness checks,  
 265 carbon opportunity cost is at least 65% larger than production emissions and soil carbon  
 266 sequestration does not fully offset production emissions (S2 Table).

267 **Pairwise comparison between pasture-finished and grain-finished**  
268 **systems**

269 The pairwise comparison found that pasture-finished systems had 20% higher mean  
270 production emissions than grain-finished systems on average ( $p < 0.01$ ). When also including soil  
271 carbon sequestration, the difference is not statistically significant at a 95% confidence level  
272 ( $p \geq 0.05$ ). When the carbon opportunity cost is also accounted for, however, the total carbon  
273 footprint of pasture-finished systems is on average 42% higher than that of grain-finished  
274 systems ( $p < 0.01$ ) (Fig 1). Compared to grain-finished systems, pasture-finished systems also had  
275 15% higher median production emissions ( $p < 0.01$ ) and total carbon footprints ( $p < 0.05$ ),  
276 indicating that while the magnitude of the difference is sensitive to extreme values, the general  
277 finding of higher emissions is robust (S3 Table).

278

279 **Fig 1: Average ratios of carbon footprints between pasture-finished and grain-finished.**

280 Ratios expressed as percentage difference. PEM denotes production emissions, SCS denotes soil  
281 carbon sequestration, and COC denotes carbon opportunity cost. Values above (below) 0 denote  
282 the carbon footprint for pasture-finished operations is larger (smaller) than for grain-finished  
283 operations. Comparisons were made within paired production systems to control for agronomic  
284 and environmental differences. Bars show means and 95% confidence intervals. On average,  
285 carbon footprints for pasture-finished operations are significantly greater ( $p < 0.01$ ) than those of  
286 grain-finished operations when only production emissions are included and when production  
287 emissions, soil carbon sequestration and carbon opportunity cost are included.  $n = 20$  pairs.

288

289 The carbon footprint of pasture-finished systems, including production emissions, soil  
290 carbon sequestration and carbon opportunity cost, is higher than that of the grain-finished  
291 systems ( $p < 0.05$ ) in the majority of robustness tests (S4 Table). Differences are not significant  
292 ( $p \geq 0.05$ ) in some cases when a smaller radius or higher rate of soil carbon sequestration is used.

### 293 **Regression analysis**

294 In the regression analysis, when only production emissions are regressed on land-use  
295 intensity, the coefficient is 0.48 (Fig 2a, Table 2). This can be interpreted as a 10% increase in  
296 land-use intensity being associated with a 4.8% increase in carbon footprint. Less land-intensive  
297 systems typically have lower carbon footprints, measured by production emissions alone. Fig 2a  
298 shows the regression line with this slope, with the level adjusted by country. When adding in soil  
299 carbon sequestration, the coefficient is reduced to 0.32, indicating that soil carbon sequestration  
300 offsets a part of the production emissions (Table 2).

301

302 **Fig 2: The relationship between land-use intensity and carbon footprint of beef production**  
303 **systems.** Results from a regression of  $\log(\text{carbon footprint})$  on  $\log(\text{land-use intensity})$  with  
304 country random effects. Dots indicate life-cycle assessment observations; colors indicate  
305 countries; and lines represent the slope of the regression that includes all countries, adjusted  
306 according to the levels of each country. A) Carbon footprint including only production  
307 emissions.  $n = 72$ . B) Carbon footprint including production emissions, soil carbon sequestration  
308 and carbon opportunity cost.  $n = 69$ .

309

310 **Table 2: Results from log-log regressions**

	<i>Dependent variable:</i>		
	PEM	PEM+SCS	PEM+SCS+COC
LUI	0.48*** (0.04)	0.32*** (0.08)	0.90*** (0.09)
Constant	5.90*** (0.27)	4.84*** (0.45)	8.70*** (0.52)
Observations	72	68	69
R <sup>2</sup>	0.67	0.27	0.63
Adjusted R <sup>2</sup>	0.66	0.25	0.63

Standard errors in parentheses. LUI = land-use intensity. PEM = production emissions. SCS = soil carbon sequestration. COC = carbon opportunity cost.

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

However, the relationship between total carbon footprint, including carbon opportunity cost, and land-use intensity is stronger, with a coefficient of 0.90 (Table 2, Fig 2b). Hence, a 10% increase in land-use intensity is associated with a 9.0% increase in the total carbon footprint of beef production. This near-proportional relationship is in part due to the large share of the total carbon footprint accounted for by carbon opportunity cost, which is proportional to land area in production.

Regressions with pooled and country fixed-effects specifications generate similar results (S5 Table). Results are robust to other specifications and assumptions checked (S6 Table).

## 311 **Discussion**

312 Our analysis is the first global comparison of the carbon footprint of grain-finished and  
313 pasture-finished beef production systems that includes production emissions as well as soil

314 carbon sequestration and carbon opportunity cost. This yields significant new insights that can  
315 inform environmental and agricultural decision-making.

316 Our results indicate that pasture-finished and other more land-intensive beef production  
317 systems have greater production emissions than grain-finished and less land-intensive systems.  
318 When we calculate carbon footprints including production emissions, soil carbon sequestration,  
319 and carbon opportunity cost, all beef production systems have a higher carbon footprint than  
320 when only production emissions are included, but pasture-finished systems have a substantially  
321 larger carbon footprint than grain-finished systems, and there is a strong positive relationship  
322 between land use intensity and carbon footprint.

323 The differences in carbon footprint between pasture- and grain-finished operations are  
324 largely due to differences in carbon opportunity cost, which account for a large share of the total  
325 carbon footprint. The carbon opportunity cost of operations was, on average, 130% larger than  
326 production emissions. These results point to the importance of accounting for carbon opportunity  
327 cost in assessing the sustainability of beef production systems.

328 Our analysis also confirms that beef operations that have been studied in life-cycle  
329 assessments are generally not carbon neutral or negative. The mean carbon footprint across all  
330 studies, including production emissions, sequestration, and carbon opportunity cost, is over three  
331 times larger than the mean value for production emissions (Table 1). One exception is that we  
332 estimate negative carbon footprints for several grass-finished operations and one grain-finished  
333 operation that are in dry eco-climate zones in Australia, for which we assume there is zero  
334 carbon opportunity cost. This suggests that grazing cattle on dry rangeland with little to no  
335 carbon opportunity cost could have a small carbon footprint when the grazing also increases soil

336 organic carbon, as has been observed in some studies of dry rangeland with finer textured soil  
337 [12].

338 Our comparison of pasture-finished and grain-finished systems builds upon and strengthens  
339 past findings. Our finding that production emissions are 20% higher on pasture-finished  
340 operations than on grain-finished operations is consistent with Clark and Tilman (2017) [6],  
341 which found average emissions were 19% higher though their estimate was not statistically  
342 significant. In our results, soil carbon sequestration from grazing offsets only a portion of  
343 production emissions. This finding is consistent with the conclusions of Garnett *et al.* (2017)  
344 [19], which estimated that soil carbon sequestration from grazing can offset 20-60% of annual  
345 emissions from ruminant grazing.

346 Our finding that land-use intensity and carbon footprint are positively correlated strengthens  
347 similar findings from previous studies, none of which included production emissions, soil carbon  
348 sequestration and carbon opportunity cost, which is a more comprehensive approach for  
349 assessing the carbon footprint of land use than conventional land-use change approaches [16].  
350 Poore and Nemecek (2018) [9] found that beef and lamb systems with lower land-use intensity  
351 have a lower carbon footprint when considering land-use change-related greenhouse-gas  
352 emissions, but not carbon opportunity cost. Balmford *et al.* (2018) [14] used generalized linear  
353 mixed models to analyze the relationship between land-use intensity and carbon footprint,  
354 including a measure of carbon opportunity cost based on IPCC (2006) methods. Their analysis,  
355 limited to Brazil and tropical Mexico, also found that the carbon opportunity cost of agriculture  
356 was typically greater than production emissions, and that incorporating opportunity costs  
357 generated strongly positive associations between carbon footprint and land-use intensity.  
358 Searchinger *et al.* (2018) [14] calculated global-average carbon opportunity costs for beef similar



359 to the average calculated for all operations included in this study. Their estimates of 165.3 and  
360 143.9 kg CO<sub>2</sub>e kg<sup>-1</sup> carcass weight were based on the potential carbon that could be gained or  
361 lost, respectively, on land used for production. The authors applied the values to five production  
362 systems in Brazil and found, consistent with our results, that systems with the lowest land-use  
363 intensity had the greatest carbon benefits.

364 Our study has several limitations although we do not believe these substantially alter our  
365 conclusions. The pairwise comparison of grain-finished and pasture-finished operations has a  
366 relatively small sample of 20 pairs. This means that assumptions of asymptotic normality, which  
367 are the basis for the paired t-test, may not hold. However, our robustness checks (S4 Table) and  
368 nonparametric test of the median (S3 Table), which is robust to small sample sizes, extreme  
369 outliers, and heavy-tailed distributions, reinforce the conclusion that pasture-finished operations  
370 have greater production emissions and total carbon footprints than grain-finished operations. In  
371 addition, our results cannot be considered to be globally representative or representative of all  
372 operations. The life-cycle assessments that underlie our study were not conducted to be globally  
373 representative. For instance, we include one study from Asia (Indonesia) and none from Africa.

374 In our study, we assume that a change in land-use intensity results in a proportionate change  
375 in land under production and thus the land area with native ecosystems. While this has the  
376 advantage of simplicity, it is unlikely to be exactly true in reality, as a result of economic  
377 mechanisms. The real effect may be more or less than proportional depending, in part, on how  
378 differences in land-use intensity and carbon footprint are associated with total factor  
379 productivity. For instance, an operation shifting from grain-finished to pasture-finished may  
380 lower total factor productivity. This would increase prices and lead to a reduction in overall  
381 demand, while at the same time making that operation less profitable and thus induce producers

382 elsewhere to produce more. The reduction in demand would reduce land use and the spillover of  
383 production would increase land use, with an ambiguous net impact.

384 It is also challenging to predict where a change in farmland area and native vegetation will  
385 take place as a result of changes in land-use intensity and production system in a given location.  
386 We calculate three measures of carbon opportunity cost: local, national, and global. These  
387 roughly correspond to different levels of market connectedness, which will differ between  
388 locations. For example, changes in US production can have large effects on global markets,  
389 whereas changes in less globally connected regions such as sub-Saharan Africa will likely see  
390 mostly local or national effects [24]. Furthermore, for those producers connected to global  
391 markets, effects of changes in production are not likely to be evenly distributed across the world,  
392 but are likely to be concentrated in those regions that are more globally integrated [24]. In the  
393 last few decades, much of the expansion of pasture has taken place in tropical countries like  
394 Brazil [25]. Following this logic, it is possible that higher land-use intensity in the US as a result  
395 of shifting to pasture-finished systems would displace production to these places, and is thus  
396 more likely to displace highly carbon-rich tropical ecosystems.

397 In addition, we use several simplifying assumptions. We use global mean estimates of soil  
398 carbon sequestration and current carbon stocks in cropland and grazing land vegetation due to  
399 lack of spatially-explicit data with global coverage. Our assumed rate is drawn from estimates  
400 for improved grazing management, so as to lessen the risk of overestimating the carbon footprint  
401 of grass-finished systems. Our measures of carbon opportunity cost are also based on mean  
402 potential carbon sequestration values in grazing land and cropland, if restored to native  
403 vegetation. They do not account for livestock diet rations, which crops are used for feed, or crop  
404 yields for instance. This may contribute to us underestimating potential carbon sequestration and

405 carbon opportunity costs if feed crops such as soy are grown in areas with higher potential  
406 carbon sequestration, such as former forest, than other crops.

407 Future research could build upon our analysis by integrating more spatially explicit  
408 estimates of soil carbon sequestration and carbon stocks and calculating carbon opportunity cost  
409 based on how different cropland and grazing land is used in beef production. Further types of  
410 beef and other livestock operations, such as pork or milk, could also be studied with similar  
411 methods.

412 Overall, this study provides a novel assessment of the carbon footprint of beef operations,  
413 building upon life-cycle assessments of production emissions to also include carbon  
414 sequestration and carbon opportunity cost. Our conclusion that beef operations with low land-use  
415 intensity, including grain-finished operations, have lower total carbon footprints than pasture-  
416 finished operations and others with high land-use intensity provides important insights for  
417 agricultural stakeholders. Accounting for products' total carbon footprint, not just production  
418 emissions, could shift which production systems government programs, corporate procurement,  
419 investors, and consumers incentivize.

420

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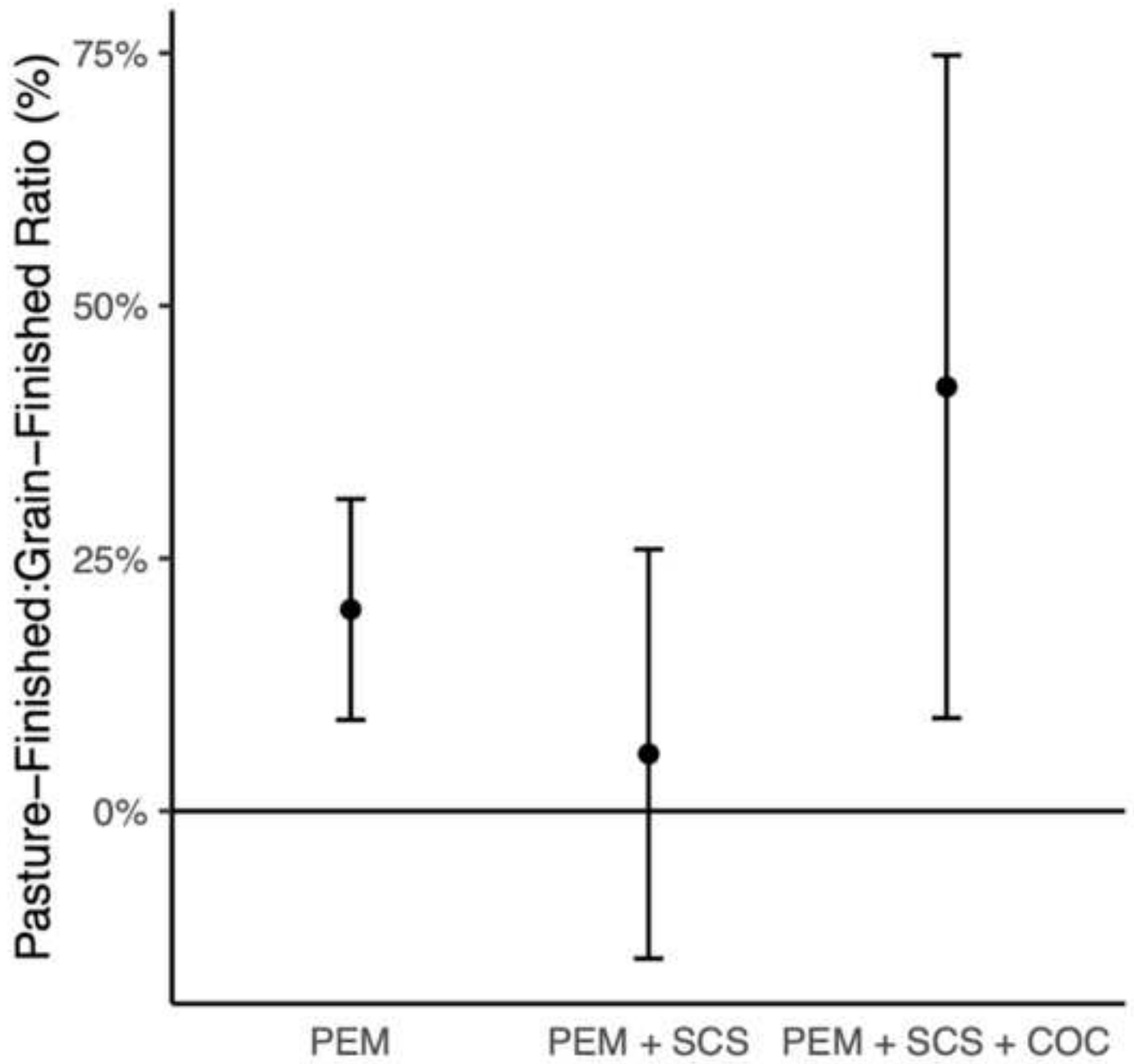
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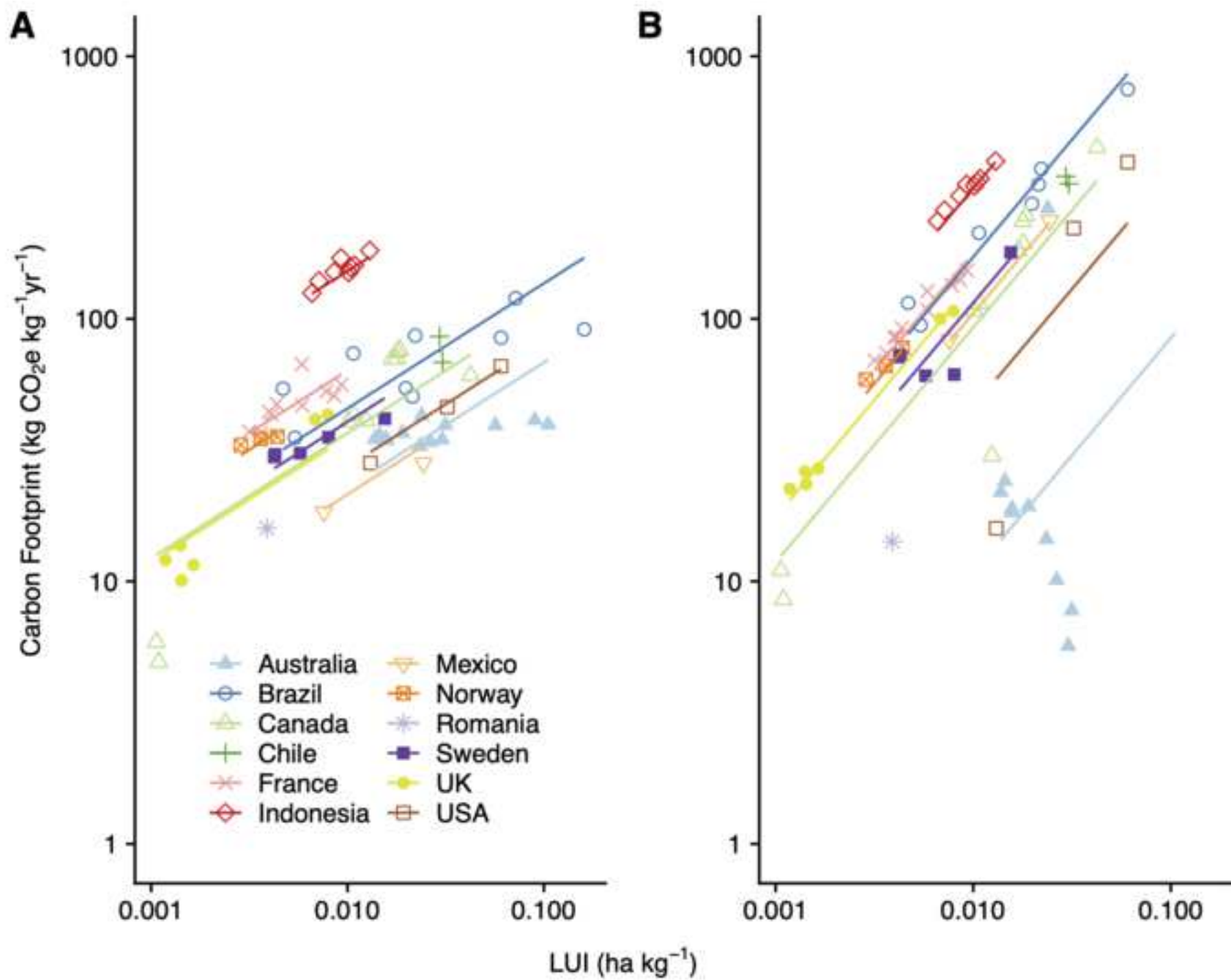
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## 508 **Supporting information**

509 **S1 File: Supplementary methods, figures and tables.**









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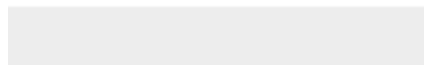




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1 ~~Full Title:~~ Carbon opportunity cost increases carbon footprint advantage of grain-  
2 finished beef

3 ~~Short Title: Carbon footprint of grain and grass finished beef~~

4

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## 15 **Abstract**

16 Beef production accounts for the largest share of global livestock greenhouse gas emissions and  
17 is an important target for climate mitigation efforts. Most life-cycle assessments comparing the  
18 carbon footprint of beef production systems have been limited to production emissions. None  
19 also consider potential carbon sequestration due to grazing and alternate uses of land used for  
20 production. We assess the total carbon footprint of 100 beef production systems in 16 countries,  
21 including production emissions, soil carbon sequestration from grazing, and carbon opportunity  
22 cost—the potential carbon sequestration that could occur on land if it were not used for  
23 production. We conduct a pairwise comparison of pasture-finished operations in which cattle  
24 almost exclusively consume grasses and forage, and grain-finished operations in which cattle are  
25 first grazed and then fed a grain-based diet. We find that pasture-finished operations have 20%  
26 higher production emissions and 42% higher total carbon footprint than grain-finished systems.  
27 We also find that more land-intensive operations generally have higher carbon footprints.  
28 Regression analysis indicates that a 10% increase in land-use intensity is associated with a 4.8%  
29 increase in production emissions, but a 9.0% increase in the total carbon footprint, including  
30 production emissions, soil carbon sequestration and carbon opportunity cost. The carbon  
31 opportunity cost of operations was, on average, 130% larger than production emissions. These  
32 results point to the importance of accounting for carbon opportunity cost in assessing the  
33 sustainability of beef production systems and developing climate mitigation strategies.

## 34 **Introduction**

35 Beef production accounts for about 6% of all anthropogenic greenhouse gas emissions [1].  
36 Given rising demand in developing countries, reducing the greenhouse-gas (or carbon) footprint

37 of production, measured as [kilograms](#) carbon dioxide-equivalent (CO<sub>2</sub>e) per [kilogram](#) of beef,  
38 is an important climate mitigation strategy [2-3].

39 Whether beef is produced in pasture-finished or grain-finished systems affects its carbon  
40 footprint. In both pasture-finished and grain-finished systems, cattle are raised initially on  
41 pasture or rangeland. The primary difference lies in the finishing stage—in grain-finished  
42 systems, cattle are fed a grain-based diet and often kept in feedlots, whereas cattle in pasture-  
43 finished systems continue to eat fresh and stored grasses and hay until they reach slaughter  
44 weight [\[4\]](#). The finishing stage therefore accounts for any potential difference in the carbon  
45 footprint of these systems. Pasture-finished systems are common in many parts of the world and  
46 account for approximately 33% of global beef production. Grain-finished systems account for  
47 15%, and other systems, such as mixed crop-livestock production, account for the remainder  
48 [\[45\]](#).

49 Most life-cycle assessments [comparing of](#) the carbon footprint of grain-finished and pasture-  
50 finished systems have been limited to emissions directly attributable to cradle-to-farmgate  
51 activities (here referred to as production emissions) [\[6\]](#). Reviews and meta-analyses of these  
52 studies conclude that pasture-finished systems have a higher average carbon footprint [\[4,6,75-7\]](#).  
53 Grain finishing typically leads to much higher growth rates. As a result, proportionally less  
54 energy is expended on maintenance rather than growth, such that inputs and emissions per unit of  
55 beef is lower [8].

56 In addition to emissions associated with production, beef's carbon footprint is also  
57 influenced by land use. Recent meta-analyses show that pasture-finished systems have higher  
58 land-use intensity (measured as area per unit production) on average, since the amount of pasture

59 needed in the finishing stage of pasture-finished cattle is much larger than the amount of  
60 cropland needed to provide grain for the finishing stage of grain-finished cattle [46–7].

61 Greater land requirements influence the carbon footprint in two ways. First, pasture and crop  
62 management can increase soil carbon sequestration [9-10]. Use of improved grazing practices in  
63 some pasture-finished systems has sequestered enough carbon to offset production emissions  
64 from finishing [11]. Yet large soil carbon sequestration rates are only possible under particular  
65 agro-ecological conditions and for a limited time period [9,12].

66 Second, greater land use for beef production can displace native ecosystems and reduce land  
67 available for restoration. The amount of CO<sub>2</sub> that could be removed on land used for production  
68 through reforestation or other restoration has been referred to as the “carbon opportunity cost”  
69 [13].

70 Existing global comparisons of pasture-finished and grain-finished systems are incomplete  
71 as they do not account for both carbon opportunity cost and soil carbon sequestration. For  
72 instance, Poore and Nemecek (2018) [67], in a global meta-analysis of life-cycle assessments, do  
73 not account for potential soil carbon sequestration from production or the carbon opportunity  
74 cost of land use. The authors do account for emissions from land-use change, but only from  
75 recent changes in which total area for the crop or livestock product increased in the country of  
76 production. This approach, unlike the carbon opportunity cost approach, can result in zero carbon  
77 costs associated with many types of land use (see Searchinger *et al et al.* 2018 [14]  
78 Supplementary Discussion for a detailed treatment). Balmford *et al et al.* (2018) [154] estimate  
79 the relationship between the carbon footprint and land-use intensity of beef production including  
80 foregone carbon sequestration from land use—finding that there is a strong positive  
81 correlation—but their analysis is limited to Latin America and does not estimate soil carbon

82 sequestration from grazing. Schmidinger and Stehfest (2012) [1516], Searchinger *et al et al.*  
83 (2018) [1614], and Hayek *et al et al.* (2020) [13] estimate the carbon opportunity cost of beef  
84 production at different geographic scales, but do not compare grain-finished and pasture-finished  
85 systems or estimate soil carbon sequestration from grazing.

86 Here, for the first time, we assess the total carbon footprint – defined as the sum of carbon  
87 emissions from production, soil carbon sequestration, and carbon opportunity cost – of pasture-  
88 finished and grain-finished systems from across the world. We compare the total carbon footprint  
89 of pasture-finished and grain-finished systems that exist in the same region and that have been  
90 studied using the same methodology.

91 ~~We find that grain finished production has a significantly smaller total carbon footprint than~~  
92 ~~pasture finished production. Pasture finished systems have higher average production emissions~~  
93 ~~than grain finished systems. Incorporating soil carbon sequestration reduces the carbon footprint~~  
94 ~~gap between pasture finished and grain finished systems. But when carbon opportunity cost is~~  
95 ~~also included, pasture finished systems have a 42% larger carbon footprint than grain finished~~  
96 ~~systems.~~

97 ~~The lower land use intensity of grain finished systems is a large factor in their lower carbon~~  
98 ~~footprint. To confirm that this assess the relationship between land-use intensity and carbon~~  
99 ~~footprint holds in general, regardless of the system, we also regress several carbon footprint~~  
100 ~~measures on land-use intensity. This shows that a 10% increase in land use intensity is~~  
101 ~~associated with a 4.8% increase in production emissions, and a 9% increase in total carbon~~  
102 ~~footprint, including soil carbon sequestration and carbon opportunity cost.~~

103 Beef production systems are changing rapidly across the world, and decisions about the  
104 future direction of this change will have important implications for climate mitigation as well as



105 other environmental impacts. Accounting for the total carbon footprint, including the carbon  
106 opportunity cost, as we do in this paper, should help guide these decisions.

## 107 **Materials and methods**

108 We calculate the total carbon footprint (the sum of production emissions, soil carbon  
109 sequestration, and carbon opportunity costs in ~~kilograms~~ kg CO<sub>2</sub>e per ~~kilogram~~ kg of retail weight  
110 beef) of 100 beef production operations across 16 countries, including those from beef and dairy  
111 herds, drawn from a dataset of food and beverage life-cycle assessments [9] and from Stanley ~~et~~  
112 ~~et al.~~ (2018) [11]. Poore and Nemecek (2018) [9] includes production emissions and land-use  
113 intensity data. Stanley ~~et al.~~ (2018) [11] reports production emissions, carbon sequestration,  
114 emissions from soil erosion, and land-use intensity for the finishing stage of a pasture-finished  
115 and grain-finished operation in the Midwestern USA; we derive values from earlier stages from  
116 Pelletier ~~et al.~~ (2010) [17] which also studied operations in the Midwest. We conduct a pair-  
117 wise comparison of carbon footprints between pasture-finished and grain-finished beef  
118 production systems, and a regression analysis of the relationship between land-use intensity and  
119 carbon footprint.

### 120 **Production emissions ~~&~~ and land-use intensity**

121 Production emissions represent cradle-to-farmgate life-cycle greenhouse gas emissions. This  
122 includes emissions associated with enteric fermentation, animal housing, manure management,  
123 and inputs associated with feed production such as fertilizers, pesticides, and machinery.

124 Land-use intensity represents land required for grazing and crop production, in hectare ~~(ha)~~  
125 per ~~kilogram~~ kg of retail weight beef. Land use for pasture is calculated as the sum of temporary

126 and permanent pasture, and land use for cropland is calculated as the sum of seed, arable and  
127 fallowed crop land. We use and standardize production emissions and land-use intensity values  
128 from Poore and Nemecek (2018) [9] and Stanley *et al.* (2018) [11].

## 129 Soil carbon sequestration

130 Soil carbon sequestration (SCS) in kg CO<sub>2</sub> per kg of retail weight beef is calculated as the  
131 product of land-use intensity of grazing (LUI) and carbon sequestration due to grazing (CSG) in  
132 kg C ha<sup>-1</sup> yr<sup>-1</sup> (Equation 1).

$$133 \quad SCS = LUI \cdot CS \cdot \frac{44 \text{ CO}_2}{12 \text{ C}} \quad (1)$$

134 There is insufficient data to calculate a specific carbon sequestration rate for each life-cycle  
135 assessment location. This is in part because sequestration rates depend on environmental and  
136 management factors, such as soil texture and grazing intensity, not consistently described in the  
137 life-cycle assessments. Instead, for all life-cycle assessments we use the mean carbon  
138 sequestration rate of 0.28 Mg ~~carbon (C)~~C ha<sup>-1</sup> yr<sup>-1</sup> for “improved grazing management”  
139 estimated in a synthesis of the grassland management literature [18]. This estimate, drawn from  
140 studies with an average soil depth of 23 cm, is within the range of peer reviewed estimates: 0.03  
141 and 1.04 Mg C ha<sup>-1</sup>yr<sup>-1</sup>, with the lowest values corresponding to dry climates and the highest to  
142 specific grassland management practices and regions [19]. Given that not all the life-cycle  
143 assessments included are of operations with improved grazing practices, the true carbon  
144 sequestration rates across operations may be lower. To be conservative in our carbon footprint  
145 for grain-finished operations, we assume that no carbon sequestration occurs on cropland used  
146 for feed production, consistent with research that shows that CO<sub>2</sub> emissions from agricultural  
147 land are generally balanced by removals [20].

## 148 Carbon opportunity cost

149 Our measure of carbon opportunity cost calculates how much carbon sequestration would  
150 have occurred had land been occupied with native ecosystems instead of pasture or cropland.  
151 This assumes that reducing land-use intensity results in proportionately less agricultural land area  
152 locally.

153 We calculate carbon opportunity cost (COC) as the sum of the carbon opportunity cost of  
154 pasture (*p*) and cropland (*c*) used in production. For each of these two land uses, the carbon  
155 opportunity cost is calculated as the product of land-use intensity (LUI) and potential carbon  
156 sequestration (PCS) of the land in the area where the life-cycle assessments was conducted, in kg  
157 C ha<sup>-1</sup> yr<sup>-1</sup> (Equations 2 and 3).

$$158 \quad COC = \sum_i LUI_i \cdot PCS_i \cdot \frac{44 \text{ CO}_2}{12 \text{ C}} \text{ for } i = c, p \quad (2)$$

159 ~~Where~~where

$$160 \quad PCS_i = \frac{NPP_i \cdot k_i \cdot r - s_i}{r} \text{ for } i = c, p \quad (3)$$

161 *NPP<sub>i</sub>* denotes the potential net primary productivity of native vegetation (kg C ha<sup>-1</sup> yr<sup>-1</sup>) that  
162 could be restored on agricultural land within a given radius of where the life-cycle assessment  
163 was conducted. We report results using a radius of 2 degrees (~223 km at equator). *k<sub>i</sub>* is the  
164 conversion factor from net primary productivity to carbon sequestration in vegetation and soils  
165 or, put differently, the average level of carbon sequestration generated by devoting one  
166 ~~kilogram~~kg of NPP to restoring native vegetation. This value is 0.42 kg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> for every kg  
167 of NPP for cropland and 0.44 for pasture, as calculated by Searchinger *et al et al.* (2018) [14]. *r*  
168 denotes the time period over which carbon sequestration is averaged, in this case 100 years; and  
169 *s<sub>i</sub>* denotes existing vegetation carbon stocks (kg C ha<sup>-1</sup>), 1100 for cropland and 3100 for pasture,  
170 based on global averages for cereals and pasture, respectively, from Searchinger *et al et al.*

171 (2018) [14]. Although spatially explicit estimates of cropland carbon stocks exist [21], we are not  
172 aware of any for pasture carbon stocks.

173 The logic behind Equation 3 is as follows. The numerator represents the difference in  
174 potential carbon stocks between current land use and native vegetation.  $NPP_i \cdot k_i$  is a flux  
175 measure, in kilograms of carbon per hectare per year, which we multiply by 100 to turn into a  
176 stock measure. In effect, this assumes that the equilibrium carbon stock in native ecosystem is  
177 reached after 100 years. The numerator, the difference in potential carbon stocks, is then divided  
178 by 100 to arrive at an annual (flux) rate. We select a time period of 100 years based on previous  
179 studies such as Searchinger *et al et al.* (2018) [14] and Schmidinger and Stehfest (2012) [16],  
180 which use it as a time period over which to calculate average carbon sequestration rates in  
181 regenerating forests.

182 Data on potential net primary productivity under native vegetation is generated by the Lund–  
183 Potsdam–Jena managed Land (LPJmL) model, a dynamic global vegetation model that simulates  
184 vegetation composition, distribution, and carbon stocks and flows at  $0.5 \times 0.5^\circ$  spatial resolution.

185 We use LPJmL results from Searchinger *et al et al.* (2018) [14].

186 We assume life-cycle assessment sites located in climate categorized as “dry” in Poore &  
187 Nemecek (2018) [9] have zero potential carbon sequestration because they either cannot support  
188 substantial additional biomass or are native grasslands or savannas for which restoration does not  
189 typically involve reforestation [22].

190 **Pairwise comparison between pasture-finished and grain-finished**  
191 **production systems**

192 We compare the carbon footprint of 20 pairs of pasture-finished and grain-finished  
193 production systems, across 12 countries, in the Poore and Nemecek (2018) [9] database and one  
194 recent comparative life-cycle assessment [11] with and without soil carbon sequestration and  
195 carbon opportunity cost included. Systems were selected for inclusion if they were in the same  
196 subnational region or country, if the study was national in scope, and reported in the same study  
197 or within two studies by the same primary author. Details of the ~~operations-pairs~~ are listed in ~~S8~~  
198 Table-S8. Fourteen of the pairs were reported for the same geographic region, but lacked  
199 coordinates. For those, we estimated carbon opportunity cost by calculating mean potential net  
200 primary productivity on cropland and grazing land within the subnational region or country the  
201 life-cycle assessment was located (Supplementary Methods). We used a paired t-test to test if the  
202 mean difference between the pasture-finished and grain-finished system was significantly  
203 different from zero.

204 **Regression analysis**

205 We also assess the relationship between carbon footprint and land-use intensity using ~~cross-~~  
206 section regression analysis of beef production operations. We include 72 operations from life-  
207 cycle assessments that report geographic coordinates, including a total of 24 studies in 12  
208 countries.~~We only include life-cycle assessments with coordinates for the location of the analyzed~~  
209 ~~beef production system, a total of 72 operations across 24 studies in 12 countries (S1 Fig-S1, S7~~  
210 Table-S7). We log-transform the carbon footprint and land-use intensity because the input data is  
211 heavily right-skewed and because this enables us to present results as elasticities—the expected

212 percent change in the carbon footprint with a percentage change in land-use intensity. ~~This yields~~  
213 ~~the following regression equation:~~

$$214 \log(\text{carbon footprint}) = \alpha \log(LUI) + \epsilon \quad (4)$$

215 ~~Where the parameter of interest,  $\alpha$ , represents the elasticity between land-use intensity and the~~  
216 ~~carbon footprint, and  $\epsilon$  is an error term.~~

217 We run three different regressions, starting with production emissions as the only regressor,  
218 adding carbon opportunity cost in the second regression, and then also including soil carbon  
219 sequestration in the third regression. We use a linear model to facilitate comparison of the  
220 relationship across the regressions. Since there may be variables operating at the country level

221 that influence the carbon footprint (e.g. climate, national policy), we use a multilevel model with  
222 country-level random effects, particularly varying intercepts and constant slopes (Gelman and  
223 Hill, 2007). ~~we consider a fixed effects or random effects model. This yields the following~~  
224 ~~regression equation:~~

$$225 \log(\text{carbon footprint}_{i,j}) = \beta_0 + \beta_1 \log(LUI_{i,j}) + u_j + \epsilon_{i,j} \quad (4)$$

226 where j indexes countries, i indexes operations within countries,  $\beta_0 + u_j$  is the intercept for  
227 each country,  $\beta_1$  represents the elasticity between land-use intensity and the carbon footprint, and  
228  $\epsilon_{ij}$  is an error term.

229 We choose this specification over a fixed effect model as there is substantial variation in the  
230 independent variable within units (i.e. countries), the level of correlation between unit effects and  
231 the independent variable is not extremely high, and we are interested in accounting for the  
232 variability between units but not in estimating specific unit effects, in which case a random  
233 effects model can be appropriate to use and result in superior estimates (Clark and Linzer 2015).  
234 ~~Random effects estimators require that there be no correlation between the covariate of interest~~

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235 ~~(here,  $\log(LUI)$ ) and the unit effects (in this case, *country*). A Hausman test on the~~  
236 ~~specification with production emissions and carbon opportunity cost included suggests that the~~  
237 ~~correlation is relatively low, motivating our choice of a random effects model. This is further~~  
238 ~~justified by the relatively small sample size, in which case a random effects model is likely~~  
239 ~~superior to a fixed effects model [23].~~ Regressions with fixed effects produced results very  
240 similar to those with random effects (S5 Table S5). Our analysis examines differences in net-total  
241 carbon footprint across operations with different land-use intensity and does not attempt causal  
242 inference per se.

### 243 **Robustness checks**

244 We vary four parameters to assess the robustness of the results. First, we run the analysis  
245 with 0.25, 0.5, 1.0 and 4 degree radius. We do this to confirm our results cannot be explained by  
246 the choice of radius as NPP values can vary widely over a small area.

247 Second, we run the analysis with alternative calculations for carbon opportunity cost at the  
248 national and global levels. The national and global carbon opportunity costs assume that if the  
249 amount of land needed to support a given level of food production declines by one unit as a  
250 result of lower land-use intensity, then one unit of land will be restored to native vegetation  
251 somewhere in the country or world, respectively. These are relevant comparisons in cases where  
252 domestic and international trade allow land-use intensity reductions to be spatially disconnected  
253 from pasture and cropland expansion/contraction. We calculate national carbon opportunity cost  
254 using the average NPP values over all crop and pasture land across the country each production  
255 system is located in. This method could be improved by using crop-specific values; however, not  
256 all life-cycle assessments in our dataset describe which crops are used in production. We also  
257 calculate global carbon opportunity cost using average global net primary production values.

258 Third, we run the analysis using a carbon sequestration rate of  $0.47 \text{ Mg}_C \text{ ha}^{-1} \text{ yr}^{-1}$ , the  
259 average value reported across all studies of improved grassland management included in Conant  
260 *et al et al.* (2017). This reduces the total carbon footprint of more land-intensive operations such  
261 as pasture-finished systems more than it reduces the carbon footprint of less land-intensive  
262 operations.

263 Fourth, we run the analysis with and without the potential carbon sequestration, and thus the  
264 carbon opportunity cost, set to 0 for operations in dry climates.

## 265 Results

266 In this study we calculated the total carbon footprint of beef production systems as the sum  
267 of production emissions, carbon opportunity cost, and soil carbon sequestration, and assessed the  
268 relationship of total carbon footprint and land-use intensity. After presenting summary statistics,  
269 we show the results of the pair-wise comparison of the carbon footprints of pasture-finished and  
270 grain-finished beef production systems. We then present results from regression analysis of  
271 carbon footprints on land-use intensity, with separate regressions for the different approaches for  
272 calculating carbon footprint.

273 The total carbon footprint across the 72 beef production operations with reported latitude  
274 and longitude, and the 28 operations without latitude/longitude included in the pasture-  
275 finished/grain-finished comparison ranged from -68.3 to 2169.3  $\text{kg CO}_2\text{e kg}^{-1}\text{kg-retail weight}$ ,  
276 with mean 177.37 and median 107.14 (Table 1). Four pasture-finished and one grain-finished  
277 production systems in Queensland, Australia are estimated to have negative carbon footprints, in  
278 part because we assume that the dry climate results in zero carbon opportunity cost. If soil  
279 carbon sequestration rates are lower in dry climates than other climates, as some studies such as



280 Smith *et al.* (2008) suggest, these operations would be more likely to also have positive  
 281 carbon footprints. The total carbon footprint was similar in robustness checks, with the mean  
 282 value ~~net carbon footprint~~ ranging from 141.6 to 210.0 kg CO<sub>2</sub>e kg<sup>-1</sup>/kg retail weight when  
 283 different radii are used and when we do not assume zero carbon opportunity cost for arid  
 284 climates (S1 Table-S1).

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286 **Table 1: Summary statistics for beef operations.**

Variable	Mean	Median	Range	95% CI	Units
Production emissions	52.64	41.42	4.9, 182	45.48, 59.8	kg CO <sub>2</sub> e kg <sup>-1</sup>
Soil carbon sequestration	-15.11	-7.41	-164.8, 0	-19.96, -10.26	kg CO <sub>2</sub> e kg <sup>-1</sup>
Carbon opportunity cost	139.85	68.46	0, 2243	87.1, 192.59	kg CO <sub>2</sub> e kg <sup>-1</sup>
Total carbon footprint	177.37	107.14	-68.3, 2169.3	124.79, 229.96	kg CO <sub>2</sub> e kg <sup>-1</sup>
Land-use intensity	0.02	0.01	0, 0.2	0.01, 0.02	ha kg <sup>-1</sup>

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287 All units are per kilogram retail weight.  $n = 100$ .

289 In individual systems, carbon opportunity cost was, on average, 130% larger than production  
 290 emissions. Soil carbon sequestration offset 31.5% of production emissions and 18.9% of the  
 291 production emissions and carbon opportunity cost, on average. Across all robustness checks,  
 292 carbon opportunity cost is at least 65% larger than production emissions and soil carbon  
 293 sequestration does not fully offset production emissions (S2 Table-S2).

294 **Pairwise comparison between pasture-finished and grain-finished**  
295 **systems**

296 The pairwise comparison found that pasture-finished systems had 20% higher mean  
297 production emissions than grain-finished systems on average ( $p < 0.01$ ). When also including soil  
298 carbon sequestration, the difference is not statistically significant at a 95% confidence level  
299 ( $p \geq 0.05$ ). When the carbon opportunity cost is also accounted for, however, the total carbon  
300 footprint of pasture-finished systems is on average 42% higher than that of grain-finished  
301 systems ( $p < 0.01$ ) (Fig 1, Table S3). Compared to grain-finished systems, pasture-finished  
302 systems also had 15% higher median production emissions ( $p < 0.01$ ) and total carbon footprints  
303 ( $p < 0.05$ ), indicating that while the magnitude of the difference is sensitive to extreme values, the  
304 general finding of higher emissions is robust (S3 Table S3).  
305

306 **Fig 1: Average ratios of carbon footprints between pasture-finished and grain-finished.**

307 Ratios expressed as percentage difference. PEM denotes production emissions, SCS denotes soil  
308 carbon sequestration, and COC denotes carbon opportunity cost. Values above (below) 0 denote  
309 the carbon footprint for pasture-finished operations is larger (smaller) than for grain-finished  
310 operations. Comparisons were made within paired production systems to control for agronomic  
311 and environmental differences. Bars show means and 95% confidence intervals. On average,  
312 carbon footprints for pasture-finished operations are significantly greater ( $p < 0.01$ ) than those of  
313 grain-finished operations when only production emissions are included and when production  
314 emissions, soil carbon sequestration and carbon opportunity cost are included.  $n = 20$  pairs.

315

316 The carbon footprint of pasture-finished systems, including production emissions, soil  
317 carbon sequestration and carbon opportunity cost, is higher than that of the grain-finished  
318 systems ( $p < 0.05$ ) in the majority of robustness tests (S4 Table-S4). Differences are not  
319 significant ( $p \geq 0.05$ ) in some cases when a smaller radius or higher rate of soil carbon  
320 sequestration is used.

### 321 **Regression analysis**

322 In the regression analysis, when only production emissions are regressed on land-use  
323 intensity, the coefficient is 0.48 (Fig 2a, Table 2). This can be interpreted as a 10% increase in  
324 land-use intensity being associated with a 4.8% increase in carbon footprint. Less land-intensive  
325 systems typically have lower carbon footprints, measured by production emissions alone. Fig 2a  
326 shows the regression line with this slope, with the level adjusted by country. When adding in soil  
327 carbon sequestration, the coefficient is reduced to 0.32, indicating that soil carbon sequestration  
328 offsets a part of the production emissions (Table 2).

329 ~~However, the relationship between total carbon footprint, including carbon opportunity cost,~~  
330 ~~and land-use intensity is stronger, with a coefficient of 0.90 (Table 2, Fig 2b). Hence, a 10%~~  
331 ~~increase in land-use intensity is associated with a 9.0% increase in the total carbon footprint of~~  
332 ~~beef production. This near proportional relationship is in part due to the large share of the total~~  
333 ~~carbon footprint accounted for by carbon opportunity cost, which is proportional to land area in~~  
334 ~~production.~~

335 ~~Regressions with pooled and country fixed effects specifications generate similar results~~  
336 ~~(Table S5). Results are robust to other specifications and assumptions checked (Table S6).~~

337

338 **Fig 2: The relationship between land-use intensity and carbon footprint of beef production**  
 339 **systems.** Results from a regression of log(carbon footprint) on log(land-use intensity) with  
 340 country random effects. Dots indicate life-cycle assessment observations; colors indicate  
 341 countries; and lines represent the slope of the regression that includes all countries, adjusted  
 342 according to the levels of each country. A) Carbon footprint including only production  
 343 emissions.  $n = 72$ . B) Carbon footprint including production emissions, soil carbon sequestration  
 344 and carbon opportunity cost.  $n = 69$ .

345

346 **Table 2: Results from log-log regressions**

	<i>Dependent variable:</i>		
	PEM	PEM+SCS	PEM+SCS+COC
LUI	0.48*** (0.04)	0.32*** (0.08)	0.90*** (0.09)
Constant	5.90*** (0.27)	4.84*** (0.45)	8.70*** (0.52)
Observations	72	68	69
R <sup>2</sup>	0.67	0.27	0.63
Adjusted R <sup>2</sup>	0.66	0.25	0.63

*Note:*

Standard errors in parentheses. LUI = land-use intensity. PEM = production emissions. SCS = soil carbon sequestration. COC = carbon opportunity cost.

\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

However, the relationship between total carbon footprint, including carbon opportunity cost, and land-use intensity is stronger, with a coefficient of 0.90 (Table 2, Fig 2b). Hence, a 10% increase in land-use intensity is associated with a 9.0% increase in the total carbon

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**Commented [A1]:** The extra 0 was a typo introduced by the authors when converting the image of the table, generated programmatically in R, to text in Word prior to submission. This is now corrected. We regret the error and note that it was limited to this line of the table only, and does not affect or apply to any of the text or results presented.

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footprint of beef production. This near-proportional relationship is in part due to the large share of the total carbon footprint accounted for by carbon opportunity cost, which is proportional to land area in production.

Regressions with pooled and country fixed-effects specifications generate similar results (S5 Table-S5). Results are robust to other specifications and assumptions checked (S6 Table S6).

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## 347 Discussion

348 Our analysis is the first global comparison of the carbon footprint of grain-finished and  
349 pasture-finished beef production systems that includes production emissions as well as soil  
350 carbon sequestration and carbon opportunity cost. This yields significant new insights that can  
351 inform environmental and agricultural decision-making.

352 Our results indicate that pasture-finished and other more land-intensive beef production  
353 systems have greater production emissions than grain-finished and less land-intensive systems.  
354 When we calculate carbon footprints including production emissions, soil carbon sequestration,  
355 and carbon opportunity cost, all beef production systems have a higher carbon footprint than  
356 when only production emissions are included, but pasture-finished systems have a substantially  
357 larger carbon footprint than grain-finished systems, and there is a strong positive relationship  
358 between land use intensity and carbon footprint.

359 The differences in carbon footprint between pasture- and grain-finished operations are  
360 largely due to differences in carbon opportunity cost, which account for a large share of the total  
361 carbon footprint. The carbon opportunity cost of operations was, on average, 130% larger than

362 production emissions. These results point to the importance of accounting for carbon opportunity  
363 cost in assessing the sustainability of beef production systems.

364 Our analysis also confirms that beef operations that have been studied in life-cycle  
365 assessments are generally not carbon neutral or negative. The mean carbon footprint across all  
366 studies, including production emissions, sequestration, and carbon opportunity cost, is over three  
367 times larger than the mean value for production emissions (Table 1). One exception is that we  
368 estimate negative carbon footprints for several grass-finished operations and one grain-finished  
369 operation that are in dry eco-climate zones in Australia, for which we assume there is zero  
370 carbon opportunity cost. This suggests that grazing cattle on dry rangeland with little to no  
371 carbon opportunity cost could have a small carbon footprint when the grazing also increases soil  
372 organic carbon, as has been observed in some studies of dry rangeland with finer textured soil  
373 [12].

374 Our comparison of pasture-finished and grain-finished systems builds upon and strengthens  
375 past findings. Our finding that production emissions are 20% higher on pasture-finished  
376 operations than on grain-finished operations is consistent with Clark and Tilman (2017) [6],  
377 which found average emissions were 19% higher though their estimate was not statistically  
378 significant. In our results, soil carbon sequestration from grazing offsets only a portion of  
379 production emissions. This finding is consistent with the conclusions of Garnett *et al.*  
380 (2017) [19], which estimated that soil carbon sequestration from grazing can offset 20-60% of  
381 annual emissions from ruminant grazing.

382 Our finding that land-use intensity and carbon footprint are positively correlated strengthens  
383 similar findings from previous studies, none of which included production emissions, soil carbon  
384 sequestration and carbon opportunity cost, which is a more comprehensive approach for

385 assessing the carbon footprint of land use than conventional land-use change approaches [16].  
386 Poore and Nemecek (2018) [9] found that beef and lamb systems with lower land-use intensity  
387 have a lower carbon footprint when considering land-use change-related greenhouse-gas  
388 emissions, but not carbon opportunity cost. Balmford ~~et al.~~ (2018) [14] used generalized  
389 linear mixed models to analyze the relationship between land-use intensity and carbon footprint,  
390 including a measure of carbon opportunity cost based on IPCC (2006) methods. Their analysis,  
391 limited to Brazil and tropical Mexico, also found that the carbon opportunity cost of agriculture  
392 was typically greater than production emissions, and that incorporating opportunity costs  
393 generated strongly positive associations between carbon footprint and land-use intensity.  
394 Searchinger ~~et al.~~ (2018) [14] calculated global-average carbon opportunity costs for beef  
395 similar to the average calculated for all operations included in this study. Their estimates of  
396 165.3 and 143.9 kg CO<sub>2</sub>e kg<sup>-1</sup> carcass weight were based on the potential carbon that could be  
397 gained or lost, respectively, on land used for production. The authors applied the values to five  
398 production systems in Brazil and found, consistent with our results, that systems with the lowest  
399 land-use intensity had the greatest carbon benefits.

400 Our study has several limitations although we do not believe these substantially alter our  
401 conclusions. The pairwise comparison of grain-finished and pasture-finished operations has a  
402 relatively small sample of 20 pairs. This means that assumptions of asymptotic normality, which  
403 are the basis for the paired t-test, may not hold. However, our robustness checks (S4 Table-S4)  
404 and nonparametric test of the median (S3 Table-S3), which is robust to small sample sizes,  
405 extreme outliers, and heavy-tailed distributions, reinforce the conclusion that pasture-finished  
406 operations have greater production emissions and total carbon footprints than grain-finished  
407 operations. In addition, our results cannot be considered to be globally representative or

408 representative of all operations. The life-cycle assessments that underlie our study were not  
409 conducted to be globally representative. For instance, we include one study from Asia  
410 (Indonesia) and none from Africa.

411 In our study, we assume that a change in land-use intensity results in a proportionate change  
412 in land under production and thus the land area with native ecosystems. While this has the  
413 advantage of simplicity, it is unlikely to be exactly true in reality, as a result of economic  
414 mechanisms. The real effect may be more or less than proportional depending, in part, on how  
415 differences in land-use intensity and carbon footprint are associated with total factor  
416 productivity. For instance, an operation shifting from grain-finished to pasture-finished may  
417 lower total factor productivity. This would increase prices and lead to a reduction in overall  
418 demand, while at the same time making that operation less profitable and thus induce producers  
419 elsewhere to produce more. The reduction in demand would reduce land use and the spillover of  
420 production would increase land use, with an ambiguous net impact.

421 It is also challenging to predict where a change in farmland area and native vegetation will  
422 take place as a result of changes in land-use intensity and production system in a given location.  
423 We calculate three measures of carbon opportunity cost: local, national, and global. These  
424 roughly correspond to different levels of market connectedness, which will differ between  
425 locations. For example, changes in US production can have large effects on global markets,  
426 whereas changes in less globally connected regions such as sub-Saharan Africa will likely see  
427 mostly local or national effects [24]. Furthermore, for those producers connected to global  
428 markets, effects of changes in production are not likely to be evenly distributed across the world,  
429 but are likely to be concentrated in those regions that are more globally integrated [24]. In the  
430 last few decades, much of the expansion of pasture has taken place in tropical countries like



431 Brazil [25]. Following this logic, it is possible that higher land-use intensity in the US as a result  
432 of shifting to pasture-finished systems would displace production to these places, and is thus  
433 more likely to displace highly carbon-rich tropical ecosystems.

434 In addition, we use several simplifying assumptions. We use global mean estimates of soil  
435 carbon sequestration and current carbon stocks in cropland and grazing land vegetation due to  
436 lack of spatially-explicit data with global coverage. Our assumed rate is drawn from estimates  
437 for improved grazing management, so as to lessen the risk of overestimating the carbon footprint  
438 of grass-finished systems. Our measures of carbon opportunity cost are also based on mean  
439 potential carbon sequestration values in grazing land and cropland, if restored to native  
440 vegetation. They do not account for livestock diet rations, which crops are used for feed, or crop  
441 yields for instance. This may contribute to us underestimating potential carbon sequestration and  
442 carbon opportunity costs if feed crops such as soy are grown in areas with higher potential  
443 carbon sequestration, such as former forest, than other crops.

444 Future research could build upon our analysis by integrating more spatially explicit  
445 estimates of soil carbon sequestration and carbon stocks and calculating carbon opportunity cost  
446 based on how different cropland and grazing land is used in beef production. Further types of  
447 beef and other livestock operations, such as pork or milk, could also be studied with similar  
448 methods.

449 Overall, this study provides a novel assessment of the carbon footprint of beef operations,  
450 building upon life-cycle assessments of production emissions to also include carbon  
451 sequestration and carbon opportunity cost. Our conclusion that beef operations with low land-use  
452 intensity, including grain-finished operations, have lower total carbon footprints than pasture-  
453 finished operations and others with high land-use intensity provides important insights for

454 agricultural stakeholders. Accounting for products' total carbon footprint, not just production  
455 emissions, could shift which production systems government programs, corporate procurement,  
456 investors, and consumers incentivize.  
457

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553 **Supporting information**

554 **S1 TextFile: Supplementary methods, figures and tables.**

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