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Research Article

Carbon accounting per unit of food and unit of land in food production systems of Argentina

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Abstract: Based on the notion of Life Cycle Assessment (LCA), the carbon footprint (CF) is an extensively used concept that quantifies and informs carbon load per unit weight (e.g., kg C/ton food) in the food system. In line with LCA, the CF computes emissions at pre-farm, farm and post-farm stages throughout a given food chain. However, the CF contribution to C accounting may sound incomplete because gains of C by photosynthesis at the farm stage are set aside. The notion of carbon balance (CB), which computes both C emission and capture (e.g., in ton C/ha), may be relevant in food production systems based on the extensive use of land. Because of the high weight that farm processes have on entire food chains, in this investigation we focused the analysis on the farm stage. In order to assess the suitability of CF and CB in extensive food production systems, we analyzed results from CF and CB in 70 surveyed commercial farms distributed across three large climatic regions (subtropical and temperate) of Argentina. The CF and CB of four relevant farming activities (beef, maize, soybean and wheat production) were compared during the year 2019. The comparison yielded contrasting results and opened space for different interpretations: The notion of CF seems to be useful in intensive food-production systems that rely on inputs and activities that depend on a high consumption of fossil fuels. Conversely, CB appears to be useful in food-production systems associated with an extensive use of land and the gain of C through a large plant-photosynthesis platform.

***Keywords*:** emissions per product; emissions per area; carbon balance; food systems

1. Introduction

There is a growing reference to the carbon footprint (CF) in supply chains, which is a systematic analysis that aims at evaluating the potential C emissions throughout the entire life cycle of a product, process or service. Well-known studies on food systems increasingly rely on CF to identify different emission typologies (Finkbeiner et al., 2014). People in well-informed societies are increasingly sensitive to the CF of food (Wood et al., 2020; Ottelin et al., 2019), so the C emitted by the use of fossil-dependent inputs (e.g., fertilizers, pesticides, energy carriers) is subject of scientific and social scrutiny. Current standardization programs look at thoroughly assessing the impact of C emissions at different stages in food chains (Hauschild et al., 2013), such as the pre-farm, the farm and the post-farm stages. Eventually, users may decide where to stop calculations, for example, at the farm-exit gate or, alternatively, at some specific post-farm stage (Röös et al., 2014). Data from CF analysis may be used to guide policies, regulate food trade and inform people about the impact of foods on global warming (Clune et al.,

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2017; Camilleri et al., 2019). On the other hand, the CF may provide a partial picture because gains of C by photosynthesis at the farm stage are set aside. The notion of carbon balance (CB) expressed in ton C/ha, computes both C emission and capture. It may be relevant in areas of extensive production where land is an abundant resource (West & Marland, 2003, Viglizzo et al., 2011, Oliveira et al., 2018).

In line with this reasoning, does C accounting per unit of product or per unit of land yield similar outcomes both in intensive and extensive food production systems? Hypothetically, we assumed that accounting per unit of land could offer an alternative way to analyse the C issue in extensive food production systems where land abounds. It is clear that CF and BC assess different processes through different methods. In practical terms, it is not feasible to account for C and compare a complete food chain (from cradle to grave) with a hectare of land. However, it is possible to implement a comparison on a common scale: the farm stage, which explains most of the emissions in food chains. As Poore & Nemecek (2018) stated, the farm stage globally accounts for 61% of food's C emissions and 81% if deforestation is included.

In order to address the issue, our purpose in this study was to compare C emissions per unit of food and unit of land, and C capture by hectare as well, in 70 extensive geo-referenced commercial farms distributed across three main climatic regions of Argentina.

2. Methods

2.1 The analytical approach

We divided this study in four parts: i) we estimated C emissions per ton of food, ii) we did the same per hectare of land, iii) we calculated C balances per hectare, and iv) we compared the outcomes.

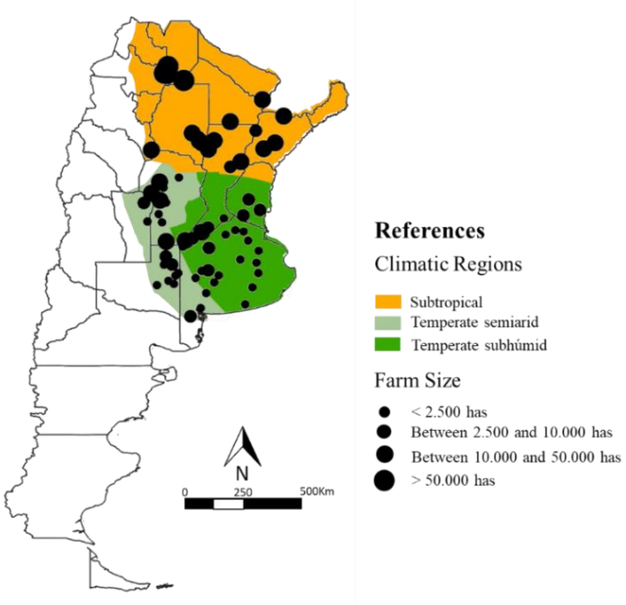

Figure 1. Geographical location of 70 surveyed farms scattered across three climatic regions of Argentina

To do that, in 2019 we surveyed data on 70 geo-referenced commercial farms scattered across three large climatic regions of Argentina, namely Subtropical, Temperate Semiarid and Temperate Subhumid that cover about one million hectares (Figure 1). We sampled farms based on their availability of reliable records. Farm owners and agronomic advisors provided data on land use, land cover, land conversion, areas affected by wildfires and burning, native forest logging, composition of the cattle herd, management practices, on field use of agricultural inputs and productivity of beef and crop activities. In those cases in which quantitative data on applied pesticide and fertilizer was scarce or uncertain, we relied on data from published regional reports about common practices. After a thorough data checking, we had to set aside several farms retaining only those whose records fell within the known regional ranges of variation. Farms differ in their size from less than 2500 to more than 50000 hectares, and they hosted the most important farming activities of Argentina nowadays. Figure 1 shows the location of farms within the Argentine territory.

2.2 *The system boundary*

Based on the notion of Life Cycle Assessment (LCA), the CF analysis comprises a system boundary that included calculation on various stages: pre-farm C emissions due to input manufacturing, on-farm emissions due to field farming activities, and post-farm emissions due to processing, transportation, distribution and domestic consumption, etc. As mentioned above, given the practical difficult to compare C accounting in a complete food chain and in a hectare of land, we undertook a comparison at the farm-stage level, which explains most of C dynamics in food production. In order to define the system boundary, the box of dotted line in **Figure 2** shows the focus of our study where we identified activities and processes causing emissions and gains of carbon at the farm stage. The box in dotted line shows the focus of the study system at the farm stage only, with a detail of the activities and processes causing emissions and gains of carbon. We do not consider pre-farm and post-farm stages in this study.

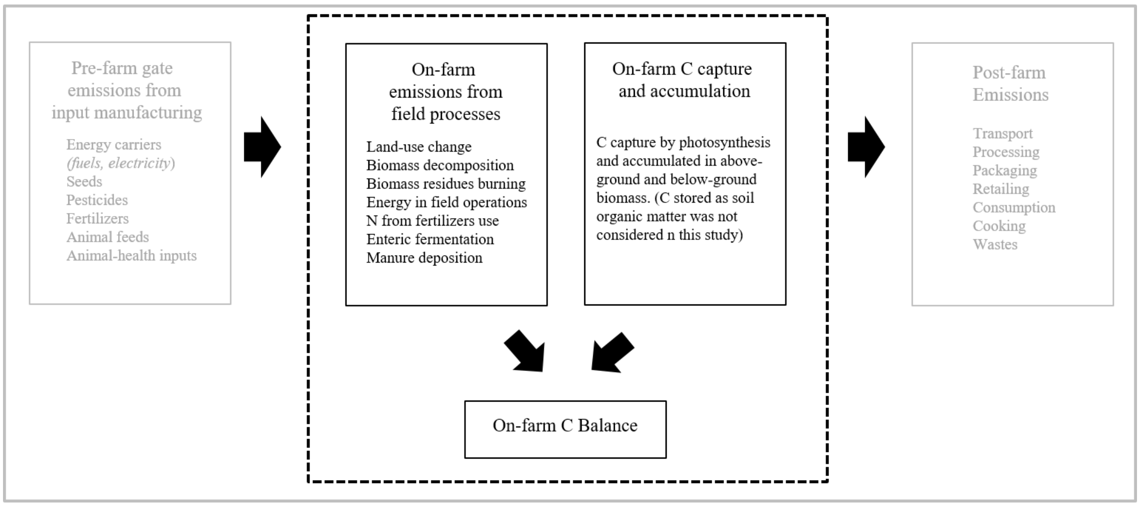

Figure 2. The analytical boundary to study carbon emissions per unit of product, per hectare of land, and the carbon balance for the farming activities of beef, soybean, maize and wheat production

2.2.1 *Calculation of carbon emissions*

Our calculations for estimating GHG emissions included carbon dioxide (CO_2) from land use change, biomass burning, fossil fuels use, methane (CH_4) from enteric fermentation in animals and nitrous oxide (N_2O) losses from soils, N-fertilizers and animal manure deposition. Following IPCC (2006) guidelines, such gases were converted in CO_2eq and then into C multiplying by a factor of 0,273. We used the same data to compute both emissions per unit of product (kg C/ton product) and emissions per unit of land (kg C/ha/year). We expressed production outputs in terms of kilograms of live weight leaving the farm gate in the case of beef, and in terms of fresh weight in the cases of maize, soybean and wheat production.

We have to point out four limitations in our research regarding the analytical process: First, we did not account for other GHG out of CH_4, N_2O, and CO_2. Second, we did not include the impact of agronomic practices such as zero tillage, cover crops, fertilization and irrigation that have an influence on carbon accounting. Third, we did not consider the year-to-year variations in the Argentine energy matrix in its effects on C emissions. Regarding this, we decided to rely on international data sources. Fourth, we did not consider the atmospheric persistence GHG in the atmosphere (e.g., the case of short-lived CH_4 in comparison to the long-term life of CO_2 and N_2O).

The calculation of C emissions for Agriculture, Forestry and Other Land Use sector (AFOLU) comprised several components: i) C emissions from C stock changes in organic matter, which includes above-ground biomass (AGB), below-ground biomass (BGB), dead organic matter (DOM) and soil organic matter (SOM), ii) non-CO_2 emissions from fire and combustion of organic matter and iv) methane (CH_4) enteric emissions, iii) CH_4 and N_2O emissions from manure kept on pasture by grazing animals, or managed by humans, iv) N_2O emissions from managed soils, v) CO_2 emissions due to land conversion, vi) CO_2eq emissions associated with nitrogen (N) fertilizers applied to managed soils and vii) CO_2eq emissions due to on-farm fuel use.

We relied on numerical factors from different sources that included FAO (2010), Tubiello et al. (2016), Allen et al. (2018), Cain et al. (2019) and Smith et al. (2021), but also default data were get from more specific sources. For example, for energy carriers (fuels, electricity, and other energy sources) we based on default data from Brander et al. (2011), Colomb et al. (2015), FAO (2020) and ICSU EU (2021). To estimate on-farm emissions, we used data from IPCC Tier 1, chapters 2 and 4 (Eggleston et al., 2006). We also followed Vol. 4, Chapters 2 and 5 to estimate CO_2, CH_4 and N_2O emissions from burned biomass, and Vol. 2, Ch. 2 and 3 for burning of forests and grazing-lands.

IPCC (2006) provided default data on N_2O and CO_2 emissions: i) Regarding the use of synthetic N-fertilizers, we based our calculations on the direct and indirect N_2O emissions for managed soils following Tier 1, Vol. 4, Ch. 11). ii) for emissions from biomass decomposition we relied on Tier 1, Ch. 2 and 11). iii) Tier 1, Ch. 5 for changes in soil C stocks.

C emissions from enteric fermentation consisted of CH_4 produced in the digestive tract of beef cattle (Tier 1, Vol. 4, Ch. 10). We based on Tier 1, Vol. 4, Ch. 10 and 11 to compute C emissions from manure deposition on pasture.

In Supplementary Information SI-1, SI-2 and SI-3 we show the default factors on C emissions that we used in this work.

2.2.2 *Calculation of carbon captured and accumulated in biomass*

While the ability of forestlands to capture and accumulate C as aboveground (AGB) and belowground (BGB) biomass is not in dispute, the C captured and stored in grazing lands is still controversial. Here we focused on AGB-BGB ratios in different biomes (forests and shrublands, croplands, grasslands, pasturelands and crops) to estimate C accumulation by photosynthesis in shoot-root relations (see default data in Supplementary Information SI-4). We relied on different Argentine sources (Ansín et al., 1998; Faggioli, 2004; Álvarez et al., 2013; Mónaco et al., 2017; Viglizzo et al., 2019; Kehoe & Salvagiotti, 2020) and international literature (Liebman et al., 2013; Mitsch et al., 2013; Yue et al., 2017; Florence et al., 2019; Spawn et al., 2020; Steinahuer et al., 2020). AGB and BGB were both considered fractions that capture and accumulate C in the case of forests and other woody vegetation (AGB and BGB) because harvesting of both fractions is unlikely for food production. On the other hand, BGB was considered in the case of crops and grasslands because the aerial biomass is the harvestable fraction. So BGB is the biomass fraction that annually provides a quantifiable amount of C. In Supplementary Information SI-5 we show default data on C accumulation in the biomass of different biomes.

2.3 *Estimation of the carbon balance if beef and crop production activities*

The annual carbon balance in areas of beef, maize, soybean and wheat production was the result of the difference between the emissions (described in item *2.2.1*) from different carbon sources, and the carbon captured and accumulated in active biomass sinks (described in item *2.2.2*). The annual balance can be positive, neutral or negative. Positive balances only involve cases in which C accumulation is greater than emissions. We expressed accumulations and emissions in ton C/ha/year.

Thus, beyond C emissions per unit of product (ton) or land (hectare), the C balance offers a third option to assess and compare the C account in farming activities.

2.4 *Statistical analysis*

We used three descriptive statistics. Since we worked with quantitative variables, we used the mean and the median as measures of central tendency, and the standard deviation as a measure of dispersion.

To assess the sensitivity of the estimated emissions to different farm configurations we used linear regression analysis. We started by stating a null hypothesis that emissions were not sensitive to land-use change. A high P value (>0.05) was used in our analysis as statistics to confirm the null hypothesis. A low (<0.05) or very low (<0.01) P value of our determination coefficient (R^2) indicating that we can reject our null hypothesis, and that our model efficiently detected a significant sensitivity of C emissions to different land-uses. Regarding emission estimations, we used a logarithmic scale in some graphics to represent the high dispersion or variability of results.

A parametric test was carried out for independent data in the comparison of the different products (beef, maize, soybean and wheat) under both C accounting approaches and for each climatic region (subtropical, temperate semiarid and temperate sub-humid). A null hypothesis, which is normally the equality of means, as opposed to the alternative hypothesis, which encompasses a difference between the means (bilateral contrast) was applied in every test. In Student's t-test, the null hypothesis was tested through the difference between means and

SD. The statistics slightly varied based on whether the variances of the two study groups were known, unknown similar or unknown different. To find out if the variance in both groups is the same or not, and under the assumption that the two populations followed a normal distribution and have the same variance (H0: $\sigma 1 = \sigma 2$), we relied on the F Snedecor distribution. If its P-value was less than 0.05 the null hypothesis was rejected and it was assumed that the variability between groups significantly differed.

3. Results and Discussion

3.1 Emissions per unit of product

We used a method from the LCA to estimate C emissions per unit of product (kg/ton). Based on resource and energy studies, the use of LCA tools begun at the end of the 1980s. Since then, policy and decision makers faced the challenge of developing frameworks, definitions and methods to assess the impact of the food system on global warming. Literature normally express C flows in terms of mass or volume (for example, C emitted per kg or ton of wet or dry weight, protein or energy). The approach should help interpreting a process through the assessment of C emissions from different practices, products, services and production systems (McLaren et al., 2021). Regarding the system boundary, ideally it should include all stages through the life cycle of given supply chain. However, it is not always possible due to data lacking at one or more stages.

To test the consistency of our calculations, we compared our results with results from several authors that published data about C emissions per unit of product for beef, maize, soybean and wheat production. Regarding beef production, we compared our results with those provided by Subak (1999), Cederberg & Stadig (2003), Schlich & Fleissner (2005), Casey & Holden (2006), Williams et al. (2006), Ogino et al. (2007), Verge et al. (2008), Peters et al. (2010), Ledgard et al. (2010), Nijdam et al. (2012), Röös et al. (2014), Clune et al. (2016), Clune et al. (2017), Wiedemann et al. (2015) and Poore & Nemecek (2018). For maize, soybean and wheat we compared with those from Clune et al. (2016) and Poore & Nemecek (2018). A synthesis of such comparison is shown in Table 1 for the cases of beef, maize, soybean and wheat production.

Table 1. Details about the descriptive statistics of C emissions comparing data from international literature (n=195 cases) and results from this research (n=70 cases)

			C emissions (Kg C/ton product)			
Data form	**Study system**	**Statistics**	**Beef**	**Maize**	**Soybean**	**Wheat**
International literature	Various stages in the supply chain	Mean	8198.88	281.87	253.21	229.32
		Median	6688.50	274.37	210.21	219.77
		SD	6732.57	165.57	170.16	168.65
This research	On-farm stage only	Mean	3032.15	45.02	82.90	85.31
		Median	2217.89	24.85	23.52	40.90
		SD	1908.87	24.10	227.28	20.65

The number of stages explains most differences in absolute emissions recorded by literature and our results. Literature reported emissions from a variable number of pre-farm and post-farm stages, and such unequal accounting gives account of the higher absolute emissions shown by data from literature.

The great difference in terms of emission that we estimated among beef on the one hand, and maize, soybean and wheat on the other hand, tend to agree with literature estimations (Table 2). A plausible explanation to this relates to the rigidity of the LCA method, which is deterministic in the way it accounts for emissions. Results came from dividing the C emissions of each product by its gross productivity. In this way, the activities that have higher biological productivity always show a lower C emission per unit of product. On the contrary, the lower gross productivity of beef production results in a high C emission per unit of product or, in other terms, a high CF.

Table 2. Absolute (kg C/ton product) and relative (100-base) emissions in CF analysis from beef and grain crops in the 70 surveyed farms of Argentina

	Data from literature		Data from this research	
Product	**Carbon emissions (Kg C/ton product)**	**Relative impact (%)**	**Carbon emissions (Kg C/ton product)**	**Relative impact (%)**

Beef	8198,88	100,00	3103,32	100,00
Maize	281,87	3,44	45,02	1,45
Soybean	253,21	3,09	82,90	2,67
Wheat	229,32	2,80	85,31	2,75

As Table 2 shows, we assigned a value = 100 to beef, and then, we estimated the relative emissions of the three study annual crops. Barely, crops show relative figures that ranged between 1.5% and 3.5% of beef cattle emissions, which are typical ratios in LCA estimations. It is noticeable that the farm-stage, by itself, was sensitive enough to detect the huge ratio that separates beef from crop activities.

3.2 Emissions per product vs emissions per hectare

Related to some intrinsic limitations of the LCA method, Opio et al. (2013) and McLaren et al. (2021) pointed out that approaches exclusively based on LCA may fail to provide sufficient guidance on total C emissions in food-supply chains. They argued that results could vary if other reference units, such as the hectare of land, are accounted.

Here we aimed at developing this reasoning line by comparing C emissions estimated per unit of product and per unit of land. As presumed, results varied when estimations followed one or the other analytical way. The agronomic practices and technologies applied by the farmers can have a significant influence on results per hectare. The large ratios between beef and crops when measured per unit of product in the LCA approach may drastically change in calculations per unit of land.

To test that hypothesis, we analyzed beef and crop emissions against the percentage of farm area allocated to annual crops (Figure 3). We used a semi- logarithmic scale to comprise the high variability of data on emissions. Figure 3a shows that emissions per kg of product are insensitive ($P>0.05$) to the land-use configuration, so the big difference between beef and grain emissions remains relatively constant through different percentage of crops. In contrast, emissions per hectare (Figure 3b) are noticeably sensitive to land use ($P<0.01$). The difference between beef and crop tends to narrow, and emissions from crops can even be higher than emissions from beef at high percentages of crops. We considered that this behavior confirms our hypothesis that both approaches differ and show different results.

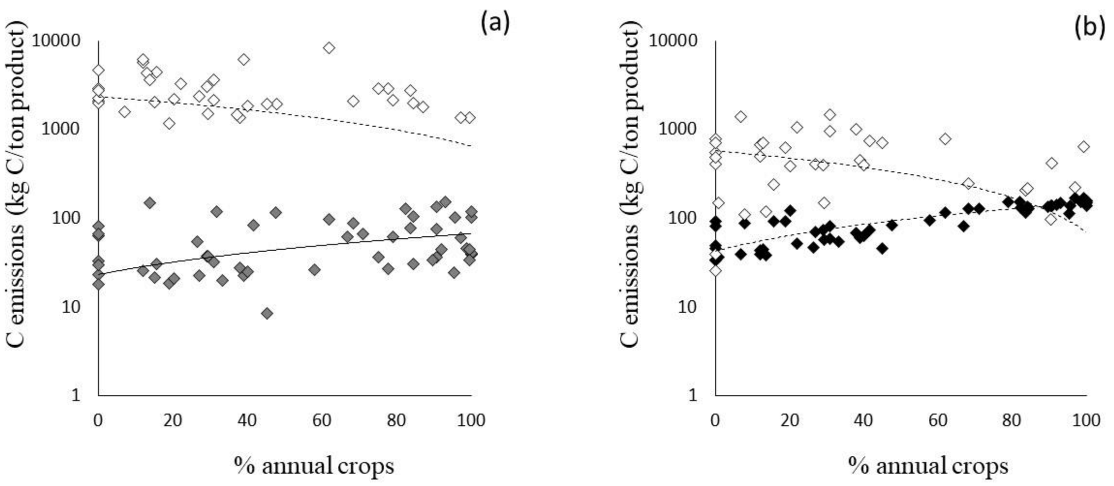

Figure 3. Sensitivity of the indicators of C emissions per ton of product **(a)** and annual C emissions per hectare **(b)** both in response to alternative uses of land (land % allocated to annual crops)

3.3 Comparing accounting methods

The case of C emissions per hectare deserves attention in geographically extensive countries like Argentina, where lands are abundant. Each time we address the C emissions per hectare, we should not omit another equally important biological process: the ability of lands to photosynthesize, capture and store C in biomass. In fact, carbon emission and capture can occur simultaneously in one hectare of land, and the balance between them opens a third option to account for carbon at the farm stage. Table in Supplementary Information SI-6 details common statistics (mean, median and standard deviation) comparing the approaches that assess C emission per ton of product, annual C emission per hectare and annual C balance per hectare in three study climatic regions of Argentina.

As shown in Table 3, if a value = 100 is assigned to beef in order to compare it with crops, the relative ratio tended to amplify when we assessed C accounting per hectare. The value amplifies to 23.54 when we assessed the C balance per hectare. Again, this tends to confirm our hypothesis that both approaches differ and produce different results. It also shows that the emissions per unit of product reflects the rigidity of the LCA approach to compare foods, independently of the farmer action. On the contrary, per-hectare approaches indicate that results can be modified by farmer interventions in terms of land use or adoption of technologies and agronomic practices.

Table 3. Comparison of mean values of C emissions and C balance, and the average weight of crops in relation to beef production (beef=100)

C emission per Kg product (Relative value of crop as % of beef)	Annual C emission per hectare (Relative value of crop as % of beef)	C emission per Kg product (Relative value of crop as % of beef)
1.58	16.11	23.54

In Figure 4 we graphically represent with more detail the results shown in Table 3. In statistical terms, the letters inserted above the bars indicate whether the calculated values coincide or differ between the four analyzed farming activities within each applied approach. Based on a 95 % (α=0.05) confidence level, bars with the same letter mean no statistical difference among comparisons. See statistical details in Supplementary Information (Tables SI-7 and SI-8).

The most notable detail of the analysis occurred when we compared beef and crops. Coinciding with what has been reported in the literature regarding CF, the C emissions per ton of product in the case of beef production exceeded by 20 times or more the emissions from annual crops. However, that superlative difference tended to differ greatly when emissions referred to one hectare of land. That relationship between beef and crops suffered much greater alteration when referred to the carbon balance in which both, the emissions and the C stored in biomass, were computed into calculations. This suggests that the C accounting per kg or ton of product can still differ much more when C is accounted per hectare in an integrated farm-production system. The analysis leads us to accept our working hypothesis that both approaches evaluate the carbon problem from different perspectives and consequently generate different results.

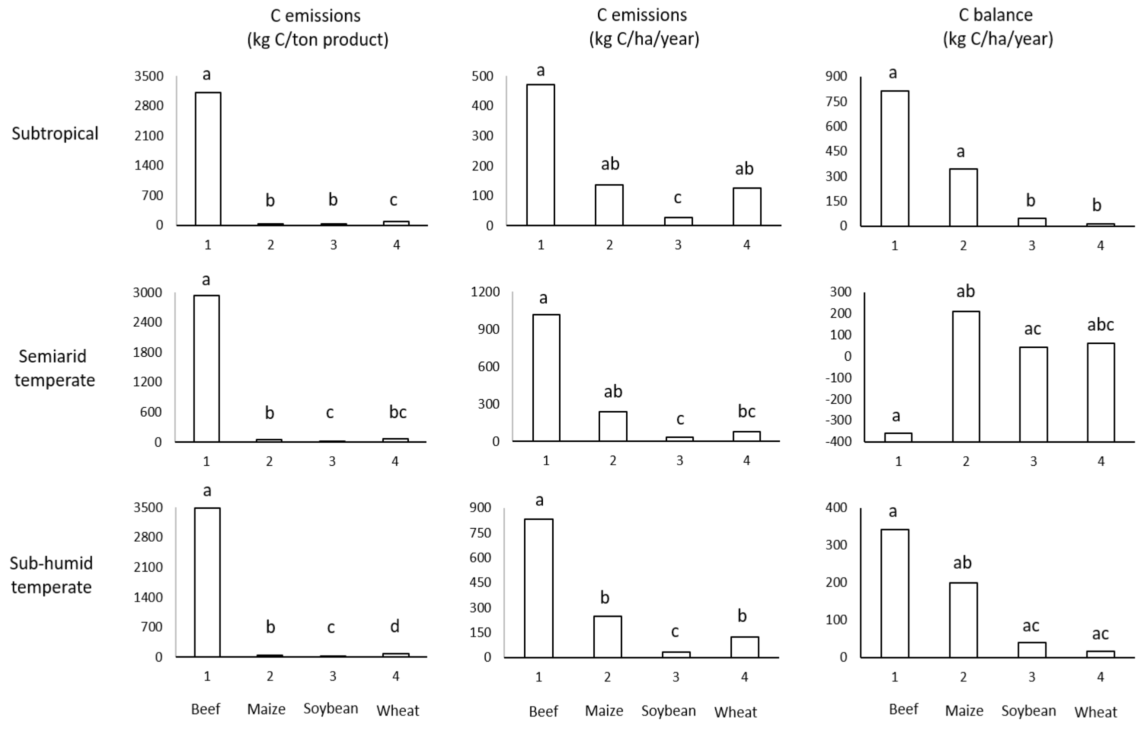

Figure 4. Application of different approaches of C accounting to crops and beef production in 70 surveyed farms in three climatic regions of Argentina

By unifying the three climatic regions into one, we undertook an additional analysis that looked at comparing the accounting approaches by type of product. Table 4 summarizes basic statistics indicators that show figures on mean value, median and SD when we compared the performance of three different C accounting approaches. Again, it is clear that contrasting results confirm that C accounting per unit of product can greatly differ from the account per unit of land, opening a large space for alternative interpretations of the same process.

Table 4. Details about the descriptive statistics of C approaches by product type considering all the case studies without discriminating by climatic region

		Emission (Kg C/ton product)	Emission (Kg C/ha/year)	Balance (Kg C/ha/year)
Beef	Mean	3176.13	774.56	265.72
	Median	2590.91	494.22	226.12
	SD	2006.07	922.52	1235.39
Maize	Mean	43.71	205.79	254.21
	Median	37.11	167.09	285.93
	SD	27.55	164.00	172.06
Soybean	Mean	27.03	31.99	43.01
	Median	25.65	31.80	43.20
	SD	10.91	13.30	13.30
Wheat	Mean	82.30	120.04	19.96
	Median	82.79	95.23	44.77
	SD	24.87	58.94	58.94

Our results suggest that both approaches offer complementary views for C accounting. Beyond the benefits of LCA to provide consumers a full picture of C emission throughout the entire food chain, the per-hectare approach offers an alternative insight to interpret C accounting in regions where land is an abundant resource. Rønning & Brekke (2014) and van der Meer (2022) arose some skepticism about the practical use of LCA, which in their opinion, may cause confusion and mislead decisions of non-expert consumers. Furthermore, these authors argue that LCA methods are not fully transparent because of the inability of operators to collect equally reliable data from all stages within a food chain.

The approach that aims at accounting C per hectare have also limitations that require consideration. The most obvious one is that the analytical focus addresses the farm stage setting aside other critical stages in the supply chain. Thus, consumers can identify problems that occur on the farm stage, but not on other pre-farm and post-farm ones. Anyway, this approach offers a tool to reward or penalize C management at the farm level, where the bulk of emissions of the food system normally occurs.

4. Conclusions

The comparison of C accounting per unit of product (kg/ton) or per unit of land (kg/hectare) poses an analytical challenge that deserves further study. Both approaches are complementary, but the interpretation may arise some troubles because they have different meanings in different countries. For example, in countries of intensive production systems where consumers privilege the conversion of fossil energy-dependent inputs into products, in contrast with countries where extensive schemes privilege the conversion of solar energy into products per hectare of land.

The comparison of both approaches entailed methodological difficulties. As mentioned above, the LCA approach relies on a deterministic model strongly influenced by the yield of the assessed farming activity: the higher its biological yield, the lower the emissions per unit of product. The rigidity of the method is cause of its low sensitivity to technological improvements. This contrasts with the high sensitivity to farmer intervention when C is accounted per unit of land. This is not a minor issue in policy making because it opens a window to reward or penalize the ability of farmers to manage C. In line with this, achieving certifiable net-zero carbon targets at the scale of farm can be at the core of a climate-smart policy in countries where extensive food production predominates.

Beyond controversial opinions regarding its effective influence, food production is an activity that contributes to global warming. Governmental rulers, scientists and practitioners are looking for methods and tools to assess its impact on carbon emissions. Some of them are well suited to deal with the peculiarities in some societies, but not in others. A potential problem arises when one of the parties is not open to recognize the C accounting methods of the other party and this may convert into a commercial barrier. There should not be room for disagreement as long as accounting methods rest on sound science. When divergences occur, they need to be reconciled to agree on C mitigation policies that comprise cross-boundary tariffs, carbon taxes, net-zero strategies and investments. A smart combination of approaches should be a sensible way to stimulate effective agreements. The acceptance of alternative, science-based approaches is a first step to agree on common objectives regarding the global climate.

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