ORIGINAL PAPER

Carbon footprint of maize produced in Argentina

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Bongiovanni, R.[1]; Tuninetti, L.[2]; Vigneau, P.[3]; Gayo, S.[4]

ABSTRACT

The carbon footprint (CFP) of a product, such as maize, is defined by the ISO standards as the sum of greenhouse gas (GHG) emissions and GHG removals in a production system, expressed as carbon dioxide equivalent (CO_2eq) and based on a life cycle assessment using the single impact category of climate change. It is the measure of one of the impacts caused by human activities on the environment. The general objective of this study was to calculate the CFP of maize produced in Argentina by quantifying the significant GHG emissions and removals during the life cycle of the crop from the extraction of materials for the production of inputs to the delivery of the harvested grain at the farm gate. The declared unit is 1 kg of maize at the farm gate. The data were obtained through the "Survey of Applied Agricultural Technology" and were provided by the Buenos Aires Grain Exchange through an agreement to use the data for this purpose**.** The data included two sowing dates (early and late) and three technological levels (high, intermediate and low) in each of the 16 maize-producing agroeconomic zones. The data corresponded to the 2021-2022 crop season, when 51,336,000 tons were produced in an area of 7,440,000 hectares. The results show that the national average carbon footprint is 1,248 kg CO_2eq per harvested hectare and 0.178 kg of CO_2eq per kg of maize at the farm gate. A sensitivity analysis considering GHG removal from no-tillage showed that the CFP values decreased by 12% (1,099 kg CO_2eq/ha and 0.157 kg CO_2eq/kg). In addition, when the use of no-tillage and cover crops was considered, an additional CFP decrease of 2 kg CO_2eq/ha was estimated, resulting in 1,097 kg CO_2eq/ha and 0.156 kg CO_2eq/kg. The CFP was 3% lower in late maize than in early maize; however, when the removals were considered, this relationship was reversed, with the CFP being 1% lower for early maize. When considering the transportation and handling of grain from the field to the port, including loading onto a ship under FOB condition, the emissions increased by 15% compared to the baseline situation, reaching 0.204 kg of CO_2eq per kg. This work is useful for all the actors in the maize value chain because (a) it provides a comprehensive environmental scenario of primary production, showing the environmental hotspots; (b) it facilitates the communication of environmental information to society; (c) it shows possible reductions of emissions and costs; and (d) it allows for comparisons between countries or production systems.

Keywords: life cycle assessment, climate change, total global warming potential, environmental impact, environmental added value.

RESUMEN

La huella de carbono de un producto como el maíz representa la suma de las emisiones de gases de efecto invernadero (GEI) y remociones de GEI en un sistema de producción, expresadas como dióxido de carbono equivalente (CO_2eq) y basadas en una evaluación de ciclo de vida, en la que se utiliza la categoría de impacto única de cambio climático, que es la medida de uno de los impactos que provocan las actividades del hombre sobre el ambiente. El objetivo general de este estudio fue calcular la huella de carbono del maíz producido en Argentina, mediante la cuantificación de las emisiones y remociones significativas de GEI durante el ciclo de vida del cultivo: desde la extracción

[1]Instituto Nacional de Tecnología Agropecuaria (INTA), Ruta 9 km 636, X5988 Estación Experimental Agropecuaria Manfredi, Córdoba, Argentina. Correo electrónico: bongiovanni.rodolfo@inta.gob.ar
[2]Instituto Nacional de Tecnología Industrial (INTI), Subgerencia Operativa Regional Centro (Córdoba), Departamento de Química Analítica y Residuos Urbanos Centro, Avenida Vélez Sarsfield, 1561, X5000 Córdoba, Argentina. Correo electrónico: ltuninetti@inti.gob.ar
[3]Asociación Maíz y Sorgo Argentino (MAIZAR). Bouchard 468 3° piso "F" C1106ABF Buenos Aires, Argentina.
Correo electrónico: pedrovigneau@gmail.com.
[4]Bolsa de Cereales de Buenos Aires. Honduras 3724, CP 1180, Buenos Aires, Argentina. Correo electrónico: sofiagayo@gmail.com

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de materiales para la producción de insumos hasta la obtención del producto. La unidad declarada es 1 kg de maíz en la tranquera del campo. Se consideraron los planteos productivos relevados por la Bolsa de Cereales de Buenos Aires en su sistema Relevamiento de Tecnología Agrícola Aplicada mediante un convenio para el uso de los datos para este trabajo. Esto incluye dos fechas de siembra (temprano y tardío) y tres niveles tecnológicos (alto, mediano y bajo) dentro de cada una de las dieciséis zonas agroeconómicas productoras de maíz en la campaña 2021-2022, en la que se produjeron 51.336.000 toneladas en 7.440.000 hectáreas. Los resultados muestran que la huella de carbono promedio nacional es de 1.248 kg CO_2eq por hectárea cosechada y de 0,178 kg de CO_2eq por kg de maíz en la tranquera. En un análisis de sensibilidad, cuando se tuvieron en cuenta las remociones de GEI por efecto de la siembra directa, los valores cayeron un 12% y fueron de 1.099 kg CO_2eq/ha y 0,157 kg CO_2eq/kg, respectivamente. Y al considerar las remociones por siembra directa y por cultivos de servicio, las huellas se redujeron en 2 kg CO_2eq/ha adicionales, lo que dio como resultado 1.097 kg CO_2eq/ha y 0,156 kg CO_2eq/kg. La huella fue un 3% más baja en el maíz tardío que en el temprano, aunque al tener en cuenta las remociones, esa relación se invirtió y determinó un resultado un 1% más bajo a favor del temprano. Al considerar el traslado y manipulación del grano desde el campo hasta el puerto, incluyendo la carga a un buque en condición FOB, las emisiones subieron un 15% con respecto a la situación base, que llegaron a 0,204 kg de CO_2eq por kg. Este trabajo resulta de utilidad a los actores de la cadena de valor del maíz porque: (a) brinda una visión ambiental integral de la producción primaria al mostrar los puntos críticos ambientales; (b) permite comunicar la información ambiental a la sociedad y al mundo; (c) muestra posibles reducciones de emisiones y de costos; y (d) permite comparaciones.

Palabras clave: *análisis de ciclo de vida, cambio climático, potencial total de calentamiento global, impacto ambiental, valor agregado ambiental.*

INTRODUCTION

Maize (*Zea mays*) is a crop of worldwide importance. In 2021, global production amounted to 1,210,445,259 tons, with USA, China, Brazil, Argentina and Ukraine being the five major producers (FAOSTAT, 2023). In Argentina, maize is the most important crop in terms of production volume (43,861,066 tons in the 2021-2022 crop season), followed by soybean. However, it is second in terms of harvested area after soybean (15,874,266 ha for that crop season). The cultivated area in the country is distributed in the provinces of Córdoba (34%), Buenos Aires (26%), Santa Fe (13%), Entre Ríos (6%) and La Pampa (4%) (MAGyP, 2023).

Given the relevance of maize to the local economy, the Buenos Aires Grain Exchange regularly monitors the national maize production through the system "Survey of Applied Agricultural Technology" (ReTAA, 2023). This study uses the 2021-2022 survey, which includes all the crop management strategies for two sowing dates (46% early and 54% late sowing dates) and three technological levels (high, intermediate and low). Planting of maize in Argentina typically occurs from late September to early February, with two distinct periods: early-planted maize, from late September to early December, and late-planted maize, from early December to early February. ReTAA surveyed 16 maize agroeconomic areas (figure 1) during the 2021-2022 crop season, which yielded 51,336,000 tons in an area of 7,440,000 hectares. The authors of this work had access to the entire database through a cooperation agreement.

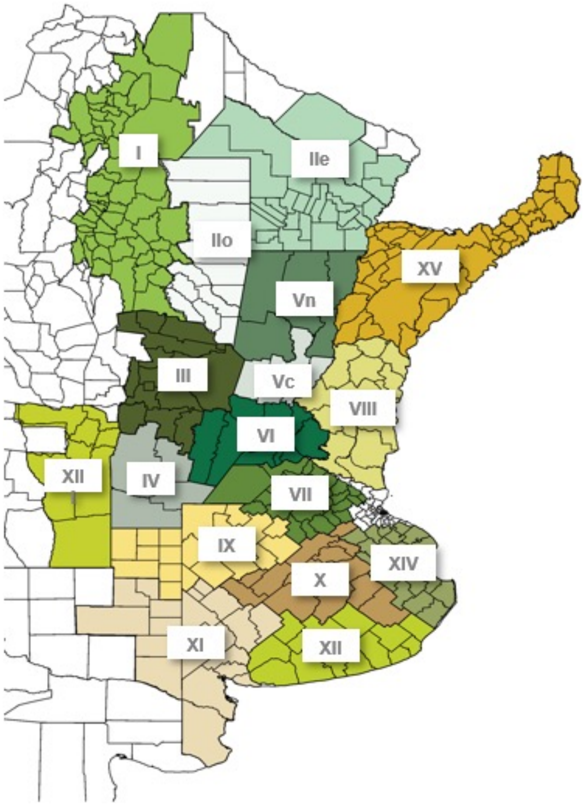
In all countries worldwide, society is increasingly concerned about the impacts of human activities, like maize production, on natural resources (Eurobarometer, 2017; Haller *et al*., 2020; IBM, 2021; Andre *et al*., 2024; Stover *et al*., 2024). Those impacts can be estimated through indicators or "environmental footprints", which not only reveal the information about the impact of production systems but also detect opportunities to conserve and improve the natural capital, optimize the use of resources and minimize the risks of the system.

In line with that concern, this study analyzes the environmental impacts of maize production in Argentina focusing on the Carbon Footprint (CFP), which represents all the Greenhouse Gas (GHG) emissions caused by direct or indirect effect of an individual, organization, event or product. Specifically, according to ISO 14067, the CFP of a product is the "sum of greenhouse gas emissions and removals in a product system, expressed as CO_2 equivalent and based on a life cycle assessment using the single impact category of climate change" (IRAM-ISO 14067, 2019). It is a measure of a single impact caused by human activities on the environment.

Studies on the CFP of maize are relatively scarce in the international scientific literature. A literature search in bibliographic databases has yielded one work from Argentina and some international works from Asia –particularly China and Thailand–, Europe, Canada, USA and Brazil. In addition, there are databases with values from different parts of the world, which can be consulted using specific software (Simapro, 2023). Both sources of information are very useful for comparative purposes.

Argentina is the fourth maize producer in the world (FAOSTAT, 2023) and the second exporter, accounting for 9.3% of the total exports of the country (INDEC, 2020); however, there is only one report about the GHG emissions from maize production (Arrieta *et al*., 2018), which did not include the estimation of GHG removal potential or carbon sequestration. These authors analyzed the intensity of maize and soybean emissions in Argentina during the 2012-2013 crop season and found significant differences in emissions between the Pampas and extra-Pampas zones. Therefore, it is important to provide updated information.

On the other hand, there are more references in the literature from different parts of the world. The global study conducted by Nemecek *et al*. (2012) evaluated the variability in warming po-



I – NOA: Northwestern Argentina
IIe – NEA Este: East of northeastern Argentina
IIo – NEA Oeste: West of northeastern Argentina
III – Center-north of Córdoba
IV – South of Córdoba
Vn – North of Santa Fe
Vc – Center of Santa Fe
VI – Core area North
VII –Core area South
VIII– Center-east of Entre Rios
IX – North of La Pampa – West of Bs. As.
X– Center of Buenos Aires
XI– Southwest of Bs As – South of La Pampa
XII– Southeast of Buenos Aires
XII– San Luis
XIV– Salado River Basin
XV– Corrientes- Misiones

Figure 1. Maize-producing areas.

tential of 27 crops in different production systems worldwide. The mean estimated value of the CFP for maize was 2,950 kg CO_2 eq/ha and 0.451 kg CO_2 eq/kg. The CFP was negatively correlated with the mean yield of the different crops.

In China, Zhang *et al*. (2018) evaluated the differences and potential of CFP in rainfed and irrigated maize systems based on a survey of 120 farmers and a lifecycle assessment (LCA). The authors found that the GHG emission of irrigated maize was 5,330 kg CO_2eq/ha, 40% higher than that in rainfed system. The authors attributed this result to the increased electricity use and greater application of fertilizers (especially N) in the irrigated system. The mean yield was 10 t/ha, 2.1 times that of the rainfed system (4.7 t/ha); therefore, the CFP was 37% lower.

Another study conducted in China (Xu *et al*., 2018) analyzed the GHG emissions from maize production during 2003-2016 using national statistical data. The low technological level was the main driver of increased GHG emissions, whereas their reduction was caused primarily by agricultural efficiency. The authors concluded that the CFP of maize decreases with increasing crop yield.

Hou *et al*. (2021) evaluated and compared the impact of farm size on the GHG emissions from wheat and maize production in the North China Plain (NCP) with the aim to determine a relationship between farm size and GHG emissions. The authors found an inverse relationship between farm size and CFP.

Zhang *et al*. (2017) estimated a CFP of 4,052 kg CO_2eq/ha or 0.48 kg CO_2eq/kg for maize in China. The most important factors determining carbon emissions were the application of nitrogen fertilizers, straw burning, and energy consumption by machinery and irrigation. Carbon sequestration was driven mainly by straw return, the application of chemical nitrogen fertilizers and no-tillage agricultural practices.

In Thailand, Moungsree *et al*. (2022) estimated the GHG emissions and life cycle costing associated with maize production. The authors found that the total GHG emissions from maize production were on average 0.429 ± 0.027 kg CO_2eq/kg of grain, with the highest emissions occurring in the dry season.

In Poland, Holka and Bienkowski (2020) determined the CFP of maize in conventional, reduced and no-tillage systems, which was 2,347.40, 2,353.40 and 1,868.70 kg CO_2eq/ha, respectively. The largest source of GHG emissions was the use of nitrogen fertilizers. Non-inversion tillage with cover crops and a large amount of crop residues left on the land increased organic C sequestration and significantly reduced the CFP in maize production.

In Spain, Amaia *et al*. (2012) determined a CFP of maize of 0.515 kg CO_2eq/kg under rainfed conditions and of 0.562 kg CO_2eq/kg in irrigated maize. The authors found that N fertilization is the most important hotspot that should be addressed to reduce the CFP. The use of diesel oil in agricultural production systems was the second most important hotspot; other aspects to consider are maize drying and energy costs associated with irrigation.

In Canada, Ma *et al*. (2012) conducted a 19-year field trial with maize under different N treatment levels in continuous cultivation or rotation with legumes to assess the sustainability of the production systems by estimating the CFP. The authors found an inverse relationship between yield and CFP. They concluded that maize production with 100 kg/ha of N under a rotation scheme can maintain a high productivity while reducing the CFP, compared to a continuous maize cropping system with 200 kg/ha of N. Another work conducted in Canada analyzed data from the Ontario census (Jayasundara *et al*., 2014). The CFP of maize grain ranged between 0.243 and 0.353 kg CO_2eq/kg grain, of which 72% was associated with N input from the use of synthetic fertilizer N, 13% from fertilizer production and 10% from applied manure.

In his PhD thesis work, Sheehan (2014) analyzed the CFP of maize produced by farmers included in the Gevo Program for emission reduction in southeastern Minnesota, USA. The author estimated a CFP of 1,718 kg CO_2eq/ha and 0.167 kg CO_2eq/kg in farms that avoided the excessive use of fertilizers, adopted no-tillage practices and replaced commercial fertilizer with animal manure.

In the USA, researchers from the CGIAR research centers conducted a trial in eastern Nebraska to quantify the GHG emissions, changes in soil organic carbon (SOC) and net global warming potential (GWP) in four irrigated systems. They concluded that the CFP can be kept low when the yield potential is optimized (Adviento-Borbe *et al*., 2007).

A literature review conducted by Snyder *et al*. (2009) reported that (1) the appropriate use of N fertilizer helps to restore and keep SOC levels; (2) best management practices for fertilization help to reduce the risk of an increase in nitrous oxide emissions; (3) reduced tillage practices can increase SOC levels; (4) differences in N_2O emissions among fertilizer N sources depend on site and weather conditions; and (5) intensive crop management systems do not necessarily increase the CFP.

In central Nebraska, USA, Grassini and Cassman (2012) evaluated the GHG emissions from irrigated maize with high inputs of N (183 kg/ha of N) and irrigation water (272 mm/ha). The CFP of irrigated maize (0.231 kg CO_2eq·/kg of grain) was lower than that of other rainfed production systems.

In Brazil, Trovo-Garofalo *et al*. (2022) estimated the CO_2eq emissions from a group of 64 crops, along with forestry and planted pastures, in the 5,570 Brazilian municipalities, at state and national levels. The main aim of that study was to provide estimations of the CO_2 eq emission rates on a yearly basis for a period of 20 years, considered appropriate for LCA by the Intergovernmental Panel on Climate Change (IPCC). The CFP of maize was estimated to be 2,000 kg CO_2eq/ha and 0.366 kg CO_2eq/kg.

The main aim of this work was to determine the CFP of maize produced in Argentina, considering 16 production regions and three levels of technology adoption in each region. The purpose was to identify hotspots in production processes that have the potential to reduce the CFP. We hypothesized that 1) the N rate and yield would be directly related (hypothesis 1); 2) the emissions per hectare (kg CO_2eq/ha) and N rate (kg/ha) would be highly correlated (hypothesis 2); and 3) the CFP and yields would be directly related (hypothesis 3). Although the proposed hypotheses respond to well-known agronomic principles, the challenge consisted of evaluating the behavior of the variables in a national-level study.

Our research is the first comprehensive assessment of the carbon footprint (CFP) of maize production in Argentina conducted in terms of the ISO 14067 standard —which considers the sum of GHG emissions and GHG removals in a product system—, covering 16 agroeconomic zones. No previous studies have provided this level of regional specificity for a crop that is central to both the national economy and global agricultural markets. The focus on Argentina, a major maize-producing country, adds an important dimension to global carbon footprint studies by offering region-specific data that may differ from that of similar studies about other maize-producing regions.

We analyze data from three distinct technological levels (high, intermediate, and low) for two planting dates. This diversity in technological practices makes the study more comprehensive and gives a nuanced understanding of how different practices impact the carbon footprint. The use of such granular data across multiple zones and seasons is rare in studies of this kind, making our dataset one of the more detailed and practical for real-world applications.

The sensitivity analysis on no-tillage and cover crops is an original feature of the study, showing how these sustainable agricultural practices can significantly reduce GHG emissions. The quantification of potential carbon sequestration when cover crops and no-tillage are included is particularly innovative, as it offers clear, actionable data for improving sustainability in maize production.

We provide actionable insights for the maize value chain by identifying environmental hotspots and suggesting methods to reduce emissions. These practical recommendations extend beyond academic research, making the work directly applicable to producers, policymakers, and industry stakeholders, contributing to the global push for sustainable agricultural systems.

This study facilitates international comparisons, allowing the global maize industry to benchmark Argentina's production system against other countries in terms of carbon efficiency, which is particularly relevant for global market players. The ability of the study to calculate the CFP at the farm gate as well as including post-harvest logistics extends the scope of typical lifecycle assessments and provides a more holistic view of the environmental impact of maize.

MATERIALS AND METHODS

The declared unit used in this study is one kilogram (1 kg) of maize at the field gate. For the sensitivity analysis, results for one hectare of production and for one kilogram of maize at the export port, under *Free On Board* (FOB) condition, were analyzed.

The scenario of the analysis is from-cradle-to-gate, i.e., from the production of all raw materials, inputs and energy used in maize production, including *in-situ* emissions, those derived from the application of N fertilizers and from the decomposition of aboveground and belowground residues. The system was temporally delimited to the 2021-2022 crop season.

This work follows the protocol of ISO International Standard 14067, which defines the CFP of a product as: "the sum of GHG emissions and removals in a product system, expressed as carbon dioxide equivalents (CO_2eq) and based on an LCA, using the single impact category of climate change (IRAM-ISO 14067, 2019). The model used to calculate the emissions follows the 2019 IPCC guidelines for emissions from the use of N fertilizers and those caused by harvest (aboveground and belowground) residues" (IPCC, 2019).

In this research, we used the 100-year time-horizon global warming potential (GWP) values from the IPCC Report on Climate Change 2021: The Physical Science Basis (IPCC, 2021). GWP is an index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO_2). The GWP thus represents the combined effect of the differing times these substances remain in the atmosphere and their effectiveness in causing radiative forcing. The main greenhouse gases (GHG) are carbon dioxide, methane and nitrous oxide. In addition to these, other GHGs include fluorinated gases (like HFCs, PFCs, SF_6), which are synthetic and used in industrial applications. However, CO_2, CH_4, and N_2O are the most relevant to agriculture and crop production.

Carbon dioxide (CO_2) is a naturally occurring gas and is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use change (LUC) and of industrial processes (e.g., cement production). It is the principal anthropogenic GHG that affects the radiative balance of the Earth. It is the reference gas against which other GHGs are measured and therefore has a GWP of 1.

Methane (CH_4) is the major component of natural gas and associated with all hydrocarbon fuels. Significant anthropogenic emissions also occur as a result of animal husbandry and paddy rice production. Methane is also produced naturally where organic matter decays under anaerobic conditions, such as in wetlands. It has a GWP of 29.8.

As for nitrous oxide (N_2O), its main anthropogenic source is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests. It has a GWP of 273.

The model included all the field operations, input production (seeds, agrochemicals, fertilizers, fuel, among others), and the emissions from the burning of fuel, application of fertilizers and harvest residues. The transport of grain to the export port was included, as well as grain handling, storage and loading into the holds of vessels. The data collected was complemented with literature information and databases used by INTA and INTI.

According to a survey of the Buenos Aires Grain Exchange (ReTAA, 2023), in the 2021-2022 crop season, 49%, 48% and 3% of the production of early maize used high, intermediate and low technology levels, whereas 39%, 59% 3% of the late maize production used high, intermediate and low technological levels. In turn, 90% of the production was grown under no-tillage systems in early maize and 92% in late maize. The ReTAA uses a zoning model based on the data provided by the Agricultural Estimates Department of the Buenos Aires Grain Exchange. It depends on homogeneous agroecological criteria, such as soil type and rainfall regime, among others.

The information is collected through 1,600 telephone surveys of qualified informants for each of the surveyed areas, structured based on a non-probabilistic sample, through the deliberate and strategic sampling of each area to efficiently cover the agricultural area considered in the analysis. The surveys include seven major items that aim to describe a representative approach to the crop: sowing, planting materials, fertilization, herbicides, insecticides, fungicides and seed treatment.

The technological level refers to a broad concept that includes both the level of use of inputs and the management practices used in each area of the country. From the conjunction of these two aspects, different schemes emerge that determine three differentiated technological levels: high, medium and/or low level. This stratification of the technological level in terms relative to each area is mainly due to the productive and economic characteristics that each region in question has. In this way, what may be a low technological level for an area with a typically high productive potential may be a high technological approach for an area with a lower agricultural capacity.

The values of fuel consumption for agricultural operations were taken from INTA (Donato, 2020), the Ministry of Agriculture, Fisheries and Feeding (Boto Fidalgo *et al.*, 2005) and agroeconomic research (Márgenes Agropecuarios, 2023). These estimates were also used in our previous publications (Bongiovanni and Tuninetti, 2021a; Bongiovanni and Tuninetti, 2021b; Bongiovanni and Tuninetti, 2018). The values were checked by technicians from the Argentine Maize and Sorghum Association (Maizar). The estimated use of diesel fuel was 6.55 L/ha for no-tillage, 18.76 L/ha for all the conventional sowing operations, 0.66 L/ha for ground spraying, 1.32 L/ha for aerial spraying, 5.24 L/ha for fertilization, and 12.87 for the entire harvest process. Table 1 shows the nitrogen rate applied in the study regions and the yield obtained.

	Early maize		Late maize	
kg CO_2 eq/ha	Yield (kg/ha)	N (kg/ha)	Yield (kg/ha)	N (kg/ha)
Production regions	**7,058**	**71.00**	**6,985**	**65.16**
I	6,246	23.92	0	0
IIe	6,868	19.51	0	0
IIo	8,230	46.88	0	0
III	6,159	69.78	7,965	62.00
IV	6,520	68.63	7,130	58.78
Vc	5,131	74.02	6,575	70.95
Vn	4,540	37.70	6,344	33.99
VI	8,050	116.57	6,796	97.95
VII	7,636	120.34	7,651	104.59
VIII	3,620	88.69	5,744	78.05
IX	9,041	95.04	7,820	88.65
X	7,712	87.29	6,784	75.14
XI	6,283	59.53	5,428	53.84
XII	5,228	78.90	6,530	72.08
XIII	3,442	38.49	4,198	41.36
XIV	6,905	77.59	7,785	69.80

Table 1. Production regions, yield and N rates.

Considering each region, the general average of fertilization in Argentina was calculated as 67.8 kg/ha of nitrogen (N), which is described in table 2.

Information on the initial carbon stock for each provincial department or district was provided by INTA Castelar and was also used for the technical report "Global Soil Organic Carbon Map V1.5" (FAO and ITPS, 2020). The initial SOC stock was averaged for each department and each agroeconomic area (table 3). On the other hand, precipitation data were provided by the Agrometeorological Information and Management System (SIGA) of INTA for each of the departments for the 2021-2022 crop season and were averaged for each zone (table 3).

To obtain the results of the declared unit (1 kg of maize) at the port under FOB condition, an average distance of 202.4 km from the farm to the port was measured. For this purpose, the distances and volumes of all the agricultural ports for exports were calculated. In the case of the port of Rosario (Rosario, San Lorenzo, Villa Constitución), the estimated distance of the course was 227 km and the load accounted for 62% of the total maize; in the case of Bahía Blanca, it was 175 km and 21% of maize; as for the port of Necochea, it was 92 km and 10% of the maize; and in the case of Zárate, 227 km and 7% of maize.

Product		Early 46%	Late 54%	% N	kg/ha of N
Starter mix	kg/ha	0.86	1.10	0.124	0.99
Nitrocomplex mix	kg/ha	0.15	0.39	0.21	0.28
Nitrodoble mix	kg/ha	0.71	0.97	0.27	0.85
Microessentials	kg/ha	0.47	0.79	0.12	0.64
Ammonium nitrate	kg/ha	0.05	0.60	0.3375	0.12
DAP	kg/ha	7.47	12.37	0.195	1.97
MAP	kg/ha	40.79	32.51	0.11	4.00
Sulfur-enriched DAP	kg/ha	2.28	1.05	0.195	0.32
Solmix	kg/ha	15.95	15.04	0.412	6.37
Simple superphosphate (SSP)	kg/ha	2.55	1.83	0	0.00
Triple superphosphate (TSP)	kg/ha	0.41	1.27	0	0.00
Calcium sulphate	kg/ha	0.94	0.08	0	0.00
UAN	kg/ha	5.27	7.97	0.3	2.01
Urea	kg/ha	117.95	102.00	0.46	50.32
TOTAL					**67.87**

Table 2. Fertilizers applied, with regional averages and sowing date.

Zone	Average initial C stock (t/ha)	Average annual precipitation (mm)
I	51.36	635
IIe	58.56	1,029
IIo	45.13	572
III	47.82	455
IV	40.47	750
IX	50.56	805
Vc	55.69	439
Vn	54.39	700
VI	54.60	730
VII	62.74	777
VIII	69.64	1,031
X	68.42	807
XI	51.46	944
XII	81.55	689
XIII	33.93	727
XIV	81.93	492

Table 3. Average initial stock of soil organic carbon (t/ha) and average annual precipitation for the 2021-2022 crop season.

For the handling and storage of the grains into the vessel's hold, the following processes were carried out for every truck that reached the port: a) reception of the truck at the terminal, b) sampling and inspection, c) weighing, d) unloading, e) movement of grain from unloading to the silos, f) ventilation and temperature control, g) transport of grain from the silo to the elevator, h) cranes, belt/chain conveyor of loader and davits, i) loading onto the ship. The whole process consumes 0.9 kWh per ton, with 900 t of grain being shipped per hour under normal conditions.

For the quantification of the CFP, the method used in this analysis follows the standard ISO 14067, which describes the CFP as the sum of GHG emissions and removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change. The term GHG removals refers to the processes that absorb or capture greenhouse gases from the atmosphere. The main sources include: 1. forests and vegetation (biological sequestration), 2. soil carbon sequestration, 3. wetlands and coastal ecosystems, 4. Carbon Capture and Storage (CCS), 5. oceanic carbon sequestration, 6. Direct Air Capture (DAC), and 7. biochar.

Due to the scope of our research, we considered the GHG removals produced by soil carbon sequestration from two sources: 1) no-tillage farming: these practices reduce soil disturbance and increase organic matter in the soil, allowing for a greater storage of CO_2; 2) cover crops and crop rotation: using cover crops and crop rotation can enhance soil health and increase carbon storage in soils. These natural processes play a critical role in balancing GHG emissions and reducing atmospheric concentrations of CO_2, contributing to climate change mitigation.

Level 1 (Tier 1) of the IPCC was used to estimate GHG removal from soil carbon sequestration or annual change in organic C stocks in mineral soils. Of the three levels proposed by the IPCC, level 1 is the most basic, with levels 2 and 3 being intermediate and most demanding, respectively, in terms of complexity and required information. The equation 2.25 was used for the annual change in organic carbon stocks in mineral soils. The factors FLU, FMg and Fi were selected, as necessary, from Table 5.5 in chapter 5, Cropland (IPCC, 2019).

To convert the value of soil organic carbon (SOC) reported in tons of C per hectare to tons of CO_2 equivalent per hectare (t CO_2eq/ha), the SOC was multiplied by the ratio of the molecular weight of carbon dioxide to that of carbon (44/12); thus, change in carbon stock is expressed in t CO_2eq/ha. Then, this value was divided by the yield (t/ha), resulting in the change in SOC stock in t CO_2eq/t. The latter value is considered the additional emission or sequestration due to change in SOC stock. Results with a negative (-) sign indicate SOC sequestration and results with a positive (+) sign indicate SOC emission or loss.

RESULTS

The results show that the average national CFP is 1,248 kg CO_2eq/ha and 0.178 kg of CO_2eq per kg at the field gate. When GHG removals due to no-tillage operations were considered, those values decreased by 12% (1,099 kg CO_2eq/ha and 0.157 kg CO_2eq/kg), and when removals due to no-tillage and service crops were considered, the CFP was additionally reduced by 2 kg CO_2eq/kg, resulting in 1,097 kg CO_2eq/ha and 0.156 kg CO_2eq/kg (table 4).

On average, the main hotspot was nitrogen fertilization, with 432.58 kg CO_2eq/ha (35%). The second hotspot was fertilizer manufacturing, with 290.09 kg CO_2eq/ha (23%). In third place was crop residue management, with 244.95 kg CO_2eq/ha (20%). The fourth most important critical point was diesel fuel consumption, with 136.02 kg CO_2eq/ha (11%). In fifth place was the production of herbicides, with 118.39 kg CO_2eq/ha (9%).

Table 5 shows the contribution of each group of inputs to the total CFP calculated for Argentina.

The CFP was 3% lower in late maize than in early maize. However, when the removals were considered, this relationship was reversed, with a 1% lower value for early maize. This result is due to the difference in soil mineralization caused by increased temperature (table 6).

When grain transport and handling from the field to the port were considered, including the loading to the vessel under FOB condition, emissions at the field gate rose by 15%, from 0.176 kg CO_2eq per kg to 0.204 kg CO_2eq per kg. The result of the LCA and its breakdown by stages and inputs are shown in figure 2.

The results according to the technological levels indicate that the CFP obtained with a high level was 3% higher than the average value, the value obtained with the intermediate level was 1% higher than the average, and the low level had a CFP that was 34% lower than the country's average (table 7).

The results show an inverse relationship between yield and CFP. As is evident, in the regions where yields were low, the CFP of the product was higher, e.g., in the zone VIII – San Luis (table 8).

The results did not reveal a relationship between the N rate and yield (figure 3). The quadratic function between yield and nitrogen is not significant (R^2<5%). This outcome is due to several factors that explain the results in each production zone (Bolsa de Cereales, 2023). Therefore, Hypothesis 1 (N rate and yield would be directly related) is rejected.

By contrast, a high correlation (R^2=93%) between emissions per ha and N rate (kg/ha) was found (figure 4). Therefore, Hypothesis 2 (emissions per hectare (kg CO_2 eq/ha) and N rate (kg/ha) would be highly correlated) is confirmed. This is obviously the case, because N fertilizer itself is a major source of greenhouse gas emissions.

However, the hypothesis proposed by Nemecek *et al*. (2012) about the direct relationship between CFPs and yields was not confirmed (figure 5), since, in this study, the relationship was not significant (R^2=19%). Therefore, Hypothesis 3 ("The CFP and yields would be directly related") is rejected.

Finally, the effect of no-tillage practices on the CFP was analyzed. According to the information provided by ReTAA for the studied crop season, the percentage of adoption was 91.09% in Argentina. The incidence of a system applying 100% no-tillage and another one applying 0% was modeled. The results are presented in table 9.

Total Argentina		Rem. Subst.	CO_2	N_2O	CH_4	SF_6	CO_2, LT	Total	
Without sequestration	kg CO_2 eq/ha	0.7	601.7	600.5	43.3	0.7	0.9	1,247.8	
Without sequestration	kg CO_2 eq/kg	0.0	0.1	0.1	0.0	0.0	0.0	0.178	
No-till with sequestration –	kg CO_2 eq/ha	0.7	453.0	600.5	43.3	0.7	0.9	1,099.0	-12%
CC with sequestration	kg CO_2 eq/kg	0.0	0.1	0.1	0.0	0.0	0.0	0.157	-12%
NT and CC WITH sequestration -	kg CO_2 eq/ha	0.7	450.7	600.5	43.3	0.7	0.9	1,096.8	-12%
NT and CC WITH sequestration	kg CO_2 eq/kg	0.0	0.1	0.1	0.0	0.0	0.0	0.156	-12%

Rem. Subst.: Remaining Substances NT: No-till CC: Cover crops

Table 4. Average national carbon footprint, considering the effect of carbon removal.

Total country			Remaining Substances	CO_2	N_2O	CH_4	SF_6	CO_2, LT*	TOTAL	
Without sequestration	**kg CO_2 eq/ha**		**0.7**	**601.7**	**600.5**	**43.3**	**0.7**	**0.9**	**1,247.8**	
Inventory	**Unit**	**Amount**								**%**
Fuel for operations	L/ha	28.66	0.41	128.72	1.17	5.45	0.13	0.14	**136.02**	11%
Seed production	kg/ha	12.32	0.01	18.66	3.95	1.52	0.05	0.03	**24.21**	2%
Fertilizer production	kg/ha	186.27	0.11	253.98	11.24	24.10	0.24	0.42	**290.09**	23%
Herbicide production	kg/ha	11.93	0.13	104.22	1.38	12.04	0.33	0.28	**118.39**	9%
Insecticide production	kg/ha	0.10	0.00	1.15	0.01	0.12	0.00	0.00	**1.28**	0%
Fungicide production	kg/ha	0.03	0.00	0.21	0.00	0.03	0.00	0.00	**0.25**	0%
Harvest residues			0.00	0.00	244.95	0.00	0.00	0.00	**244.95**	20%
Nitrogen Fertilization			0.00	94.80	337.77	0.00	0.00	0.00	**432.58**	35%
Carbon sequestration from no-tillage (NT)			0,00	-148.77	0.00	0.00	0.00	0.00	**-148.77**	
Carbon sequestration from cover crop			0,00	-2.57	0.00	0.00	0.00	0.00	**-2.57**	
Emissions from cover crop (operations)			0,00	0.25	0.00	0.01	0.00	0.00	**0.26**	
Emissions from cover crops (seeds)			0,00	0.08	0.04	0.00	0.00	0.00	**0.13**	

* LT = Land Transformation

Table 5. Contribution of the different elements of the environmental inventory to the total carbon footprint.

Carbon footprint	Early maize 46%		Late maize 54%	
WITHOUT C sequestration per ha (kg CO_2 eq/ha)	1,270		1,228	
WITHOUT C sequestration per kg (kg CO_2 eq/kg)	0.180		0.176	
WITH C sequestration – including NT – per ha (kg CO_2 eq/ha)	1,096	-14%	1,102	-10%
WITH C sequestration – only NT* – per kg (kg CO_2 eq/kg)	0.155	-14%	0.158	-10%
WITH C sequestration – including NT and CC** – per ha (kg CO_2 eq/ha)	1,093	-14%	1,100	-10%
WITH C sequestration – including NT and CC- per kg (kg CO_2 eq/kg)	0.155	-14%	0.158	-10%

* NT = No Till

** CC = Cover crops

Table 6. Carbon footprint of early and late maize, considering the carbon removal effect.

DISCUSSION AND CONCLUSIONS

This work analyzed the CFP of maize during the 2012-2022 crop season. Significant GHG emissions and removals during the maize life cycle were quantified, from the extraction of material to produce inputs to the loading of the product into vessels at the export port. Three declared units were analyzed: 1 harvested hectare, 1 kg of maize at the field gate, and 1 kg of maize at the port under FOB condition.

The values were estimated using the data from the "Survey of Applied Agricultural Technology" conducted by the Buenos Aires Grain Exchange, including two sowing dates (early and late) and three technological levels (high, intermediate and low) in each of the 16 agroeconomic maize production areas.

The results show that the average national CFP is 1,248 kg CO_2eq per hectare and 0.178 kg CO_2eq per kg at the field gate. This value is 61% lower than the global average, which considers land use change. The CFP of maize, under FOB condition, was 0.204 kg CO_2eq per kg.

Unlike the previous study conducted in Argentina in which data of the 2012-2013 crop season was used (Arrieta *et al*., 2018), no significant differences were found in the emissions between the Pampas and the extra-Pampas region. With respect to the situation of the 2021-2022 crop season, the comparison was made without C removal in order to show the results under the same conditions.

The overall result indicates that the value of CFP per hectare (kg CO_2 eq/ha) found in this work is 20% higher than that reported by Arrieta *et al*. (2018). This is due to a greater use of inputs for production (fertilizers, crop protection products, etc.). However, the CFP of the product (kg CO_2 eq/t) estimated in this work is 22% lower than the value reported by Arrieta *et al*. (2018). A possible explanation is that the yields of the 2021-2022 were higher than those in the 2012-2013 crop season due to weather effects and/or technological change.

The CFP values per hectare (kg CO_2 eq/ha) found in this work were 19% higher for the Pampas zone and 8% higher for the Extra-Pampas zone than those reported by Arrieta *et al*. (2018). On the other hand, the results of the CFP of the product (kg CO_2 eq/t) did not differ significantly for the Pampas zone; however, there were significant differences regarding the Extra-Pampas zone, with the CFP per ton being 47% lower in this work than in that of Arrieta *et al.* (2018).

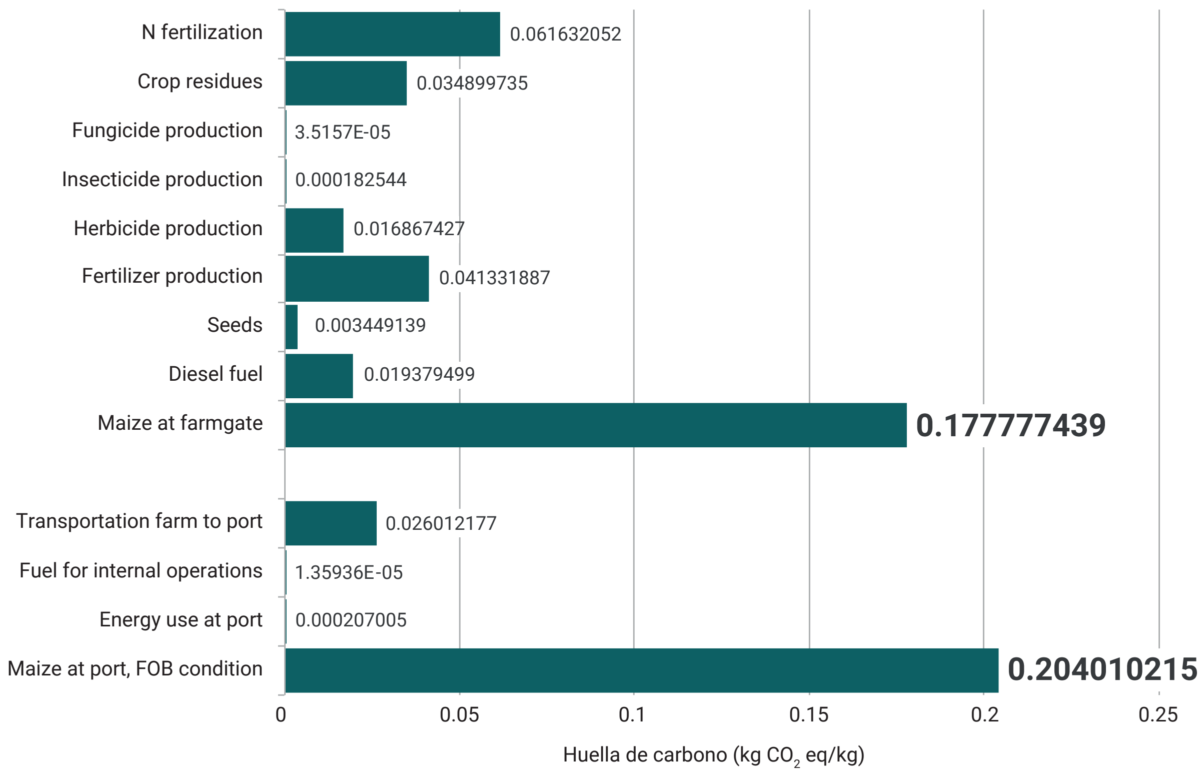


Figure 2. Carbon footprint of maize in Argentina for the 2021/2022 crop season, at the port, under FOB condition.

	Early maize	Late maize	Weighted average Argentina
kg CO_2 eq/ha			
Average	1,270.3	1,228.3	1,247.8
HIGH technological level	1,371.2	1,348.0	1,358.8
INTERMEDIATE technological level	1,165.7	1,161.0	1,163.2
LOW technological level	506.9	509.5	508.3
kg CO_2 eq/kg			
Argentina	0.180	0.176	0.178
HIGH technological level	0.186	0.183	0.184
INTERMEDIATE technological level	0.185	0.176	0.180
LOW technological level	0.128	0.107	0.117

Table 7. Carbon footprint of maize according to the technological level used for production.

	kg CO_2 eq/ha	kg CO_2 eq/kg	Yield (kg/ha)	N rate (kg/ha)
Argentina	**1,248**	**0.178**	**7,018.67**	**67.87**
I	739	0.118	2,898.3	11.1
IIe	762	0.111	3,186.9	9.1
IIo	927	0.113	3,818.9	21.8
III	1,224	0.157	7,127.0	65.6
IV	1,170	0.165	6,846.9	63.4
Vc	1,269	0.197	5,905.0	72.4
Vn	854	0.175	5,506.9	35.7
VI	1,706	0.217	7,377.9	106.6
VII	1,791	0.234	7,643.8	111.9
VIII	1,423	0.303	4,758.4	83.0
IX	1,523	0.185	8,386.6	91.6
X	1,407	0.197	7,214.6	80.8
XI	1,069	0.184	5,824.7	56.5
XII	1,287	0.219	5,925.8	75.2
XIII	822	0.198	3,847.2	40.0
XIV	1,336	0.182	7,376.7	73.4

Table 8. Carbon footprint of maize per zone (per hectare and per kg of product) and its relationship with yield and N rate.

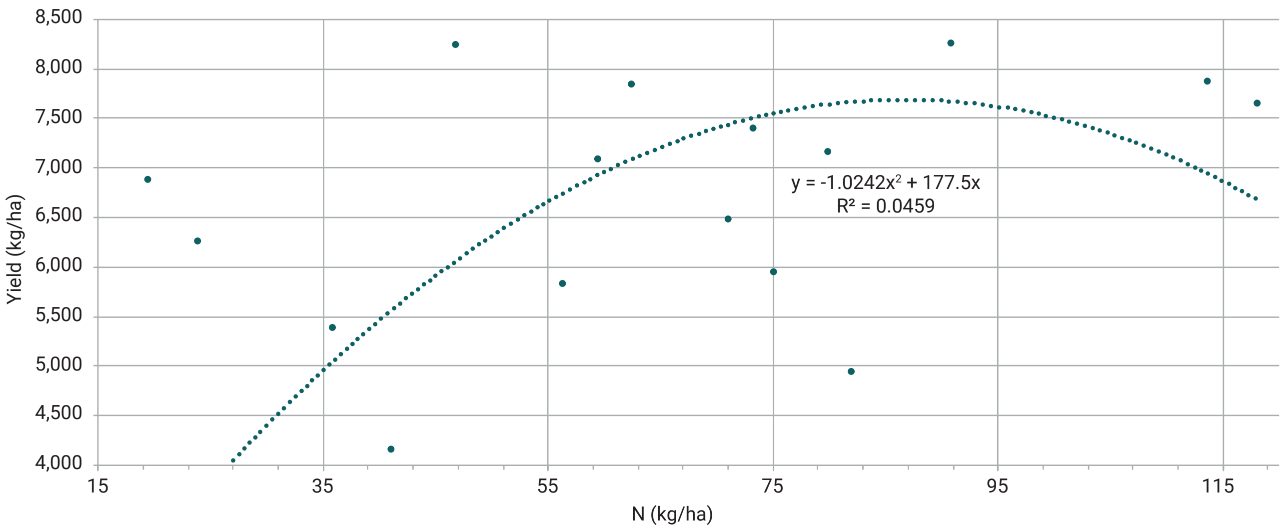


Figure 3. Relationship between yield and N rate.

The comparison of the CFP values obtained in Argentina and the values reported in databases for other countries provides an interesting insight into the local situation. Table 11 shows the CFP published by Agrifootprint for Argentina, which is 0.176 kg CO_2eq/kg; this value differs only by -1% with respect to the values estimated in this study for the baseline case, without taking into account the effect of Land Use Change (LUC), reported by Agrifootprint, since we assume there has not been any LUC in the last 20 years. All the countries with published scientific data have higher values than those estimated for our country using the same methods.

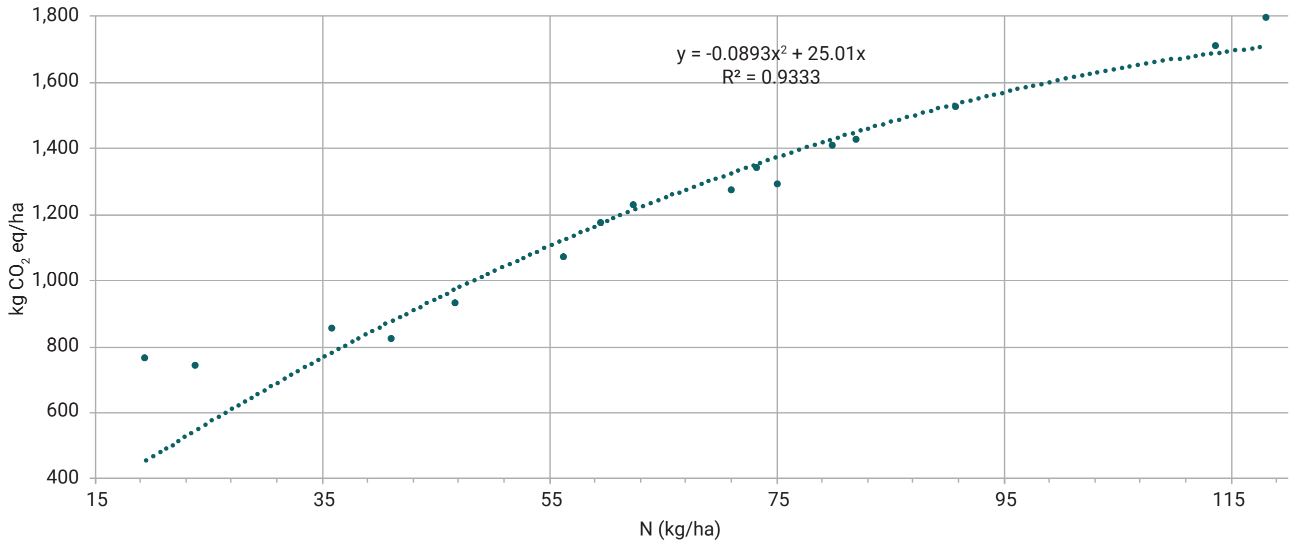


Figure 4. Relationship between emissions per ha and N rate (kg/ha).

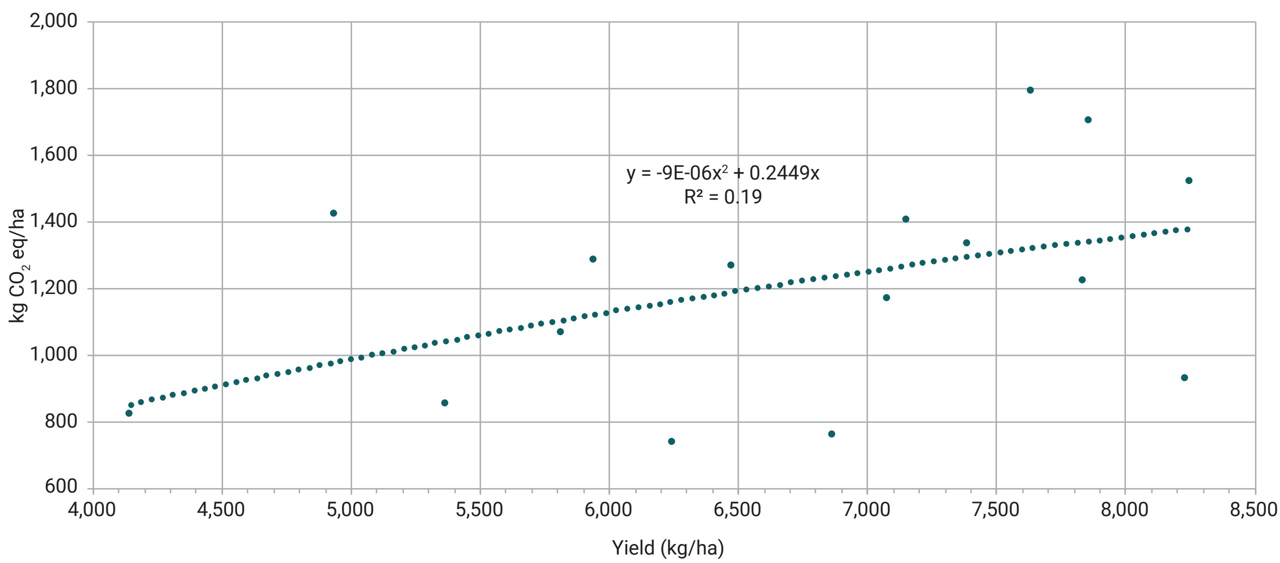


Figure 5. Relationship between CO_2eq emissions per ha and yield (kg/ha).

Carbon footprint scenarios	100% NT	NT data from ReTAA	0% NT
WITHOUT C sequestration per ha (kg CO_2eq/ha)	1,243	1,248	1,301
WITHOUT C sequestration per kg (kg CO_2eq/kg)	0.177	0.178	0.185
WITH C sequestration –including NT- per ha (kg CO_2eq/ha)	795	800	853
WITH C sequestration –including NT-per kg (kg CO_2eq/kg)	0.113	0.114	0.122
WITH C sequestration -including NT and CC- per ha (kg CO_2eq/ha)	780	785	838
WITH C sequestration -including NT and CC- per kg (kg CO_2eq/kg)	0.111	0.112	0.119

Table 9. Scenarios of adoption of a no-tillage system and their relationship with the carbon footprint.

Region		Yield (kg/ha)	Arrieta	This work	Difference %	Arrieta	This work	Difference %
			(kg CO_2 eq/ha)			(kg CO_2 eq/kg)		
Pampas region	III east	5,818	1,123	1,224	9%	0.193	0.157	-19%
	IV	5,241	943	1,170	24%	0.180	0.165	-8%
	V central	4,968	1,163	1,269	9%	0.234	0.197	-16%
	VI	8,754	1,374	1,706	24%	0.157	0.217	38%
	VII	8,909	1,372	1,791	31%	0.154	0.234	52%
	VIII	6,564	1,365	1,423	4%	0.208	0.303	45%
	IX	5,500	1,089	1,523	40%	0.198	0.185	-6%
	X	7,109	1,137	1,407	24%	0.160	0.197	23%
	XI	1,911	585	1,069	83%	0.306	0.184	-40%
	XII	4,993	1,353	1,287	-5%	0.271	0.219	-19%
	XIV	6,451	1,232	1,336	8%	0.191	0.182	-5%
Extra-Pampean region	I	2,041	735	739	1%	0.360	0.118	-67%
	II east	1,967	620	762	23%	0.315	0.111	-65%
	II west	2,836	706	927	31%	0.249	0.113	-55%
	III west	4,565	1,068	1,224	15%	0.234	0.157	-33%
	V north	3,355	654	854	31%	0.195	0.175	-10%
	XIII	4,125	1,159	822	-29%	0.281	0.198	-29%
Pampas region		6,020	1,158	1,382	19%	0.205	0.204	-1%
Extra-Pampas region		3,148	824	888	8%	0.272	0.145	-47%
Argentina (without C sequestration)		**7,019**	1,040	1,248	20%	0.229	0.178	-22%

Table 10. Comparison between results of Arrieta *et al*. (2018) for the 2012-2013 crop season and results of the present study for the 2021-2022 crop season.

Database	Country	kg CO_2eq / kg	Difference from values in Argentina (baseline case)
Agrifootprint	Argentina	**0.176**	-1%
EcoInvent	Brazil	0.264	33%
Agrifootprint	Brazil	0.324	45%
Agrifootprint	China	0.411	57%
Agrifootprint	USA	0.277	36%
Agrifootprint	India	0.614	71%
EcoInvent	Global	0.526	66%
Agrifootprint	Russia	0.545	67%
EcoInvent	South Africa	0.546	67%
Agrifootprint	South Africa	0.366	51%
Agrifootprint	Ukraine	0.328	46%
Agrifootprint	Vietnam	0.528	66%

Table 11. Comparison between the results from databases of different countries and the results of this study.

Regions				kg CO_2 eq/ha	Difference	kg CO_2 eq/kg	Difference
World			Yield (kg/ha)				
Nemecek *et al*, (2012)	Maize – global		6,586	2,950	-58%	0.451	-61%
Asia			Yield, (kg/ha)				
Zhang *et al*, (2018)	Maize – irrigated China 2017		10,000	2,850	-56%	0.285	-38%
	Maize - rainfed China 2017		4,700	1,701	-27%	0.362	-51%
	Maize - China 2004-2016		7,500	4,425	-72%	0.590	-70%
Hou *et al*, (2021)	Maize - China	Small-scale farmer		3,325	-62%	0.400	-56%
		Medium-scale farmer		2,724	-54%	0.335	-47%
		Large-scale farmer		2,473	-50%	0.270	-34%
Zhang *et al*, (2017)	Maize China			4,052	-69%	0.480	-63%
Moungsree *et al*, (2022)	Maize Thailand		7,630	2,970	-58%	0.429	-59%
Europe			Yield (kg/ha)				
Holka and Bienkowski (2020)	Maize – Poland 2015-17 conventional		12,700	2,347	-47%	0.185	-4%
	Maize Poland 2015-17 reduced till		12,400	2,353	-47%	0.190	-6%
	Maize Poland 2015-17 No-till		10,500	1,869	-33%	0.178	0%
Amaia *et al*, (2012)	Spain					0.515	-65%
Canada			Yield (kg/ha)				
Ma *et al*, (2012)	Average	kg N	8,364	2,402	-48%	0.283	-37%
	Maize-Maize	50	6,000	1,138	10%	0.190	-6%
	Maize-Maize	100	7,000	1,956	-36%	0.279	-36%
	Maize-Maize	150	8,000	2,828	-56%	0.354	-50%
	Maize-Maize	200	9,000	3,474	-64%	0.386	-54%
	Maize-Maize	250	9,000	4,569	-73%	0.508	-65%
	Soybean-Maize	50	8,000	1,250	0%	0.156	14%
	Soybean-Maize	100	9,000	1,962	-36%	0.218	-18%
	Soybean-Maize	150	9,000	2,883	-57%	0.320	-45%
	Forage-Maize	50	9,000	1,329	-6%	0.148	20%
	Forage-Maize	100	9,000	2,057	-39%	0.229	-22%
	Forage-Maize	150	9,000	2,971	-58%	0.330	-46%
Jayasundara *et al*, (2014)	Average Ontario		9,400	2,641	-53%	0.281	-37%
USA			Yield (kg/ha)				
Gevo Program for emission reduction		Sheehan (2014)		1,718	-27%	0.167	6%
GREET model U,S, Dept, of Energy				3,152	-60%	0.371	-52%
Continuous maize with intensive management I		Adviento-Borbe *et al*, (2007)	15,000	3,080	-59%	0.205	-13%
Maize-soybean rotation		Snyder *et al*, (2009)	14,700	3,740	-67%	0.254	-30%
– Maize-soybean rotation with intensive management			15,600	3,740	-67%	0.240	-26%
Survey Nebraska		Grassini and Cassman (2012)	13,200	3,049	-59%	0.231	-23%
Brazil							
Trovo-Garofalo *et al*, (2022)			5,459	2,000	-100%	0.366	-51%

Table 12. Comparison between the results of studies conducted in different parts of the world and those of the present study.

A comparison with the international scientific literature reveals that the carbon footprint (CFP) obtained in this study ranks among the lowest reported globally. While this is an encouraging outcome, it is based on the data of a single season and, therefore, should not be considered definitive. Although the 2021-2022 season is generally representative of Argentine maize production, the variations in CFP are possible due to changing weather conditions across different seasons. This result likely reflects both Argentina's favorable environmental conditions for maize cultivation and its relatively low input usage, which may imply a negative soil nutrient balance. In fact, recent findings by local researchers (Koritschoner *et al*., 2023) confirm a negative nutrient balance across five agricultural seasons, with a particularly pronounced nitrogen and phosphorus deficiency in summer crops.

The CFP is 52% lower than that of China and Thailand, which is explained by a lower use of N fertilizers in Argentina. Compared with Europe, the CFP is similar to that of Poland, but 66% lower than that of Spain; this difference is due to the practice of residue burning usually applied in Spain. The CFP is 27% lower than that of Canada and USA due to the lower use of N fertilizer in Argentina. The CFP estimated for Argentina is also 52% lower than that of a 20-year data series from Brazil; this difference can be attributed to the inclusion of land use change in the estimations in Brazil. The results estimated in this work are similar to those published for Argentina in the database Ecoinvent (without including land use change).

This research contributes to the understanding of the CFP of maize production, both per kg of product and per hectare, in a vast agricultural region of Argentina and sets the basis for the analysis of the sustainability of agricultural production in diverse production regions.

From our study, several political conclusions and implications emerge that could inform both national and international policy on agricultural sustainability, climate change, and trade. Here are some key points.

Environmental standards and sustainable practices: This research highlights the relatively low CFP of maize production in Argentina, which can encourage policymakers to promote national agricultural practices as a model for sustainable production. The results underline the importance of practices like no-tillage and cover cropping, suggesting that incentivizing these practices could further reduce GHG emissions across the agricultural sector.

Carbon Credits and Climate Policy: The findings support Argentina's potential role in the carbon credit market, particularly since practices like no-tillage and cover crops reduce the CFP and could qualify for carbon offset credits. Policymakers could advocate for policies that recognize and monetize these practices, thereby integrating Argentine agriculture into global carbon markets and promoting a climate-resilient agriculture.

Trade and Competitiveness: With a comparatively low CFP, Argentine maize could be positioned favorably in international markets as a low-carbon product, potentially meeting the consumer demand for environmentally responsible goods. This could inform trade policy by promoting labeling or certification standards that highlight low-emission production, improving competitiveness in global markets that prioritize sustainability.

Agricultural Emissions Regulation: The study provides critical data on the contribution of agricultural emissions to the overall GHG output. Policymakers could leverage this information to set specific sectoral emission targets, particularly for maize production, and to guide mitigation strategies that align with Argentina's climate commitments under international agreements, like the Paris Agreement.

Resource Management and Soil Health Policies: The study indicates that low input usage may lead to nutrient imbalances, raising concerns about long-term soil health. This could prompt the government to support balanced fertilization and soil management programs to maintain productivity while minimizing environmental impacts, addressing both food security and sustainability goals.

Rural Development and Financial Support: Given the environmental benefits of low-impact maize production, there is an opportunity for rural development policies that support sustainable agriculture. Financial assistance, such as subsidies or low-interest loans, could be offered to farmers adopting practices that reduce GHG emissions, fostering economic resilience and environmental responsibility.

These insights provide a foundation for policies that not only support sustainable agriculture but also position Argentina as a leader in the climate-resilient crop production, offering pathways for both economic and environmental gains.

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