ARTIGO TÉCNICO 1

Carbon Footprint in Agriculture: Insights towards neutral crop production and industry integration

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1. INTRODUCTION: CONCEPT OF CARBON FOOTPRINT

Agriculture is responsible for 10% to 12% of the total global greenhouse gas (GHG) emissions (SMITH et al., 2007) and overall level of GHG emissions from agriculture is expected to increase further due to the need to expand agricultural production to meet the growing demand for food, feed, fiber, and bioenergy. It is expected that until 2050 we will have 9 billion people on the Earth.

In Brazil, agriculture plays a significant role, contributing 25%-30% to the Brazilian gross domestic product (GDP). Brazil stands as a major global player, producing enough food to meet domestic needs and a substantial portion of international demand. Brazil ranks as the leading exporter of several agricultural products, including soybean, sugar, chicken meat, beef meat, coffee, orange juice, tobacco, ethanol, maize, and cotton fiber. Additionally, it plays a crucial role in pork meat, tropical fruits, and forest product markets. Furthermore,

Abbreviations: AN = Ammonium nitrate; C = carbon; CAN = calcium ammonium nitrate; CBIOs = decarbonization certificates; CFP = carbon footprint; CFT = Cool Farm Tool; CH_4 = methane; CN = calcium nitrate; CO_2 = carbon dioxide; DCD = dicianodiamide; DMPP = 3,4-dimethylpyrazole phosphate; FCs = food companies; GDP = gross domestic product; GHG = global greenhouse gas; H_2 = hydrogen; IPCC = Intergovernmental Panel on Climate Change; K = potassium; LCA = life cycle assessment; MRV = carbon measurement, reporting, and verification; N = nitrogen; N_2O = nitrous oxide; NDC = Nationally Determined Contribution; NUE = nutrient use efficiency; P = phosphorus; PCF = Product's Carbon Footprint; UAN = urea ammonium nitrate; WBCSD = World Business Council for Sustainable Development; WRI = World Resources Institute.

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Brazil is self-sufficient in various products such as beans, cocoa, cassava, banana, and various vegetable crops.

Agriculture, without deforestation-related emissions, is the second-largest contributor to GHG emissions; Brazil's agricultural sector is responsible for over 9.8% of Brazilian emissions (1.35 billions tons of CO_2eq), while Brazil per se shares approximately 3.3% of overall GHG emissions. According to the Brazil's Climate Observatory (Alencar et al., 2023), enteric fermentation, a natural digestive process that occurs in ruminant animals (e.g. cattle), accounts for 63% of Brazilian emissions. Notably, cattle production holds tremendous potential for transitioning from the current carbon footprint of Brazilian agricultural production to a low-carbon model. In other agricultural products, Brazil serves as a model to be followed. Brazil's agriculture is characterized by high land-use efficiency, particularly in the cultivation of crops such as soybeans, maize, and cotton, which are often produced in double-cropping systems. The wide adoption of technology has enhanced the efficient use of energy and while at the same time yields continue growing.

Among the inputs employed in the rainfed agricultural sector, fertilizers and seeds (via plant breeding) are crucial tools for enhancing crop yields. The utilization of mineral fertilizers is imperative for supplying plant nutrients to support food production (Dobermann et al., 2022). However, they also significantly contribute to the carbon footprint (CFP) of agricultural products and, consequently, crop-based food items (Hillier et al., 2009). The impact of fertilizers, majorly nitrogen (N) fertilizers, on GHG emissions become evident during their production, transportation to their application sites, and the release of nitrous oxide (N_2O) emissions from soils after their application (Brentrup et al., 2018). Other agricultural inputs such as fossil fuels to sustain mechanized operations, and energy/electricity in irrigated agriculture, are paramount sources of GHG emissions. Pesticides may contribute for the C footprint in some high value crops; however in most row crops their magnitude can be negligible.

For a long time, there has been a discussion about the need for a significant effort to reduce global temperatures, which impacts food production, the economy's dynamics, and the survival of species. The Paris Agreement, signed in 2015, was a landmark commitment to efforts to limit the global increase to below 2 Celsius degrees in relation to pre-industrial levels. Climate change resulting from this increase can cause severe impacts on the environment and society, threatening agriculture and food security. It was in this context that countries signed the NDC (Nationally Determined Contribution) and multinational companies, in particular food companies (FCs), began to discuss and formalize their emission reduction targets in their production chains.

The growing demand from consumers for more sustainable products and the interest of shareholders have made FCs aware of the need to reduce emissions from their production chain, and consequently, make efforts to reduce emissions in the field, implementing sustainable agricultural practices and seeking greater efficiency. The need to mitigate climate change has led many FCs to publish ambitious emissions reduction targets in the search for climate neutrality, investing heavily in initiatives that bring them closer to achieving these goals. Company goals can be easily consulted in their sustainability reports. For example, Nestlé has committed to reducing its emissions by 50% by 2030 and achieving net zero emissions by 2050 (NESTLÉ, 2022). American PepsiCo seeks to reduce 40% of GHG emissions across the entire value chain by 2030 (PEPSICO, 2022). In order to monitor the achievement of such goals, companies need to follow certain procedures and indices that have been validated and reviewed by the scientific community.

From its origins in energy analysis, in the 1960s and 70s, life cycle analysis (LCA) has grown into a wide-ranging tool used to explore potential impacts to a range of environmental metrics and resource depletion including the carbon footprint of products. LCA has been used nowadays to guide challenging decisions and select between technology paths, driven by C footprints (McManus and Taylor, 2015).

As society increasingly focuses on understanding and mitigating GHG emissions, the term "Carbon Footprint" has gained popularity. This term has been widely searched in countries recognized by their capacities in food production. This shows how committed the sectors are in finding solutions to enhance energy and resources use efficiency. In order to standardize comparisons and to demonstrate to society the real impact of producing an amount of product, the metric of C footprint is normally preferred. However, with that, many examples of misuses may also be observed, especially in the primary sector. It is crucial to clarify the concept and methods associated with the Product Carbon Footprint (PCF) to prevent misunderstandings. This is particularly important in agriculture, where recognizing and addressing the PCF has become a key element of sustainable practices and may differentiate products, creating a new factor for competitiveness in the agribusiness sector.

The concept of carbon footprinting follows the life-cycle assessment methodology, i.e. it accounts for all GHG emissions that are related to a product over its life-cycle. The boundaries of the life-cycle are ideally from "cradle-to-grave", which means from extraction and supply of any raw materials needed for the product under investigation up to the final disposal of the product after it has completed its function and reached the end-of-life as a waste. However, in practice, the boundaries of a PCF analysis are set more narrow, for instance from "cradle-to-factory gate" or from "cradle-to-farmgate". In a PCF analysis all GHG emissions within the defined boundaries are collected in an inventory, converted into a common unit (CO_2- equivalents) and finally expressed per unit of product examined, e.g. as kg CO_2eq ton^{-1} of maize grain.

Typically, PCF analyses of agricultural products apply a "cradle-to-farmgate" boundary. This provides valuable information about the climate impact of agricultural products and allows farmers to document improvements or provide low-carbon agricultural raw materials towards their customers. The PCF data is also important information for food chain companies that are often committed to sustainability targets e.g. within the SBTi framework (Science-based Target initiative). Within the corporate accounting of GHG emissions of food companies, the emissions from agricultural raw material production is part of their so-called Scope 3 emissions. The PCF data can be used by the FCs to quantify and monitor these upstream emissions in their corporate GHG inventories.

Our primary goal in this article is to delve into the concept of the carbon footprint associated with agricultural food and energy crops, elucidating its various components. We aim to shed light on the primary contributors to emissions within this context, with a specific focus on nitrogen fertilizers. Additionally, we will explore the efforts made by the fertilizer industry to mitigate emissions during the production process. Furthermore, our paper will underscore the role of farmers in implementing practices that effectively reduce emissions, contributing to an overall reduction in the environmental impact of agriculture in Brazil.

2. CARBON FOOTPRINT OF RAW MATERIAL, FERTILIZERS AND PROCESSES IN THE FERTILIZER INDUSTRY

The fertilizer industry plays a crucial role in global agriculture by providing nutrients to enhance crop growth and productivity. Fertilizers are categorized based on the primary nutrients they contain, with the three main categories being nitrogen (N), phosphorus (P), and potassium (K). If a fertilizer contains all three primary nutrients, it is categorized as NPK.

Nitrogen is not found in mineral forms like phosphorus or potassium, it is extracted from the air where it is in the form of N_2. N is considered a vital nutrient for vegetative growth, leaf development, and overall plant health. Fertilizers typically include nitrogen in one or more of the following forms: nitric, ammoniacal or amidic. Ammonium nitrate (AN), calcium ammonium nitrate (CAN), calcium nitrate (CN), urea (UR) and urea ammonium nitrate (UAN) are some of these nitrogen fertilizers that are produced chemically and each has its own characteristics and applications. Ammonia (NH_3) is the basic molecule for the synthesis of most N fertilizers. Part of the GHG emissions of N fertilizers derive from natural gas, the principal raw material from which hydrogen (H_2) is extracted to make ammonia. A Product's Carbon Footprint at factory gate denotes the amount of greenhouse gas emissions generated or utilized throughout its partial lifecycle. The CFP captures all the GHG emissions related to the raw materials, manufacturing and transport of a product.

Quantifying the carbon footprint of nitrogen fertilizer production involves assessing the GHG emissions associated with various stages of the production process within the boundary. For the calculation of the PCF up to the factory gate of nitrogen fertilizer production, the scope should encompass primary sources of emissions like:

• Raw material extraction: The extraction and processing of raw materials used in nitrogen fertilizer production, such as natural gas (during drilling and transportation) can result in emissions.

• Hydrogen for ammonia production: Approximately 65% of the natural gas used in the ammonia production process is dedicated to producing hydrogen by reforming natural gas and steam.

• Energy: Roughly 35% of the natural gas utilized in the ammonia production process is dedicated to maintaining the necessary high temperature of the process. There are other energy-intensive processes within the production chain, such as compression, cooling, and separation, that can contribute to emissions.

• Nitric acid: Nitric acid is another essential component of nitrogen fertilizers. Its production involves the oxidation of ammonia, which can release nitrous oxide (N_2O), whose global warming effect is 273 greater than carbon dioxide (CO_2) (Smith et al., 2021).

• Transportation: The transportation of raw materials to the production facility can result in higher emissions.

Figure 1 displays a comparison of product carbon footprints for ammonium nitrate, whether or not in aqueous solution, as reported by the European Commission (Vidovic et al., 2023). It demonstrates that the average emissions intensity of ammonium nitrate produced in Europe (EU27) is over 50% lower than the universal weighted average.

Balancing the need for increased crop yields with responsible and eco-friendly fertilizer practices is a key focus as the industry evolves to meet the demands of agriculture and environmental conservation.

N_2O abatement projects are being developed successfully around the world, utilizing secondary and tertiary abatement technologies. After reducing N_2O emissions and improving energy efficiencies in the fertilizer factories, the primary focus should shift towards producing ammonia from alternative sources, rather than relying on natural gas. Blue and green ammonia are two emerging forms of ammonia production with an emphasis on sustainability and environmental impact reduction.

Blue ammonia is produced using a traditional method (grey ammonia), but the key distinction is that the carbon dioxide (CO_2) generated during this process is captured and stored, preventing it from entering the atmosphere. Green ammonia is produced using renewable and sustainable sources of hydrogen, often obtained through processes like water electrolysis powered by renewable energy sources such as wind or solar. Ammonia synthesized with renewable biomethane is also considered green (Figure 2).

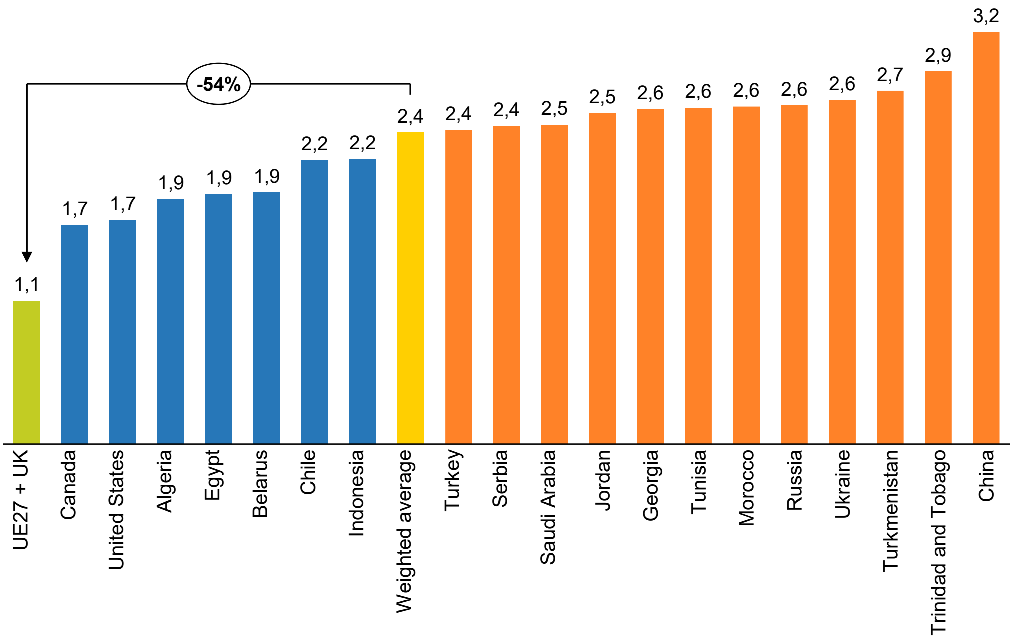


Figure 1. Product carbon footprint of ammonium nitrate in different locations.

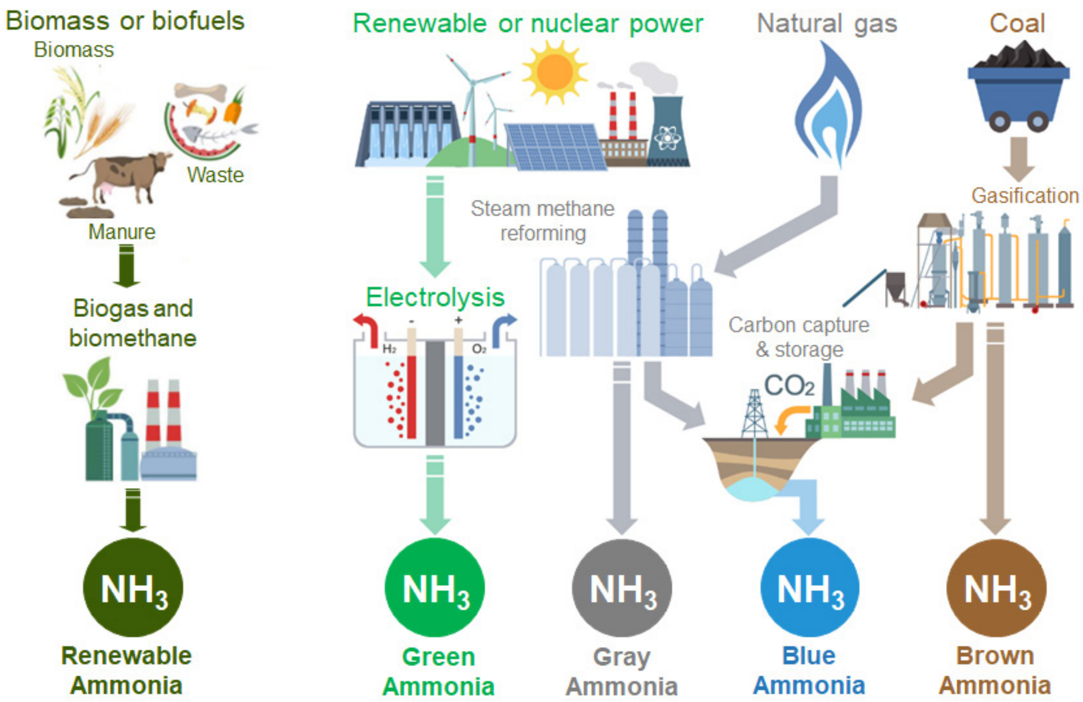


Figure 2. Pathways of NH_3 production.

Renewable Ammonia: this is the term used by Yara Brasil to describe ammonia produced with H_2 from biomethane from the sugar-energy industry.

Green Ammonia: is produced using renewable energy sources, such as wind or solar power, to generate hydrogen through electrolysis. This process aims to reduce carbon emissions and environmental impact compared to traditional methods.

Grey Ammonia: is synonymous with conventionally produced ammonia. It is generated through the Haber-Bosch process, which relies on fossil fuels like natural gas and results in substantial carbon emissions.

Blue Ammonia: is produced by capturing and storing the carbon emissions generated during the ammonia production process. It combines the conventional Haber-Bosch method with carbon capture and storage (CCS) technologies to mitigate environmental impact.

Brown Ammonia: refers to ammonia produced through traditional and energy-intensive methods, often involving the use of coal. The production process emits a significant amount of carbon dioxide.

Source: Adapted from BRASIL, 2021.

Figure 3 displays a comparison of CFP for NPK 15-15-15 manufactured at various plants. NPK 15-15-15 created using gray ammonia and N_2O abatement technology has a CFP that is 50% lower compared to a standard-performing plant. When utilizing NPK produced from green ammonia, the CFP can drop by as much as 80%. This creates an opportunity for farmers to choose the product that allows them to minimize emissions during their production process.

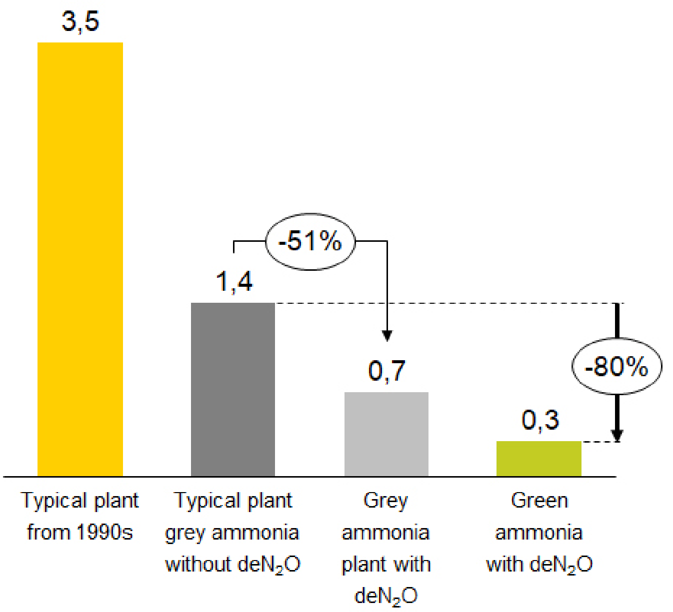


Figure 3. Carbon footprint (t CO_2 eq ton^{-1} of product) of NPK 15-15-15 in plants using different strategies of C footprint reduction.

3. METHODOLOGIES FOR CARBON FOOTPRINT ASSESSMENTS OF AGRICULTURAL PRODUCTS

The carbon footprint usually refers to the emission of GHG associated with a product or process. The emissions are not restricted to C or CO_2 only but, in agricultural studies include also methane (CH_4) and N_2O. The footprint is expressed as CO_2 equivalent (CO_2e) for which factors are applied to GHG other than CO_2, as mentioned earlier.

The carbon footprint of products (PCF) can be assessed in different ways. The boundary conditions of the calculations can be set depending on the purpose and scope of the evaluation. The PCF may refer to one phase of the production (for instance, the manufacture of the fertilizer, emissions of GHG at the field scale, or other suitable conditions). The most complete account of PCF is done through Life Cycle Assessment (LCA), which accounts for a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste, known as cradle to grave LCA (EUROPEAN COMMISSION, 2010).

Different general guidelines and protocols for the CFP calculations have been developed in order to ensure quality, consistency and comparability of analyses and results. The International Organization for Standardization has published ISO 14067 as an international standard that "specifies principles, requirements and guidelines for the quantification and reporting of the CFP, in a manner consistent with International Standards on life cycle assessment (LCA) (ISO 14040 and ISO 14044)" (https://www.iso.org/standard/71206.html). The World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) developed an international standard for corporate GHG accounting and reporting already in the late 1990s. Their GHG Protocol is today widely used and includes a standard for "Product Life Cycle Accounting and Reporting" (https://ghgprotocol.org/product-standard). Another CFP standard is PAS 2050, which was developed by the British Standards Institute (BSI). PAS 2050 is widely used and is considered the first Carbon footprint standard used internationally (https://www.bsigroup.com/globalassets/localfiles/en-th/carbon-footprint/pas-2050-2011-guide.pdf).

Besides general standards, there are also established calculation tools available to enable concrete PCF analysis in a consistent way. One example of such tools is the Cool Farm Alliance Tool – CFT, which enables PCF calculation of agricultural products including crop and animal products. The CFT was developed more than 10 years ago by a small group of food chain companies in collaboration with the University of Aberdeen, UK. Today, the Cool Farm Alliance who owns and develops the CFT comprises about 160 members from food chain, NGOs, academia and farmer representatives. The CFT is widely used throughout the food chain e.g. for quantifying and monitoring GHG emissions for reporting and other purposes. Several academic partners and members ensure scientific backup and robustness of the tool (COOL FARM ALLIANCE, 2023), which is periodically reviewed.

Reference values for the carbon (or GHG) emissions associated with intermediate products or processes used for the calculation of LCA are available in the life cycle inventory database such as Ecoinvent. The database is frequently updated. Ecoinvent is now in the 3.9.1 version (ECOINVENT, 2023).

As commented earlier, the carbon footprint of a crop may be restricted to a specific phase (i.e. farm operations) or the whole cycle. The boundary conditions may be set for instance up to the farm gate (LCA cradle to gate) or the final consumer (LCA cradle to grave). Importantantly is that boundaries be clearly defined. In the latter, the LCA includes the GHG emitted for the manufacture of farm machines, their operation (fuel consumption), all farm inputs (seeds, fertilizers, pesticides), irrigation, harvesting, and transport to the market. More and more, food companies are delving into figuring out the full emissions in the food production chain.

The carbon footprint, in shorter or more ample versions, is increasingly being used to assess sustainability and also to aid consumers in making their decisions for which product to purchase. There are many examples of carbon footprint assessments of agricultural products. For instance, the carbon footprint of fertilizer manufacture in different regions of the world was calculated by Hoxha and Christensen (2019). Fertilizers Europe has developed an online fertilizer carbon footprint calculator (FERTILIZERS EUROPE, 2023).

It is becoming common in certain markets that products in supermarkets carry a carbon footprint value that may help environmentally concerned consumers. A cradle-to-gate LCA of orange juice for the United States was commissioned by the juice industry in order to detect where in the production chain the highest GHG occurred (Martin, 2009). In this case, the highest contribution was from nitrogen fertilizers. Another example was the carbon and water footprint study with oranges and strawberries by Mordini et al. (2009). In such cases, the LCA includes all emissions until the product reaches the supermarket shelf.

One example of cradle-to-gate LCA is the Renovabio Program in Brazil. All GHG emissions for the production of biofuels are calculated and the values are audited by certification companies. Renovabio rewards biofuel producers with decarbonization certificates (CBIOs) if they prove a reduction of GHG emissions compared to their fossil counterparts (gasoline, diesel) (BRASIL, 2020).

4. CARBON FOOTPRINT FOR AGRICULTURAL PRODUCTS

Based on the above-mentioned methods for the calculation of PCF and using data from medium to long-term studies with different crops (maize, coffee, cotton and sugarcane) and strategies for N fertilization, we estimated the PCF for the following products: maize grains, coffee beans, cotton lint and sugarcane stalks from cradle to farmgate using the CFT. Medium to long term studies are important when considering the residual effect of the fertilizers, given that short differences on yield are normally observed in the first crop cycles. Data of the selected crops presented in this study were obtained by the authors in previous studies and used in this publication to exemplify the impact of N fertilizer on the C footprint of the selected crops studied.

4.1. Maize

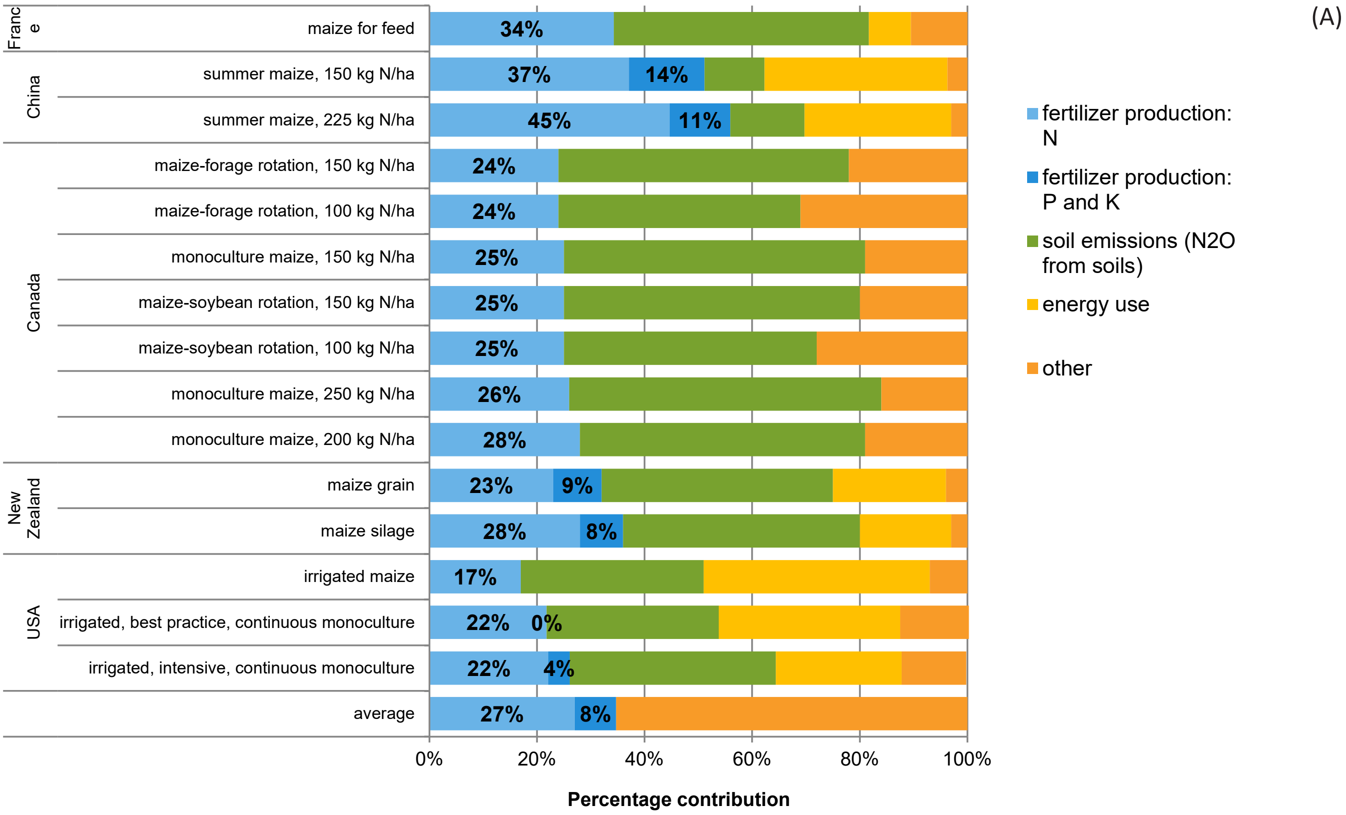
Across different countries, fertilization, primarily nitrogen-based, plays a pivotal role in the carbon footprint of grain maize crops. According to the compiled data, on average, fertilizer production contributes 32% to farm gate emissions when considering all types of fertilizers (see to Figure 4), and 27% when focusing solely on nitrogen fertilizers (see Figure 4A). In addition to fertilizer production, in-field N_2O emissions resulting from the application of nitrogen fertilizers to maize fields may contribute from 11% to 56%, averaging around 38%. Consequently, nitrogen fertilization accounts for up to 65% of the overall carbon footprint associated with maize cultivation.

Nitrogen fertilization is well documented as the main driver of CO_2 emissions in rainfed production of maize. Energy use may also be a significant contributor, especially in irrigated systems (up to 42%), however irrigation in maize production is seldom used in Brazil. It is important to emphasize that the cultivation phase is very significant in the cradle-to-gate C footprint assessment. In a study from Thailand considering the production of canned sweet corn (up to processing) cultivation was responsible by 35% of emissions (Usubharatana and Phungrassam, 2016) while in other study from Australia where C footprint of corn crisp (up to retail) was evaluated the cultivation was responsible by 42% of emissions (Yara, intern compilation). An important business demand for maize produced in the Brazilian territory is the production of ethanol in flex plants, where both saccharose (sugarcane) and starch (maize) can be processed. However, there is no available information. According to Mekonnen et al. (2018), C footprint of maize ethanol is 30% related to fertilizer production, soil emissions and farming, while 62% is associated with transport and processing. A study under Brazilian conditions has pointed out that cultivation and transport accounts for 78% of the C footpring of maize ethanol (Moreira et al., 2020). This same study showed that the C footprint of Brazilian maize ethanol is lower than that one produced in the United States due to the energy source used in processing (burning eucalyptus wood instead of natural gas) and the use of second season maize crop, which typically requires less nitrogen fertilizer than single-crop maize. The European Renewable Energy Directive adopts a fraction of 47% of emissions during farming.

Soil emissions of N_2O typically represent the main hotspot for C footprint of maize production, since maize is considered a crop with high response to N fertilization and rates near 100 kg N ha^{-1} have been practiced in Brazil (ranges from 50 to 220 kg N ha^{-1}). Although such in-field N_2O emissions do not affect maize yields in Brazil, or elsewhere, since emissions are low compared to other loss pathways such as NH_3 volatilization, and N runoff, the concept of 4R's suitably fits to further reductions in PCF.

In a long-term study conducted in the Cerrado region from Brazil (Santo Antônio de Goiás, GO), the performance of maize grain production was assessed, and three nitrogen (N) sources with high N concentration were compared to supplement the N required for maize at V4 growth stage. The sources included calcium ammonium nitrate (CAN), common urea, and ammonium sulfate. Partial results of this study were presented in a previous edition of the Informações Agronômicas newsletter (Otto et al., 2021).

The results indicate a response of maize crop to N doses and a clear effect of the N source used, which was observed only after the fourth crop-growth cycle. This delayed effect of applying different sources is related to the distinct effects of each source and due to the clayey soil where the test is



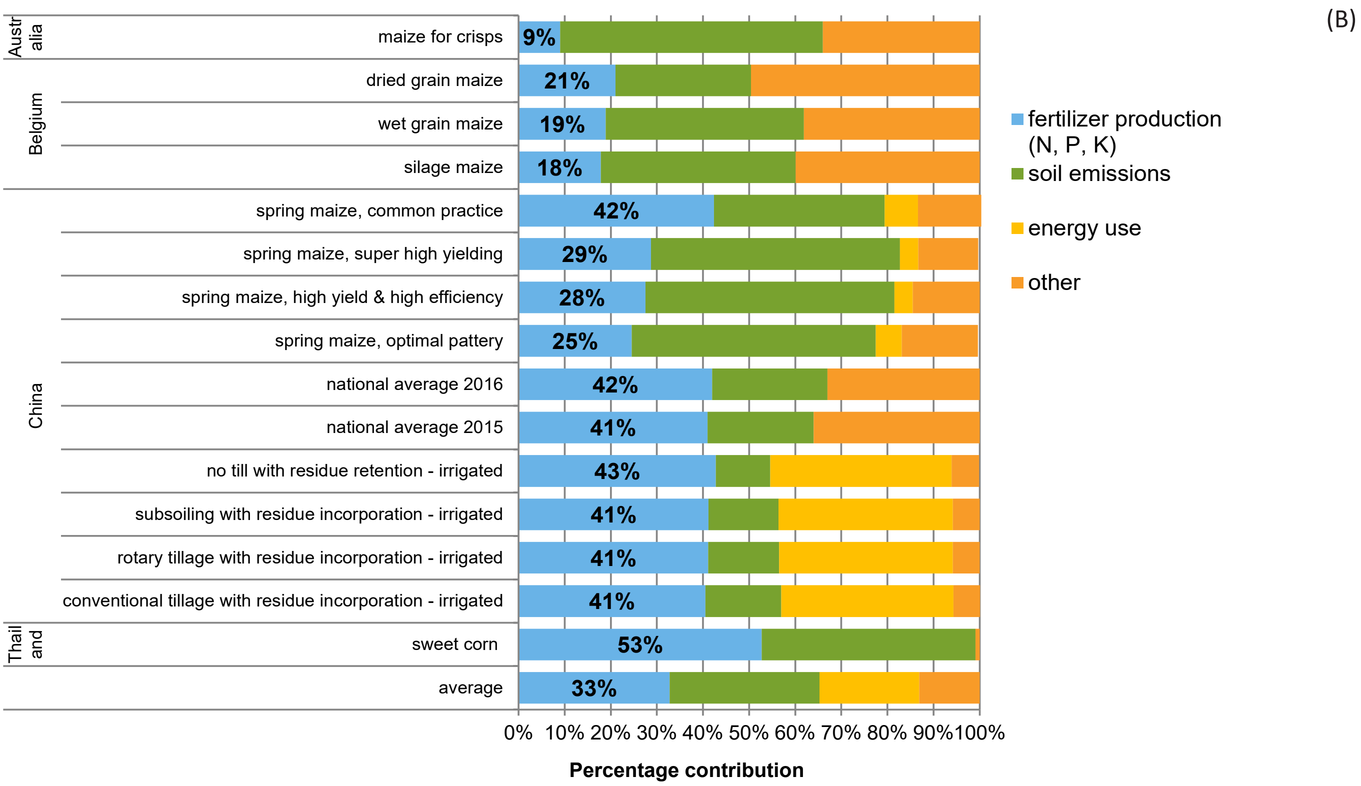


Figure 4. Contribution to the carbon footprint of maize cultivation (various uses) in relation to fertilizer production (N, P, and K), N_2O emissions, and energy use. In Figure 4A, the impact caused by nitrogen fertilizer production was assessed separately from the impacts caused by phosphorus and potassium fertilizer production, while in (B) they were assessed collectively.

Sources: (A) Adviento-Borbe et al. (2007), Barber et al. (2011), Grassini e Cassman (2012), Ma et al. (2012); Middelaar et al. (2013), Wang et al. (2015).

(B) Beer et al. (2005), Qi et al. (2018), Usubharatana e Phungrassami (2016), Stappen et al. (2018), Xu et al. (2018), Zhang et al. (2016).

placed, with high soil organic content, which acts as a buffer, providing the soil the capacity to supply N to the crop. After ten years of study, it was found that the maximum agronomic efficiency rate for CAN was 138 kg N ha^{-1}, whereas for urea was 226 kg N ha^{-1}, a 63% increase. The experiment did not evaluate the response of maize to N doses as ammonium sulfate. Comparing the sources at the dose considered usual by the maize grower, maize performance increased by 7.2% with the adoption of CAN compared to urea or ammonium sulfate. This reflects the lower losses of NH_3 from this fertilizer, as well as the lower soil acidification. These were probably the major reasons to explain lower yields achieved in plots with urea and ammonium sulfate, respectively. Both ammonia losses and soil acidification alter the N supply dynamics to plants, limiting maize plant growth and consequently restricting the achievement of higher yields.

When analyzing the Carbon footprint of maize grains (Figure 5) accounted by Cool Farm® tool, we took into consideration the demand for N at maximum economic efficiency, understanding that the growers aim to achieve high productivity while respecting established margins to ensure the efficiency of their business. Considering maize prices at US$ 15.00 per 60 kg-bag and fertilizer prices at the time (CAN US$ 539 ton^{-1} and urea US$ 567 ton^{-1}), the maximum economic efficiency was identified for CAN and Urea at doses of 102 and 145 kg N ha^{-1}, respectively. It is crucial to compare different doses since the results demonstrate different efficiencies between the two nitrogen sources, as well as distinct responses of the crop to fertilizer use. Several studies conducted under tropical conditions have outlined the issue related to NH_3 emissions, which regularly range from 20% to 30%. In the long term, volatilization losses may accelerate soil mining process under agricultural fields, especially if the farmer is considering N reposition based on an enhanced efficiency fertilizer. In this study, NH_3 volatilization from urea in the maize crop was, on the average of ten years, equivalent to 17% (data not presented). Moreover, by comparing different N rates we are considering the need of different amounts of fertilizers being produced and transported.

The results of C footprint of maize production based on the maximum economical N rate for urea and CAN are displayed in the Figure 5 and show a distinguished pattern for fertilizers and the contribution of each origin, which demonstrates the main sources of energy in their local fertilizers factories. There is a reduction of 29% in the C footprint of maize replacing CAN from Russia by CAN from EU. On the other hand, such reduction is not observed for urea, since the decrease with the replacement of a urea produced in the EU represents only 6.5 and 3.1% compared to urea from Russia and Qatar, respectively. By comparing the C footprint of maize grown with the topdressing fertilization with urea or CAN is important to highlight the absence of effect if the fertilizers

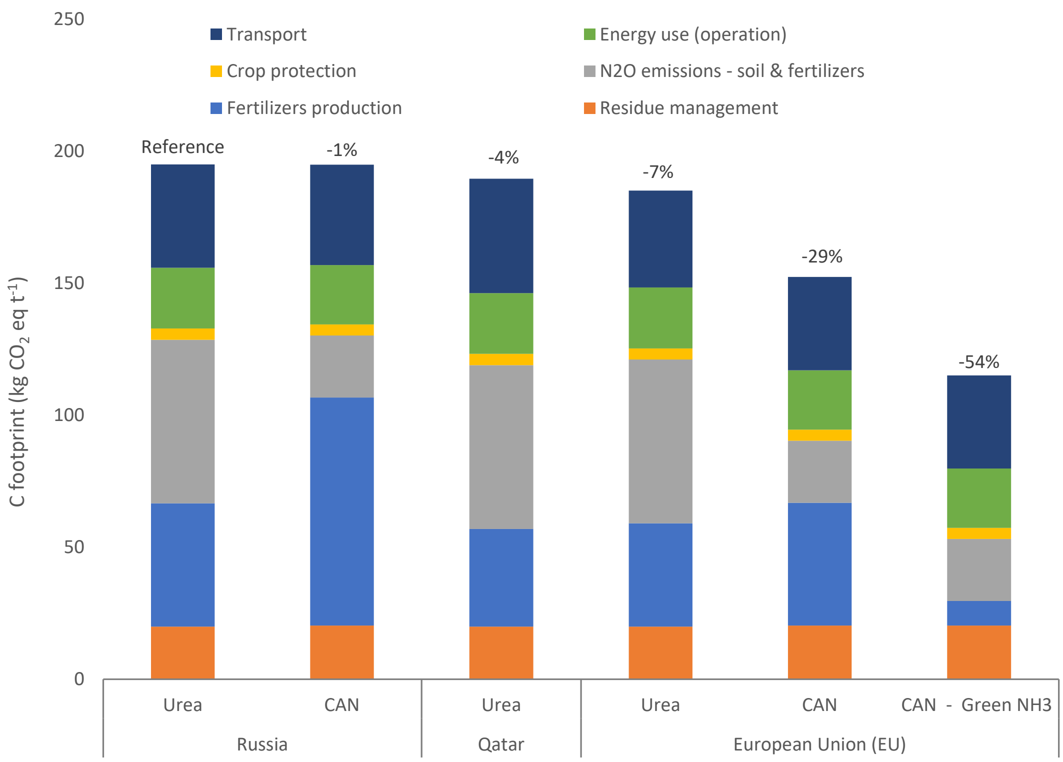


Figure 5. Carbon footprint of maize grain cropped with optimal N rates of two N sources (urea and calcium ammonium nitrate) applied in topdressing under tropical conditions in Brazil. Estimates also consider the origin of N source and a further reduction based on enhancement of fertilizer production with Green ammonia processing. Data based on the research by EMBRAPA in Goiás State, with results published previously in Informações Agronômicas newsletter as Otto et al. (2021).

are from Russia, however for fertilizers produced under the usage of N_2O abatements in the EU industry there's a significant reduction on CO_2 emissions with CAN. By applying this N source, there was a reduction by 24.2%. When CAN is produced with green NH_3, such reduction achieves 50.5%.

According to Snyder et al. (2009) the C footprint for maize production in the USA ranged from 120-220 kg CO_2 eq ton^{-1} of grain in no-tillage systems and from 140 to 250 kg CO_2 eq ha^{-1} for conventional tillage, while the contribution of N fertilizers represents 67%-75% in the more conservative system, in conventional they represent on the range of 45%-60%. In China the C footprint was shown by Yan et al. (2015) based on a large survey that was equivalent to 330 kg CO_2 eq ton^{-1} of grain with a contribution of N fertilization around 75%. Numbers from this study are within the range observed in the US and lower than in China, which is associated with higher N inputs observed in that country.

Over the ten-year study period, fertilization with calcium ammonium nitrate (CAN) increased aboveground biomass production by approximately 6.5%, equivalent to a 1.1-ton increase in straw per hectare. There was also a 12.5% increase in the concentration of accumulated N in the aboveground portion (data not shown). Considering the decomposition of residues, wherein accumulated N is transformed into N_2O, a fractional analysis of factors contributing to the carbon footprint of maize estimated that CAN fertilization has a higher proportion of equivalent CO_2 derived from residues compared to urea. The carbon footprint of maize related to residue decomposition ranges from 13% to 29%.

Concerning fertilizer production, the primary impact is attributed to the energy source, with the exception of Green NH_3 treatment. In this study, the contribution of fertilizer production was equivalent to 37%. On the other hand, when considering fertilizer usage emissions, urea exhibits a higher footprint due to the release of CO_2 that was previously consumed during its production. In this case, processes associated with urea transformation accounted for over 40% of the total carbon footprint of maize, whereas for CAN, this proportion was 24%.

It is crucial to emphasize that carbon footprints for maize vary regionally, contingent on several factors such as yield potential and input consumption. These factors, in turn, are influenced by soil quality and the accessibility of inputs that farmers have at their disposal.

4.2. Cotton

Cotton supplies approximately a quarter of global textile fibers (Zhang et al., 2023). Brazil is one of the world's leading cotton exporters and producers, and projections indicate a growth production rate of 2.8% a year up to 2032/2033 (MAPA, 2023). In 2022/2023, Brazil planted approximately 1.7 million hectares of cotton and produced 4.5 million tons of fiber and seed, of which, approximately, 71% came from the Center-West state of Mato Grosso (CONAB, 2023). Most of the production in Mato Grosso is a rainfed second-season crop, sown from January to the beginning of February and following soybean harvest.

A medium-term trial located in Diamantino, MT with cotton sown after soybean was established in 2016 and continued up to 2019, encompassing four cotton cropping seasons. The purpose of the trial was to evaluate the effect of different N rates (0, 48, 96, 144 and 192 kg N ha^{-1}) and sources (urea versus CAN) on cotton yield and fiber quality (OTTO et al., 2021; Otto et al., 2022). Accumulated over the entire four growth cycle, N application up to 192 kg N ha^{-1} increased cotton yield by 50% compared to the treatment without N. Statistical differences between urea and CAN on cotton yield were observed only in the fourth-growth cycle. However, when considered the average of the four cotton cropping seasons (from 2016 to 2019), CAN resulted in a higher yield per unit of N compared with urea, and the calculated N rates for optimum economic efficiency for CAN was 171 kg N ha^{-1} and for urea was 189 kg N ha^{-1}.

Looking at the PCF per ton of cotton produced and the calculated N rates for optimum economic efficiency from the two sources (CAN and urea) (Figure 6), the main factors affecting these emissions are from producing the N fertilizers (6% to 30% from total CFP) and their use in soil (32% to 50% from total PCF). The highest PCF is observed for CAN produced in Russia, followed by urea produced in Russia, urea produced in Europe, CAN produced in Europe, and, finally, by CAN produced in Europe using green ammonia. Data reveals a possibility of reducing PCF by 27% when CAN produced in Europe using green ammonia replaces CAN produced in Russia. The main factor increasing the PCF from CAN produced in Russia is the production of the fertilizer which emits more (307 CO_2 eq t^{-1} of cotton seed and fiber) compared to CAN produced in Europe using green ammonia (42 CO_2 eq t^{-1} of cotton seed and fiber). Considering the 32%-50% of the PCF deriving from N use in the production phase of cotton, strategies to improve N use efficiency and reducing N losses during cotton crop cultivation emerges as an alternative to reduce C footprint for cotton production, reducing the chances of substituting cotton by other alternatives fibers in the future (Zhang et al., 2023).

4.3. Coffee

The food industry has been undergoing important transformations and making commitments to reduce GHG emissions throughout the production process. This is the case of Nestlé and Illy (ILLY, 2022), large companies that operate in the coffee market. Nestlé, for example, has been accelerating its initiatives to address climate change and is committing to net zero emissions by 2050. To achieve this goal, one of the company's actions consists of encouraging farmers to use sustainable practices, which reduce GHG emissions and increase carbon sequestration in the soil (NESTLÉ, 2022).

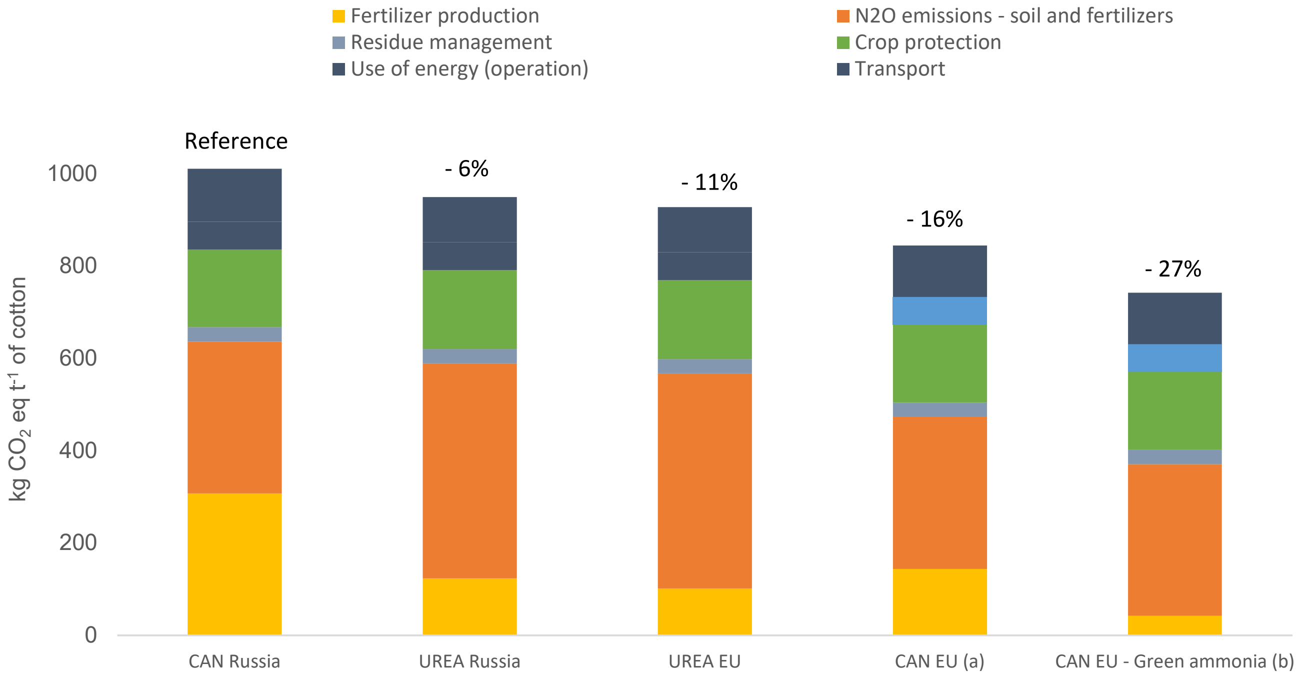


Figure 6. Carbon footprint (CFP) of cotton (fiber and seed) yield (kg CO_2 eq t^{-1}) based on trial from Mato Grosso state, and determined N rates for optimum economic efficiency from two nitrogen sources (CAN = calcium ammonium nitrate and urea) arriving from Europe and Russia and from using the green ammonia technology. (a) CAN from Europe; (b) CAN from Europe produced with GA = green ammonia technology. Data from the research carried out by ESALQ/USP (Otto et al., 2022).

The efficient use of fertilizers, especially N, will significantly contribute to the success of the established goals. For that, it will be necessary to implement a set of good practices that increase nutrient use efficiency and restore soil health. Fertilizers with a low carbon footprint and efficient management that provide lower N losses will be key in this process. It is estimated that GHG emissions related to N fertilization can represent up to 70% of the total GHG emitted in the coffee production chain.

With the objective to evaluate the use of N forms on yield and GHG emissions in coffee Arabica, a long-term study conducted by Federal University of Lavras (UFLA), at the NKG Farm, in Santo Antônio do Amparo, south of Minas Gerais, was carried out to estimate the CFP for coffee (Figure 7). With the support of the tool Cool Farm®, the following data were considered in this study: two N forms, ammonium nitrate (AN) and urea (UR), the adequate N rate for coffee according to leaf analysis and yield expectation (400 kg ha^{-1}), the coffee average yield in eight years (plants from 4 to 11 years old), and the origin of the fertilizers (Russia and Europe).

Considering the eight years of trial development (2016 to 2023), the rate of 400 kg ha^{-1} resulted in an average coffee yield of 2.93 t ha^{-1} for AN and 2.66 t ha^{-1} for UR. The CFP for producing coffee was 16% lower when the N source was coming from AN produced in Europe as compared to UR produced in Russia. This number was even lower with AN produced in Europe via green ammonia technology (31%). It is interesting to note that the origin of the fertilizers, the production technology, the N form, rate, and yield are important factors that determine the carbon footprint of products (Figure 7).

Sustainable management of coffee cultivation is important, as it is considered a crop with low nutrient use efficiency and requires high rates of N. Fertilization management practices that improve coffee quality and reduce GHG emissions are fundamental strategies to add value to the coffee production chain.

4.4. Sugarcane

The choice of N fertilizer may affect N_2O emissions from soils and, therefore, it may change the CFP of sugarcane production. A long-term field trial with sugarcane variety IAC-5000 was set up in Piracicaba, São Paulo state, in an Alic Clayey Red Oxisol, to study the effect of N forms (CAN and UR) on yield, NH_3 volatilization, N_2O emissions, and CFP of sugarcane production in Brazil.

Considering the whole cycle of evaluation, from plant cane to 7th ratton, the average sugarcane stalk yield for UR and CAN was 85.0 t ha^{-1}. No difference in yield was observed between N sources. The NH_3 losses for UR, expressed as a percentage of the applied N, varied from 2.8% to 16.0%. For CAN, NH_3 losses were significantly lower, varying from 0.4% to 0.7% in all cycles evaluated. The N_2O emissions from UR were significantly higher than CAN; the N_2O emission factor for UR was on average 0.90% and 0.47% for CAN throughout the evaluation period (Cantarella et al., 2022 and Degaspari et al., 2020).

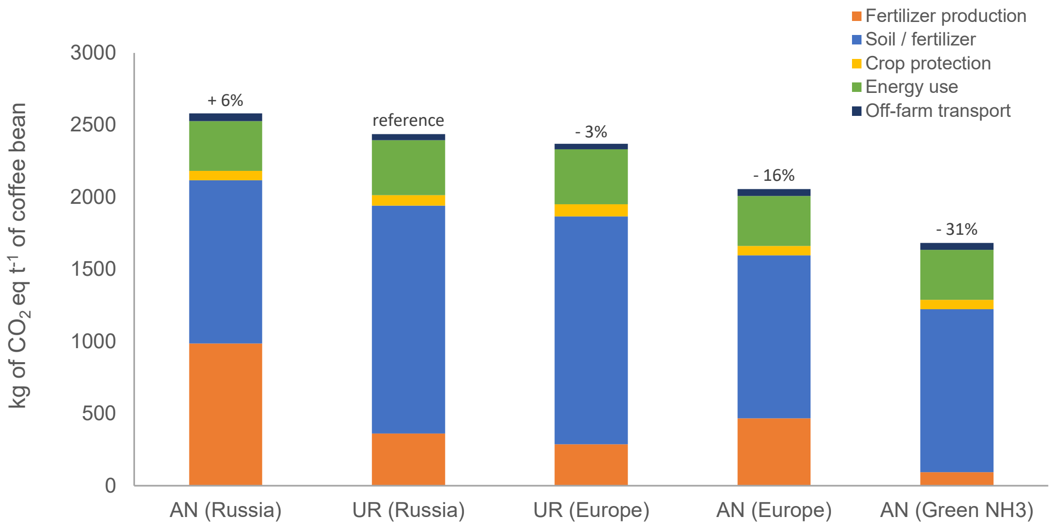


Figure 7. Carbon footprint estimation for coffee considering the nitrogen rate of 400 kg ha^{-1}, the fertilizer forms ammonium nitrate (AN) and urea (UR) from different origins and technologies of production. Data from the research carried out by the Federal University of Lavras in the south of Minas Gerais (Sarkis et al., 2023 and Souza et al., 2022).

Based on the data from Fertilizers Europe 2011 (Ecoivent 2.0 – Figure 8), considering the sugarcane stalk yield, the soil acidification, and the real NH_3 and N_2O emissions from the field trial, the CFP for producing sugarcane were respectively 30% and 68% lower when CAN and CAN produced via green NH_3 technology were the N sources as compared to UR. The total of CO_2 in kilograms emitted per ton of sugarcane was on average 14 for CAN green NH_3, 31 for CAN, and 44 for UR. The CO_2 emitted by liming to neutralize soil acidification caused by fertilizers was also considered in the CFP calculation as an indirect emission.

Urea, the most-used N fertilizer in sugarcane, is subject to high losses of N through NH_3 volatilization when surface-applied to soils, especially when applied to ratoon cycles, in which a thick mulch of plant residues remains on the soil surface. Recent studies show that the N_2O emissions in sugarcane fields occur mainly due to the nitrification process and, to a lesser extent, in denitrification (Lourenço et al., 2018). Normally, sugarcane is planted in well-drained soils, such as Oxisols and Ultisols, and for this reason, amidic and ammoniacal N sources may have higher N_2O emissions than those containing nitrate.

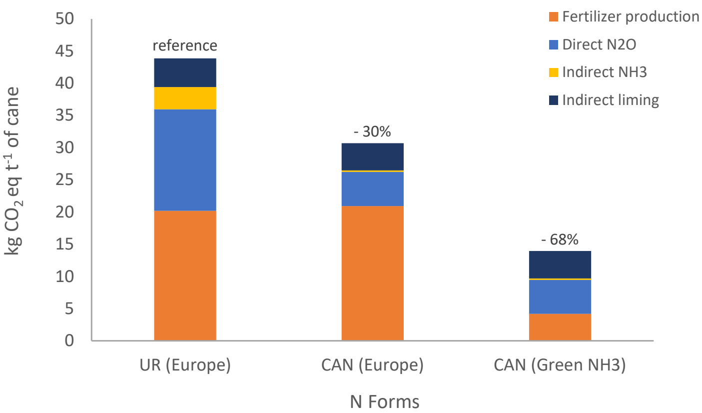


Figure 8. Carbon footprint estimation for sugarcane considering the fertilizer forms calcium ammonium nitrate (CAN), green CAN, and urea (UR). Data based on the research carried out by Agronomic Institute in São Paulo state (Cantarella et al., 2022 and Degaspari et al., 2020).

Emissions of GHG, especially N_2O, can represent 30% to 50% of the total GHG emitted in the production of ethanol from sugarcane (Bordonal et al., 2013). With the new Brazilian legislation (Renovabio), ethanol production is being rewarded for reducing GHG emissions through carbon credits. As a result, the efficient use of nitrogen fertilizers and the reduction of GHG emissions begin to add financial value to farmers.

5. REGIONAL N_2O EMISSION FACTORS

Considerable uncertainty pervades national agricultural nitrous oxide (N_2O) inventories worldwide, consequently affecting the accurate estimation of the PCF of major agricultural products. For the majority of crops, the PCF associated with direct and indirect emissions resulting from crop cultivation is related to N fertilization and may range between 30% and 50% of the total CFP calculated. In this way, it is important that regional *in situ* emission factors be calculated since influences of edaphoclimatic conditions and new management technologies may decrease nitrous oxide emissions. The prevailing assumption in many studies, this one included, is that PCF estimates should consider the emission factor stipulated by the Intergovernmental Panel on Climate Change (IPCC), conventionally set at 1%. As we can surmise, direct emissions of N_2O do not manifest as an agronomic quandary solely due to their magnitude; however, their environmental repercussions are substantial, owing to the global warming potential of the N_2O molecule, and therefore, as more precise its indication, more precise will be the CFP estimate.

Over the past years, numerous studies conducted in diverse countries, including Brazil, have measured in detail the impact of N fertilization on nitrous oxide emissions from soils cultivated with many crops. These studies aim to foment regional inventory reporting by cultivating an enhanced comprehension of the processes and factors that govern emissions. In the Brazilian context, crops such as sugarcane, maize, and rice have been subjected to intensive evaluations, primarily due to the expanse of their cultivation areas and their high N demands (Bayer et al., 2015; Martins et al., 2015; Zschornac et al., 2018; Mascarenhas et al., 2020; Signor et al., 2015; Soares et al., 2015; Degaspari et al., 2020).

Given the influence of environmental conditions on N_2O emissions, with a marked emphasis on soil moisture and soil organic matter content, these emissions may diverge significantly even between fields that have similar crops and yield potentials. This accentuates a critical concern that reliance on the IPCC's proposed methodology for determining CFP may not be adequate, potentially yielding an overestimated penalty for Brazilian cropping systems. Several recent field studies in Brazil have shown that most of the N_2O emission factors (proportion of N input emitted as N_2O) are lower than the IPPC default value (Besen et al., 2021; Galdos et al., 2023; Monteiro et al., 2023; Sarkis et al., 2023). In a recent study by Carvalho et al. (2021), the authors show that the N_2O emission factor for N fertilizers used in sugarcane ratoon in Brazil was 0.6%. The use of regional emissions of N_2O in life cycle assessment was responsible for reducing the contribution of N fertilization to the overall CFP of ethanol in Brazil from 17% to 22% compared to the IPCC default value. Apart from edaphoclimatic conditions, crop management practices affect the pattern of N_2O emissions, allowing tailor emission factors, as observed by Sarkis et al. (2023) for coffee and Degaspari et al. (2020) for sugarcane, whose studies provided specific emission factors for N sources.

6. STEPS TOWARDS NEUTRAL OR LOW CARBON PRODUCTION OF AGRICULTURAL PRODUCTS

Numerous nations have established ambitious targets to attain carbon neutrality by 2050. Given that food production contributes significantly, comprising 34% of global greenhouse gas emissions (Crippa et al., 2021), it is imperative to identify practices capable of mitigating emissions, thereby reducing the environmental impact of food production to face the climate change-related challenges. Potential enhancements involve augmenting crop yields and carbon sinks, or diminishing carbon sources. Consequently, there is mounting pressure to optimize production strategies and curtail emissions. This chapter aims to deliberate on advancements in the energy efficiency of crop production up to the farm gate, raising insights to technicians and farmers on how to lower their crop footprints.

A key approach to meeting the anticipated surge in food demand is to increase agricultural production on existing land by increasing the yield per unit area. Advances in crop yield primarily stem from genetic improvements in plant breeding, enhanced input utilization, and improved field management practices.

Plant breeding has a particular significance in the context of climate change, with the likely escalation of abiotic stresses such as heat and drought, which adversely affect a multitude of crops. Adapting crops to impending climate changes necessitates in-depth research and development to understand how crops respond to climatic constraints. Crucially, adjusting crop phenology to moisture availability and investing in varieties with distinct growth stages to mitigate or avoid predictable stress occurrences at critical periods is fundamental. Significant investments by breeding institutions, employing both transgenic and conventional breeding processes, have been directed towards enhancing crop resilience.

Agronomic practices offer substantial room for improvement. These practices encompass optimizing plant arrangement, ensuring uniform seed distribution and plant emergence, and managing plant populations, especially for grain crops. Hou et al. (2020) demonstrated a potential 5.6% increase in maize yield across China without the need to increase the amount of N. Advancements in drilling systems to improve distribution have gained traction; however, such systems are less available to smallholders. The timing of crop sowing aligned with agricultural zoning is critical. This is of particular importance for 2nd season crops since there is a straight relation to the 1st season crop cycle. In the last few years more early-season soybeans varieties have been offered to farmers allowing that a larger proportion of maize fields have been set within optimal sowing window (IMEA, 2022). Matching maize hybrids with superior architecture and lowering its hydric demands, improving light interception, and achieving higher density without relying on additional inputs, beyond seeds, presents a viable alternative for reducing the carbon footprint.

In recent years Embrapa has performed exhaustive research on the use of plant-growth-promoting bacteria to enhance nutrient use efficiency (NUE). Among microorganisms that have been studied, *Azospirillum brasilense* was shown to increase NUE by stimulating root growth (Barbosa et al., 2022); it has been used in crops such as soybean (co-inoculation) and cereals. According to Hungria et al. (2022) the adoption of the inoculation can potentially reduce 25% of side-dress N fertilization in maize crop and mitigate up to 236 kg CO_2 eq ha^{-1}. It's important to highlight that such reductions were mostly observed in fields with low yields. Anyway, the combination of growth promoters to the crop nutritional programs is a new frontier to adaptive agriculture since it fits to crop resilience and increases resource use efficiency.

Prior to making recommendations, understanding the specific conditions where crops will be cultivated is fundamental. Continuous monitoring of fields enables informed decision-making by farmers. Furthermore, the evolution of precision agriculture techniques, facilitated by advancements in technology, empowers farmers to manage substantial volumes of data. Precision agriculture facilitates the utilization of variable rates for various inputs, such as seed, water, and nitrogen, contributing to fine-tuning the use of resources.

The use of 4R's framework and nutrient optimization is also fundamental to increase nutrient use efficiency. Amidst the 4R the right rate, especially for N, plays a central role in decreasing N_2O emissions and consequently in decreasing C footprint of crop products. For that reason it is pivotal to monitor nutrient availability and based on soil analysis and local crop response, farmers must tailor their crop nutritional programs accordingly in order to optimize N rate. Other 3R's (right place, right source and right time) are also important because they affect the crop performance and farmers must follow recommendations according to crop, environmental conditions and product availability.

Often, food producers define good practices based solely on their on-farm activities. However, as agriculture relies on input supply, improvements in industrial processes for input production, such as fertilizers are important drivers for decarbonization. By endorsing processes committed to reducing emissions, significant opportunities arise for a substantial reduction in CO_2 equivalent emissions. It is noteworthy that the manufacture of fertilizers contributes between 30%-40% to the carbon footprint of major crops in Brazil. The substitution of energy sources in nitrogen production, transitioning from natural gas to electricity, allows the production of green ammonia, which may result in a 90% reduction in footprints (Ausfelder et al., 2022; Cantarella et al., 2023). While this process is still limited and incurs high costs, some companies are deeply committed to this energy transition that will impact the carbon footprints of agricultural feedstock. The adoption of fertilizers with low carbon footprints will allow farmers to improve their sustainability metrics.

Amending fertilizers with nitrification inhibitors (NI) can potentially decrease N_2O emissions. NIs act in the first step of nitrification, hindering the conversion of ammonium into nitrite. The reduction of N_2O emission, according to Carvalho et al. (2022), ranges from 45%-100% being a promising management option to mitigate N_2O emissions and therefore decrease the C footprint of major crops in Brazil. Among NIs, DMPP (3,4-dimethylpyrazole phosphate) has been more promising than DCD (dicianodiamide).

Decoupling N fertilizer applications from manure or slurry disposals: maize plantations, for silage and sugarcane usually make use of manures, slurries or vinasse. Lourenço et al. (2018) showed that anticipating or postponing vinasse application relative to N fertilization, may reduce N_2O emissions by 50%, while the application of vinasse and fertilizers at the same timer increases N_2O emissions above the IPCC default values, which significantly increases C footprint of products. Slurries carry water and soluble C, two causes of the depletion of soil oxygen triggering N_2O emissions. More than decoupling application of both fertilizers, it is important that farmers avoid over fertilization and define their crop nutrition programs combining both fertilizers. Some situations organic slurries may supply all P and K demand (Jate and Lammel, 2022). Several regions in Brazil already especific recommendations of organic residues (Cantarella et al., 2022).

Some studies have shown an increase in carbon emissions per ton or hectare from irrigated agriculture compared to rainfed agriculture (Daccache et al., 2014; Esmaeilzadeh et al., 2019; Zheng et al., 2019). However other studies suggest that the effect depends on the measurement unit of the PCF (Zhang et al., 2018) and the geographical location of crops (Grassini and Cassman, 2012). Regarding water use efficiency and energy efficiency, there are significant differences among irrigation systems (furrow, sprinkler, pivot, drip, and others). On the other hand, irrigation/fertigation has become an important tool considering climate change, mainly in regions with frequent drought periods that can occur during specific stages of crop development, which can compromise yield. Another important aspect is food security, according to FAO (2023), irrigated agriculture accounts for 20% of the total cultivated land but contributes to more than 40% of the total food worldwide. One of the main benefits of fertigation is the increase in yield when compared to solid fertilization or areas that are only irrigated. Depending on the crop and location, gains on yield can double. In fertigated areas, the use of tractors is reduced, which helps prevent soil compaction and decrease the use of diesel. Fertigation also allows frequent nutrient application according to crop demand, which reduces losses and increases efficiency. Studies in citrus showed that NUE increased by around 25% in fertigated areas (Quaggio et al., 2019) and the N_2O emissions were significantly lower (0.2% of applied N) than the reference factor of the IPCC (Martins et al., 2014), enabling a lower footprint of oranges in such conditions.

Best management practices (BMP) can help farmers to reduce their footprint by increasing sinks, through C sequestration. Increasing biological C sequestration in the soil is a well-known approach to CO_2 removal and storage, primarily in cropland and grazing lands. However, for the C stored in the soil organic matter to be accounted for in C footprint schemes, a minimal residence time in the soil is required.

Conservation systems contribute by reducing CFP by accumulating C in the soil profile or by increasing nutrient cycling and, therefore, supporting mechanisms to reduce fertilizer and pesticide inputs. Additional benefits derive from increased water infiltration and storage, lowering dependence on irrigation. According to Snyder et al. (2009), C footprint of maize production in the USA was reduced by 12%-15% with the adoption of conservative tillage, which included a lower contribution of fuel since mechanical practices for no-tillage are less demanding. Conservation tillage systems are based on minimal disturbance (lower energy input and minimal SOM depletion), crop rotation and maintenance of crop residues over the soil surface. Adoption of legumes in the crop rotation lowers the dependence of exogenous N and consequently diminishes CFPs. In a long-term study conducted in the USA, Ma et al. (2012) comparing continuous maize monoculture to maize succeeding forage (alfafa) and grains (soybeans) legumes estimated greater GHG emissions in the systems with legumes; however, the footprint was decreased in all levels of N tested due to higher yields. When compared to maize monoculture treated with a regular N rate (100 kg N ha^{-1}), following a forage legume resulted in a reduction of 17% of maize CFP. For the rotation with soybean the reduction was equivalent to 8%, by accounting the contribution of N from legume residues and comparing 200 kg N applied to monoculture to 100 kg N applied to maize under rotation with legumes, C footprint was reduced by 42% to 46%. At the same time, conservationists management practices contribute by sequestering C in the soil, they are highly beneficial from the standpoint of soil health and soil fertility (Paustian et al., 2019).

Brazil has one of more successful examples of combination with legumes with double-cropping systems with soybean as 1st season crop prior to maize and cotton. Nitrogen use efficiency (NUE) in these cropping systems is high, especially when maize is the succeeding crop. New cropping systems combining two or more crops are alternatives to increase the production of food/wood/energy per hectare. Very well-established examples are agroforestry systems with perennial crops such as coffee, cocoa and fruit trees, cropping and livestock systems, including or not forestry, are another good example. For row crops, intercropping with grasses or legumes is an important way of promoting sustainable agriculture. Grasses as ruzigrass may increase C accumulation in the soil, reduce N losses through a deeper exploration of soil, enabling a more efficient nutrient recycling, whereas biological N fixation by legumes may reduce the dependence on exogenous N fertilization. Studies evaluating the contribution of non-cash crops to overall N_2O emissions are missing and must be stimulated to understand the real effect of such practices on crop carbon footprints.

7. IMPORTANCE OF PRODUCT C FOOTPRINT IN PUBLIC POLICIES AND VALUE CHAIN INTEGRATION

Scientific research assumes a pivotal role in addressing climate change and mitigating the environmental impact of agriculture. It furnishes indispensable information, facilitating informed decision-making for corporations and governmental entities. The examination of GHG emissions improves the understanding of production chains, pinpointing sectors and inputs with the most substantial emissions impact. This, in turn, enables the formulation of more precise mitigation strategies.

The Brazilian agricultural realm is no exception to this paradigm. As research progresses, the acquisition of sustainable production practices contributes not only to ecological discourse but also underpins the establishment of objectives, ensuring compliance with environmental legislation. Consequently, this aligns with the overarching goal of global emissions reduction. Accurate field data aids companies and governments in crafting policies, targeted incentives, and access to subsidies grounded in environmentally sound solutions.

This paper helps to shed light on critical aspects of Brazilian agriculture. This includes insights into the innovative production of fertilizer technologies that reduce emissions at production sites, an understanding of the impacts of various nitrogen sources on crop yields and resource efficiency, leading to a reduction in crop footprints. Solely relying on innovative green N fertilizer production may result in footprint reductions ranging from 27% to 68% for crops like cotton, coffee, sugarcane, and maize in Brazil. When combined with other low-emission and conservative management practices, these strategies propel Brazilian agriculture toward carbon neutrality. Strategic alignments and business models that foster partnerships for low-carbon production are essential for advancing Brazilian agriculture on the global stage, reinforcing Brazil's position as an agri-environmental powerhouse.

A significant proportion of the carbon footprint of agricultural products comes from the utilization of nitrogen fertilizers. Therefore, adopting sources derived from more efficient processes, such as catalysts or green fertilizer production, holds the potential to substantially curtail emissions. This not only aids in achieving government-set targets but also contributes to the reduction of emissions from food companies. The pivotal role nitrogen fertilizers play in agriculture, primarily in increasing crop yields must be acknowledged. Furthermore, low-carbon footprint fertilizers can enhance profitability for producers, adding commercial value to agricultural products in international markets and ensuring market access. The choice of N fertilizers from factories that are reducing N_2O emissions in production sites is an available strategy, while green fertilizer production has not been scaled to larger volumes yet. Rigorous homologation and traceability processes are imperative to guarantee emissions mitigation throughout the production chain, especially considering the forthcoming markets which require carbon measurement, reporting, and verification (MRV).

Region-specific and reliable indices, such as emission factors and carbon accumulation are of great relevance.

Long-term research aids in comprehending tropical soil dynamics, offering examples and helping in improving emission calculators. As observed with N_2O, a uniform default value may not be universally applicable, necessitating tailored emission factors based on specific circumstances.

Collaboration between the government and research entities can be pivotal in directing programs like the National Fertilizer Plan. Research insights, aligned with the environmental strengths of the agricultural sector, guide investments in more efficient sources, concurrently decarbonizing production chains and augmenting food production.

The rise of the "C footprint" term and its relevance to Brazilian farmers is driven by a combination of global environmental concerns, regulatory pressures, market demands for sustainability, and the pursuit of innovative and efficient agricultural practices. Knowing its metrics and actively managing the C footprint is becoming integral to the long-term sustainability and competitiveness of the agricultural sector, both in Brazil and worldwide.

The journey ahead is substantial, demanding coordinated efforts between the public and private sectors to confront climate change and decarbonize food production chains, ultimately safeguarding food security.

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