Measuring and Mitigating GHGs: **Maize**

Authors: Ranjan Parajuli, Anushree Chaudhuri, Emily Moberg, Greg Thoma

There are millions of farms globally, each using a unique set of practices to cultivate their products in the local climate and soil. Thus, for any commodity, there are many thousands of different production systems and many thousands of different sources of greenhouse gases (GHGs). The relative GHG emissions of producing the same product may differ drastically depending on how and where it is grown. To fully understand how to mitigate emissions and on which farms to focus mitigation efforts, we need a better grasp of the variations and gaps in data.

The authors do not think all the information to quantify GHG emissions from the maize value chain exists – at the very least, not in one place. This document is our attempt to collate currently available information. This is a working draft; debate, discussion, and comments are welcomed to advance the understanding of this topic. WWF will be producing similar pieces on other key food commodities to stimulate similar discussions. All comments should be justified with evidence and data and sent to Emily Moberg at GHGCommodities@wwfus.org.

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ABOUT MAIZE

Maize is the second-most-produced crop in the world. While most maize goes toward animal feed (over 50% to feed; about 12% to human consumption),[1] it is also a critical food staple: maize is the most important food crop in sub-Saharan Africa and Latin America.[2] On an areal basis, it is a high-yielding crop, with a global average yield of 5.8 tonnes per hectare, per year (t/ha/yr), compared to 4.7 t/ha/yr for rice, 3.5 for wheat, and 1.4 for sorghum.[3] However, these yields are geographically variable; farms with higher yields include France, the U.S., and South Africa. In the U.S., the productivity of the crop was increased from 1.6 t/ha/yr (reported for the first third of the 20th century) to 9.5 t/ha/yr or more, which was influenced largely by improved agronomic practices and breeding.[4] Irrigation can dramatically increase yields, often doubling them.[5] Variability in yields has also been reduced over time, with irrigation playing a critical role.[6]

Production is increasing; the global harvested area of maize increased by 1.32% annually from 1990 through 2016. However, while consumption is expected to increase twofold, yields may decline 10% by 2050 because of climate change, leading to higher global prices and malnutrition, making the impetus for efficient production even greater.[7]

Maize is widely grown as both a commercial and subsistence product; it is grown at dramatically different scales across the world. As of 2020/21, global maize production was 1.13 billion tonnes, of which 32% was produced in the U.S., 23% in China, 10% in Brazil, and the rest in other countries. The U.S. is the largest exporter of maize worldwide, with a total volume of the trade in the past decades exceeding that of the next-largest exporter by more than fourfold.[8] Argentina, France, China, and Brazil are other large maize exporters.

MAIZE SUPPLY CHAINS

For each kilogram of maize grain produced, about a kilogram of stover (stalks, cob, etc.) is also produced.[9] This stover may be used for animal feed or for biofuel, it may be left on the field for nutrients, or it may be burned. The grain is also used for multiple purposes. Globally, 54% of production goes toward livestock feed, 12% is used for human food, and 20% has non-food uses, with wide geographic variability.[10] For example, of the total amount of maize produced in the U.S. in 2020, 39% was used as feed and 37% for fuel (ethanol), 18% was exported, 7.4% was used as animal feed (ethanol by-product), 5.3% as sweeteners, 1.6% as starch, 1.5% as cereals, and the rest was used for beverages and other products.[11] In many developing regions, such as Africa, Asia, and Latin America, maize is an important food crop.[12]

Given the variety of end uses for maize, there are many actors within maize supply chains. We highlight three sectors here:

- **Primary sector:** Suppliers who provide farm inputs, actors who produce grain and stover, and the silo owners. Producers and silo owners facilitate the safe storage of maize and ensure round-the-year supply to the buyers.
- **Secondary sector:** Major actors here are the millers and animal feed manufacturers. They transform the harvested raw grains into maize meals for human consumption. The feed manufacturers produce and supply to the livestock industries (e.g., yellow maize for broiler and layer feed rations, and they also convert the white maize to use in feedlots).
- **Tertiary sector:** This includes the major traders, retailers, and transporters. Traders play an important role in shifting the produce to either the local or export market, whereas the retailers facilitate the distribution of maize products from millers to final consumers. The transporters ensure movements of maize from farmers to silo owners, then to millers, and from the agents to final consumers.[13]

When accounting for GHG emissions, the amount allocated to the grain versus stover is important. The amount of stover harvested (for animal feed or biofuel) is highly variable, as are the prices. The default economic allocation (for the maize grain) used in this paper is 88%.[14]


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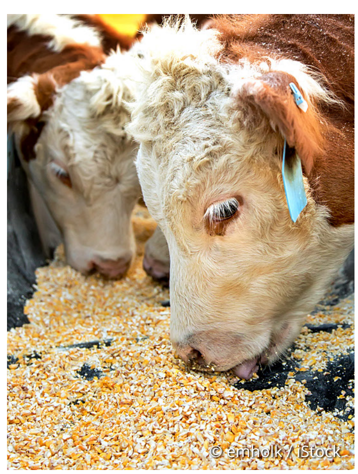
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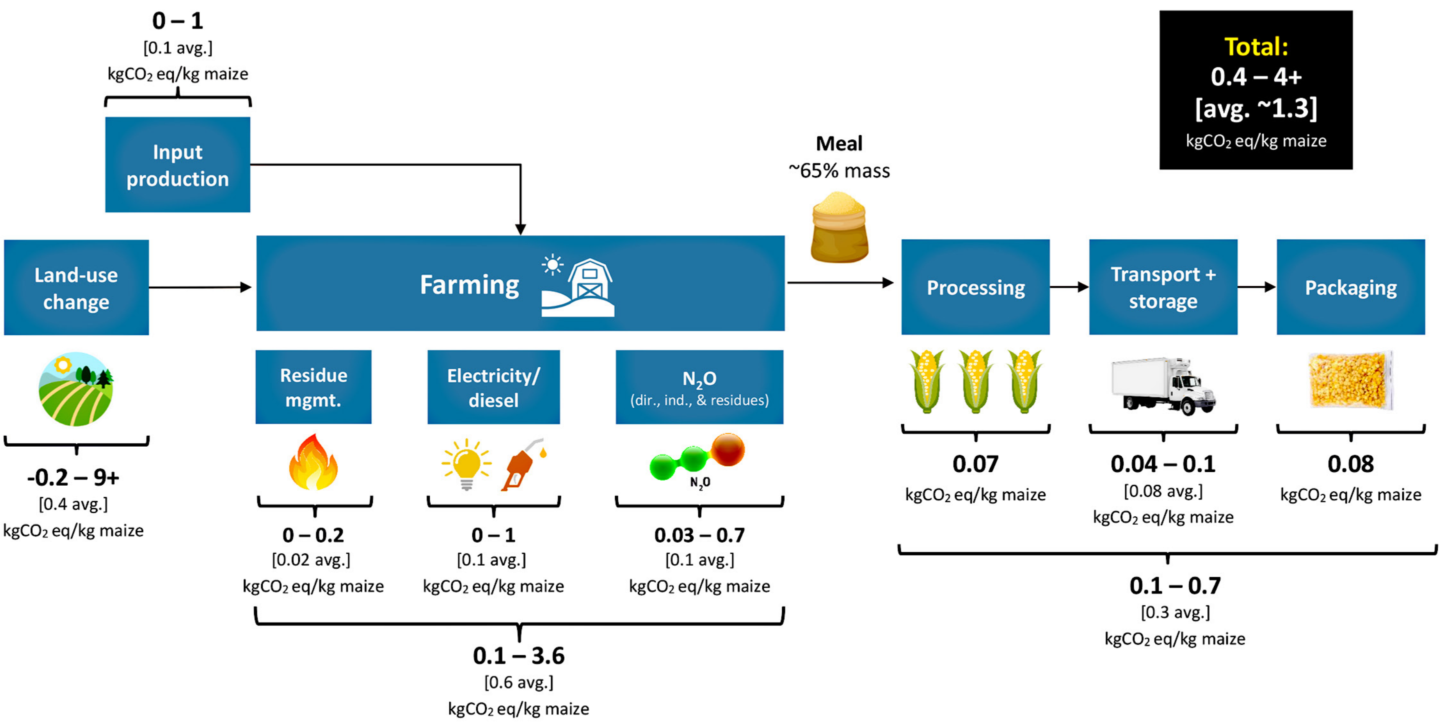
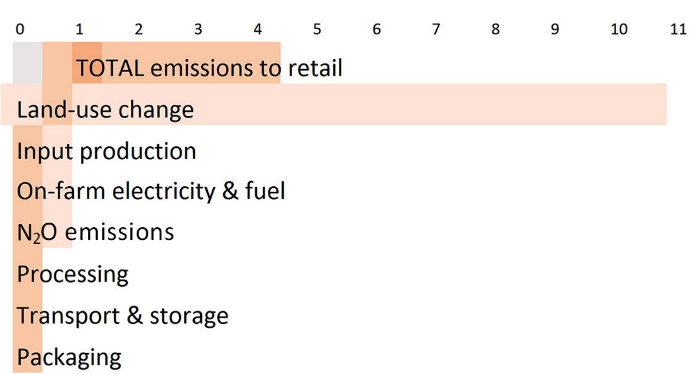
GHG EMISSIONS FROM MAIZE SUPPLY CHAINS

Emissions from maize production to retail are about 1.3 $kgCO_2e$/kg maize (excluding stover). The on-farm GHG emissions (excluding land-use change [LUC]) for a kilogram of maize average about 0.6 $kgCO_2e$/kg maize (range: 0.12 – 4.2). The contribution due to LUC was about 0.2 $kgCO_2e$/kg maize (ranged from -0.2 to 60).

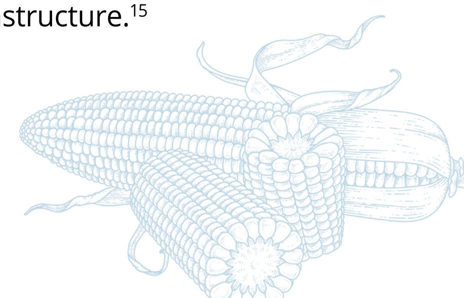
Figure 1: Range of GHG emissions from maize supply chains



This variability arises from variable emissions across each stage of production. The full range of impacts (in $kgCO_2e$/kg maize) is shown below, with the typical range highlighted in darker orange.



The major sources of GHG emissions in maize production are LUC (including burning of forests during conversion), fertilizer production, soil emissions (including nitrous oxide [N_2O] and CO_2), and energy/fuel inputs for operating farm machinery. Minor emission sources include seed production, machinery production, and other related infrastructure.[15]



LUC

LUC is when one land-use type is converted to another; when the original land-use type is cleared, the carbon that was stored in aboveground and belowground biomass is assumed to be (almost entirely) released into the atmosphere as CO_2. The carbon stored in the soil often also decreases through microbial decomposition. Because this carbon is typically lost within a decade of clearing (often much faster), we assign these emissions to the clearing event.

Compared to crops like soy, oil palm, coffee, and cocoa and to livestock like cattle, maize is not a primary driver of deforestation or habitat change; emissions from land use are largely in carbon stock changes as effects of management practices (i.e., tillage). However, given the expansion of maize cultivation, conversion of habitats like prairie can be commonplace and are often unaccounted for in analyses that focus on deforestation.

When LUC does occur, the GHG intensity can be very large; for example, the contribution due to LUC in Angola was 11 $kgCO_2e$/kg maize.[16]

Estimates of global LUC emissions resulting from maize:

- **geoFootprint estimate (deforestation only):** 0.05 $GtCO_2e$/yr, or 0.06 $kgCO_2e$/kg maize (weighted average emissions for the U.S., Brazil, Argentina, China, Ukraine, Mexico, and Nigeria multiplied by 2017 maize production; this represents 76% of global maize production)
- **Poore and Nemecek estimate:** 0.4 $GtCO_2e$/yr, or 0.4 $kgCO_2e$/kg maize (emissions factor direct estimate from their paper multiplied by average yearly maize production over the last five years from the U.S. Department of Agriculture (USDA); this estimate may also include changes in soil carbon from farming practices alone)

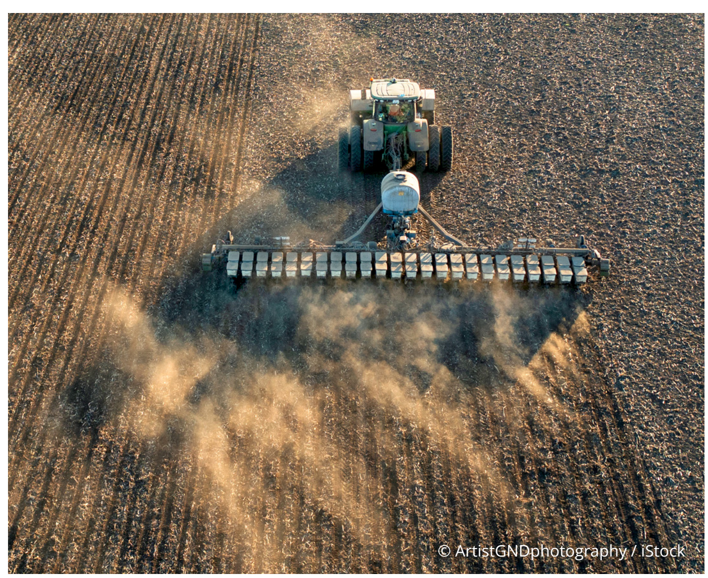
- **Global Feed LCA Institute Feedprint estimate:** 0.1 $kgCO_2e/kg$ maize (emissions factor direct estimate for Brazil, Ukraine, and the U.S. multiplied by average yearly maize production over the last five years from the USDA)

Tillage/soil organic matter: Low- or no-till farms often have higher concentrations of soil organic carbon in the upper soil layer.[17] Conventional tillage (with both rain-fed and irrigated farms) had higher GHG emissions compared to no-till farms. For instance, with conventional tillage of rain-fed and irrigated farms, respectively, the GHG emissions ranged from 0.16 to 2.8 $kgCO_2e/kg$ maize and 0.24 to 0.76 $kgCO_2e/kg$ maize, while the no-till farm had 0.09 to 0.25 $kgCO_2e/kg$ maize. Likewise, in strip-tilled farms (with and without irrigation), the GHG emissions ranged from 0.54 to 0.61 $kgCO_2e/kg$ maize.[18]

Changes in soil carbon can be a major contributor to overall GHG footprints. For example, in a typical Danish farm, about 13% of the total GHG emissions (0.04 out of 0.315 $kgCO_2e/kg$ maize) was induced because of the loss of soil organic carbon during maize production.[19] Whether stover is harvested or left on the field drives sequestration dynamics, which can either be a net source or sink. As soil organic matter positively contributes to yields, this effect could be magnified on a per kilogram grain basis.[20] However, this carbon may not be permanently stored in these soils, as later changes in production practices may remove it.

LUC for maize is not currently as large as it is for other crops and is likely between 0.1 and 0.3 $kgCO_2e/kg$ maize. However, significant conversion of natural habitats, including grasslands, occurs for maize, which also increases emissions but is not well quantified globally.

Tillage can also increase soil carbon losses, often by a similar amount.



Input Production

The production of fertilizers also contributes to emissions for maize. Average embedded emissions from fertilizer production and transport to farm range from 0 to 1 $kgCO_2e/kg$ maize, with an average of about **0.1 $kgCO_2e/kg$ maize**.[21] Different fertilizers (e.g., urea vs. ammonium nitrate) have different emissions during their production.[22]

- **Nitrogen fertilizers:** Nitrogen fertilizer is important for growing corn, but it also has negative environmental effects, such as its embedded GHG emissions during the production phase and its release of N-related pollutants after use (N_2O, nitrogen oxides [NO_x], nitrate (NO_3) – leaching, etc.). The application of N-fertilizers is generally governed by the local agroecological characteristics of specific farms, such as soil properties and soil organic nitrogen availability.[23] Soil-generated N_2O emissions are one of the great concerns in farm based environmental impacts and are one of the largest contributors to GHG emissions.[24]
- **Other fertilizers:** In addition to nitrogen, maize also requires phosphorus and potassium fertilizers. Use of potassium and phosphorus varies depending on soil conditions. The application of potassium fertilizers is generally guided by the critical soil fertility values. The amount of nutrients removed from the field during harvest depends on whether stover is also harvested.[25] For each kilogram of potassium fertilizer, both conventional potassium fertilizer and potash can emit 0.5 $kgCO_2e/kg$ fertilizer produced.[26] Phosphorous emissions can be lowered substantially with the use of phosphate rock, which is also six times lower in global warming potential than the typical conventional phosphorus fertilizer, but mixed results have been found in practice.[27]

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Soil Emissions: One main source of GHG emissions from the soil is the direct and indirect emissions of N_2O from nitrogen-based fertilizers.

- **N_2O emissions:** N_2O emissions come from soils that have nitrogen added to them – this can be from fertilizers or crop residues; these emissions are roughly proportional to the amount of nitrogen added. Generally, the default N_2O emissions factor is 1% of the nitrogen applied to soil.[28] Direct and indirect emissions averaged about 0.1 $kgCO_2e/kg$ maize (range: 0.03 – 0.63 $kgCO_2e/kg$ maize); almost half of this is from direct N_2O emissions from synthetic fertilizer.[29]
- **Crop residue management:** Crop residues, either left on the field or when burned, also emit N_2O. The contribution from crop residue management ranged from near 0 to 0.1 $kgCO_2e/kg$ maize; emissions from burning residues range from 0 to 0.01 while carbon stock change from burning ranged from 0 to over 60 $kgCO_2e/kg$ maize. Note that while burning residues is often done in developing countries to rapidly clear fields,[30] removing residues not only creates GHG emissions but also decreases soil water-holding potential, and can increase erosion. Potential options to mitigate N_2O emissions are thus better management of crop residues[31] and more careful choice of land for cultivation.[32]

DIESEL AND ELECTRICITY (DURING CULTIVATION):

Energy consumption (both electricity and diesel) contributed 0.06 $kgCO_2e$/kg maize (range: 0 – 0.9),[33] most of which is from diesel use.[34] This included the operation of farm machinery and irrigation units. GHG emissions due to the use of fuel for operating farm implements totaled 0.04 $kgCO_2e$/kg maize (range: 0 – 0.4), with larger values for farms that had a conventional tillage system due to the heavy use of agricultural machinery.[35] GHG emissions from the production of farm machinery and infrastructure were small (<0.03 $kgCO_2e$/kg maize). In general, farm electricity and diesel contribute between 10% and 20% of on-farm emissions.

Post-farm Emissions

Post-farm emissions add a little over 0.2 $kgCO_2e$/kg maize. The grain is dried and milled to produce maize meal.

- **Drying:** For the grain drying, the GHG emissions were 0.07 $kgCO_2e$/kg maize.
- **Milling:** For the dry milling process, the GHG emissions for 1 kilogram of maize meal were 0.07 $kgCO_2e$ (range: 0.04 – 0.08). On a dry matter basis, 1 kilogram of maize grain produced about 0.5 – 0.6 kg of meal, and the rest of the grain resulted in other by-products produced during the milling process, such as corn gluten meal, gluten feed, and germ meal.[36, 37]
- **Transport:** Emissions from transportation depend on the destination and mode of transit; trucks are more GHG-intensive per mile than trains, while boats' emissions are similar to those of trains. The transport-related GHG emissions amounted to 0.08 $kgCO_2e$/kg maize meal (range: 0.03 – 0.09).
- **Packaging:** For maize meal, packaging adds an average of 0.08 $kgCO_2e$/kg of maize meal.

PRODUCTION SYSTEMS

Maize can be grown in many different ways, and many different cultivars are grown globally. Here, we highlight the tillage system and crop rotation.

Tillage system: Tillage practices have received attention for their potential effect on the soil organic matter in the upper soil; low- or no-till farming increases that near-surface organic matter relative to conventional tillage,[38] although the longevity of that carbon is unclear. The GHG emissions listed exclude LUC and burning emissions.

- **Conventional tillage:**[39] Conventional tillage uses practices like plowing to invert the surface soil to prepare it for seeding; it also typically leaves minimal residue on the soil. For rain-fed, conventionally tilled maize, average emissions at farm gate were 1.4 kgCO_2e/kg maize (range: 0.2 – 2.8), with yields around 6.2 t/ha/yr (range: 0.7 – 14.78).[40] Irrigated systems had lower emissions and higher yields: average GHG emissions were 0.4 kgCO_2e/kg maize (range: 0.2 – 0.8), with yields around 11.35 t/ha/yr (range: 6.98 – 13.2).[41]
- **No-till:** No-till farming does not involve plowing and often uses a combination of chemical weed control and residues on the field. There are few studies of GHG emissions from no-till maize, but emissions for those cases were low (0.1 and 0.2 kgCO_2e/kg maize). High yields likely drove these results.
- **Strip-till (low-till):** Strip-tillage disturbed the soil only in strips where seeds will be planted. Again, studies on GHG impacts are few; emissions ranged from 0.5 – 0.6 kgCO_2e/kg maize, with similar average yields to those of the no-till studies.

Cropping rotations: Maize is often grown in rotation with other crops, such as in sequences like winter wheat-maize-peanuts, winter wheat-summer maize; grasses-cotton, winter wheat-summer maize, and sweet potato-summer maize-cotton.[42, 43] Because of the large number of potential rotations, studies on GHG footprints for specific combinations are few. Note that because these rotations influence which agrochemicals are needed, allocating the inputs among these crops is often necessary.

- **Monoculture:** Average GHG emissions of 0.4 kgCO_2e/kg maize (0.4 – 0.5), excluding LUC, with yield ranging from 3.5 to 8 t/ha/yr.
- **Rotation (various):** Average GHG emissions were 0.6 kgCO_2e/kg maize (0.3 – 0.9), with yields around 8.0 t/ha/yr (5.34 – 11.2).

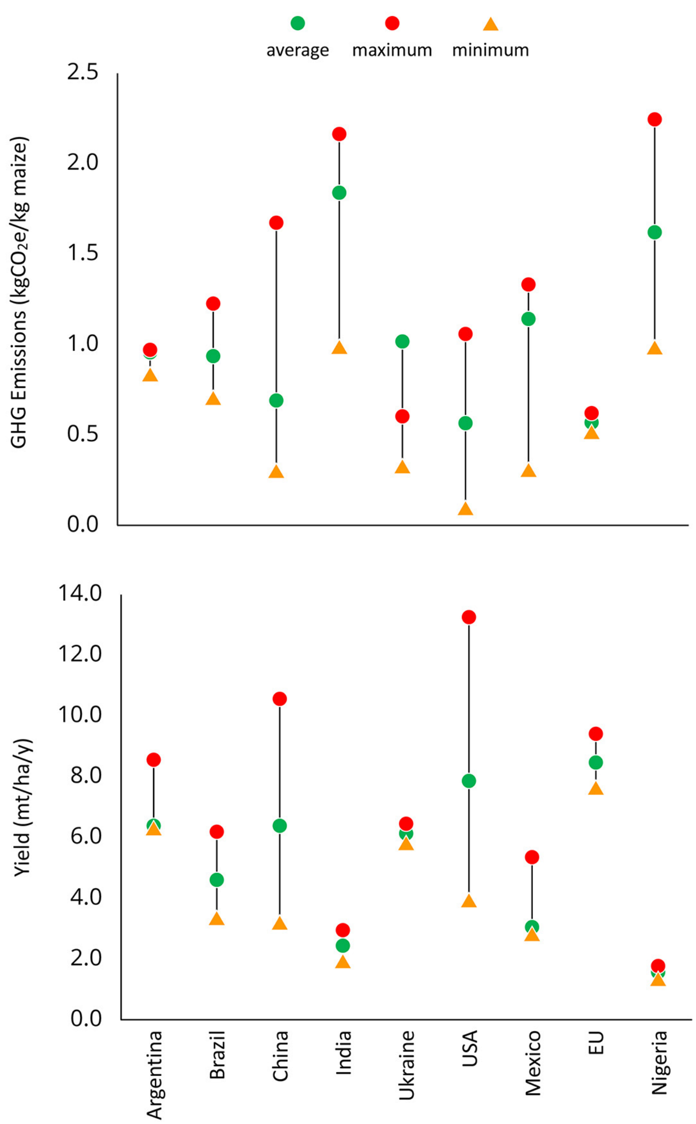
Farm size was weakly related to emissions intensity: small farms (<0.5 ha) had GHG emissions of 0.5 kgCO_2e/kg maize (range: 0.3 – 0.6), with the yield averaged at 5.2 (range: 2.6 – 6.27 t/ha/yr), whereas large farms (>0.5 ha) had GHG emissions of 0.4 kgCO_2e/kg maize (range: 0.3 – 0.5), with yield ranging from 3.16 to 6.37 t/ha/yr.[44]

REGIONAL VARIATION

The U.S. and China together produce over half the world's corn. Argentina, Brazil, Ukraine, and the EU each produce less than 10% of the total. Large differences in GHG emissions were also found across these regions, driven largely by predominant production practices.

Figure 2 shows the range of GHG emissions (on-farm) and yields,[45, 46] for selected major maize-(including stover) producing countries.[47] Note that low yields (e.g., in India and Nigeria) correlate with high emissions intensity.

Figure 2: GHG emissions (with LUC and residual burned) per 1 kilogram maize produced in major maize-producing countries



These major maize-producing countries use a variety of practices and inputs. Within each country, there is a mix of tillage and irrigation practices, (e.g., in the U.S., there was a mix of rain-fed and irrigated farms with various tillage practices, including conventional, no-till, and strip-till systems). A study by Wang and Hu (2021) found the inputs used often range by 10 – 100x across farms (seed input ranged from 1 to 29 kg/ha, total fertilizer 86 to 472 kg/ha, pesticides 29 to 124 kg/ha, and average farm size 26 to 2180 ha).

Irrigated vs. rain-fed maize production is generally guided by the growing seasons and varies within countries.

Below, we have highlighted a few countries representing both some of the largest producers and production from different geographies.

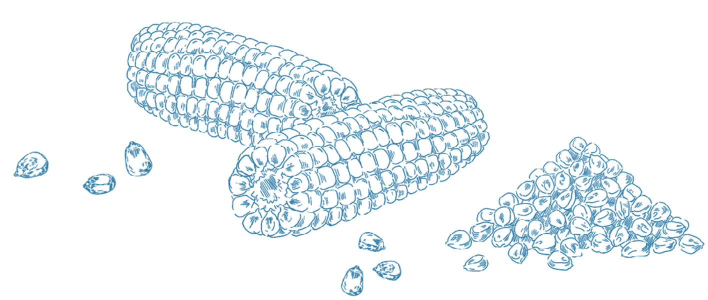
Table 1: Characteristics of selected maize-producing countries

	Production (million tonnes/yr)[48]	Export (%)[49]	Yield (t/ha)[50]	Percentage to animal feed[51]	GHG intensity ($kgCO_2e$/kg maize)[52]
U.S.	365	16	10.9	39	0.4
Ukraine	31	79	6.5	17	0.3
China	260	0	6.2	74	0.7
Brazil	94	33	5.2	59	1.0
Argentina	45	71	7.8	20	0.4
Nigeria	11	1	1.7	18	1.6

OUTLIER EMISSIONS SOURCES

The variability in emissions per kilogram of maize highlights the large mitigation potential that exists across current practices. Here we highlight the "low hanging fruit," or practices that drive unusually high emissions intensity. These practices may be good targets for initial screening for improvement.

- **Prevent habitat conversion for maize:** LUC emissions increase the total footprint of maize significantly, and elimination of these emissions is necessary to reach climate targets.
- **Improve tillage:** Less intensive tillage can reduce on-farm diesel use and decrease losses of soil carbon.
- **Optimize fertilizer application:** The amount and timing of fertilizer for optimal uptake by maize is critical for plant growth and for emissions. In some regions, fertilizer is over applied, and in others it is under-applied (yields and revenue could be boosted with higher application).



MITIGATION

For row crops, GHG mitigation is primarily through changes in field management, particularly tillage systems and nutrient management. Adoption of reduced tillage systems can provide the opportunity to reduce net GHG emissions through increased carbon sequestration in cropland soils. Improved nutrient management practices, such as the rate, timing, form, and method of nitrogen application, can also help reduce N_2O emissions from agricultural soil.[53] While increased organic matter in the soil may be critical to mitigating climate change, the permanence of the carbon sequestered in a particular location is not assured, and indirect benefits (reduced input use, higher yields) may be better-measured outcomes from a GHG perspective.

Because local soil, climate, and infrastructure influence what agronomic practices are effective for growing crops, and these practices vary even within small regions, the combination of changes that benefit the climate and the farmer are likely different and may be different in subtle ways (i.e., which different cover crops are used and when they are planted during the year).

Here we list a few key mitigation efforts, but we recognize that many of these need local tailoring and need to be used in conjunction with each other.

Prevent further habitat conversion: The conversion of natural habitats to cropland is still a source of GHG emissions that should be addressed; once habitats are converted to cropland, it can take hundreds of years for that carbon to be regained even when the original land cover is reestablished. The conversion of pasture lands is a major LUC that is ongoing, including in places like the U.S.

Reduce tillage: Reducing tillage increases organic matter buildup in the upper layers of the soil. However, other practices (herbicide application, etc.) must also be altered in concert with reducing tillage to ensure proper crop emergence and growth. There are also concerns about how permanent the sequestration of carbon in a low- or no-tillage system is – if that ground is later tilled, how much carbon will be lost? Research into the benefits of reduced tillage on water retention, yields, and resilience to extreme events suggests that these practices may deliver benefits that indirectly benefit GHG emissions as well.

While studies on the emissions intensity for maize grown with no- or low-till practices are limited, these practices tend to produce a higher rate of soil organic carbon accumulation and lower fuel consumption, and lower nitrogen emissions were reported compared to the conventional tillage practices.[54] However, yield reductions may come as a consequence of the initial transition.[55]

Optimize fertilizer usage: Many farmers apply nitrogen fertilizer exceeding the crop demand;[56] excessive application reduces the net farm return and increases the potential environmental impacts. In many cases, the application can be reduced by more than 50% without significant impacts on the corn yield.[57, 58] Shifts in timing of application could also bring small GHG benefits. In other cases, use of fertilizers to close the yield gap could dramatically increase the efficiency of production.

Apply nitrification inhibitors: Studies also showed that nitrification inhibitors can reduce N_2O emissions by an average of 32% – 38% compared to conventional fertilizers.[59]

Table 2: Mitigation summary

Intervention	Target	Cost	Mitigation Potential	Barriers
Prevent future habitat conversion	Landowners, governments	\$10–\$100/tCO_2e/y [60]	0.05 – 0.5 $GtCO_2e$/yr (based on current conversion rates)	
Tillage practices				
• Conventional till to reduced till	Feed producers, farmers, input producers		0.05 $kgCO_2e$/kg maize (assuming 0.37 tCO_2e/ha[61] and 8 t/ha yield)	Technical expertise; potential yield decreases
• Conventional till to no-till	Feed producers, farmers, input producers		0.16 $kgCO_2e$/kg maize (assuming 1.3 tCO_2e/ha[62] and 8 t/ha yield)	Cost of equipment purchases; potential yield decreases; technical expertise
Better fertilizer practices	Input producers, farmers		?	
Nitrification inhibitors	Input producers, farmers	Low (<\$10/ac)[63]	0.03 $kgCO_2e$/kg maize (assuming a 30% reduction of direct fertilizer emissions)	
No burning residues	Farmers in developing countries	~\$50/ac/yr[64]	0.05 $GtCO_2e$/yr (based on current emissions)	Cost, equipment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TOOLS AND DATA AVAILABILITY

The GHG footprint of maize is well characterized in the literature, although the focus is on commercial rather than subsistence production. LUC emissions from the conversion of non-forest to maize cropland are also poorly characterized but are a major concern for biodiversity and for climate impacts.

Given that the majority of emissions for maize are on-farm, a selection of farm-focused GHG calculators is highlighted here:

- **Cool Farm Tool:** An online tool produced by the Cool Farm Alliance that allows farmers to specify fertilizer use and cultivation practices to calculate a GHG footprint. The footprints are not regionally tailored, but the tool works globally.
- **EX-ACT:** FAO Excel-based tool that focuses on project-based improvements for crops.
- **National tools:** Many countries have nationally specific calculators for crops, e.g., Comet-Farm for the U.S. and the Farm Carbon Toolkit for the U.K.

Emily Moberg, Research Lead Specialist,
Markets Institute, World Wildlife Fund
Emily.Moberg@wwfus.org

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