Measuring and Mitigating GHGs: Soy

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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 soy 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 SOY

Soybeans are one of the most important legumes and oil seeds in the world. They are high in protein, delivering 35%–38% of their calories from protein (compared to approximately 20%–30% in other legumes). Soy fixes nitrogen and can improve soil fertility[1] when used as a cover crop[2] or in crop rotation.[3]

Soy production has grown exponentially over the last 70 years, and the increased amount of cropland devoted to soy has been a major cause of deforestation and habitat conversion. The average global harvested area of soybean in 2018 was 130 million hectares (Mha), with cumulative yield of 361 million tonnes (Mt). Between 1961 and 1991 and until 2011, soybean yield almost doubled (from 1.55 to 2.24 t/ha), which was further increased later in 2018 (2.61 t/ha).[4] The local yields in countries like the U.S. can be even higher. This increase resulted from the use of new seed varieties, improved fertilizer and pesticide application, and new management practices.[5] The use of genetically engineered soybeans with herbicide-tolerant and pest-management traits boosted yields through improved weed and pest control and reduced the cost and application of pesticides.[6] About 94% of the global soybean supplies are from Argentina, Brazil, Canada, China, India, Iran, Switzerland, Thailand, the U.S., Paraguay, and Ukraine (based on the average global production during 2016–2021).

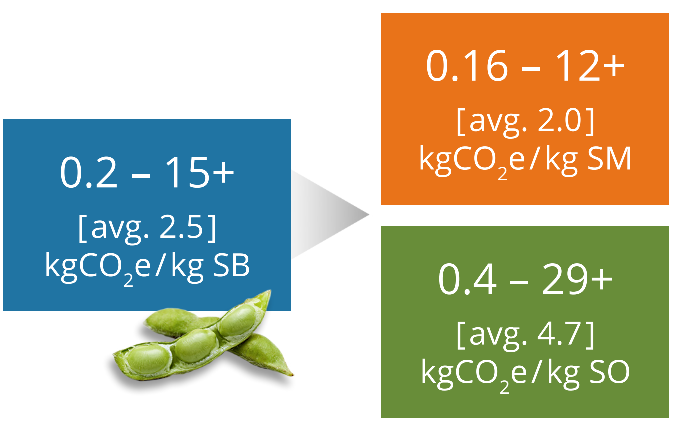
Soy production is expected to grow 371 Mt in 2030, with an improvement of 1.8% in yield relative to 2020.[7]

The rapid expansion of soy production has come at the expense of habitats worldwide but is concentrated in South America.

SOY SUPPLY CHAINS

Less than 10% of soybeans are consumed in bean form. Approximately 85% of the global soybean harvest is processed, or "crushed," into soybean meal and oil. About 98% of the soybean meal is further processed into animal feed; the remaining 2% is consumed to make soy flour and proteins. For soy oil, of the 15% used for oil production, 95% is consumed as edible oil, and the remaining 5% is used for industrial products such as fatty acids, soaps, and biodiesel. About 90% of the U.S. biodiesel is made from soybean oil; this share is lower in Europe.[8]

Figure 1: Soy product GHG footprints



Crushing:
1 kg soybean = 0.2 kg oil + 0.8 kg meal

Note that after crushing (Figure 1), some of the soybean's mass goes to oil and some to meal. However, the emissions here are allocated based on their economic value (~37% to oil and 63% to meal). At farm gate, if a kilogram of soybean had 2.5 $kgCO_2e$, a kilogram of soy meal would have about 2 $kgCO_2e$, while a kilogram of oil would have 4.7. This paper keeps the units in kilograms of soybean.

Soy is usually grown on large commercial farms. The global trade of soybean is typically between the processors and the industrial farms, and, increasingly, the world supply comes from genetically engineered seed. Brazil resisted genetically modified soy for years, but now these seeds dominate the production there too.[9] Soybean crushing is a capital-intensive industry; hence larger companies dominate in all the major exporting countries. Within the U.S., the larger firms process 71% of the crop.[10]

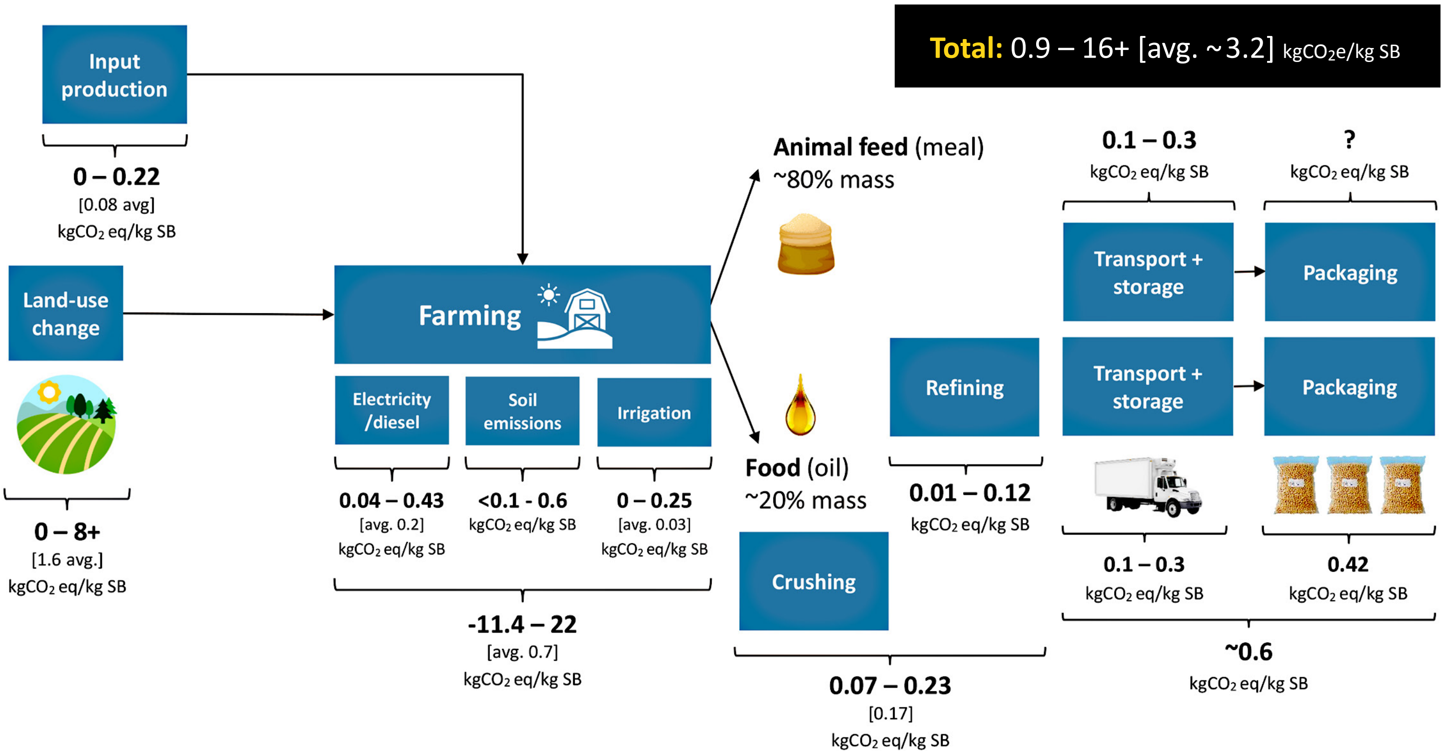
Soy is produced primarily in North America, South America, Europe, and Asia. Most production comes from the U.S., Brazil, Argentina, China, Canada, and India. Yields for the major producing regions in the Americas are over 3 t/ha/yr, while yields in China are just over 2, and in India, just above 1. The following table shows the yields of a selection of different countries.

Table 1: Soy production in key countries

	Production (Mt soybean/yr)	Export (%)	Yield (t soybean/ha)
U.S.	112	48	3.3
Ukraine	4	60	2.1
China	14.3	1	1.8
Brazil	108	62	3.2
Argentina	53.6	13	3.0
India	11.8	2	1.1

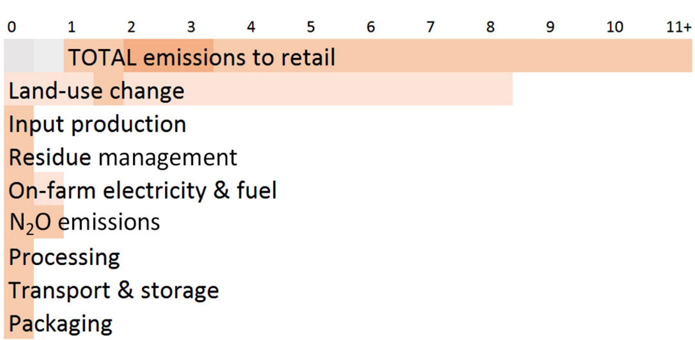
GHG EMISSIONS FROM SOY SUPPLY CHAINS

Figure 2: Range of GHG emissions from soy supply chains



The major sources of GHG emissions in soy production are (1) land-use change (LUC), (2) fertilizer production, (3) nitrous oxide (N_2O) and carbon dioxide (CO_2) from soil, and (4) diesel use for farm machinery. Minor emission sources include seed production, machinery production, and production related to the infrastructure.[11]

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



Estimates of GHG emissions for soybeans from cradle to farm gate typically range from about 0.3 to 11 $kgCO_2e$/kg SB. Average emissions excluding LUC are likely to be about 0.7[12] to 0.8[13] $kgCO_2e$/kg SB; LUC adds an average estimated 0.2[14] to 1.6[15] $kgCO_2e$/kg SB. This can be locally much higher. Many life cycle assessments (LCAs) report GHG emissions lower than 0.7 $kgCO_2e$/kg SB, which do not reflect this serious LUC.[16]

Studies investigating soy production for biodiesel may report very low emissions because they credit displaced fossil fuel use. We do not investigate those dynamics here as they are not aligned with major reporting frameworks.[17]

Land-Use Change: LUC occurs 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.

GHG emissions are often assigned based on country of origin, so locations with high deforestation for soy will have high footprints.

Table 2: Land conversion emissions for soy

Land-use change		
When land is cleared for soy, the carbon stored in plants both aboveground and belowground and in the soil is emitted into the atmosphere. The aboveground and belowground biomasses are expected to release their carbon relatively quickly; soil carbon may take longer to decay.		
Land-cover	Aboveground C	Belowground C
Tropical dry forest	105	29
Tropical savanna	30	
American rainforest	150	37
Grassland[18]	6 (4)	8 (5)
Carbon in tC/ha, if not otherwise specified, from IPCC 2006 Chapter 4.		

For example, in Brazil and Argentina, which have significant deforestation, average farm-gate emissions are 2.9 and 2.4 $kgCO_2e/kg$ SB, respectively. When emissions from LUC are removed, these numbers drop to 0.47 and 0.41kg CO_2e/kg SB, respectively.[19]

Emissions due to LUC depend on the climate and the land's previous use. If the land taken under cultivation for soybeans was previously used for other crops, or if that land was poorly managed and already severely damaged, LUC emissions won't be very significant. Additionally, areas with cooler and drier climates generally have less vegetation, less soil organic carbon, and therefore lower LUC emissions compared to warmer and wetter areas. Soybean cultivation on Brazilian land that was previously tropical rainforest produces around 15.7 $kgCO_2e/kg$ SB.[20]

However, deforestation is not the only type of habitat conversion; the conversion of prairie and grassland to cropland can also cause significant losses of carbon. For example, losses of prairie in the U.S. add about 0.28 $kgCO_2e/kg$ SB to the footprint. In Brazil, about 75% of the land conversion takes place in savanna/shrubland (in Central-West Brazil),

and in Argentina, about 90% of the conversion takes place in dry and moist savanna/grassland.[21] The induced soil organic carbon stock change due to LUC for grassland conversion scenarios in the warm temperate dry region (Argentina) is lower than 1.5 kgCO_2e/kg SB. In the tropical region (Central-West Brazil), the induced GHG emissions due to LUC vary between 3.5 and 7.0 kgCO_2e/kg SB.[22]

Estimates of global LUC emissions resulting from soy:

- **World Resources Institute estimate (deforestation only):** 0.3 GtCO_2e/yr, or 1.2 kg CO_2e/kg SB (8.6 Mha deforestation between 2001 and 2018, assuming 175 tC/ha lost from forest and using FAOSTAT values for production)[23]
- **geoFootprint estimate (deforestation only):** 0.07 GtCO_2e/yr, or 0.21 kgCO_2e/kg SB (weighted average emissions for the U.S., Brazil, Argentina, Canada, China, India, Ukraine, and Russia multiplied by average yearly soybean production over the last five years from the U.S. Department of Agriculture [USDA])
- **Poore and Nemecek estimate:** 0.5 GtCO_2e/yr, or 1.6 kgCO_2e/kg SB (emissions factor direct estimate from paper multiplied by average yearly soybean production over the last five years from USDA; this may include some emissions from changes in soil carbon from cultivation)

Tillage/soil organic matter: Low- or no-till farms have higher concentrations of soil organic carbon in the upper soil layer.[24] Data on the emissions from different tillage systems are limited; tillage practices may influence yields as well. Reduced- and no-till farms have on-farm emissions (excluding those from LUC) ranging from 0.2 to 0.6 kgCO_2e/kg SB; conventional tillage emissions ranged from 0.2 to 3.7, with an average of 0.9 kgCO_2e/kg SB.[25]

The main sources of GHG emissions on conventional and no-till farms are still synthetic fertilizer production and on-farm energy use.[26]

LUC dominates the GHG footprint for soy, adding a globally averaged 1.2–1.6 kgCO_2e/kg SB from deforestation alone. In some sourcing locations, this footprint is more than three times as high.

Changed tilling practices may also influence the soil carbon stored in the soil, but their impact is dwarfed by the carbon lost through conversion.

Input Production

Fertilizers and lime are the most impactful inputs for soy. Average embedded emissions from fertilizer production and transport to farm range from 0 to 0.22 kgCO_2e/kg SB, with an average of about **0.08 kgCO_2e/kg SB**.[27] Different fertilizers (e.g., urea vs. ammonium nitrate) have different emissions associated with their production.[28] Emissions from fertilizer production are not strongly correlated with yield.

- **Nitrogen fertilizers:** Soybean is a nitrogen-fixing crop, therefore most soybean farmers apply very little nitrogen fertilizer. For soybeans, the N_2O emissions due to nitrogen fertilizer production were thus reported to be usually less than 1% of the total emissions related to the cultivation and harvesting of the crop.[29] However, in the regions where large amounts of fertilizer are added, higher GHG emissions result.[30] Some nitrogen fertilizer is needed for high yields, depending on the soil quality. As discussed later, nitrogen fertilizer use also contributes to direct and indirect N_2O emissions.

- **Other fertilizers:** In addition to nitrogen, soybeans also require 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. For example, soybeans remove, respectively, 1.15 and 0.8 pounds of potassium oxide (K_2O) and phosphorus oxide (P_2O) per bushel.[31,32] Both conventional potassium fertilizer and potash emit 0.5 $kgCO_2e$/kg fertilizer produced.[33]

Soil Emissions

For soy, two main sources of GHG emissions from soil need to be considered: N_2O from nitrogen-based fertilizers and CO_2 from lime.

- **N_2O emissions:** N_2O emissions occur 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 widely assumed in the agricultural LCA is 1% of the nitrogen applied to the soil.[34] Direct and indirect emissions averaged 0.1 $kgCO_2e$/kg SB (range: 0–0.6 $kgCO_2e$/kg SB).[35] Of these, the contribution from crop residues ranged between 0 and 0.1 $kgCO_2e$/kg SB. Reduced or no-tillage practices that reduce soil erosion can also decrease N_2O emissions.[36] Likewise, other potential options to mitigate N_2O emissions include better management of crop residues[37] and more careful choice of land for cultivation.[38]

- **Lime:** Lime is applied to soils to correct soil pH. Because lime is composed of carbonates, the Intergovernmental Panel on Climate Change (IPCC) recommends treating these applications as eventually being released into the atmosphere as CO_2. The CO_2 emissions factors due to lime application ranged from 0.44 to 0.48 $kgCO_2e$/kg lime and varied by the source of lime, e.g., limestone or dolomite.[39] In the U.S., the highest lime emissions come from the South and Midwest due to the naturally acidic soil. In these two regions, lime use was responsible for emitting 0.12 and 0.11 $kgCO_2e$/kg SB, respectively. In other U.S. regions, lime emissions are only 0.03 $kgCO_2e$/kg SB.[40]

Emissions from inputs are typically low because of the low fertilizer needs for soy. However, fertilizer application does influence N_2O emissions, which are about twice as large as the fertilizer input (0.1+ $kgCO_2e$/kg SB).

Crop Residue Management

After harvest, soybeans leave behind crop residues in the form of straw. The most environmentally friendly way to deal with these residues is to remove them from the field and use them as animal feed[41] or compost.[42] However, many farmers leave the crop residues in the field. When the straw decomposes, CO_2 and N_2O are released.[43] Some farmers, especially those in developing countries, burn the straw, which releases even more emissions.

The contribution of residue burning averages **0.01 kgCO_2e/kg SB** (0 – 0.09 kgCO_2e/kg SB). In some regions, burning residue is common. Organic farms, which use residue for compost, tend to have a lower incidence of burning. Note that burning crops also endangers children and others who are sensitive to air pollution.[44]

Burning of residue, when it occurs, releases up to 0.38 kgCO_2e/kg SB, averaging a little less than 0.1 kgCO_2e/kg SB.

Diesel and Electricity (during cultivation)

Energy consumption (both electricity and diesel) contributed 0.2 kg CO_2e/kg SB (range: 0.04 – 0.43), most of which comes from diesel use.[46, 47] Diesel emissions are most prominent on farms that use a tillage system because of the heavy use of agricultural machinery. Countries with significant uptake of no-till (e.g., Argentina and Brazil[48]) had many farms with lower-end emissions from diesel.

Post-Farm Emissions: Soybeans are crushed to produce oil and meal. One kilogram of soybeans produces about 0.2 kilogram of oil and about 0.8 kilogram of meal.

- **Crushing:** Soybeans are crushed or solvent is used to extract the oil. The crushing and refining process during oil production emits 0.1 – 0.26 kgCO_2e/kg SB (0.21 – 0.5 kgCO_2e/kg soy oil [SO] and 0.08 – 0.19 kg CO_2e/kg soy meal [SM]).
- **Transport:** Transport emissions are a function of distance and mode of transport; trucks are more GHG-intensive per mile than trains, while boats are similar to trains. For soybeans shipped overseas, the mode of ground transportation used from farm to port has a huge impact on overall transportation emissions. In Brazil, where road transportation is predominant, the average distance between plantation and port is 1,456 kilometers. The emissions during this stage average 0.19 kgCO_2e/kg SB.[49] Meanwhile, soybeans moved from Jilin Province, China, to the port of Dalian travel around 1,080 kilometers. Even after accounting for the shorter travel distance in China, the emissions from the ground transportation stage are still much lower because of train freight, with an average of only 0.034 kgCO_2e/kg SB. Despite the longer distance in the former case, a soybean's trip from China to Denmark produces fewer emissions than the trip from Brazil to Portugal, with emissions averaging 0.24 and 0.28 kgCO_2e/kg SB, respectively.
- **Packaging:** For soy oil, packaging adds an average 0.4 kgCO_2e/kg SB (0.8 kgCO_2e/kg SO). For animal feed, packaging is likely negligible.

OUTLIER EMISSIONS SOURCES

The variability in emissions per kilogram of soy 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:** LUC emissions increase the total footprint of soy significantly, and elimination of these emissions is necessary to reach climate targets.
- **Improve fertilizer application:** Nitrous oxide emissions from fertilizer application are a major source of emissions for soy.
- **Improve tillage:** Less intensive tillage can reduce on-farm diesel use and decrease losses of soil carbon.

PRODUCTION SYSTEMS

Soybean production systems are typically classified as conventional or organic, by tillage practices, and by crop rotations.

Tillage system: Soybeans are produced with conventional and low- or no-till practices. The minimal use of tillage influences soil carbon directly and often implicates on-farm machinery use emissions. It may also impact yields.

- **Conventional tillage:** Average emissions at farm gate were 0.9 kgCO_2e/kg SB (range: 0.2 – 3.7), excluding LUC, with yields around 2.1 t/ha/yr.[50]
- **Reduced tillage:** Average emissions at farm gate were about 0.2 kgCO_2e/kg SB (excluding LUC) with yields around 2.4 t/ha/yr.[51]
- **No-till:** Average emissions at farm gate were 0.6 kgCO_2e/kg SB (0.2 – 0.6 kgCO_2e/kg SB), excluding LUC, with yields around 2.0 t/ha/yr.[52]

Cropping rotations: Soy is often grown in rotation with other crops, like corn. Little data is available on how these cropping rotations influence the GHG emissions for soy. However, soy can also be grown intercropped with other crops, which tends to produce lower emissions.

- **Double/intercropping:** GHG emissions at 0.18 kg CO_2e/kg SB; yields over 3 t/ha/yr.[53]

Conventional or organic production: Organic production avoids the use of synthetic fertilizers and other inputs, although the exact regulations vary by country. Because of these differing inputs, the emissions from producing the inputs and the resulting yields are likely to be affected; whether emissions are greater or fewer from organic farms is not clear.[54] Organic on-farm emissions range from 0.33 to 1.36 kgCO_2e/kg SB.[55] Organic farms typically have lower yields.

Irrigated or non-irrigated production: Irrigation can dramatically increase soy yields; the magnitude of the yield increase is a function of several variables. Electricity use in pumping water drives GHG emissions. The energy mix used for pumping, amount of water pumped, and distance and height pumped determine the overall footprint. The GHG impact of irrigation itself tends to be low and is likely outweighed by the increased yield on a per unit of production basis.

In addition, the **previous land use** is typically the determining factor for the magnitude of GHG emissions. The contribution of LUC for soybeans averaged at 1.55 kgCO_2e/kg SB (range: 0 – 8.1 kg CO_2e/kg SB),[56] with the highest emissions from Brazil due to deforestation.[57] However, the conversion of other habitats to cropland is also a major threat to climate and habitats. For example, in the Northern Great Plains (NGP) of the U.S., grassland conversion results in emissions of about 10 tCO_2e/ha/yr, or about 1.8 million tCO_2e/yr in the NGP, and 31.4 Mt CO_2e/yr in the U.S. overall.[58]

Table 3: Production system GHG emissions

GHG emissions of soybean production (on-farm, in kgCO_2e/kg SB). Data are for the impact, excluding the LUC and residues burned.[59]				
		GHG (kgCO_2e/kg SB)		
	Avg. yield (t/ha/y)	Min.	Average	Max.
Reduced tillage	2.4		0.2	
Conventional tillage	2.1	0.2	0.9	3.7
No-till	2	0.2	0.6	0.6
Intercropping	3.3		0.18	
Rain-fed system	1		0.46	

REGIONS

Soy is produced primarily in North America, South America, Europe, and Asia. Most production comes from the U.S., Brazil, Argentina, China, Canada, and India. Yields for the major producing regions in the Americas are over 3 t/ha/yr, while yields in China are just over 2, and in India, just above 1.

Differences in yields and impacts from deforestation and other habitat conversion to cropland drive the regional differences. The table below highlights key differences across selected countries.[60]

Note that these values are for production; the footprint of soy consumed in a country is a function of the importing locations. The EU has the largest carbon footprint per unit of imported soy, followed by China.[61]

Table 4: Characteristics of top soybean producing countries

	Production (MtSB/yr)	Export (%)	Yield (tSB/ha)	% cropland irrigated	GHG intensity (kgCO_2e/kg SB)	% GHG emissions from LUC
U.S.	112	48	3.3	16.7	0.6–0.9[62]	2
Ukraine	4	60	2.1	6.4	0.6	4
China	14.3	1	1.8	55.4	1.1–1.5	?
Brazil	108	62	3.2	12.9	1.3–2.9	73
Argentina	53.6	13	3.0	7	0.6–2.4	7
India	11.8	2	1.1	41.6	1.6–7.9	?

MITIGATION

Without LUC, soybean production is not particularly GHG-intensive. Thus, the most critical priority for soybean GHG mitigation is preventing deforestation and other habitat conversion.

Prevent further deforestation: While deforestation (particularly in South America) is a leading cause of GHG emissions for soy, emissions from the conversion of other habitats are also a major contributor. Boosting yields on current soy lands may be critical to meeting demand without expanding the overall soy area.

Beyond that, other interventions are very sensitive to location — steepness, rockiness, the acidity of the soil, climate, etc., all impact yields and costs for current and potential practices. The following potential interventions may be suitable for some regions and not for others; local tailoring is critical.

Intercropping: Compared to a continuous monocropping system, an integration of crop rotation aspects in soybean production (e.g., a soybean–wheat rotation) was argued for providing higher yields with the same amount of fertilizer, grazing feed, and enhanced pest and weed control.[63]




Reduced 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.

A shift from conventional tillage to reduced tillage can reduce 0.12 tCO_2e/ha (range: 0.1 – 0.15 tCO_2e/ha). Similarly, conversion to no-till farms from those using conventional tillage can mitigate 0.59 tCO_2e/ha (range: 0.32 – 0.96 tCO_2e/ha), and reduced tillage to no-till can mitigate 0.58 tCO_2e/ha (range: 0.32 – 0.84 tCO_2e/ha). However, these numbers are highly regionally dependent.[64]

Shifting to no-till production can require a shift in equipment and inputs used and may impact yields.

Changes in agronomic practices: Small changes in some practices can produce reasonably large GHG benefits. Precision agriculture, for example, can reduce input usage to save both costs and embedded emissions in those inputs. The benefits depend on current practices and whether changes can be made without affecting yields. Other interventions like nitrification inhibitors or changes in fertilizer application timing have relatively low GHG benefits and are very expensive (>$100/$tCO_2e$).[65]

The following table summarizes the GHG emissions reduction potential for soybeans. The reduction potential in the category "tillage practices" accounted for the effects on the estimated soil carbon because of shifts in tillage practices.[66] Compared to a continuous monocropping system, an integration of crop rotation aspects in soybean production (e.g., a soybean – wheat rotation) was argued for providing higher yields with the same amount of fertilizer, grazing feed, and enhanced pest and weed control.[67]

Table 5: GHG emissions reduction potential under different soybean management practices

Intervention	Target	Cost	Mitigation potential	Barriers
Prevent future deforestation	Landowners, governments	$10–$100/tCO_2e/yr[68]	0.1–0.3 GtCO_2e/yr (based on current deforestation rates)	
Prevent future habitat conversion	Landowners, governments		?	
Tillage practices				
Conventional till to reduced till	Feed producers, farmers, input producers	~$7–$60+/ac	<0.1 tCO_2e/ha/yr[69] (soil carbon changes)	Technical expertise; potential yield decreases
Conventional till to no-till	Feed producers, farmers, input producers	~$17–$50/ac	<1.7 tC/ha/yr[70] (soil carbon changes)	Cost of equipment purchases; potential yield decreases; technical expertise

TOOLS AND DATA AVAILABILITY

The GHG footprint of soy is well characterized in the literature. However, the magnitude of LUC remains contentious. Given that the majority of emissions for soy are on-farm, a selection of farm-focused GHG calculators are 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.

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