Advancing Reliable Climate-Smart Solutions for Farmers

First Results from BASF's Global Carbon Field Trial Program

BASF
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Note from sustainability leadership

Climate change is already happening. Farming methods need to be adapted to meaningfully **reduce emissions without compromising yield.** This is a challenge, but I am convinced that **if you love farming, you have to be committed to sustainability.** For us, the way to provide farmers with **reliable climate-smart solutions** is through testing them in the dynamic environment of the farm. In our Global Carbon Field Trial Program, we experience the real challenges farmers face to lower the carbon footprint of farming. Insights we gain from our field trial program support our Global Carbon Farming Program, where our recommendations empower farmers to become pioneers for positive change in climate and nature.

In many cases **we achieved a 30% reduction** in greenhouse gas emissions compared to standard farming practices, with **the right combinations of technologies, products and interventions** for the type of crop, regional farming practices and local climate and environment. There is **no one-size-fits-all solution,** and we will continue evaluating approaches to find what works for all our targeted crops.

While there is still much work to be done, we are proud of the progress we have achieved thus far. Applying more than 100 years' experience in agriculture, we do everything in our power to build a sustainable future for **farming, the biggest job on Earth.**

Marko Grozdanovic
Senior Vice President responsible for Global Strategic Marketing & Sustainability-BASF Agricultural Solutions

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30% reduction in greenhouse gas intensity in farming **is possible.**

Reaching this target* varied by crop and region and required tailored climate-smart approaches.

*In 2020, BASF committed to a target of a 30% reduction in greenhouse gas emissions per ton of crop produced by 2030 in wheat, soy, rice, canola and corn.

Emissions and **Yield** are both levers to lower footprint.

The key is to find solutions that improve greenhouse gas intensity in farming by reducing emissions or increasing yield, but at the very least maintaining productivity for food security and farmer livelihoods.

Greenhouse gas intensity (GHGi) is defined as carbon dioxide equivalent (CO2e) emissions per ton of crop.

No “one size fits all” but **we show what works.**

In real field conditions, we evaluated different combination of technologies and interventions for what works to reduce the greenhouse gas intensity for the type of crop, regional farming practices and local climate and environment.

Global Carbon Field Trial Program

Finding solutions to reduce greenhouse gas intensity for different farmers and crops around the world.

Continue to test **in the field** and **scale up**

Our Global Field Trial Program continues to help identify footprint lowering interventions. Climate-smart farming practices are amplified through our Global Carbon Farming Program.

BASF
We create chemistry

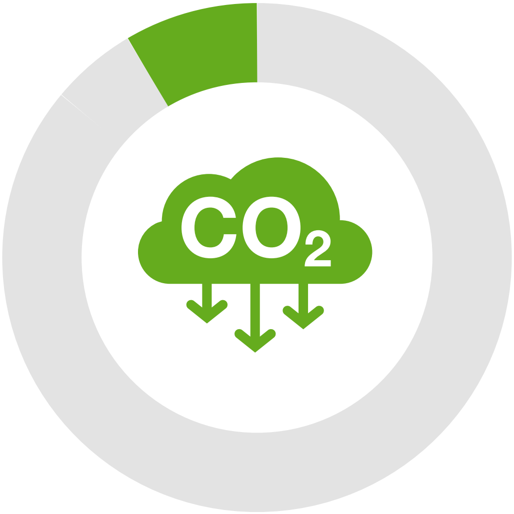
Overview

Introduction

While climate change remains one of the most pressing challenges facing the world today, agriculture is in a unique position to address this challenge. A transformation is underway to adapt farming practices to meaningfully reduce greenhouse gas emissions while providing food for the growing population.

Now more than ever, farmers must pursue productivity and sustainability. They are called on to adopt climate-smart methods and new technologies, making it crucial for them to have access to tested and reliable practices.

This is why we at BASF do everything in our power to build a sustainable future for agriculture – for the love of farming, the biggest job on Earth. We are creating a positive impact on the agricultural food system by supporting farmers of today and tomorrow to be successful in its transformation. We combine innovative thinking and practical action to develop solutions that truly work for farmers in the field.



~17%

of global greenhouse gas (GHG) emissions are generated by agricultural practices during the food production phase, according to the Intergovernmental Panel on Climate Change.

Our commitment to climate-smart agriculture

Climate-smart agriculture is an approach that aims to enhance food security and farmer incomes while building resilience to climate change and reducing greenhouse gas emissions. To help farmers take this approach, BASF has committed to a clear and measurable agricultural emissions target: a 30% reduction in greenhouse gas (CO_2, N_2O, and CH_4) emissions per ton of crop produced by 2030 in wheat, soy, rice, canola and corn compared with standard farming approaches.

To achieve this climate-smart agriculture target, it is crucial to understand the right combination of technologies and practices that bring greater carbon efficiency and resilience to farmers across different agricultural regions. Therefore, we initiated a series of multi-year field trials to determine our best offers as alternative practices that improve the greenhouse gas efficiency in crop cultivation. This emissions efficiency measure takes into account both the reduction of emissions and the improvement of yield as levers in climate-smart agriculture.

This report shares the first results from our Global Carbon Field Trial Program, both our progress and challenges in identifying climate-smart farming practices that are effective for different crops, farming regions and production systems.

Supporting farmers to become **more carbon efficient** and **resilient to volatile weather conditions**

-30%
greenhouse gas emissions per ton of crop produced by 2030 in wheat, soy, rice, canola and corn

To feed a population of roughly 9.73 billion by 2050, experts estimate farmers will need to **increase agricultural productivity by 50%**

First learnings from our global carbon field trials

Results from the first two years of the global carbon field trials (Q4 2021 until Q4 2023) show that a 30% reduction in greenhouse gas emissions in farming is possible, but the extent of this reduction varies greatly depending on the specific crop, local conditions and weather. This is why there is not a one-size-fits-all solution to the global challenge of climate-smart farming across all countries, crops, and farms. Instead, the most effective emissions reducing practices are tailored to specific agricultural production systems, requiring a combination of different interventions, products and technologies.

Key drivers we identified at a high level were (digital) decision support systems to help manage reductions in fertilizer usage without compromising yield, nitrogen stabilizers to limit emissions associated with fertilizer application, and the use of high-performing seeds combined with effective crop protection programs to safeguard and optimize yield.

Challenges to identifying climate-smart practices

Some promising emissions reducing alternatives unfortunately are not practical for certain crop production systems or result in lower yield, risking farmer livelihoods and food security. Therefore, in some crop production systems, a reduction in emissions intensity meeting our climate-smart agriculture target was not achieved. The challenge is to find solutions that improve greenhouse gas efficiency in farming by reducing emissions or increasing yield, but at the very least maintaining productivity.

Adverse weather during the trials, such as reduced rainfall, unusual rainy periods, record heat and drought, negatively impacted yield, and therefore also negatively impacted interventions aimed at improving the greenhouse gas efficiency in crop production. Although weather challenges are not new to farmers, our trials confirm the importance of resilience and yield protecting strategies to reliable climate-smart solutions and to reaching our climate-smart emissions target.

Farming practices that support carbon sequestration in the soil contribute to the reduction of the greenhouse gas intensity of a crop production system. Therefore, it is important to account for changes in soil carbon which occur over a longer period. In our future field trials, we plan to include soil organic carbon stocks to further evaluate the greenhouse gas intensity of crop production resulting from alternative practices.

Continuing our journey to provide growers with climate-smart solutions

Solutions supported by science and by data are essential to provide farmers with reliable products and interventions that reduce emissions intensity while maintaining or increasing yields. Therefore, our Global Carbon Field Trial Program is ongoing to continue identifying climate-smart practices that work for farmers in different regions. Additionally, soil organic carbon stock changes might show additional reductions in emissions intensity from alternative practices tested in our trials. Through the continued field trials, we also expect to observe further improvements of emissions intensity from interventions that may take more time to manifest, such as improved soil health from implementation of reduced tillage.

The findings derived from our Global Carbon Field Trial Program play a crucial role in providing valuable insights to our farmer customers worldwide. These insights enable us to offer recommendations aimed at helping farmers lower their carbon footprint through our Global Carbon Farming Program and other customer interactions.

As other complex problems, the challenge of climate change and its impacts to agriculture are best addressed from different angles and by different players and stakeholders. Already, many governments provide tax incentives or subsidies to farmers who adopt specific practices aimed at reducing their carbon footprint. Along the agricultural value-chain, various stakeholders are actively seeking ways to minimize the carbon footprint of their products, driven by their own sustainability targets or to meet the growing demand from consumers for sustainable products.

As a part of this system and the solution, BASF is fully committed to a value chain and multistakeholder approach to improve the carbon footprint and climate resilience in the agricultural sector and participates in targeted efforts including its Carbon Farming Program, Global Carbon Field Trial Program and collaboration with key research institutions like the *International Rice Reseach Institution* (IRRI).

Summary of first field trial results by crop

In trials for wheat cultivation, we were able to achieve 30% reduction in greenhouse gas intensity (GHGi) relative to standard farming approaches by using alternative approaches focusing on tailored combinations of nutrient management and (digital) decision support systems (DSS). Nitrogen stabilizers drove reductions, with additional reductions in GHGi achieved with lower rates of nitrogen fertilizer. Digital DSS can enable yield preservation with fertilizer reductions. Not all alternative farming approaches tested resulted in the targeted GHGi reduction, varying from 2% to 37% lower than the standard approach.

Standard practices including use of inoculants and no-till adopted by Brazilian farmers have resulted in a good climate-smart farming baseline during soy cultivation. In the United States, soil regenerating and yield improving practices will be assessed as solutions to reduce GHGi. Alternative practices for soy cultivation in our trials so far have led to up to 9% GHGi reduction.

Corn field trials also resulted in promising alternative farming approaches to reduce GHGi, with potentials ranging from 6% to 32% lower than standard approaches. Similar to wheat, use of nitrogen stabilizers along with nutrient management via DSS delivered footprint reductions over our 30% target, in some cases without compromising yield. Additional long-term effects of soil conservation practices in the United States will be further evaluated for benefits to soil fertility and compounding improvements to GHGi.

Paddy rice is one of the most emissions intense crop systems, but there are promising technologies and interventions that help to reduce emissions associated with its production. Direct seeded rice with herbicide tolerant traits is an already highly adopted practice by Italian farmers. Therefore, our trials in Italy focused on reducing water use and optimizing seeding rate, and showed reduced GHGi in rice cultivation ranging from 2% to 16% lower than standard approaches. We will implement trials in Asia, also exploring the benefits of reduced water use, nutrient management, nitrogen stabilizers, direct seeding and high-performance rice varieties.

In the case of canola/OSR, we were also successful in meeting our emissions target, with alternative farming approaches tested in trials resulting in GHGi reductions ranging from 20 to 63%. These reductions were achieved through a comprehensive farm management program with multiple alternatives including high yielding seed, soil conservation practices, nitrogen stabilizers and crop protection.

Technical Report

Scope

As a critical step to reach our climate-smart agriculture target, we initiated a Global Carbon Field Trial Program to continue identifying practices that support farming to become more carbon efficient and resilient. For the crops defined in the target, field trials were established to demonstrate combinations of sustainable practices, innovative products, and digital solutions that reduce emissions and/or increase yield compared to standard practices. “Greenhouse gas intensity”, or GHGi, is an emissions efficiency metric accounting for emissions by yield and was used as an estimate of the carbon footprint of the various crop cultivation scenarios.

The GHGi is reported for our target crops for each season that they are cultivated. The trials include other crops typically rotated with those and GHGi is not reported.

Field trials for wheat, soy, corn, canola/OSR, and rice are ongoing in different agricultural regions including North America, South America, Europe.This report shares preliminary findings from this program, including climate-smart recommendations for different crops and regions, as well as challenges to reducing the carbon footprint.

Wheat field trials, Rhineland-Palatinate, Germany (DE-RP)

Approach

Our research focuses on identifying practical solutions that not only reduce the carbon footprint of farming, but also enhance the overall sustainability in agriculture.

> Through this comprehensive approach to tackling the environmental impact of agriculture, we aim to **promote resilient agricultural practices** that contribute towards **a more sustainable future of food production** while addressing the challenges of climate change.

Our Global Carbon Field Trial Program is designed to document the GHGi from each of the crop cultivation systems when farmed under standard practices, identify the main drivers of emissions, test the limits of fertilization reduction, and identify alternative solutions and practices predicted to enable a reduction in GHGi. Results from the trials support the development of recommendations of climate-smart agricultural practices for different farmers around the world.

To estimate the carbon footprint of crop production, we use the concept of greenhouse gas intensity (GHGi). This is the ratio between the emissions of the production system in a specific area (kg $CO_2e \cdot ha^{-1}$) and the yield (ton $crop \cdot ha^{-1}$). The GHGi (kg $CO_2e \cdot ton\ crop^{-1}$) is a measure of the efficiency of the crop production system with respect to its emissions (reported as CO_2 equivalent, CO_2e); therefore the lower the value, the higher its carbon efficiency.

In relation to our target, we aimed to identify combinations of climate-smart practices that lower the GHGi by 30% compared to standard farming approaches. The calculations of GHGi shown in this report do not include the soil compartment as a potential source or sink of carbon. This aspect will be addressed in future research through soil sampling and/or biogeochemical models. Therefore, interpretation of the reductions in GHGi in this report should take this into consideration.

The findings from the Global Carbon Field Trial Program are used to provide farmers around the world with recommendations to lower their carbon footprint. The implementation of climate-smart practices is driven through our Global Carbon Farming Program and other customer interactions.

Critical levers to reduce the emissions intensity in crop production

We identified the following three critical areas to **help support de-carbonization** of agricultural production.

1. Reduce emissions in-field and upstream

Some amount of GHG emissions is unavoidable during both the growing season and off-season due to essential agricultural activities and various natural processes. These include emissions occurring during agricultural operations such as fuel consumption by farm equipment as well as upstream emissions produced during the manufacturing of agricultural products (particularly fertilizer production). Additional emissions can occur from the decomposition of crop residues, denitrification in soil, methane production in flooded fields, and limestone dissociation after liming. However, there are several strategies that can help to mitigate these emissions.

Some of the options to reduce GHG emissions include:

(1) Promote microbial activity that leads to humification of soil carbon from plant material (e.g., crop residues and/or cover crops).

(2) Minimize nutrient loss during off-season by promoting immobilization of nitrogen with cover crops.

(3) Optimize the timing of fertilizer application and reduce the rates of denitrification or volatilization of nitrogen with nitrogen stabilizers.

(4) Reduce the level of water in flooded fields (typically in paddy rice systems) to limit the activity of methanogenic bacteria.

(5) Reduce the application rate of products derived from energy-intensive operations, such as mining for lime and phosphate or the industrial synthesis of ammonia.

(6) Reduce diesel consumption during farming operations by minimizing tractor usage or reducing energy intensive operations such as (deep) soil cultivation.

2. Increase stocks of organic matter in the soil

Farming practices that increase stocks of soil organic carbon over time, like cover copping and reduced tillage, can reduce GHGi by removing carbon from the atmosphere. Soil stores a significant amount of carbon: in the order of thousands of gigatons worldwide[1]. This is three times more carbon than the kilometer-thick atmosphere[2], yet it only runs a few meters deep. The high capacity of soil to store carbon underscores the responsibility that economic sectors that use of large amounts of land such as agriculture, livestock, and forestry, have to sustain and foster this storage resource. Therefore, preservation of soil carbon stocks is essential, in additional to goals to increase storage.

The importance of soil goes beyond carbon storage and its role in climate change mitigation[3]. Essential nutrients for plant growth are bound to soil organic matter, allowing it to act as a natural source of plant nutrition[4], particularly in crop systems with little external nutrient input. Efforts to increase soil organic matter can then preserve or increase productivity and drive down GHGi.

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1 Lal, R. (2004) Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 304:1623-1627.
2 Oelkers, E. H., Cole, D. R. (2008) Carbon Dioxide Sequestration A Solution to a Global Problem. Elements 4 (5): 305–310.
3 Other fundamental services provided by soils include natural suppression of pest and diseases, curtailing of eutrophication of downstream water bodies, storing of water to plans in the soil surface and filtering of water prior to underground storage.
4 FAO (2007) International Conference on Organic Agriculture and Food Security, Italy.

Diversity of life in soil

Microbiologists have made considerable strides to demonstrate the diversity of life in soil, especially as DNA extraction methods became more available and less expensive. Billions of microorganisms can be found in a single teaspoon, and soil can even be heard with bioacoustics[5]. The life in the soil, or the soil microbiome, is an engine that drives the accumulation and stabilization of organic matter in soil[6]. Fostering the biodiversity of the soil microbiome is key to realizing the soil health benefits that result from soil organic matter improvements.

While there is a clear benefit for food production to preserve soil, the resource itself is practically non-renewable considering the time it takes to make it[7]. Soil that is a few thousand years old is comparatively young; while soil that is dozens of millions of years old would be considered old[8]. Therefore, the less soil resources are perturbed, the better.

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[5] Eberle, U. (2022) Why soil is a surprisingly noisy place. BBC.com.

[6] Paul, E. A. (2016) The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. Soil Biology & Biochemistry 98:109-126.

[7] Food and Agriculture Organization of the United Nations (2015) Soil is a non-renewable resource. 2015 International Year of Soils.

[8] Delgado-Baquerizo, M., et al. (2020) The influence of soil age on ecosystem structure and function across biomes. Nature Communications 11: 4721.

3. Increase (or at least maintain) yields

An increase in the emissions efficiency of agricultural production can also be achieved through yield increases. This requires continuous innovation in agricultural technology and management practices. Higher yields can also be achieved through the increase in soil organic matter, which improves the ability of soils to provide nutrients and water to crops. Particularly in low fertility soils or in low intensity agriculture, this is an important mechanism of crop nutrition.

Likewise, by reducing the loss of nutrients to the environment (some of which are lost as GHG) and by adopting practices to physically protect the soil surface, mitigation of stress (nutrients and water) can help maintaining or increasing crop yields.

Technologies & Interventions

The following technologies and interventions (*Figure 1*) were considered for alternative practices in each trial as possible means to reduce emissions and/or increase or at least maintain yield.

Seed solutions

As part of the trials, but not exclusively, BASF seed and trait solutions for canola and soy were tested. Seed technologies alone have little impact on the reduction of GHG emissions, but they contribute to the reduction of GHGi by assuring the maintenance or the increase in crop yields.

Nitrogen stabilizers

Nitrogen stabilizers regulate biogeochemical processes through which nitrogen may be ultimately lost from the soil or transferred to the atmosphere as a GHG (denitrification and volatilization). These technologies are offered by BASF and tested in the trials. The contribution from nitrogen stabilizers is two-fold:

(1) they can reduce the outflux of nitrogen and limit its potential transformation to a GHG

(2) they optimize the availability of this nutrient to the crop and thereby potentially increasing crop yield.

Crop protection products and growth regulators

The protection of crops against biotic stress reduces the risk of yield loss and can be delivered either via foliar application or as an on-seed treatment. Likewise, growth regulators manage the physiological processes in certain crops to synchronize crop development across the field. The manufacturing and application of crop protection products is generally only a very small contributor to the GHG emissions associated with producing a crop. However, crop protection is extremely important to protect or increase yield and thereby contributes to lowering the final GHGi of the crop. Depending on the country and crop, products from the BASF portfolio could fully or partially substitute those used in the standard practices.

Digitally informed decision support system

The decision support systems from BASF and other parties used in our field trials contains models thoroughly tested on country and crop specific conditions to recommend optimal spraying programs and optimal nutrient management. In cases where these models are still under development, weather forecast and weather stations from the experimental sites were used to inform occasional decisions.

Inoculants and biostimulants

Biobased products can contribute to a reduction in GHGi through different means. Inoculants used with legume crops can reduce or in certain cases eliminate the need for nitrogen-based mineral fertilizers. In a similar way, biostimulants can benefit crop yields through various mechanisms. Some of these mechanisms include physical protection of the rhizosphere, amplification of an enzymatic activity that promotes nutrient availability to the crop, or the bolstering of a specific functional group of soil microorganisms that contribute to stabilization of soil organic carbon, e.g., glycoprotein producers[9]. The methods of application of biobased products are various, e.g., on-seed treatments, foliar, broadcast or in-furrow applications. Biobased products from BASF and other parties were tested in our field trials.

Agricultural interventions

Interventions that minimize soil cultivation such as no-till and different types of reduced tillage are key to reducing current rates of carbon mineralization in agricultural soil. Cover crops grown during fallow periods, in between seasons, or in intercropping, help bolster the belowground biomass and reduce exposure of the soil surface to weathering. Other agricultural interventions may also contribute to reducing GHGi, with the extent depending on context.

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[9] Agnihotri et al. (2022) Glycoproteins of arbuscular mycorrhiza for soil carbon sequestration: Review of mechanisms and controls. Science of the Total Environment 806:150571.

Figure 1
Products or interventions considered in alternative approaches to reduce greenhouse gas intensity relative to the standard approach.

Modification of current management

- Optimal/reduced nutrient management
- Optimal crop protection program
- Optimal growth regulator management
- Optimal seeding rate

Partial/full substitution with BASF technologies

- Seeds
- Nitrogen stabilizers
- (Seed treated) crop protection product
- (Seed treated) biopesticide
- Growth regulator
- Digital Descision Support System (DSS)
- Inoculant

Additional interventions or products

- Cover cropping
- Crop rotation
- Biostimulant
- Organic fertilization

Soil and water conservation measures

- Shift in crop establishment
- Shift to cultivation technique (e.g., no-till, reduced till)
- Optimal/reduced water use
- Straw management
- Intercropping

Preliminary results

Here we report our first results and learnings since the initiation of our global carbon field trials in late 2021. Results are summarized below by each crop and trial.

Wheat

The GHGi for standard wheat cultivation in Germany, Spain and Canada was compared with various alternative approaches indicated by the production system requirements and products available in each country. The key learnings for wheat are listed in *Table 1*.

In Rhineland-Palatinate, Germany, the GHGi in the winter wheat Standards were 268 (DE-RP1-22, pollinated winter wheat) and 279 kg CO_2e ton·crop^{-1} (DE-RP2-22, hybrid wheat) *Figure 2*. A strong reduction in GHGi (21% in DE-RP1-22 and 23% in DE-RP2-22) was observed with the use of a nitrification inhibitor (NI) as an alternative from the standard approach. In the case of trial DE-RP2-22 comprising of hybrid winter wheat, this scenario has in addition a mild increase in yield (3%). When the nitrogen fertilization rate was reduced by 30% from standard approach without the use of a digital DSS, a GHGi reduction by more than 30% was achieved but at the expense of yield. The German trial was located in a nitrogen vulnerable zone (usually referred as “red zones”). These are areas where the nitrogen fertilization rates have a regulated ceiling to reduce risk of groundwater contamination. This means that a 30% reduction in fertilizer use on top of this obligatory reduction was overambitious (causing a reduction in the yield between 2 to 9%). The incorporation of DSS technology to better inform about the timing and reduced rate of application of nitrogen served to offset some of the yield reductions and further reduce the GHGi.

In Andalusia, Spain, the GHGi Standards were 421 (ES-AN1-22) and 456 kg CO_2e ton· crop^{-1} (ES-

Field trials, Rhineland-Palatinate, Germany (DE-RP)

AN1-22). For this particular crop and region, the crop protection program used in this region can be fully substituted by BASF offers. The introduction of a nitrification inhibitor as an alternative approach from the standard resulted in a small reduction in GHGi, but was offset by a 4% reduction in yield. In the other scenarios in Spain, the combination of the NI with other BASF technologies (i.e., full crop protection substitution and DSS) rendered an increase in yield (up to 4%). The implementation of a program where nitrogen fertilizer use is reduced up to 30% rendered a decrease in the GHGi from the benchmark by 16 to 26%. In one trial (ES-AN2-22), this reduced nutrient program reduced yield by 1% relative to the standard. Nonetheless, in trial ES-AN1-22, a strong GHGi reduction by 26% was accompanied by an increase in yield by 4%. A reduction in GHGi in wheat in Spain can indeed be achieved in combination with a mild increase in yield through a nitrogen stabilizer combined with existing BASF crop protection offers in the country. Additional savings can be achieved using a reduced fertilizer program, although mild reductions in yield start to take effect.

Results for wheat grown in Saskatchewan, Canada, were the most promising. Canadian wheat trials were set up as a 2-year rotation with canola (CA-SK2-22 and CA-SK4-23) and as a 3-year rotation with canola and lentils (CA-SK5-22 and CA-SK1-23). The standard treatments were conventionally tilled, fertilized according to standard practice, and treated with a basic crop protection regiment. In Canada, GHGi in the standard practices were 358 (in both CA-SK2-22 and CA-SK5-22), 407 (CA-SK1-23) and 548 kg CO_2e ton·crop^{-1} (CA-SK4-23). The alternatives were zero-tilled enabled in large part by a BASF herbicide, fertilizers were treated with a urease inhibitor, and crops were treated with BASF crop protection products. The alternative treatments in both trials in 2022 (CA-SK2-22 and CA-SK5-22) resulted in a 10% decrease in GHGi, and slightly higher yield (+2%). In the following year (CA-SK1-23 and CA-SK4-23), GHGi was reduced by 33% and 4% respectively, and yield results were mixed, with the alternative treatment yielding 14% lower in CA-SK4-23 but 15% higher in CA-SK1-23.

Decision support systems can optimize nutrient use efficiency to support increasing yield and lowering the carbon footprint.

Field trials, Rhineland-Palatinate, Germany (DE-RP)

Table 1 Learnings for wheat so far.

What works and what does not?	Nitrogen stabilizers (nitrification and urease inhibitors) are key to achieve meaningful reductions in GHGi wheat cultivation. Reducing the nutrient management program as the means to achieve GHGi reductions works better when those optimizations are adequately informed with a DSS and soil tests.
What are the challenges?	Reducing the nutrient management program risks yield declines. Maintaining or increasing yield is critical to farmer revenue and livelihoods in addition its positive impact on GHGi. This indicates that the nutrient program in standard wheat production in Spain and Germany is already operating close to the limit below which yields can be jeopardized. Even though unexpected and adverse weather events impact GHGi across scenarios, realizing the intended GHGi reductions from the designed strategy under adverse weather conditions is more challenging. The late Springs in Rhineland-Palatinate (Germany) in 2022 and 2023 were abnormally dry. This is problematic as it coincides with the reproductive phase of wheat. In 2023, Spain had its driest and hottest weather in decades. This is particularly impactful for a crop that has high sensitivity to warm temperatures.
What are the next steps?	Farmers in the European Union are under pressure to reduce nitrogen use[10,11]. Therefore, despite the risk of yield declines with a reduction in nutrient use, we will continue to pursue this alternative practice and optimize it through the use of DSS. Inclusion of soil organic carbon stock is planned and will bring a better understanding of the impacts on GHGi from alternative approaches to wheat cultivation.

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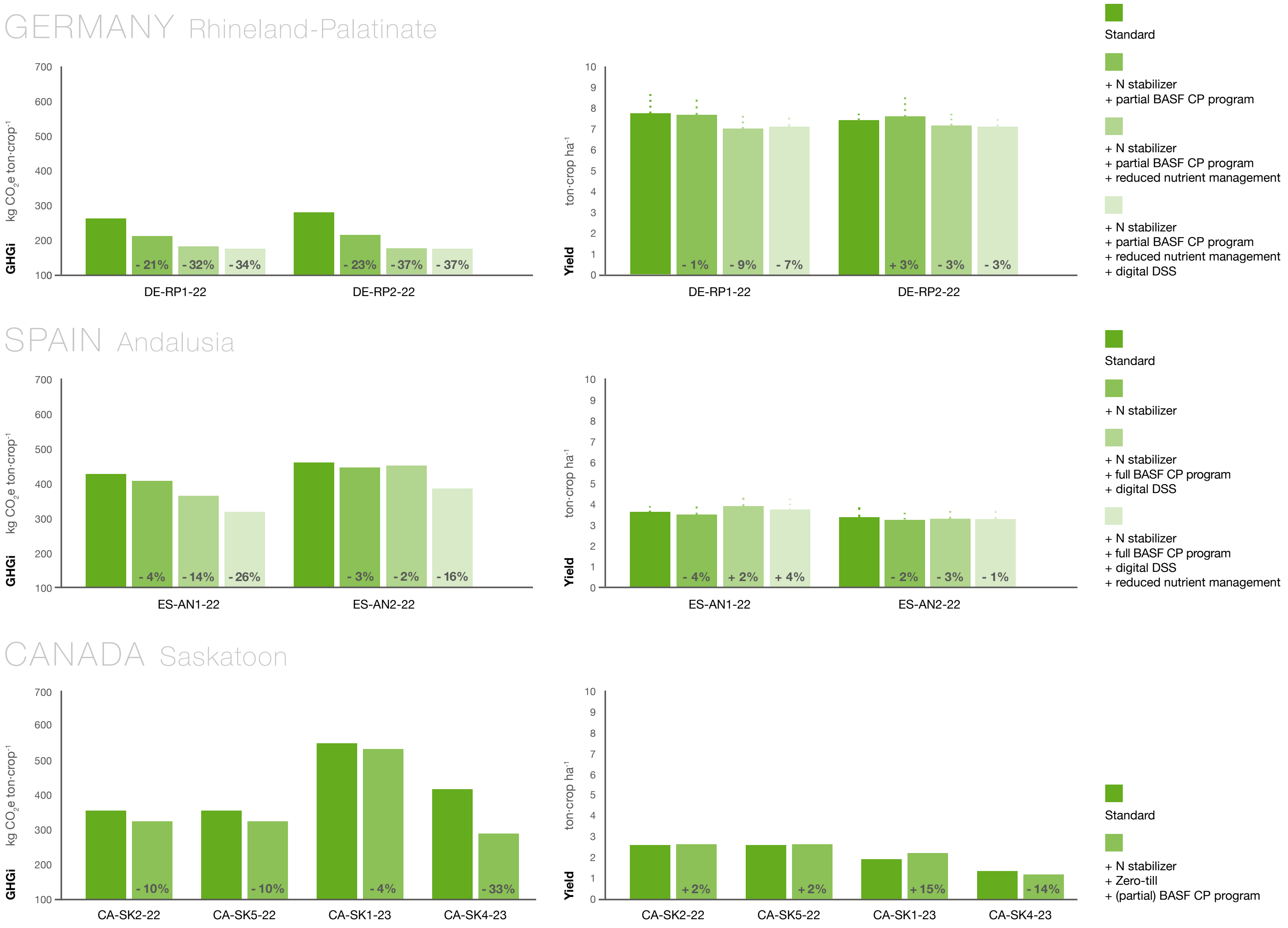
[10] Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.

[11] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy

Figure 2

For each trial conducted with wheat, greenhouse gas intensity (GHGi, left) and yield (right) resulting from a standard approach of the region (dark green) are compared to alternative approaches (CP: Crop Protection, DSS: Decision Support System, N: Nitrogen). Data was collected from field trials in Rhineland-Palatinate, Germany (DE-RP1 and DE-RP2 in 2022), Andalusia, Spain (ES-AN1 and ES-AN2 in 2022), and Saskatchewan, Canada (CA-SK2 and CA-SK5 in 2022 and CA-SK1 and CA-SK4 in 2023). Percent changes from the relevant standard are shown for each alternative approach. When available, error bars for yield mean show standard deviation. Note: changes in soil organic carbon stocks not currently considered in GHGi estimation.



Reduced tillage can improve soil health, increase yield and reduce the carbon footprint.

Soy

No-till has been a standard practice in Brazilian soy cultivation for several years[12]. Soy farmers have experienced long-term success by implementing locally adapted nitrogen fixating bacteria strains that have relieved the need for nitrogen fertilizer use considerably[13]. A reduction in the nutrient program in soy (comprised of phosphorus and potassium) could help with additional reductions in the GHGi. However, given that the bioavailability of these nutrients is typically limited, there is a high risk of yield declines. The combination of these factors creates a limited capability to reduce overall emissions.

Across the two alternatives that we tested for soy cultivation in Mato Grosso, Brazil, the greatest reduction in GHGi that we observed was 9% (*Figure 3*). The standard fields were under no-till conservation for 20 years, and we estimated the GHGi for soy cultivation as 540 kg CO_2e ton·crop^{-1}.

In 2023, the harvest of soy was delayed by nearly two weeks due to persistent rainfall. Furthermore, reducing the fertilization rate of phosphorus and potassium by 30% caused a 4% yield decline. This is expected given that the soil in the region has low bioavailability of phosphorus and base cations. The best option for GHGi reduction for soy cultivation in this Brazilian region may be technologies or interventions that improve yield rather than approaching the limits for safeguarding yield with a reduced fertilization program.

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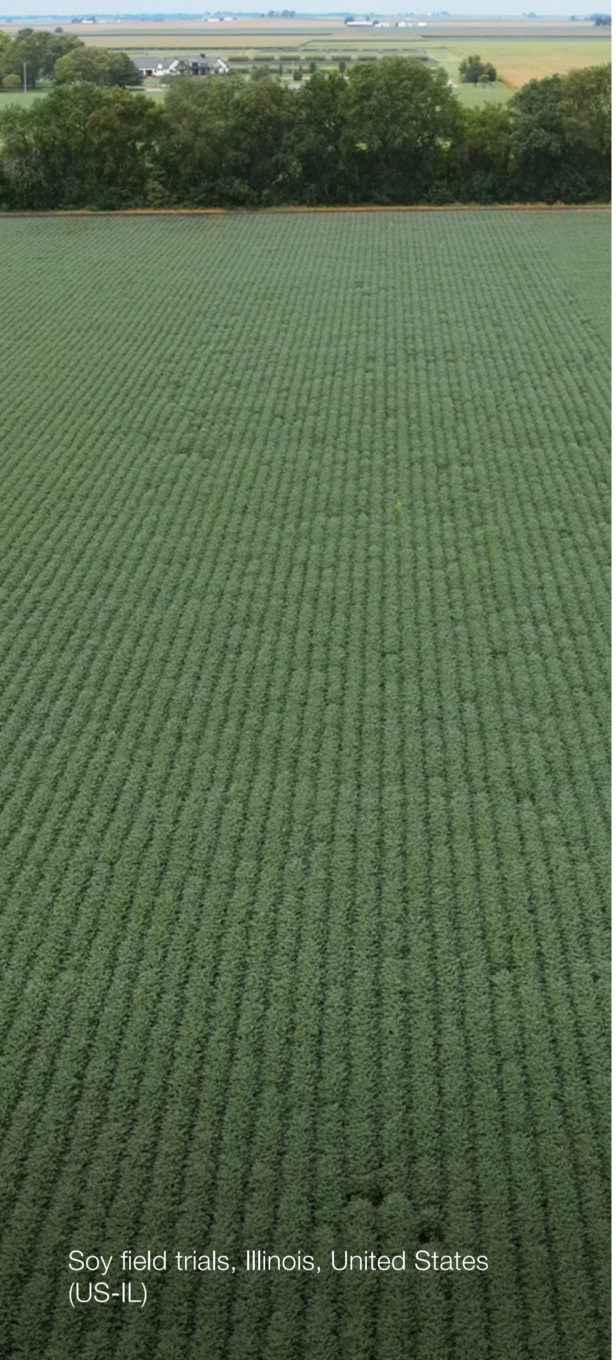
[12] Fuentes-Llanillo et al. (2021) Expansion of no-tillage practice in conservation agriculture in Brazil. Soil and Tillage Research 208:104877.

[13] Prando et al. (2024) Benefits of soybean co-inoculation with Bradyrhizobium spp. and Azospirillum brasilense: Large-scale validation with farmers in Brazil. European Journal of Agronomy 155:127112.



Soy field trials, Illinois, United States (US-IL)

In Illinois, United States, reduced tilling practices are not as widely adopted as in Brazil[14]. Therefore, our field trials in the United States also compared different approaches of soil cultivation in a crop rotation of soy followed by corn. Prior to installing the trial in 2022, all the treatments were in conventional tillage and the standard was conventionally tilled in wide rows (76 cm). The standard scenario consists of a basic crop protection package and no seed treatment. The GHGi of the Standard was 374 kg CO_2e ton·crop^{-1} (*Figure 3*, US-IL1-22). We tested BASF crop protection consisting of seed treatment(s) and foliar fungicides, as well as no-till planted in narrow rows (38 cm) and strip-till planted in wide rows. For 2022, yields were relatively equal between the standard and strip-till, but the narrow rows in the no-till scenario resulted in a 6% higher yield and corresponding 5% reduction in GHGi. Soil conservation tillage was the most effective at reducing GHGi but could be further improved with additional soil interventions like cover cropping with cereal rye, to control weeds and improve soil health.

The key learnings for soy are listed in *Table 2.*

To ensure farmer livelihoods and food security, it is key that climate-smart solutions **maintain or ideally increase yield** while improving greenhouse gas efficiency.

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[14] Derpsch et al. (2010) Current status of adoption of no-till farming in the world and some of its main benefits. International Journal of Agricultural and Biological Engineering 3:1.

Soy field trials, Mato Grosso, Brazil
(BR-MT)

Table 2 Learnings for soy so far.

What works and what does not?	In Brazil, the opportunity to reduce GHGi with nitrogen stabilizers is limited due to already low use of nitrogen fertilizers. A reduction in the nutrient program (phosphorus and potassium) is also of limited benefit as soil fertility tends to be low. Therefore, technologies or interventions that improve yield will be most effective at reducing GHGi in soy cultivation in this region. In the United States, there is good potential for reduction of GHGi through the adoption of soil regenerating agriculture practices, like soil conservation tillage. Soil health improvements should ultimately overcome initial and expected declines in yield in the transition from conventional tilling[15], and contribute to meaningful GHGi reductions. Further reductions could also come from additional practices, like cover cropping to control weeds and improve soil health.
What are the challenges?	Climate-smart practices already well-established for cultivation of soy in Brazil pose an extra challenge for further reductions in emissions. The negative impact of weather on yield counters GHGi-reduction efforts. In Brazil, soybean is harvested in the middle of the summer season, when frequent tropical rains can delay harvest and might result in yield loss. Pest and disease pressure are especially high in the summer, making it critical to have a highly effective crop protection program. There are challenges to adopting soil conservation tillage practices that could improve GHGi, especially for soy cultivation in the US. The transition from conventional tilling requires financial investment and effort to refine the on-farm execution. In addition, a yield decline can be experienced in the first few years of implementation.
What are the next steps?	The trials in the United States and in Brazil are planned to be continued focusing on solutions that bring CO_2e reduction while maintaining yield. To understand the impact of different soil regenerating practices over time, measurements are being taken on soil health, soil nutrition and soil organic carbon at both trial locations.

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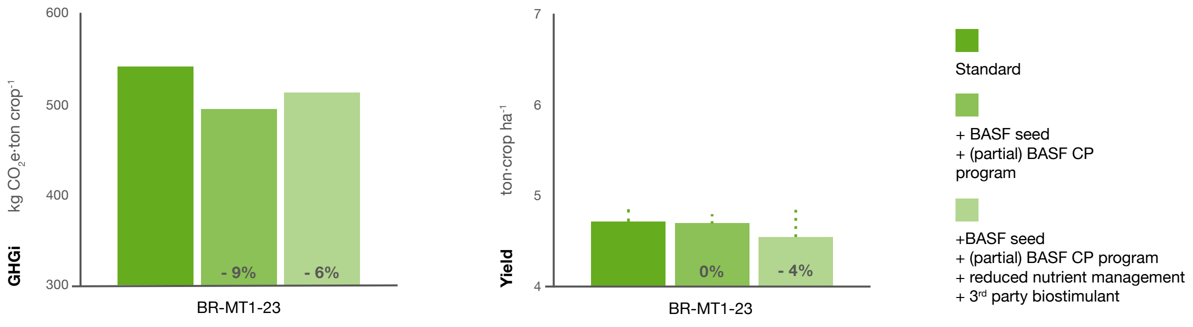
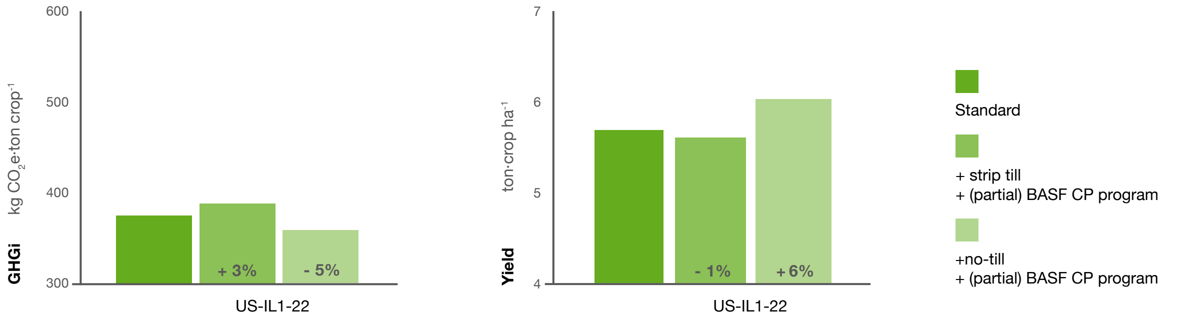
[15] Pittelkow et al. (2015) When does no-till yield more? A global meta-analysis. Field Crops Research 183:156-168.

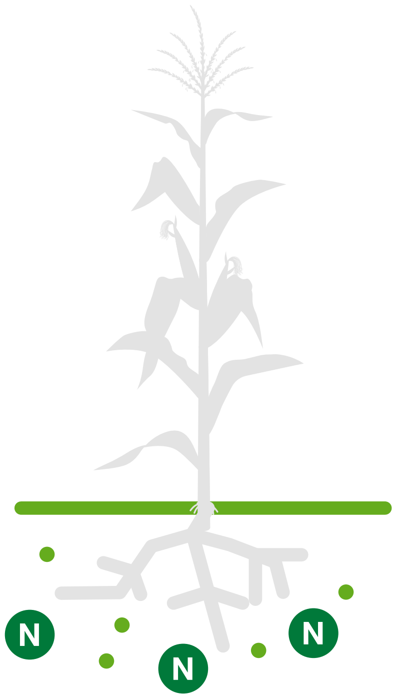
Figure 3
For each trial conducted with soy, greenhouse gas intensity (GHGi, left) and yield (right) resulting from a standard approach of the region (dark green) are compared to alternative approaches (CP: Crop Protection). Data was collected from field trials in Mato Grosso, Brazil (BR-MT1 in 2023) and in Illinois, United States (US-IL-22) in 2022. Percent changes from the relevant standard are shown for each alternative approach. When available, error bars for yield mean show standard deviation. Note: changes in soil organic carbon stocks not currently considered in GHGi estimation.

BRAZIL Mato Grosso



UNITED STATES Illinois





Nitrogen stabilizers help prevent the loss of nitrogen from fertilizers to the environment and optimize nutrient delivery to the plant, which supports yield.

Corn

The GHGi for standard corn cultivation in Brazil, Germany, and the United States was compared with various alternative approaches as indicated by the production system requirements and products available in each country. The key learnings for corn are listed in *Table 3*.

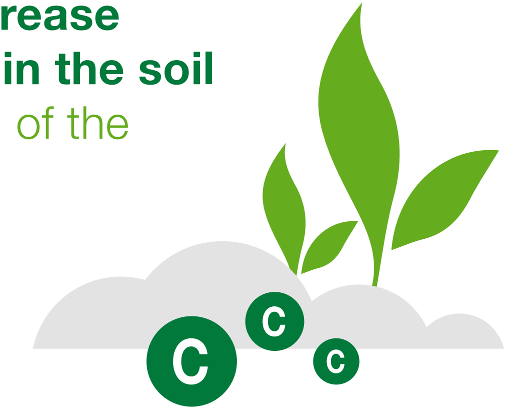
In Mato Grosso, Brazil, the GHGi estimated for the standard cultivation of corn was 302 kg CO$_2$e ton·crop^{-1} (BR-MT1-23) *Figure 4*. BASF technology partially substitutes the crop protection product list in the standard approach. A reduction in GHGi of by 15% was observed with the partial substitution of the standard crop protection products with BASF technologies as available and the addition of a nitrification inhibitor as an additive in the nitrogen fertilizer for corn. The reduction in fertilization by 30% with the use of a third-party biostimulant caused a strong reduction in GHGi (32%) but also a reduction in yield by 9%. Similarly to soy and wheat, a 30% reduction in the fertilization rate was overambitious. In contrast to soy, the preceding crop in the intra-annual soy-corn rotation, the standard practices for corn cultivation include nitrogen fertilization. Therefore, use of a nitrogen stabilizer greatly benefits the reduction of GHGi.

In Rhineland-Palatinate, Germany, the GHGi estimated for the standard cultivation of corn was 250 kg CO$_2$e ton·crop^{-1} (DE-RP2-23). Similar to outcomes in Brazil, a reduction in GHGi resulted from the use of a nitrification inhibitor. In Germany, an optimized fertilizer program informed by a digital DSS resulted in an additional small yield gain (1%), although the yield was higher when the fertilizer program remained unchanged.

Corn field trials, Mato Grosso, Brazil (BR-MT)

In Illinois, United States, the GHGi estimated for the standard cultivation of corn was 167 kg CO_2e ton·crop^{-1}. Corn was grown in 2023 as part of a soy/corn rotation. Following soybean harvest in the fall of 2022, cereal rye was planted as a cover crop and no-till was implemented in the alternative approaches. The rye was terminated prior to planting corn. The alternative approaches utilized a urease inhibitor. In addition, one of the treatments had a split nitrogen application for nitrogen use-efficiency. A slight yield decrease was observed relative to the standard (1% to 3%), which can occur in the first year of a significant management transition, for example to no-till. Furthermore, early season drought conditions resulted in an overall lower than expected yield for all scenarios. However, the impact on GHGi from these minor yield losses was made up for by an improved nitrogen management plan based on the urease inhibitor with rates informed by soil testing, and (in one of the treatments) split applications. These practices led to GHGi reductions between 6 and 12%.

Farming practices that **increase organic carbon storage in the soil** contribute to the reduction of the greenhouse gas intensity of the crop system.

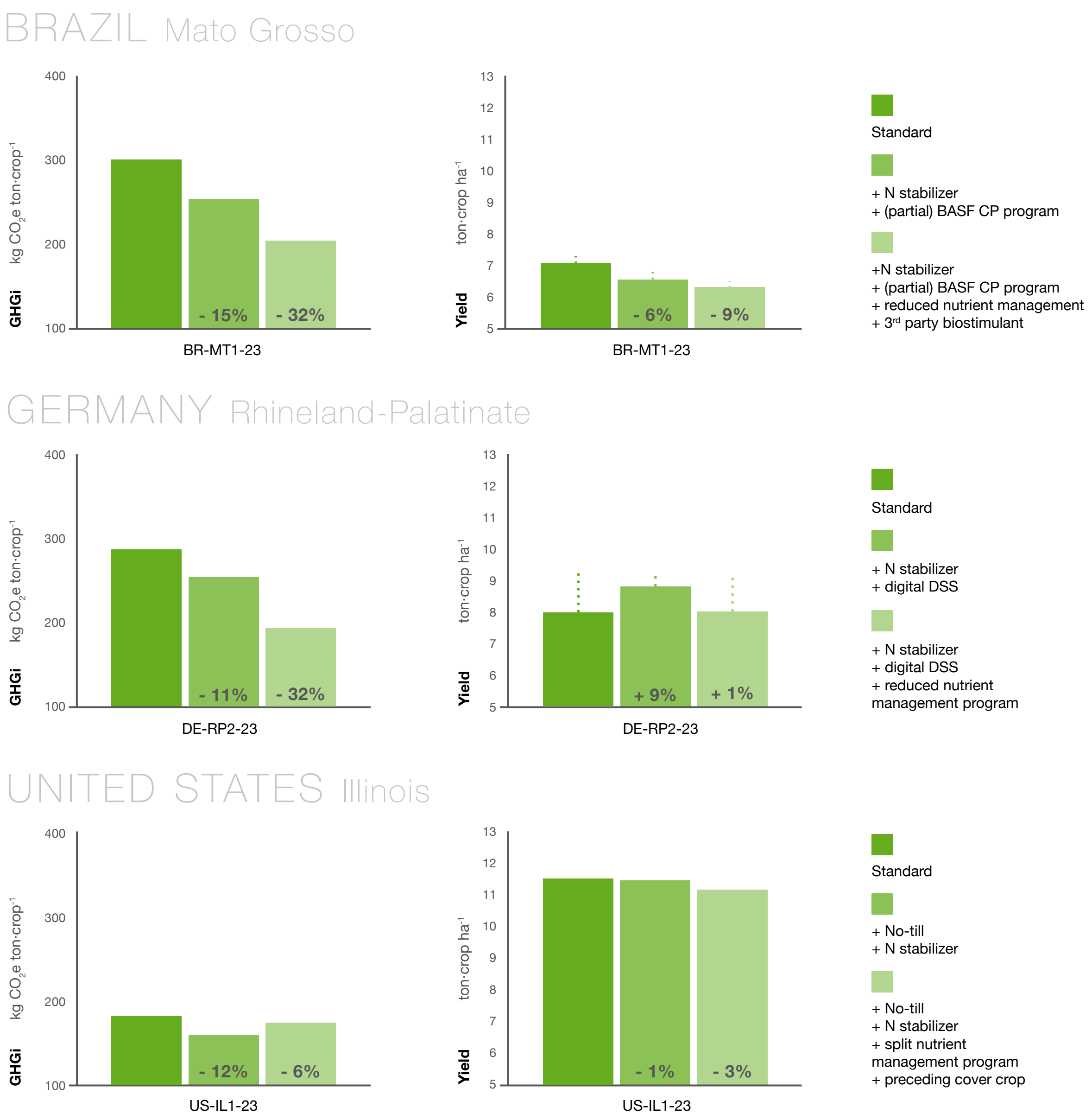


Corn field trials, Mato Grosso, Brazil (BR-MT)

Table 3 Learnings for corn so far.

What works and what does not?	Similar to wheat cultivation, nitrogen stabilizers (nitrification and urease inhibitors) are key technologies to achieve meaningful GHGi reductions in the cultivation of corn. The potential to reduce GHGi by lowering nutrient input rates are of limited value to EU farmers since these production systems already operate at close to the limit below which yields can be jeopardized. However, small gains can still be achieved when the nutrient program is adequately informed by a DSS. In Brazil, a reduction in the fertilization rate by 30% was overambitious since this caused detrimental effects to the yield. In the United States, further improvements to GHGi can be made with split nitrogen applications and customized fertilization rates based on soil sampling.
What are the challenges?	Adverse weather was a challenge to drive down GHGi in corn cultivation due to its impact on yield. Field trials in Illinois experienced drought conditions and in Mato Grosso, heavy rains prior to soybean harvest delayed the start of the corn season immediately after. Soil regenerative practices implemented in the United States showed mild yield declines. This can be expected during a significant management transition but benefits to yield and GHGi are expected to improve with continued implementation over time. Furthermore, pest and disease pressure should be closely monitored as the type of biotic stress can be expected to change following the adoption of reduced or no-till.
What are the next steps?	Field trials for corn cultivation in the United States and in Brazil are planned to be continued to find a better equilibrium between CO_2e reduction while maintaining yield in the medium and long term. We will also investigate co-benefits of climate-smart practices, such as soil health.

Figure 4
For each trial conducted with corn, greenhouse gas intensity (GHGi, left) and yield (right) resulting from a standard approach of the region (dark green) are compared to alternative approaches (CP: Crop Protection, DSS: Decision Support System, N: Nitrogen). Percent changes from the relevant standard are shown for each alternative approach. Greenhouse gas intensity (left) and yield (right) of corn in different treatments in field trials in Mato Grosso (BR-MT1 in 2023), Rhineland-Palatinate (DE-RP2 in 2023), and in Illinois, United States (US-IL1 in 2023). When available, error bars for yield mean show standard deviation. Note: changes in soil organic carbon stocks not currently considered in GHGi estimation.



Rice field trials, Lombardy, Italy (IT-LO)

Rice

The GHGi for standard rice cultivation in our trials in Piemonte and Lombardy, Italy, was compared with various alternative approaches as indicated by the production system requirements and products available. The key learnings for rice are listed in *Table 4.*

In all cultivation scenarios including the standards, BASF traits in seeds cultivated via direct seeded rice (DSR) were used in combination with a digital DSS, as these are readily available climate-smart practices for Italian farmers today. The trials therefore focused on the benefits of reduced water use and seeding rate in rice paddies. Optimization of seeding rate can improve yield and profitability.

In Italy, the GHGi for the standard cultivation of rice was between 962 (IT-PI2-23) and 1146 kg $CO_2e \cdot ton\ crop^{-1}$ (IT-LO1-23), *Figure 5*. A reduction of up to 16% in GHGi was observed in two of the three cases with reduced water use. An optimal seeding rate was an important measure to increase yield. In the scenarios where this practice was adopted, yields were 25% (in IT-PI3-23 as a single measure) to 37% (in IT-LO1-23 as a measure coupled with a reduced water use) higher than in the standard.

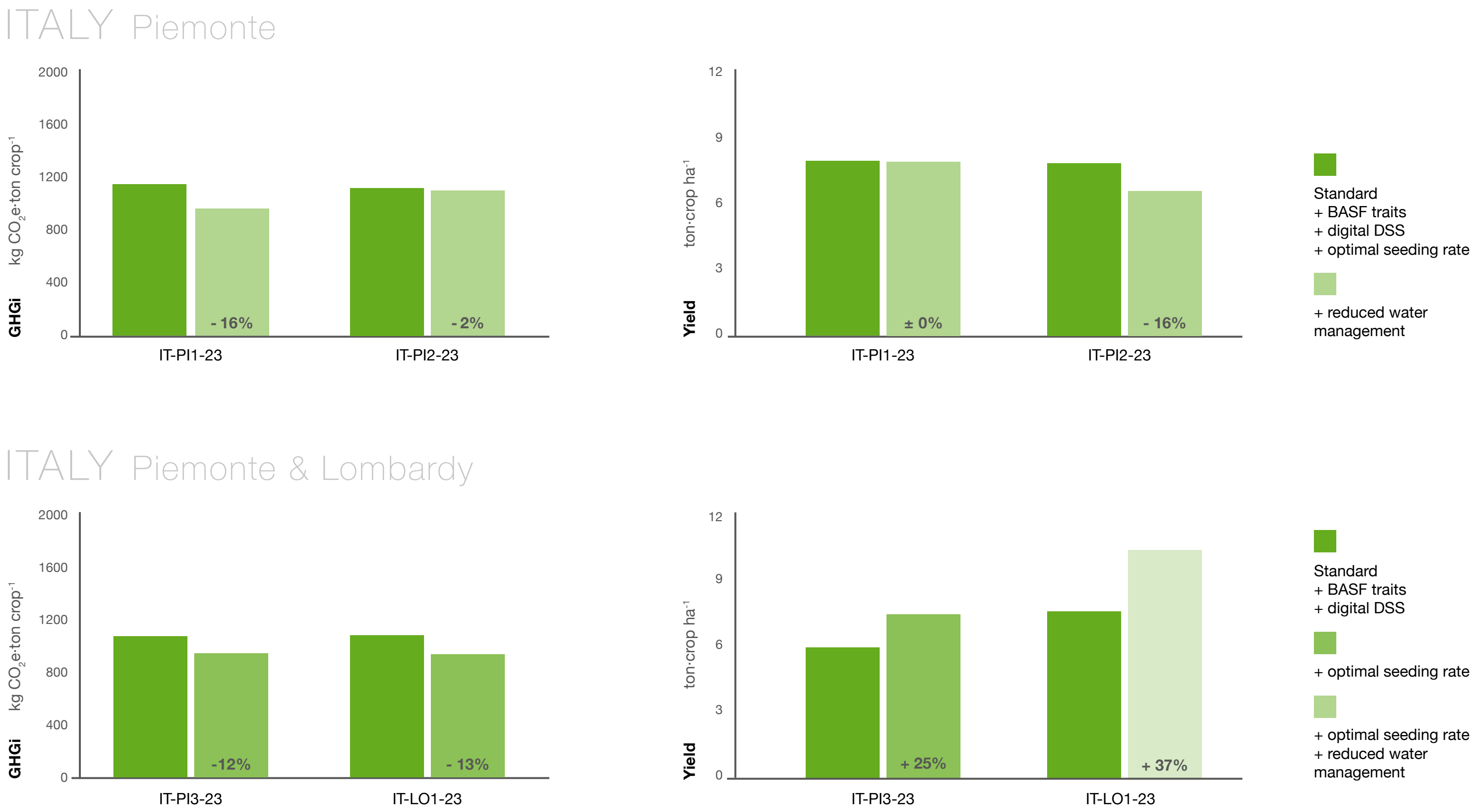
> A **reduced water program** can improve carbon intensity but must be **carefully designed** to not impact yield.


Rice field trials, Piemont, Italy (IT-PI)

Table 4 Learnings for rice so far.

What works and what does not?	Use of direct seeded rice varieties with herbicide tolerance traits in combination with digital DSS insights are standard practices in Italy that already benefit greenhouse gas intensity in rice production. Optimal seeding rate alone has a clear benefit in improving yields while additionally optimizing costs from buying seeds. A reduced water program can add to this GHGi benefit, although this was not observed in all rotations.
What are the challenges?	Rice is a naturally water demanding crop, so a program focused on reducing water use and GHGi needs to be carefully tested and designed.
What are the next steps?	Field trials for rice cultivation are planned to be extended to Asia, the major region for rice production and consumption. New and promising technologies and interventions are emerging for rice cultivation that will also be assessed for improvements to GHGi and yield in our field trials.

Figure 5
For each trial conducted with rice, greenhouse gas intensity (GHGi, left) and yield (right) resulting from a standard approach of the region (dark green) are compared to alternative approaches (CP: Crop Protection, DSS: Decision Support System). Data was collected from field trials in Piemonte and Lombardy, Italy in 2023 (IT-PI1-23, IT-PI2-23, IT-PI3-23, and IT-LO1-23). Percent changes from the relevant standard are shown for each alternative approach. Note: changes in soil organic carbon stocks not currently considered in GHGi estimation.



OSR/canola

The GHGi for standard cultivation of oil seed rape (OSR) in Spain and canola in Canada was compared with various alternative practices indicated by the production system requirements and products available in each country. The key learnings for canola/OSR are listed in *Table 5.*

In Andalusia, Spain, the GHGi in the OSR standard was 795 kg CO_2e ton·crop^{-1}, *Figure 6.* The reduction of the GHGi in the standard by 21% was achieved through a combination of a modified crop protection program, a nitrification inhibitor, and a DSS based on a weather station to inform about disease risk. Similar to corn cultivation in Germany, a reduction in the standard fertilization program informed through a DSS reduced the GHGi by 39%. Yields were considerably higher for both alternative approaches than in the standard (by 28 and 33%).

In Saskatchewan, Canada, GHGi had a wide range between 773 (CA-SK1-22) and 1600 kg CO_2e ton·crop^{-1} (CA-SK3-23). In alternative approaches, GHGi was reduced by 21% in 2022 and by between 20 and 63% in 2023. This was a result of the remarkable high yields in the alternative approaches relative to the standard cultivation of canola in Canada (between 34 and 152% higher). Yield was improved through advanced BASF genetics, improved weed control with BASF herbicides, the addition of an insecticide seed treatment to control flea beetles, the incorporation of zero-till, and the use of a nitrogen stabilizer. It is important to note that this location in Canada has been under drought conditions for the last five years and overall yield potentials have been negatively impacted.

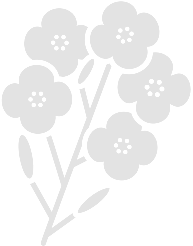
While **seed technologies** and crop protection don’t typically influence emissions, they can contribute to reducing greenhouse gas intensity by **safeguarding yields.**


OSR crop field trials, Andalusia, Spain (ES-AN)

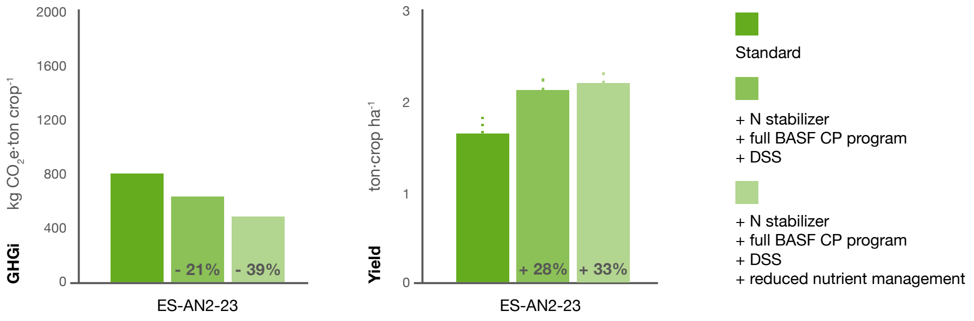
Table 5 Learnings for canola/OSR so far.

What works and what does not?	A comprehensive farm management program with multiple interventions can result in higher yields and lower GHGi in Canada, especially during drought years. Nitrogen stabilizers (nitrification and urease inhibitors) are additional technologies available to farmers in Spain and Canada to achieve additional GHGi reductions.
What are the challenges?	Weather challenges make it difficult to implement successful strategies to reduce GHGi while at least maintaining yields. Canola in Saskatchewan was impacted by multiple dry years, which affected yields relative to previous years.
What are the next steps?	Field trials are planned to continue for canola/OSR cultivation to assess the benefits of alternative practices, including on crop yields and to soil.

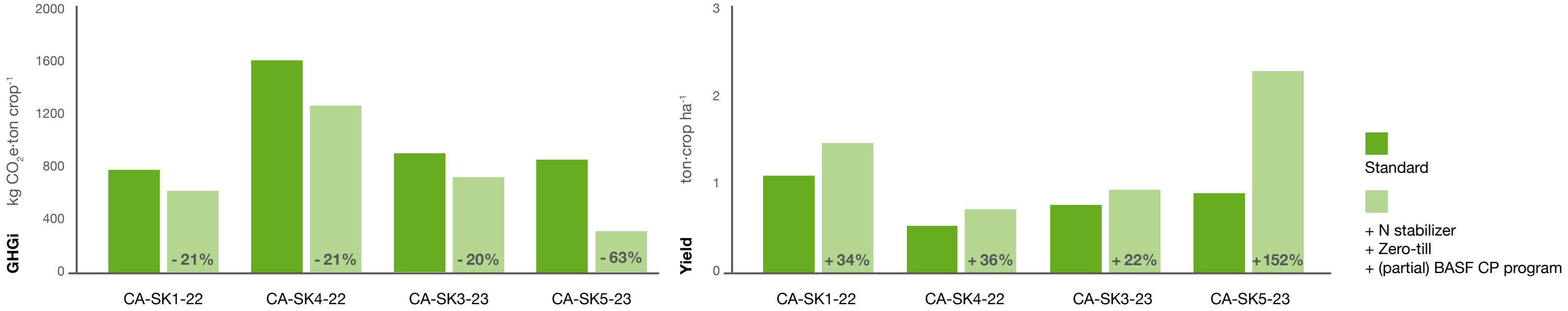
Figure 6
For each trial conducted with canola/OSR, greenhouse gas intensity (GHGi, left) and yield (right) resulting from a standard approach of the region (dark green) are compared to alternative approaches (CP: Crop Protection, DSS: Decision Support System, N: Nitrogen). Data was collected from field trials in Andalusia, Spain (ES-AN2 in 2023) and Saskatchewan, Canada (CA-SK1 and CA-SK4 in 2022 and CA-SK3 and CA-SK5 in 2023). Percent changes from the relevant standard are shown for each alternative approach. When available, error bars for yield mean show standard deviation. Note: changes in soil organic carbon stocks not currently considered in GHGi estimation.



SPAIN Andalusia



CANADA Saskatoon



Relationship between production intensity and GHG emissions

Throughout this report, GHGi has been the key metric, the ratio between GHG emissions and yield (kg $CO_2e \cdot ton\ crop^{-1}$). However, emissions can also be viewed with respect to the amount of crop production for a given area. The former is an indication of the efficiency of the production system, and the latter represents the absolute emissions of the system. *Figure 7* shows the absolute emissions per hectare of the crop production scenarios evaluated in our program (ton $CO_2e \cdot ha^{-1}$).

Some amount of GHG emissions in food production is unavoidable. In our field trials, we observe a slight positive correlation between absolute emissions (ton $CO_2e \cdot ha^{-1}$) and yield (ton $crop \cdot ha^{-1}$), indicating that increased food production tends to be associated with more emissions (*Figure 7*), with the exception of soy. The key for sustainable production of food, fuel, and fiber is that as more is produced the efficiency of production is improved (reduced GHGi). This is why our emissions target was defined with GHGi as the metric.

Figure 7

Relationship between absolute values for yield and for GHG emissions. Data from each crop is represented by letters: “W”, wheat; “S” soy; “C”, corn; “O”, OSR/Canola; “R”, rice. Continuous black line shows a crop-generic positive correlation between yield and GHG emissions. Dotted lines represent the correlations for specific crops. Note: changes in soil organic carbon stocks not currently considered in estimation of GHG emissions.

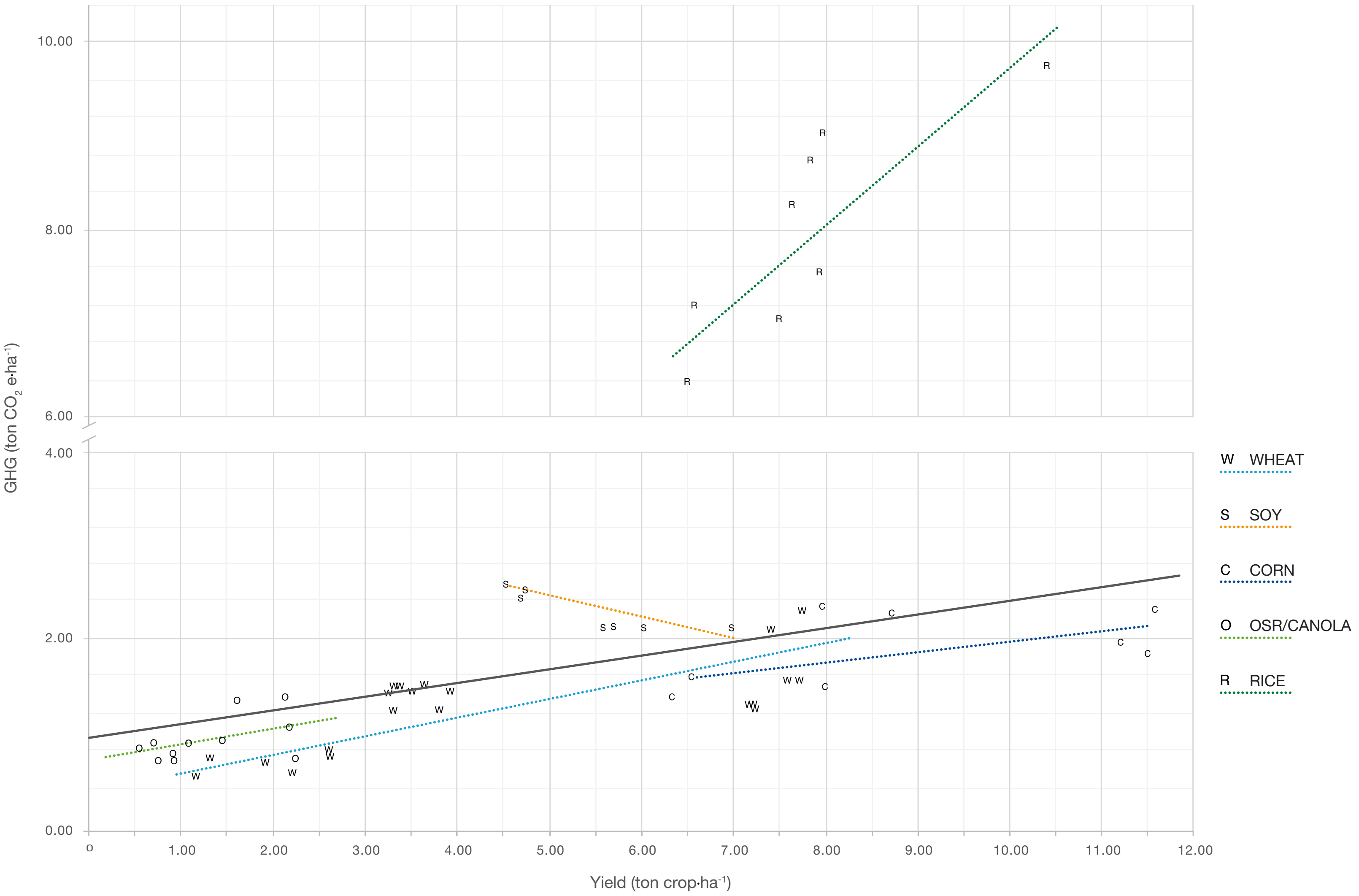
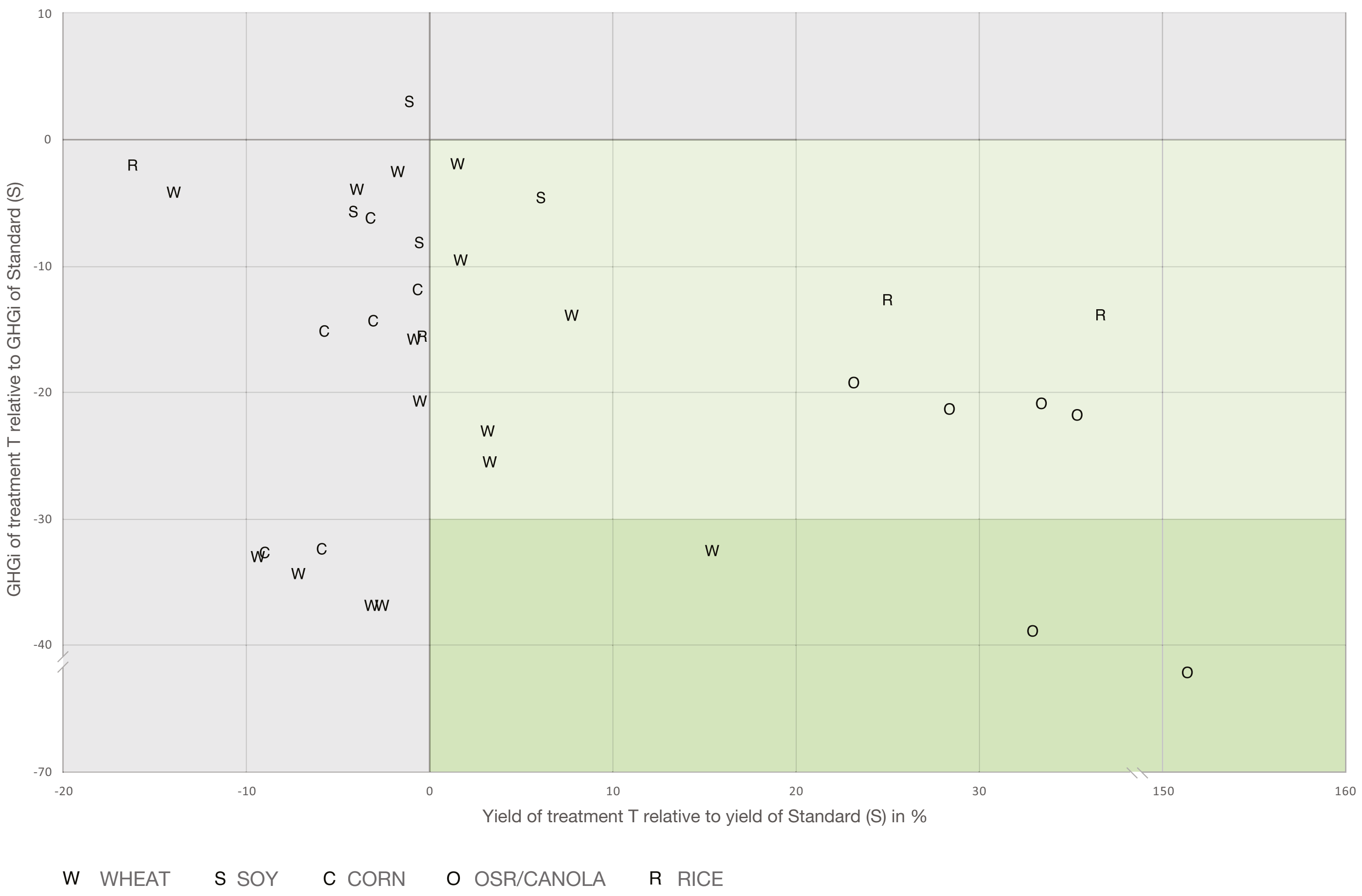


Figure 8
Relationship between changes in yield and in GHG intensity relative to the corresponding standard approach. Data from each crop is represented by letters: “W” wheat; “S” soy; “C” corn; “O” OSR/Canola; “R” rice. The darker green zone shows trials meeting our climate-smart agriculture target, where a reduction of at least 30% in the GHG intensity was achieved without negatively affecting crop yield. The lighter green zone shows trials where GHG intensity was reduced but below the target of 30% and without negatively affecting crop yield. The grey zones represent outcomes where either the GHG intensity increased or the yield decreased relative to the standard approach. The horizontal axis shows the yield of alternative approach (A) relative to standard approach (S) where $\left(\frac{Y_A - Y_S}{0.01 \cdot Y_S}, \%\right)$

The vertical axis shows the GHGi of alternative approach (A) relative to standard approach (S) where $\left(\frac{GHGi_A - GHGi_S}{0.01 \cdot GHGi_S}\right)$

Note: changes in soil organic carbon stocks not currently considered in estimation of GHGi.



Conclusion

It is possible to achieve a 30% reduction in CO_2e emissions in crop production compared with standard farming approaches, although the extent of this reduction can vary greatly depending on the crop and local conditions. There is not a single approach to climate-smart agriculture to successfully reduce emissions. Although we were able to achieve our target in many of the trials in this study, our Global Carbon Field Trial Program continues to advance our understanding of the right combination of practices that allow for meaningful reductions for every crop system in our target.

Our results underscore the importance of leveraging both emissions reductions and yield improvements for reducing the emissions footprint of food production. In many cases increasing yield was a major driver for gains in greenhouse gas emissions efficiency during food production. At the same time, it is crucial to ensure that the improvement in the greenhouse gas intensity does not compromise yield. Preserving yield and decreasing environmental impact is essential, which is why our solutions focus on addressing these challenges simultaneously.

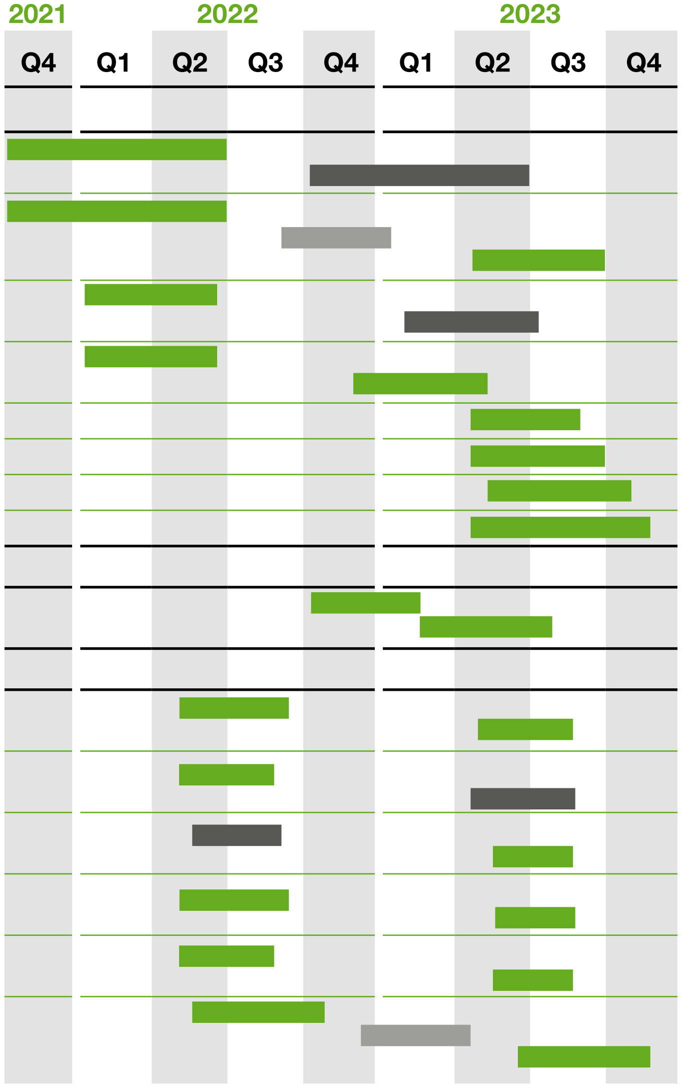
See full summary of main learnings and challenges in the *overview*.

Supporting information

Field trials and crop system view – status report until Q4 2023

BASF Agricultural Solutions conducted multiple trials: in (1) Rhineland-Palatinate (Germany), Andalusia (Spain), Mato Grosso (Brazil), Piemonte and Lombardy (Italy), Canada (Saskatchewan), and the United States (Illinois), see *Supplemental Figure 1*. They took place during multiple seasons and, in many cases, in the same location. In each case, the typical crops of the region were represented, focusing on the five crops defined in BASF's climate-smart agriculture target. Additional crops were included in some trials to respect the typical crop rotation of farming practices in the region of the trial and represented realistic conditions of agricultural production. In addition, the experimental designs vary depending on the trial. Some trials have replicated treatments, while others do not.

Supplemental Figure 1
Overview of field trials with crop rotation cycles completed until end of 2023. Rotations that started in 2023 and continued into calendar year 2024 are not included in this report. Field trials are labeled by rotation IDs in the right column, where locations are abbreviated: Rhineland-Palatinate (RP) Germany (DE), Andalusia (AN) Spain (ES), Piemonte (PI) and Lombardy (LO) Italy (IT), Mato Grosso (MG) Brazil (BR), Saskatchewan (SK) Canada (CA), and Illinois (IL) in the United States (US). Green bars indicate crops defined in the sustainability target and dark grey bars are additional crops that are typically rotation of farmers in the region. Light grey bars indicate cover crops.



	Rotation	Technologies and interventions
EUROPE		
Wheat Barley	DE-RP1	N stabilizer, reduced nutrient management, digital DSS, CP
Wheat Cover crop Corn	DE-RP2	N stabilizer, reduced nutrient management, digital DSS, cover crop, CP
Wheat Chickpea	ES-AN1	N stabilizer, reduced nutrient management, digital DSS, CP
Wheat OSR	ES-AN2	N stabilizer, reduced nutrient management, digital DSS, CP
Rice	IT-PI1	Germplasm*, digital DSS*, optimal seeding rate*, optimal irrigation
Rice	IT-PI2	Germplasm*, digital DSS*, optimal seeding rate*, optimal irrigation
Rice	IT-PI3	Germplasm*, digital DSS*, optimal seeding rate, optimal irrigation
Rice	IT-LO1	Germplasm*, digital DSS*, optimal seeding rate
SOUTH AMERICA		
Soybean Corn	BR-MT1	Germplasm, reduced nutrient management, CP, 3rd party biostimulant
NORTH AMERICA		
Canola Wheat	CA-SK1	N stabilizer, zero-till, CP
Wheat Lentil	CA-SK2	N stabilizer, zero-till, CP
Lentil Canola	CA-SK3	N stabilizer, zero-till, CP
Canola Wheat	CA-SK4	N stabilizer, zero-till, CP
Wheat Canola	CA-SK5	N stabilizer, zero-till, CP
Soybean Cover Crop Corn	US-IL1	Strip-till, No-till, N stabilizer, cover crop

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* Already included in Standard

For each crop and country trial location, we tested realistic alternatives to current standard practices in commercial agriculture with the objective to reduce GHG intensity. This follows the standard Research & Development practices of BASF, where multiple scenarios/treatments are tested to determine which could be realistically implemented by our customers. The approaches which we understand as suitable alternatives are described in this report.

Standard practices vary from country to country and crop to crop. Depending on the context, standards varied with regard to their seed options, crop protection options, fertilizer types and rates, and agricultural practices like soil cultivation. Starting from the standard practices, a sequence of technology adoptions (described in throughout this report) and interventions were tested. Alternative approaches in crop cultivation were developed based on the production system requirements and products available (or soon to be available) in each country. In each trial and for each scenario (the standard practice and the alternative scenarios), the inventory of products and agricultural practices comprising the Standard were designed by regional experts, either from BASF or external consultants. They were meant to depict realistic conditions of their corresponding region and crop. In the case of the alternative scenarios, products listed in the Standard which can be substituted by upcoming BASF products were also included.

For each treatment, the GHG emissions were estimated with AgBalance® following a detailed inventory of agricultural products used, while the crop yield was determined empirically.

For these field studies, the aim is to give recommendations to our customers that optimize yield and reduce emissions. Therefore, we report effect sizes (i.e.,% changes from the baseline yield in fields cultivated with standard practices) and, whenever possible, mean variances. No further statistical analysis was performed.

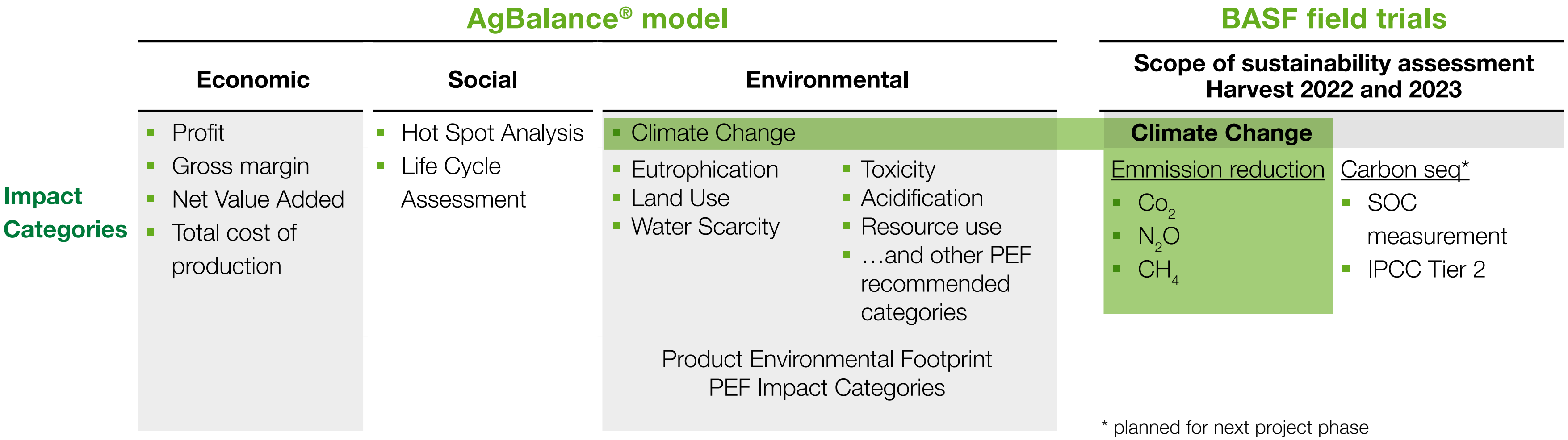
We compared GHG emissions, yields, and GHG intensities across treatment scenarios within the same trial location. We do not compare the field trial outcomes from the same crop grown in different regions, for example soy results from Illinois, United States and Mato Grosso, Brazil, as the context for cultivation is very different. For instance, environmental conditions (including climate) will render different CO_2 mineralization estimates, patterns in soil fertility, correction of soil acidity using lime, and phytosanitary controls.

For the scenarios tested in the field trials, we do not include a financial analysis of the Profit & Loss (P&L) for farmers since the agricultural products or interventions included or excluded in each scenario vary depending on the location, the retail conditions, and the time in which they are purchased by farmers. In addition, we do not speculate what would be the revenue stream to a farmer who implements a scenario and reduces their GHGi since the revenue is dependent on the country's access to credits, subsidies, enrollment in carbon accreditation programs, voluntary carbon market prices, etc.

GHGi assessment by AgBalance®

To assess the GHGi of different crop cultivation practices, the AgBalance® model was used (*Supplemental Figure 2*). The model was developed by BASF to wholistically assess the economic and environmental impact of agricultural systems. In this report, only the climate change environmental impact category is reported although the model includes others as recommended by PEF[16].

AgBalance® was developed in 2010 and has been continuously improved and updated according to accepted methodologies[17,18]. The model follows the concept of life cycle thinking (LCT), applying principles of the LCA framework defined by the International Organization for Standardization (ISO) 14040 and 14044 standards. It is built in GaBi software for LCA environmental and economic results. In 2020, the model underwent validation by the DNV-GL[19], an independent expert in assurance and risk management, and received a statement of assurance with regards to meeting the criteria of adequacy, robustness, reliability, and transparency, which are non-negotiable guiding principles.



	AgBalance® model			BASF field trials	
	Economic	**Social**	**Environmental**	**Scope of sustainability assessment Harvest 2022 and 2023**	
			▪ Climate Change	**Climate Change**	
Impact Categories	▪ Profit ▪ Gross margin ▪ Net Value Added ▪ Total cost of production	▪ Hot Spot Analysis ▪ Life Cycle Assessment	▪ Eutrophication ▪ Land Use ▪ Water Scarcity ▪ Toxicity ▪ Acidification ▪ Resource use ▪ …and other PEF recommended categories Product Environmental Footprint PEF Impact Categories	Emmission reduction ▪ Co_2 ▪ N_2O ▪ CH_4	Carbon seq* ▪ SOC measurement ▪ IPCC Tier 2

* planned for next project phase

Supplemental Figure 2. The AgBalance® tool was used to model emission reduction in different crop cultivation scenarios tested within the global field trials. Changes in soil carbon organic stocks are not included in the estimation of emissions.

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[16] EU 2021/2279: COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.

[17] IPCC. (2019). Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, forestry and other land use.

[18] EU 2021/2279: COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.

[19] DNV GL ASSURANCE STATEMENT by DNV GL Business Assurance, May 18 2020. BASF AGBALANCE V2.0.

LCA Methodology

Life cycle assessment (LCA) is a standardized scientific method for systematic analysis of flows (e.g., mass and energy) associated with the life cycle of a specific product, technology, service, or manufacturing process system to assess environmental impacts. The environmental impacts have been assessed following the ISO 14040/44 standards for environmental impact assessment (ISO 14040)[20] (ISO 14044)[21].

GHG Intensity assessment

Each crop greenhouse gas intensity (GHGi) was calculated according to Product Environmental Footprint (PEF) version 3.0 by the European Commission[22]. Only climate change (emissions, excluding carbon sequestration) is reported here, but not the additional PEF impact categories portfolio shown in *Supplemental Figure 2*.

The most climate change relevant gases for agricultural crop cultivation can be found at the website of the European Commission[23], and are provided here (*Supplemental Table 1*). Impact values are normalized to CO_2, with increasing values indicating an increased impact on climate change.

Supplemental Table 1

Gases included in the climate change impact category

Gas	kg $CO_2e \cdot kg^{-1}$ (PEF 3.0)
CO_2	1
CO_2 biogenic	0
CH_4 biogenic	34
CH_4 fossil	36.8
N_2O	298

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[20] ISO 14040 Environmental Management - Life Cycle Assessment – Principles and Framework. Geneva: International Organization for Standardization.

[21] ISO 14044 Environmental Management - Life Cycle Assessment – Requirements and Guidelines. Geneva: International Organization for Standardization.

[22] EU 2021/2279: COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.

[23] European Platform on LCA | EPLCA. Superseded Environmental Footprint reference packages.

We take into consideration all CO_2, CH_4, N_2O, SF_6, NF_3, and relevant HFCs and PFCs measured by mass and converted them into CO_2 equivalents using the coefficients from PEF 3.020. The total impact is described in CO_2 equivalents. For CO_2, only emission reductions were factored into our GHGi calculation, while the contribution of soil organic carbon stock changes were not.

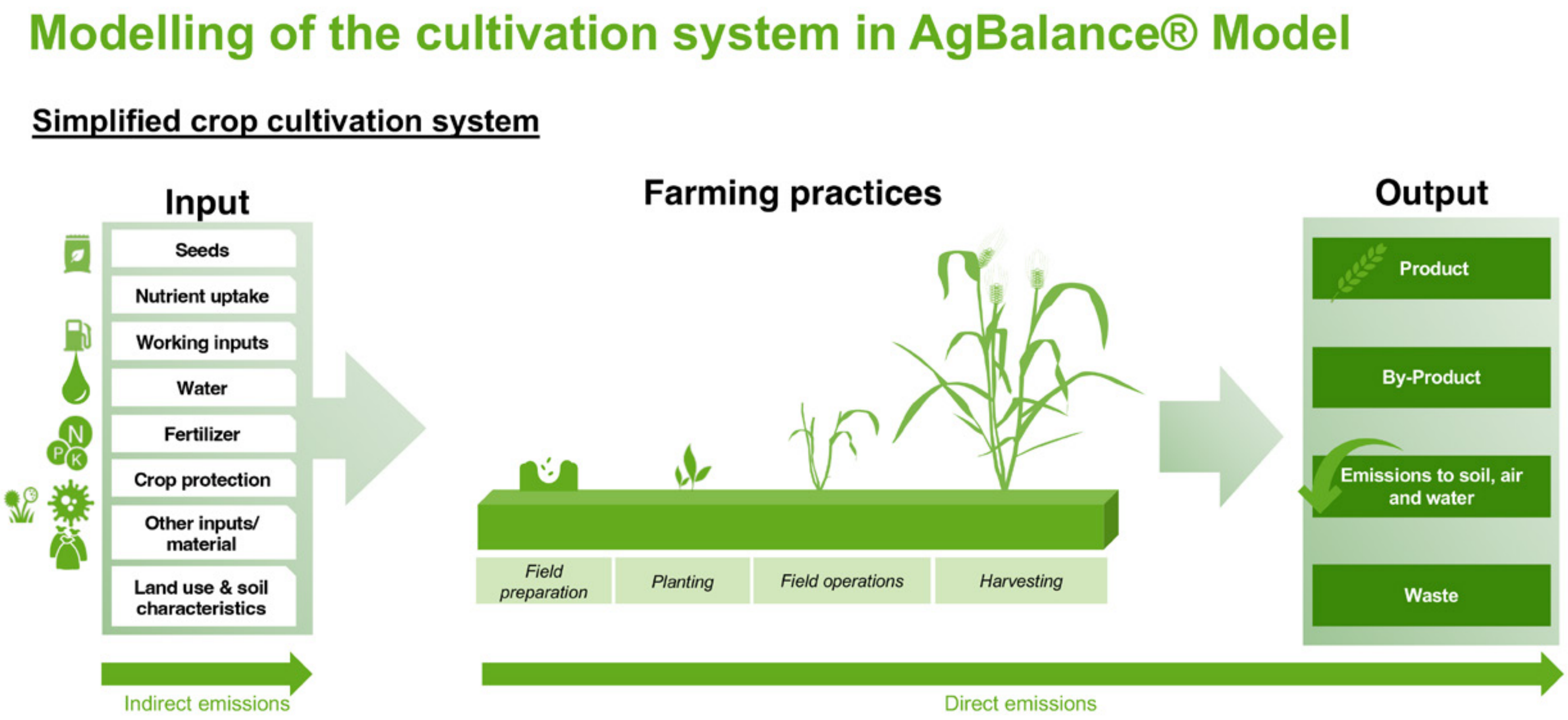
System definition for modeling GHGi

In the field trials, we assess the impact of crop cultivation on climate change by emissions attributed to target crop per kilogram crop (fresh matter), "kg CO_2e/ton crop".

The AgBalance® model uses a simplified cultivation system, where the impact of the emission production of different agricultural products can be analyzed with the same model. It follows ISO 14040/44 to model the life cycle of agricultural products, considering the unit processes with elementary and product flows, performing one or more defined functions within an agricultural cultivation system. In general, the sustainability analysis of AgBalance® model includes processes up to the field border, or following a "cradle-to-gate" approach. A simplified representation of this system, with the respective material inputs, farming practices and outputs included in the AgBalance® model, is shown in *Supplemental Figure 3.*

The cultivation system includes all 'upstream' processes related to the provision of inputs. These inputs are used for farming practices, which comprise all cultivation activities performed to produce the agricultural product and result in other outputs as well. The seed and seedlings, nutrient uptake by the plant, working inputs, water, fertilizer, crop protection, other inputs, land use and soil are considered as inputs to the system. The outputs of the system include the agricultural product, the by-product, emissions to soil, air, water and waste.

Supplemental Figure 3
System boundaries of the generic cultivation system depicted in AgBalance®.



Methods for GHGi determination

Upstream emissions from fertilizer production contributes significantly to emissions in agricultural systems and are used in determining GHGi. Besides fertilizer production, upstream emissions from diesel, seed and crop protection production were taken into account. To calculate the indirect emissions contributions from the production process of the various products used on field, the amount of product used was multiplied with a product specific emission factor from the Sphera database[24]. In the case of fertilizers, mainly datasets from Fertilizers Europe[25] were used.

To determine GHGi, we used the method IPCC recommended[26] in the PEF guidelines. This method provides emission factors for relevant sources of direct GHG emissions from farming practices, such as carbon dioxide from urea and lime fertilizers, nitrous oxide emissions, nitrogen fertilizers, organic or mineral origins, as well as emissions from ammonia, leached Nitrogen and NOx. In the European field trials documented in this report, ammonia emissions were modelled in more detail following the method of EMEP/EEA 2016[27] instead of the IPCC method.

According to IPCC, emissions contributions from land-use changes are excluded from the calculation of GHGi if there was no land-use change in the past 20 years. For the fields used in these studies, each has remained as cropland for at least 20 years. Therefore, we do not factor in emissions contributions from land use change.

Types and source of data inputs to AgBalance® model

The model was given primary data inputs from the various field trials to return GHGi for each cultivation system by harvest. This included information such as the seed variety and amount, the type and amount of fertilizer (with or without additives), the crop protection program, plant specifications, yield data, and weather data. The diesel input amount was adjusted to reflect fuel use on commercial field sizes and conditions rather than the actual amount of diesel used in the trials, which is inflated due to the inefficiencies of mechanical operation of farm equipment in a small field trial design.

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[24] Sphera Solutions, Inc. (2019) LCA Databases. Retrieved from Sphera™ GaBi Solutions.

[25] Fertilizers Europe (2011) Carbon Footprint Reference Values. Brussels: Fertilizers Europe

[26] IPCC. (2019). Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, forestry and other land use.

[27] European Environment Agency (2016) EMEP/EEA air pollutant emission inventory guidebook.

Glossary

Terms are defined according to how they are used in this report.

1. BASF’s Global Carbon Program	is an initiative that promotes sustainable agricultural practices and the decarbonization of agricultural value chains by joining forces with farmers and value chain partners. The objective of the program is to implement and scale our commitment to climate-smart agriculture with the direct involvement of our customers. The program not only helps farmers track implement and profit from their sustainable practices but also measures, monitors, validates, and reports on their carbon savings. This process results in the generation of carbon credits that have been audited and validated by third party auditors, from internationally recognized and reputable certifiers, creating additional revenue streams for farmers through their carbon reduction efforts. This also allows our food value chain customers to track and account for their own carbon savings as they work to decarbonize their value chains.
2. BASF´s Global Carbon Field Trial Program	is an initiative to develop, demonstrate, and recommend climate-smart agricultural practices to reduce emissions and assess our progress towards our emissions reduction target. This program is designed to document the Standard greenhouse gas intensity (GHGi) from each of the crop cultivation systems when farmed under standard practices, identify the main drivers of emissions, and test alternative solutions and practices predicted to enable a reduction in GHGi. Results from the trials carried out for the crops covered in our target as well as other crops typically rotating with these and assessed in different agricultural regions over years. The trials are set up as multi-year effort in our strategic crops.
3. Carbon Farming	is an approach to agriculture that involves managing land in a way that sequesters carbon from the atmosphere and stores it in the soil and reduces the amount of GHGs released during production.
4. Carbon footprint	of crop production refers to the total greenhouse gas emissions that are generated in the cultivation of a crop. This is normally reported as kg $CO_2e \cdot ha^{-1}$.

5. Climate-smart agriculture	is an approach that seeks enhance food security and farmer incomes while building resilience and reducing greenhouse gas emissions. It relies on using agricultural practices and innovation that are adapted to the local climate and soil conditions, while also reducing the impact of farming on the climate.
6. Cover crops	refer to any crop grown to cover the soil and may be incorporated into the soil later for enrichment.
7. CO_2 equivalent (CO_2e)	is the standardized unit to report on the effect of different greenhouse gases (i.e., CO_2, CH_4, N_2O, SF_6, NF_3) on climate and it considers the potency of each gas with respect to CO_2.
8. Crop production system or **crop cultivation system**	describes the conditions under which a crop was grown, including all of the practices and measures implemented to produce a crop through harvest, as well as the region where a crop is grown that accounts for local variables that influence production.
9. Crop residues	are parts of the plant left on the field after harvest, such as stubbles, leaves, seed pods, and roots. They can benefit the crop system by keeping nutrients in the system, maintaining soil moisture, controlling soil weathering and erosion, and suppressing weeds.
10. Crop system	refers to crops that are commonly rotated together in a region, and the sequence they are planted over seasons and years in an agricultural field.

11. Decision support system (DSS)	integrates variables influential to farming outcomes to provide recommendations customized to each local context. It includes, for example, optimal spraying times and rates, seeding rate, nutrient management, and can be available for use at the farm level as a dedicated app or software (digital DSS).
12. Denitrification	is a naturally occurring biogeochemical process where nitrate is transformed to other nitrogen forms, i.e. from nitrate (NO_3), nitrite (NO_2), nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen (N_2), in a series of microbe mediated processes. When denitrification is incomplete, N_2O (a greenhouse gas) is not transformed to N_2 before being released to the atmosphere.
13. Volatilization	is a naturally occurring biogeochemical process where ammonium is transformed to ammonia gas.
14. Greenhouse gas intensity (GHGi)	of crop production refers to the total greenhouse gas emissions that are generated in the cultivation of a crop relative to the yield attained from that cultivation. This is conventionally reported as kg $CO_2e \cdot$ton crop^{-1}. It indicates the efficiency of the crop production with respect to GHG emissions as an estimate of the carbon footprint of the various crop cultivation scenarios, including standard farming approaches and alternatives.
15. Mineralization	is a naturally occurring biogeochemical process mediated by microorganisms where the organic matter (e.g., from crop residues or from soils) decomposes and releases compounds in its inorganic form (e.g. CO_2 and inorganic nitrogen, etc.) to the environment (e.g., soils, atmosphere).

16. Nitrification inhibitor (NI)	refers to an additive in fertilizer that inhibits nitrification. Its purpose is to slow down the transformation of ammonia to nitrate.
17. Urease inhibitor (UI)	refers to an additive in fertilizer that inhibits the activity of urease. Its purpose is to slow down the transformation of urea to ammonia.
18. Nitrogen stabilizer	refers to a generic group of fertilizer additives that regulate the rates of some biogeochemical processes of nitrogen, such as inhibition of nitrification or inhibition of urease activity. Use of these stabilizers aim to preserve nutrients in the soil for longer to improve nitrogen availability to crops and to reduce nitrogen pollution in the atmosphere.
19. No-till	refers to a farming practice in which the soil is left undisturbed by tillage and the residue is left on the soil surface.
20. Soil carbon	stocks refer to the amount of organic carbon stored within soil. They are usually reported as ton C·ha^{-1} for a specified soil depth.
21. Sequestration	of carbon in farm soil is a process in which the stocks of soil carbon increase over time.

External review

BASF commissioned Sphera to review its report titled “Advancing Reliable Climate-Smart Solutions for Farmers - First Results from BASF’s Global Carbon Field Trial Program”.

Our results can be used to develop recommendations of the combinations of products and practices to make meaningful reductions in greenhouse gas intensity of farming in the major crops described here. Sphera’s independent review provided us confidence in our data, methods, and interpretations.

We are pleased that they found our report to be scientifically and technically valid, having transparency and consistency and supported by appropriate and reasonable data.

We have implemented Sphera’s feedback for further improvement of our report and provided responses to address their recommendations regarding ISO compliance formatting and statistical significance.

The goal of this study was farmer recommendations not ISO certification, which is why it is not formatted for ISO compliance. However, we may consider ISO certification status in future reports.

Regarding statistical significance, we report effect sizes (i.e., % changes from the baseline yield in fields cultivated with standard practices) and when possible, mean variances, with no further statistical analysis performed. The significance of our data is understood from the view of our farmer customer, where even small changes in yield can be significant to their business.

A summary of Spera’s review is found on the *following page*. To access the full version, please click *here*.

Critical Review Statement – Executive Summary

Advancing Reliable Climate-Smart Solutions for Farmers First Results from BASF's Global Carbon Field Trial Program

Commissioned by: BASF

Reviewer: Daniel Thylmann (Senior Sector Lead, Agriculture, Sphera)
Dr. Iris Matzke (Senior Manager, Consulting, Sphera)

Sphera concluded that the methods used and documented in the report "Advancing Reliable Climate-Smart Solutions for Farmers - First Results from BASF's Global Carbon Field Trial Program" are scientifically and technically valid. The report is considered sufficiently transparent and consistent. The data used are appropriate and reasonable in relation to the goal of the study, and the interpretations reflect the limitations identified. The main recommendations for future updates refer to statistical testing and transferring the study into an ISO compliant format.

Sphera's statement refers to the full report provided by BASF (overview, technical report, and supporting information) and is only valid if all these sections are made available in combination to interested parties. Sphera's review does not imply an endorsement of the reports' scope or results by the affiliated organization.

Daniel Thylmann	Dr. Iris Matzke
Senior Sector Expert, Agriculture	Senior Manager, Consulting
Sphera	Sphera

Valid as of September 5th, 2024.

Published September 12, 2024

Visit *agriculture.basf.com* for more information on BASF's commitment to climate-smart agriculture.