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Healthier Soils, Lower Costs, Sustainable Yields: How Conservation Agriculture Reaps Benefits.

NABU (Nature and Biodiversity Conservation Union) e. V. | German Association of Conservation Tillage (GKB) | European Conservation Agriculture Federation (ECAF) | Weihenstephan-Triesdorf University of Applied Sciences (HSWT)

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Inhalt

1. Abstract

Agriculture faces major challenges – climate change, biodiversity loss, stagnating yields, and high operating costs. It accounts for around eight percent of Germany‘s direct greenhouse gas emissions, plus 36.5 million tons of CO_2 emissions from soil degradation.

The Land Use, Land Use Change & Forestry sector (LULUCF) has transformed from a carbon sink in 1990 to a source of emissions of 3.6 million tons of CO_2 in 2023. At the same time, not only have insect and bird populations in agricultural areas, but essential soil biological processes, nutrient cycles, and other ecological regulatory mechanisms have also been disrupted. This jeopardizes key ecosystem services such as pollination, biological pest control, water retention, and long-term soil fertility, and thus the very foundations of agricultural production. Stagnating yields and high consumption of inputs further exacerbate these challenges. Conservation Agriculture (CA) offers a sustainable solution by focusing on minimal soil disturbance, permanent soil cover, and diverse crop rotations. These approaches help to regenerate soils, reduce emissions, conserve nature, and increase the resilience of agriculture. While conservation tillage already accounts for 49 percent of agricultural land, the share of Conservation Agriculture remains negligible at only about one percent. Forty percent of arable land is still plowed.

The present study, conducted by NABU in collaboration with the German Association of Conservation Tillage (GKB) – the German branch of the European Conservation Agriculture Federation (ECAF) – and Weihenstephan-Triesdorf University of Applied Sciences (HSWT), is based on data from 17 sample farms in four soil-climatic regions of Germany that have been operating under the CA system for several years. The study examined input consumption, soil health, and yields in four key arable crops.

The results show that switching to CA offers both ecological and economic advantages: up to 75 percent less fuel consumption, up to 20 percent less fertilizer (average 14 percent), up to 70 percent lower ecological and health risks from pesticides (around 50 percent on average), and up to 16 percent higher gross margin per hectare per year. At the same time, improved soil health strengthens biodiversity and soil fertility. In view of the pressing ecological challenges, it is necessary to specifically expand approaches such as CA and regenerative agriculture in addition to promoting organic farming. Unbureaucratic support programs should support the purchase of minimally invasive machinery (e.g., direct seeding technology) and cover crop seeds. Results-based remuneration for ecological services and eco-schemes to promote permanent soil cover through diverse cover crops are crucial to driving forward the transformation of agriculture. Conservation Agriculture can represent a further development for all cropping systems – both for conventional farms and for organic farming. By combining these sustainable farming practices, the long-term resilience of agriculture can be ensured.

2. Current challenges

The German food system and agricultural businesses are facing a multitude of challenges arising from regulatory, social, and environmental requirements. Added to this are economic pressures, increasing pressure from climate change, and structural challenges such as the lack of farm successors. Whether the industry can use the large number of challenges as an opportunity for a fundamental realignment will depend largely on political, economic, and social framework conditions.

2.1 Contribution to greenhouse gas emissions

Agriculture contributes significantly to greenhouse gas emissions in Germany. In 2022, it was responsible for around eight percent of Germany's direct emissions, approximately 61.7 million tons of CO_2 equivalents[1]. In addition, there are 36.5 million tons of CO_2 from agricultural land use, through soil degradation caused by peat soils. The LULUCF sector (land use, land use change and forestry) has changed from being a significant carbon sink with an annual net storage of 40 million tons of CO_2 in 1990 to a source of 3.6 million tons of CO_2 in 2023.[2] Although emissions from German agriculture have been reduced from 80.3 million tons in 1990 to 60.3 million tons, their relative share of total emissions has risen from 6.7 percent to 8.1 percent, as other sectors have reduced their emissions more significantly and more quickly. In view of the German government's climate targets, which envisage net zero emissions by 2045, and the European Union's targets of reducing net greenhouse gas emissions by at least 55 percent by 2030 compared to 1990, the agricultural sector still has considerable efforts to make to make its contribution to decarbonization. Specific climate protection targets have been defined for agriculture in Germany and are laid down in the Federal Climate Protection Act. According to this, the sector's annual emissions are to be reduced to a total of 56 million tons of CO_2 equivalents by 2030, a reduction of around five percent.[3]

2.2 Adaptation to climate change

More frequent and intense extreme weather events, such as droughts, heavy rainfall, and storms, are affecting yields and threatening the existence of many farms. These weather extremes lead to yield fluctuations and make long-term planning considerably more difficult for farmers. The protection of soil and water resources is of crucial importance in this context. Soils that have been damaged by intensive cultivation lose their ability to store water, which weakens their resilience during periods of drought and increases the risk of erosion and flooding during heavy rainfall events. The progressive degradation and loss of organic matter further reduce soil fertility, jeopardizing agricultural production in the long term.

2.3 Contribution to biodiversity loss and natural resources

In addition, biodiversity loss in agricultural landscapes is intensifying. Various studies, such as the large-scale study Various studies, such as the large-scale study[4] by iDiv and the 2024 fact check on biodiversity[5], show that insect and bird populations in agricultural areas have declined dramatically since 1990. However, these results do not reflect the losses already suffered before 1990. The ongoing loss of biodiversity and the effects of climate change threaten ecological functions that are essential for agriculture in the long term, such as pollination, pest control, and soil fertility, and therefore pose a significant threat to economic stability, food security, and nature.

2.4 Dependence on and rising costs of inputs

Dependence on high quantities of inputs poses not only an ecological risk but also an increasing economic risk to agricultural businesses. The continued high use of fertilizers, pesticides (Fig. 1), and energy has contributed to increased productivity for several decades, but in the long term, this strategy is reaching its limits. The intensification of agricultural production has increased dependence on synthetic inputs, thereby exacerbating both ecological and economic problems. In recent years, the prices of inputs have risen sharply, particularly due to global crises and geopolitical tensions, such as the war in Ukraine. Energy-intensive production processes, especially for fertilizers, have significantly increased operating costs. The prices of fuel, which represent one of the largest cost factors in agriculture, have also risen sharply. These developments are weighing on the profitability of many farms and making the sector more vulnerable to external shocks. While price increases for grain and other agricultural products in 2022 were sufficient to partially offset the additional costs, it is questionable whether these developments will remain sustainable for all agricultural businesses in the long term.[6]

YIELD AND PESTICIDE SALES

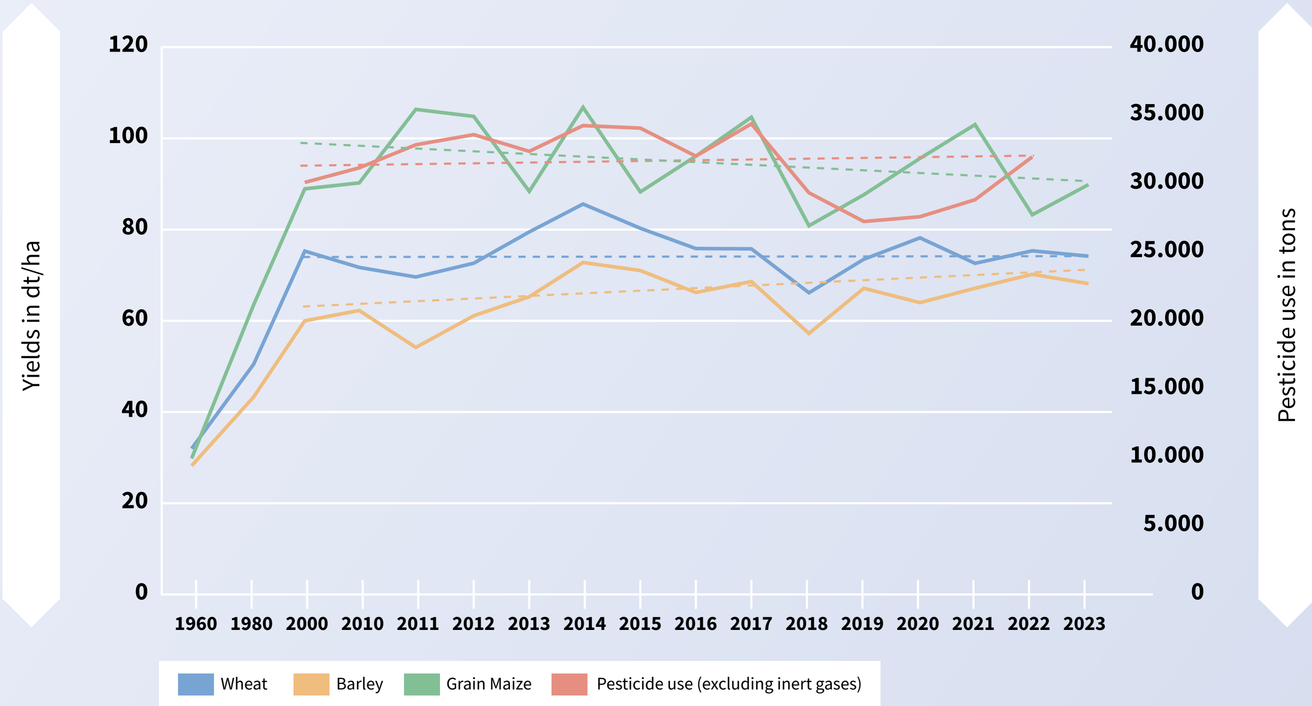


Figure 1: Comparison of the yield (dt/ha) of selected arable crops and pesticide sales (in tons, excluding inert gases) in Germany since 2000 (including trend lines)

2.5 Political and social requirements

In addition to the climate targets already mentioned, there is also growing political and social pressure on agriculture to implement sustainable changes. National and European strategies, such as the European Green Deal, the Farm to Fork Strategy, the national strategy on biodiversity and the German government's future plant protection program presented in 2024, set ambitious targets. According to the Farm to Fork Strategy, these include, for example, reducing the use of plant protection products by 50 percent and fertilizer consumption by 20 percent by 2030. The Future Plant Protection Program also continues to aim to halve the use of synthetic chemical plant protection products in Germany by 2030.[7]

Although there is currently no binding legal framework for more sustainable agriculture, there are political guidelines designed to promote sustainable practices in agriculture. They reflect a growing, scientifically based expectation that the industry will operate in a more environmentally friendly and resource-efficient manner. Since many of these guidelines have not yet been translated into applicable law, progress depends heavily on voluntary initiatives, economic incentives, and the general commitment of the agricultural sector.

2.6 Competition for land

Agricultural land in Germany is facing increasing competition for space due to many different demands. In addition to settlements and transport infrastructure, the expansion of renewable energies, especially photovoltaic systems, is also contributing to this competition. At the same time, a significant proportion of agricultural land is used for feed production, which puts further pressure on direct food production.

Geopolitical crises, such as the war in Ukraine, further highlight the importance of a stable and regionally oriented food supply, which further increases the pressure on limited agricultural land.

At the same time, social expectations are also rising: Consumers are increasingly demanding healthier and more sustainably produced food that considers animal welfare, resource conservation, and biodiversity. These expectations are putting agricultural supply chains and businesses under increasing pressure to adapt their production methods and make them more transparent – even without legal obligations.

3. Conservation Agriculture as a solution?

A promising approach in agriculture that aims to address the complex challenges mentioned above is regenerative practices and principles – in particular, conservation agriculture, known internationally as Conservation Agriculture (CA). This cultivation system, which has been implemented worldwide for a long time and has been scientifically studied, combines measures that can promote the preservation of soil fertility, the protection of ecosystems, and the reduction of synthetic inputs. Conservation Agriculture is based on three central principles: minimal soil disturbance through minimally invasive sowing, permanent and species-rich soil cover, and increased plant diversity.

A previous NABU study conducted in collaboration with the Boston Consulting Group[8] already made it clear that implementing these principles would lead to significant economic savings for agriculture in terms of energy efficiency, while at the same time reducing greenhouse gas emissions and strengthening the resilience of the agricultural system in view of the interlinked nature, climate, and biodiversity crises. This study analyzes this in greater depth for the first time and empirically compares data from CA farms with comparative data from conventional farms at the local level.

4. Clarification of terms

Many terms for different forms of soil cultivation have now become established in public discourse. These are sometimes used incorrectly as synonyms but refer to different cultivation methods and/or systems. It is therefore important to first provide some clarity and differentiation. The term “no-till farming” refers to a cultivation method in which the soil is not tilled at all. This method is also known as “direct seeding” or “direct sowing.”

Tillage (on 40 percent of German arable land) with a plow has the highest tillage intensity due to the disturbance of the topsoil to a depth of up to 35 cm. In terms of area, this category includes parts of conventional agriculture as well as organic farming, which currently accounts for about seven percent of arable land in Germany.[9] Organic farms predominantly rely on tillage and, in some cases, on conservation tillage.

Conservative tillage, often with mulch seeding (on 49 percent of German arable land), does not use plows and exclusively uses non-turning equipment such as cultivators, disc harrows, or PTO-driven machines. It is divided into two intensity levels: with and without loosening. Without loosening, the working depth is a maximum of 15 cm, with loosening the working depth can be as much as 25 cm.[10] When sowing, usually by means of mulch seeding, a minimum soil coverage of 30 percent or the incorporation of 112 dt of organic matter/ha is required. This method is used by both conventional and organic farms on around half of Germany‘s arable land. It should be noted that conservation tillage is not part of Conservation Agriculture.

Direct seeding (“no-till” or “zero tillage”) has so far been used on just over one percent of arable land and goes one step further by not tilling the soil at all and sowing the crop directly. This requires adjustments in farm management and special machinery, but it has several advantages, such as better trafficability in wet conditions, less disturbance to soil structure and soil life, and reduced labor intensity and emissions.

Conservation Agriculture (CA) goes beyond simple direct seeding by representing a holistic approach to the management of agricultural ecosystems with the aim of improving and sustaining productivity, increasing profits, and enhancing food security while preserving and improving the resource base and the environment. According to estimates, the complete CA system is currently practiced on one percent of arable land. Data on the number of farms that use CA is limited. The term Conservation Agriculture is defined by the Food and Agriculture Organization of the United Nations (FAO) and is characterized by the practical application of three interrelated principles:

1. **Minimal soil disturbance**
   Direct seeding and avoiding tillage reduce erosion, promote microbiological processes, stabilize soil structure and improve soil health in the long term.

2. **Permanent soil cover**
   Permanent soil cover—ideally through living vegetation— reduces erosion, cools the soil, promotes microorganisms, stabilizes the soil, and improves nutrient and pest management.

3. **Diversification of plant species**
   Diverse crop rotations and mixed crops strengthen the soil microbiome, optimize nutrient supply, and suppress pests. They promote microbial activity, build organic matter and increase the resilience of the system.

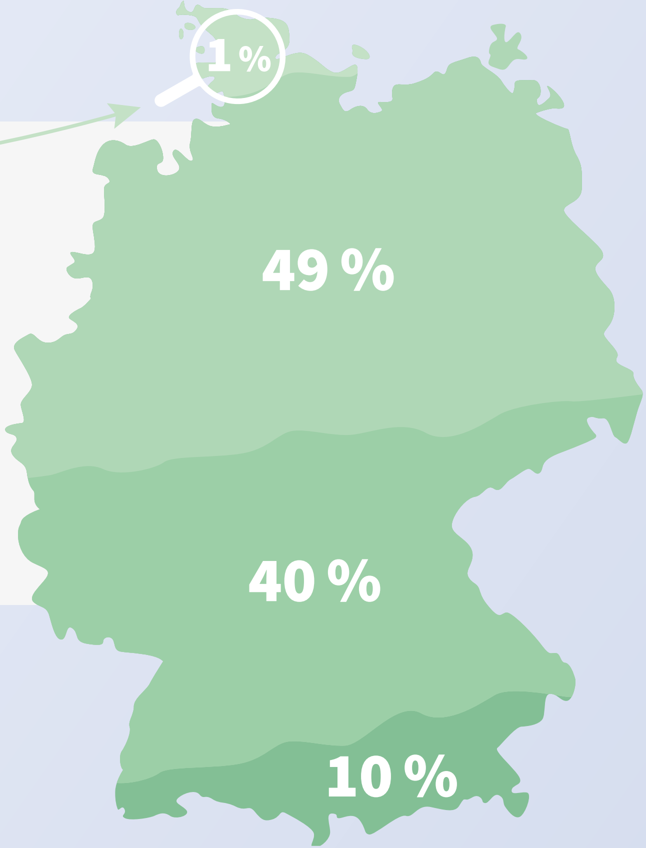
SOIL TILLAGE ON ARABLE LAND IN GERMANY 2022/2023

1 % **DIRECT SEEDING**
(No-Till, including also **Conservation Agriculture**)

49 % **CONSERVATION TILLAGE**
(e. g. Cultivating, Harrowing, Strip-Till Method)

40 % **INVERSION TILLAGE**
(Ploughing)

10 % **NO TILLAGE**
(Perennial vegetation)



Source: Statistisches Bundesamt © 2024 BLE

Figure 2: Soil cultivation on arable land in Germany in 2022/2023. Source: Statistical Federal Agency, 2024.

Regenerative agriculture (RA) is an adaptive farming system that is becoming increasingly important, especially in conventional agriculture. Although it shares common principles with conservation agriculture, the two differ in their objectives and the range of practices applied.
While RA is defined by its goal of restoring and improving soil fertility, biodiversity, and carbon storage in the long term, CA primarily describes the methods by which this goal can be achieved. CA is based on three basic principles: (1) minimal tillage, (2) permanent soil cover, and (3) increased plant diversity. These three "basic principles" are also part of regenerative agriculture, which is broader in scope and integrates additional ecological and operational aspects, such as the sensible integration of animal husbandry. Essential is the interplay of the simultaneous implementation of all principles to exploit synergistic effects in CA and RA.

Digression: Conservation Agriculture and organic farming – similarities and differences

Organic farming is a legally defined cultivation standard that specifically avoids the use of synthetic chemical inputs. It encompasses both crop production and animal husbandry, which is bound by high animal welfare standards and relies on close integration with the land. The criteria of organic farming allow for approaches of Conservation Agriculture (CA), but do not prescribe them. CA can thus be a further development of conventional and organic farming systems, which, by focusing on soil rest and reduced intervention, protects the soil in the long term and regenerates it with plant diversity.

In general, there are important overlaps between organic farming and CA, particularly in terms of wide crop rotations and species-rich cover crops, which are considered core elements for promoting soil fertility and biodiversity in all approaches. Mechanical soil cultivation in organic farming, which is often necessary due to the absence of synthetic chemical pesticides for weed control, contrasts with the minimal soil disturbance in conservation agriculture and is a key challenge for the integration of CA in organic farming. However, there are already organic farms in Germany today that successfully implement this combination and innovations such as biopesticides or alternative methods of weed control, which facilitate the transfer of CA principles to organic farming.

5. Selection of farms and data collection

This study is based on a group of 17 sample farms that fully implement the Conservation Agriculture (CA) system. The study is scientifically supported by a technical evaluation from the Weihenstephan-Triesdorf University of Applied Sciences (HSWT). To thoroughly analyze the changes and effects of the Conservation Agriculture method, farms were specifically selected that have been using CA since at least 2019 – that is, for at least three full harvest years. This makes it possible to capture not only short-term effects, but also medium-term developments. Since the use of inputs such as pesticides and fertilizers This makes it possible to record not only short-term effects, but also medium-term developments. Since the use of inputs such as pesticides and fertilizers depends heavily on weather conditions, the harvest years 2020, 2021, and 2022 were chosen as the study period. For each year, data was collected from three fields per farm to compensate for fluctuations in weather conditions and achieve reliable results.

The analysis deliberately focused on the main crops grown in agricultural practice: winter wheat, winter rapeseed, maize, and winter barley. This selection ensures that the results are broadly transferable and meet the challenges encountered in practice. Specialized crops were excluded to ensure comparability. For the selected crops, the most important operating parameters — plant protections products, nitrogen fertilization, fuel, soil health, and yield — were analyzed and subsequently evaluated.

To take regional differences and agronomic diversity into account and to be able to compare the results, the farms were clustered according to their geographical location, soil and climatic conditions, and regionally specific comparative data from an agricultural advisory service was used. More detailed information on this can be found in the appendix.

OVERVIEW OF THE PARTICIPATING FARMS

Cluster according to soil-climatic conditions

HIGH-YIELD AGRICULTURAL AREAS I
High soil qualities, high precipitation,
high yield potential

HIGH-YIELD AGRICULTURAL AREAS II
Heavy soils, high precipitation

SANDY, DRY SOIL
Lower soil qualities, low yield potential

LOAMY OR SANDY SOIL
Sufficient precipitation

Figure 3: Overview map of participating farms and corresponding clustering of similar soil and climate conditions

Digression: Risk and toxicity of plant protection products

Plant protection is one of the key challenges facing conventional agriculture. Figure 1 in Chapter 1 shows that sales of plant protection products in Germany have remained at a consistently high level of over 30,000 tons per year since 2000. However, the way in which plant protection is carried out differs greatly between conventional agriculture and Conservation Agriculture. In this study, we use the term Plant Protection Products (PPPs) as defined in EU Regulation 1107/2009. In parts of the text, the term 'pesticides' is used interchangeably, particularly in reference to their environmental impacts.

Plant protection products are divided into different categories and each fulfill specific functions:

- → **Herbicides:** weed control before and after sowing to reduce competitive pressure on crops.
- → **Insecticides:** Protection against harmful insects such as aphids or grain borers.
- → **Fungicides:** Prevention or control of fungal diseases, such as mildew and rust fungi.
- → **Growth regulators:** Control of plant growth, for example by shortening the stems for greater stability.

Assessment of the risk posed by plant protection products used

There are currently many different indicators and approaches for measuring the risk or toxicity of plant protection products. The common indicators for the use of plant protection products, such as the treatment index (German: Behandlungsindex, BI), provide information on the quantity and intensity of application, but are unsuitable for assessing the effectiveness of risk mitigation measures. They do not take into account the specific toxicity or risk of individual active ingredients, which means that a comprehensive assessment of the potential effects is lacking.

Other common indicators:

- → The Harmonized Risk Indicator (HRI) is used for reporting by individual member states at the European level..
- → The SYNOPS indicator, like the treatment index, is used as an assessment criterion in the German National Action Plan for Plant Protection (NAP).
- → The Pesticide Load Indicator (PLI), which has been tested in Denmark over several years and is used as a basis for taxation, stands out due to its comparatively simple applicability.

The Pesticide Load Indicator (PLI) was chosen for this study. The PLI has been used as the basis for taxing plant protection products in Denmark since 2013 and is based on a potential risk assessment. Due to this sound basis, it is considered legally secure and has been extensively tested.[11] The PLI is thus the first risk indicator in Europe that both assesses the health and environmental risks of plant protection products and enables their taxation.[12] The PLI is composed of three equally weighted sub-indicators: environmental behavior, ecotoxicity, and risk to human health.[13]

The active substances or products in the individual subcategories are evaluated within the framework of the PLI in comparison with the approved active substance with the most unfavorable properties. The maximum value, also known as the reference value, dates from 2007 and is interpreted as the "worst case." The ratio between the active ingredient and the reference value is therefore always between 0 and 1. If an active ingredient has only half the toxicity of the reference active ingredient, its pesticide load or toxicity is also reduced by 50 percent. Since the reference active ingredient remains unchanged, even if it is possibly banned or not reapproved, comparability is maintained, which enables long-term monitoring of risk development.[14] It is crucial to consider these values in relation to each other. A single value alone does not provide a definitive statement about the danger of a plant protection product. Rather, it must be interpreted in the context of the specific conditions of use and local environmental sensitivity.[15] The Julius Kühn Institute (JKI) has adjusted the toxicities of the PLI for meaningful transferability to Germany, as the Danish indicator is weighted much more heavily toward bee tolerance insecticides. These adjusted PLI values now exceed the range of 0 to 1, but the comparability of the data remains intact. Subsequently, the toxicity values were multiplied by the application rate to calculate the total toxicity applied.

6. Influence of Conservation Agriculture on the use of inputs

The figure on the following page shows the reduction in toxicity using plant protection products in Conservation Agriculture (CA) compared to conventional agriculture in four crops: winter wheat (WW), winter rapeseed (WRA), maize, and winter barley (WG). Toxicity is measured using the Pesticide Load Indicator (PLI), which quantifies the environmental and health impact of pesticide use.

The risk resulting from the use of pesticides varies among different crops. While maize typically requires less pesticides, winter wheat, winter rapeseed, and winter barley show significantly higher toxicity. These differences result from the specific growing conditions and challenges of each crop. Winter rapeseed, for example, is particularly dependent on the use of insecticides due to its high pest pressure. Similarly, growth regulators and fungicides are often used in winter wheat because of its susceptibility to disease, to maximize yields and prevent disease. For this study, extensive application patterns were also created to represent farms that practice less intensive farming methods. The patterns were provided by an agricultural consulting firm and are also based on average treatment patterns for the four regions and crop types. The analysis showed that the extensive application patterns were only slightly less toxic in comparison, as they do not include growth regulator and fungicide applications in April and May.

6.1 Consumption of plant protection products in comparison

The analysis shows a significant reduction in the use of plant protection overall. Toxicity was reduced by up to 71 percent in the farms studied. On average across all crops, toxicity was reduced by up to 52 percent compared to conventional application patterns.

A particularly striking result of the analysis is the significant reduction in herbicide toxicity in the crops studied, especially in winter wheat, winter rapeseed, and winter barley. It is often assumed that direct seeding systems necessarily use large amounts of herbicides to achieve stable yields and effective weed control. Our study shows that the full implementation of CA-systems reduces the herbicide toxicity applied by over 50 percent in Conservation Agriculture.

REDUCTION OF TOXICITY IN CONSERVATION AGRICULTURE

Comparison of pesticide use between Conservation Agriculture and conventional agriculture across different crops

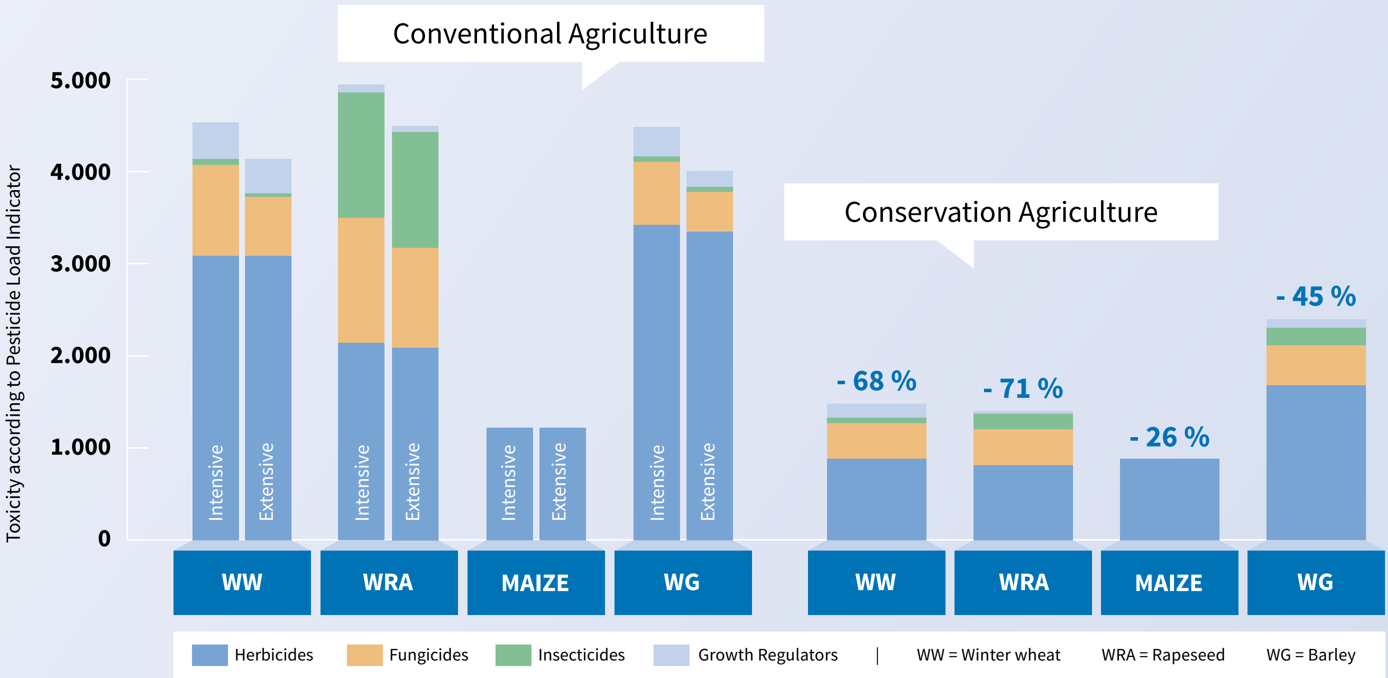


Figure 4: Comparison of the risk and toxicity of the pesticides used in the respective crops between conventional and Conservation Agriculture

The results also show a significant reduction in the use of fungicides and insecticides in Conservation Agriculture. Fungicide toxicity was reduced by 62 percent in winter wheat, 72 percent in winter rapeseed, and 39 percent in winter barley. No fungicides were used in maize, which is why there was no reduction here. The use of insecticides shows a similar picture. In winter rapeseed, a significant reduction of over 80 percent was observed.

The analysis reveals three key observations regarding the reduction of pesticide toxicity in Conservation Agriculture: active ingredient substitution, less frequent applications, and lower application rates. In the farms studied, less toxic active ingredients were used in some cases, the number of applications per crop year was lower overall, and the quantities applied were significantly reduced. These reductions are particularly pronounced in crops with high pesticide requirements, such as winter wheat, winter rapeseed, and winter barley, while they are less pronounced in maize.

6.2 Nitrogen use in Conservation Agriculture

The analysis shows a significant reduction in nitrogen consumption in Conservation Agriculture compared to the conventional variant. Across all crops, the total reduction in nitrogen use is 15.2 percent. Particularly significant savings were recorded for winter wheat at 23.3 percent, winter barley at 16.4 percent and winter rapeseed at 9.1 percent. In corn, the reduction varied greatly depending on the region, with an overall reduction of 6.7 percent, although in some regions, such as the south and east, savings of up to 20.2 percent were achieved.

6.3 Fuel consumption

The fuel consumption of the various agricultural management systems was analyzed using the KTBL calculator (standardized tool for calculating agricultural production costs and resource use in Germany, KTBL tool) and shows significant differences. These are mainly due to the intensity of soil cultivation and the number of passes required and account for a significant portion of the emissions balance. Further information on the exact assumptions can be found in the appendix.

In the conventional plowing system, diesel consumption is highest at 64.26 liters per hectare. This high consumption results from several work steps, such as plowing, cultivating, harrowing, and sowing with a rotary harrow and seed drill, each of which requires additional passes. Mulch sowing reduces fuel consumption to 56.31 liters per hectare by eliminating plowing and using a deep cultivator instead. However, the number of work steps and passes remains largely unchanged, resulting in moderate savings compared to the plowing system.

NITROGEN USE IN CONSERVATION AGRICULTURE

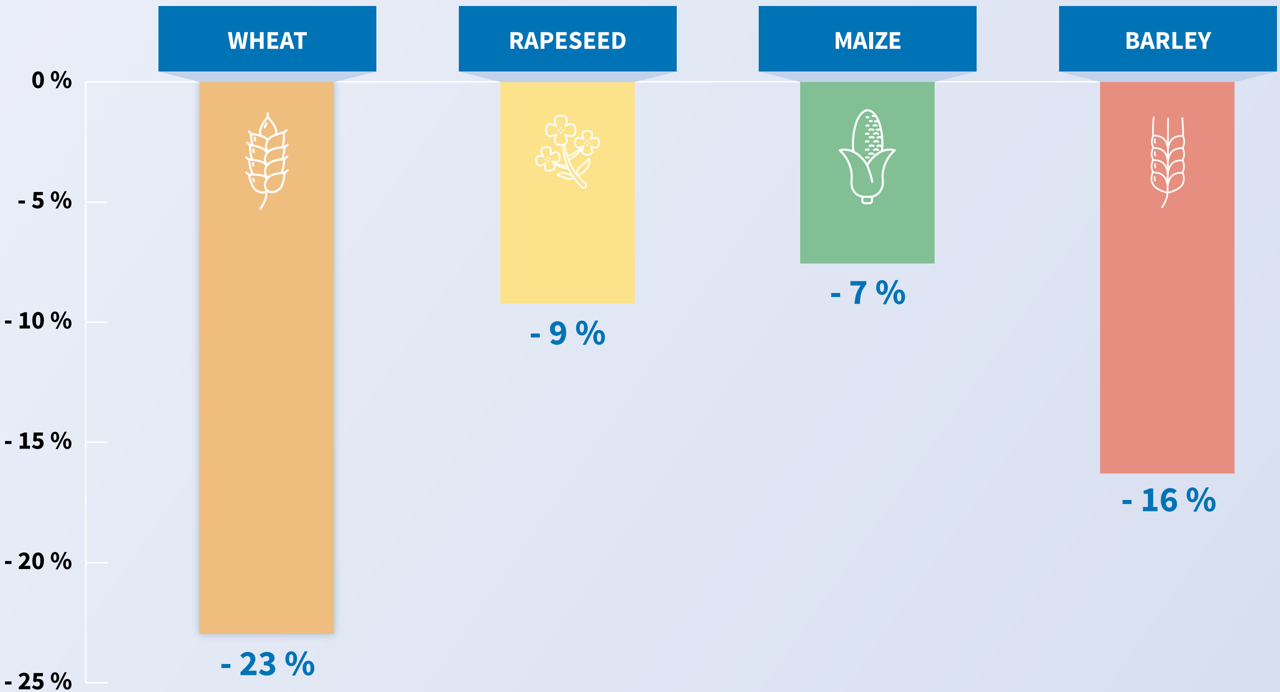


Figure 5: Nitrogen use in Conservation Agriculture compared with conventional farms

Management	Working time requirement (hours/ha)	Diesel requirement (l/ha)
Plow variant	3.28	64.26
Mulch seeding	3.06	56.31
Direct seeding (CA)	1.33	16.21
Reduction plowing --> Direct seeding (CA)	59.45 %	74.77 %
Reduction mulch sowing --> Direct sowing (CA)	56.54 %	71.21 %

Table 1: Working hours and diesel requirements for different soil management methods, evaluation by the German Agricultural Society (KTBL)

Direct seeding has the lowest consumption, at only around 16 liters of diesel per hectare. This system almost eliminates tillage, as sowing takes place directly into the undisturbed soil. In addition to direct seeding, only one additional pass with a crop protection sprayer is required, which significantly reduces the total number of passes. The savings in fuel consumption amount to 74 percent when switching from plowing systems to direct seeding and 71 percent from mulch seeding to direct seeding.

7. Soil Biodiversity and Soil Health

Soil quality is a key indicator of the long-term productivity and sustainability of agricultural systems. To better understand the impact on soil biology, an indicator was used that specifically evaluates biological parameters of the soil, thus providing a more holistic picture of soil health.

The BIOTREX Soil Health Test is a method for assessing the biological properties of soils that was developed specifically for practical use in agriculture. This test enables farmers and consultants to quantify the activity and diversity of microorganisms living in the soil, which are crucial for nutrient cycles, disease suppression, and improving soil structure.

The index used by BIOTREX to measure microbial performance (Fig. 6, left) combines various aspects of microbial activity into a single, easily interpretable value. It enables the comparison of soils from different locations and soil types and provides a solid basis for assessing soil functionality and biodiversity. Further information on the method can be found in the appendix. The results show that microbial performance in the soils examined under Conservation Agriculture was significantly higher (331,052 ± 8,896) than in the sampled conventionally farmed soils in the immediate vicinity of the test farms. This difference is statistically highly significant.

IMPROVED SOIL HEALTH IN CONSERVATION AGRICULTURE

Comparison of microbial performance and functional biodiversity between Conservation Agriculture and conventional agriculture

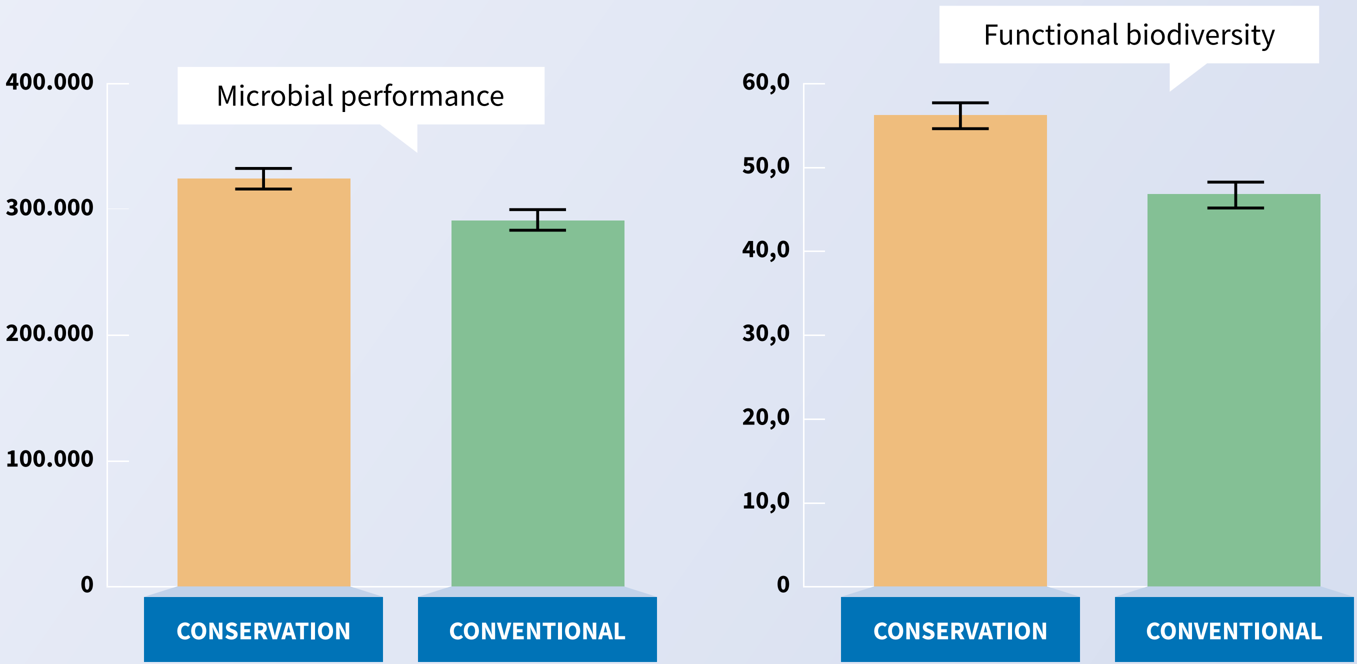


Figure 6: Microbial performance (left) and functional soil biodiversity (right) compared in conservation and conventional agriculture

Functional biodiversity (Fig. 6, right) measures the diversity of ecological functions of the soil microbiome and focuses on functional rather than taxonomic diversity. Here, too, the soils of the sample farms analyzed in the study show significantly better values with an average functional biodiversity of 56.1 ± 2.30 than conventionally farmed soils (45.9 ± 2.75) in the immediate vicinity. This difference is also statistically significant.

In addition, the soil samples were subjected to visual earthworm counts using a spade sample to assess the biological activity of the soil. The results show that the CA areas had on average up to 3.8 times more earthworms than the conventionally farmed areas. Further information on sampling can be found in the appendix.

The increased functional biodiversity in CA soils shows that practices such as minimal soil disturbance, permanent soil cover, and maximized plant diversity not only promote microbial communities but also improve biological diversity. Soils with higher functional biodiversity are better able to perform key functions such as nutrient cycling, disease suppression, and carbon storage. In contrast, the lower functional biodiversity in conventional soils indicates that this form of cultivation is less supportive of the development and diversity of functional microbial groups.

8. Yields in Conservation Agriculture

Finally, the effects of Conservation Agriculture on the yields of various crops were analyzed in comparison to conventional farming. There were clear differences, which had both positive and, in specific cases, negative effects.

The results show that yields in CA systems are generally more stable and, in many cases, even higher than in conventional farming systems. It is particularly striking that CA areas perform better in years with extreme weather conditions, such as prolonged periods of drought. Crops such as winter wheat and maize showed a significant increase in yield. However, the yield effects are highly dependent on the region and the crop. For example, winter rapeseed performed worse in some CA systems, which is associated with specific pest and disease problems. The participating farmers at the farms studied reported some yield losses in winter rapeseed due to higher pest pressure from rapeseed beetles, which contributed to an average yield reduction of around eight percent. On the other hand, the yields of winter barley, winter wheat, and especially maize were better.

While conventional agriculture often faces significant yield losses in years with extreme weather conditions, yields in CA systems remain relatively constant.

RELATIVE YIELD CHANGE UNDER CONSERVATION AGRICULTURE

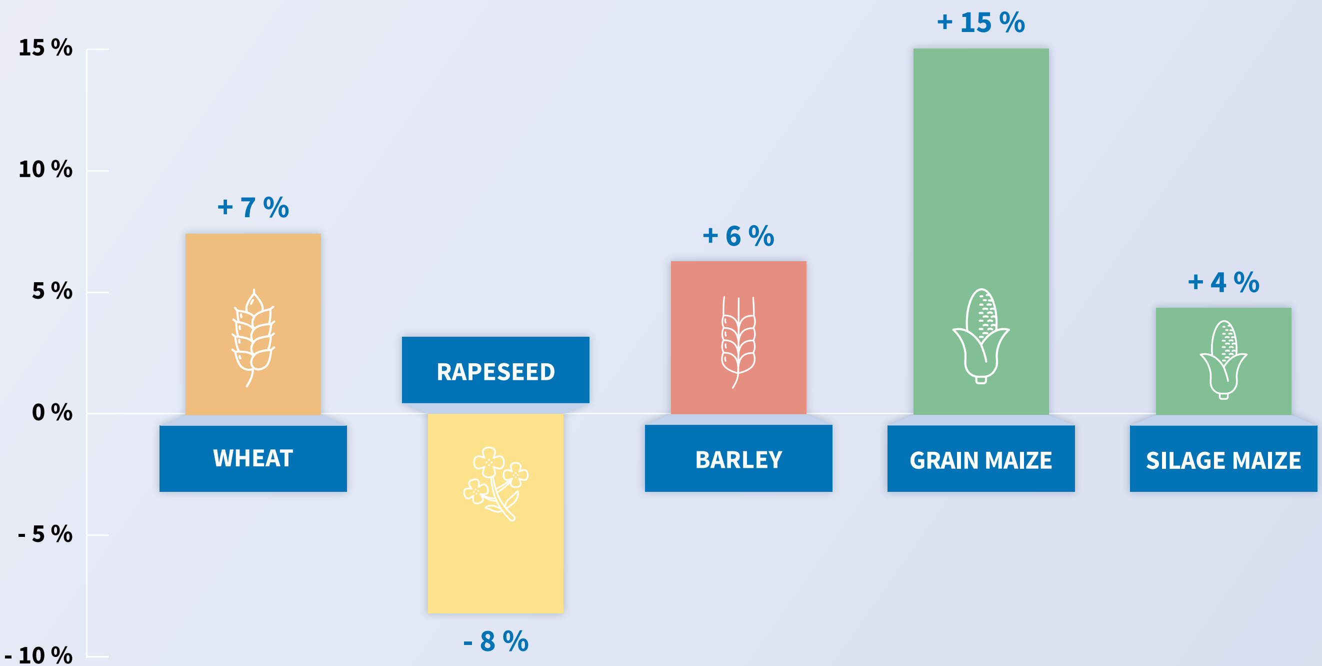


Figure 7: Relative change in yield under Conservation Agriculture

9. Economic Evaluation

9.1 Effects of the transition to Conservation Agriculture on the use of inputs and yields

The transition from conventional agriculture to Conservation Agriculture (CA) is a complex and highly context-specific process that presents both challenges and immense opportunities. This transition path, i.e. the shift from intensive, input-heavy farming methods to resource-conserving and more sustainable practices, requires careful planning and a step-by-step adaptation of farming methods and farm structures. While the benefits of CA are evident in the long term in the form of more stable yields, increased soil fertility and reduced operating costs, the transition period is often marked by uncertainties – for example, regarding possible yield losses.

The following graph illustrates the changes identified in the analysis that occur during this transition to the full implementation of Conservation Agriculture and shows how the use of inputs such as fuel, nitrogen, herbicides, fungicides, and insecticides develops in comparison to yields. Based on expert interviews with the participating farmers in the study, it illustrates how quickly various inputs can be reduced and how yields can stabilize and even improve over time. This example of the transition path provides valuable insights into the dynamics of the conversion.

Immediately after the conversion, yields may decline slightly, which is partly since experience must first be gained with the new agricultural system. From the third year onwards, a slight increase in yields to 105 percent can be seen, which is due to the increasing soil fertility because of undisturbed soil and the establishment of a stable soil ecosystem. Fuel consumption drops dramatically immediately after conversion as a result of the introduction of direct seeding and the associated minimal tillage. Already shortly after conversion, only around 30 percent of the original fuel consumption is observed. The corresponding number of working hours also decreases.

Te use of insecticides is also declining rapidly. In the first year after the changeover, only half of the original amount of insecticides was used, and in the second year only 25 percent. After about five years, insecticides were almost eliminated. The use of fungicides is also showing a slower but steady decline, as soil health improves and natural mechanisms for suppressing plant diseases take effect.

INPUT USE & YIELD DEVELOPMENT IN CONSERVATION AGRICULTURE AFTER TRANSITION

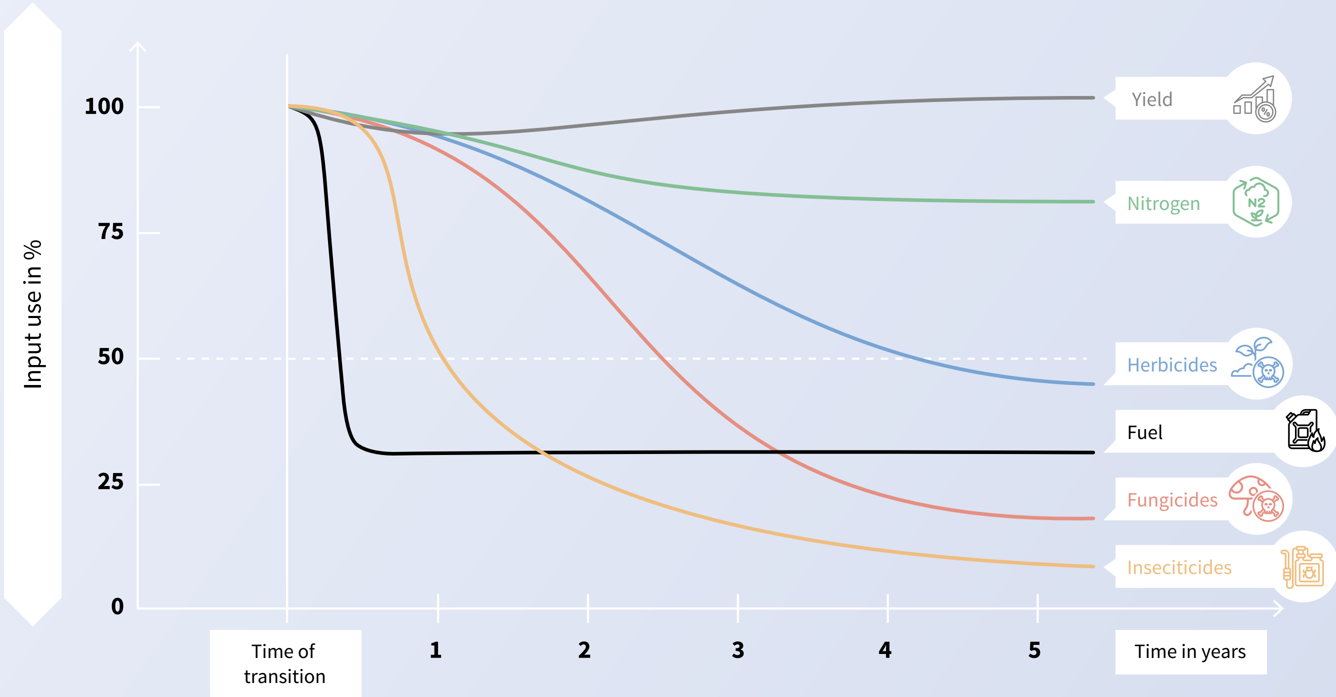


Figure 8: Use of operating resources and yield development in Conservation Agriculture after conversion

The use of herbicides, which often play a central role in weed control, also decreases after the conversion. Nitrogen consumption remains stable in the first year before it also begins to decline in the following years. Finally, after five years, a significant reduction in input consumption can be observed in all categories. Yields remain stable and even increase slightly in the long term, while input consumption is significantly reduced.

It is important to note that the use of inputs and their reductions presented here, based on expert interviews, do not yet represent stable equilibria five years after the full transition to Conservation Agriculture. The reduction in inputs can, of course, continue beyond the five-year period. The evaluation suggests that the longer the sample farms studied implemented Conservation Agriculture, the less fossil fuel inputs had to be used.

However, a context-specific transition period to the full implementation of Conservation Agriculture requires careful planning and targeted adjustments, especially in the initial phase.

9.2 Calculation of the gross margin: Comparison between conventional agriculture and Conservation Agriculture (CA)

To illustrate the economic effects after the conversion phase to Conservation Agriculture, scenarios for gross margin accounting were created. These are based on a case study from farms in the eastern region (scenario: farm has been operating under the CA system for over ten years), which are representative of the conditions in this region. Both conventional agriculture and two variants of CA are considered – one farm with the same yield and one with a five percent increase in yield. Assumptions about operating costs, yield values, and specific savings were included in the analysis.

The results show that Conservation Agriculture offers significant economic advantages through reduced inputs and more efficient production methods. Even with the same yield, savings in fuel, fertilizers, and pesticides enable a higher gross margin. If the yield is increased by five percent, as is often the case in the long term due to improved soil fertility and resilience, the gross margin increases significantly.

Other common indicators:

Parameters	**Conventional agriculture**	**CA (same yield)**	**CA (+ 5% yield)**
Yield (t/ha)	8	8	8.4
Winter wheat price	234.25	234.25	234.25
Revenue	1,639.75	1,639.75	1,721.74
N fertilizer costs	192	138	138
Plant protection costs	126	60	60
Cover crops	-	110	110
Diesel costs	112	42	42
Personnel costs	55	32	32
Total: Variable costs (€/ha)	485	382	382
Gross margin (€/ha)	1,154.75	1,257.75	1,339.74
Increase	**-**	**+ 8.9 %**	**+ 16.02 %**

Table 2: Gross margin calculation for a CA example farm in two different scenarios compared to a conventional

This gross margin calculation illustrates the potential economic differences between conventional agriculture and two scenarios of Conservation Agriculture (CA). It shows how the latter can offer economic advantages through reduced input costs and potential yield increases.

In comparison, the yield in the conventional system and in the first CA scenario is 7 t/ha, while in the second CA scenario a yield increase of five percent to 7.35 t/ha is assumed. This increases the revenue from 1,639.75 €/ha in the conventional system and in the first CA scenario to 1,721.74 €/ha in the second scenario.

There are significant differences in operating costs: Fertilizer costs in the CA system are reduced by around a quarter (from 192 €/ha in the conventional system to 138 €/ha in both CA scenarios) thanks to the more efficient use of nitrogen fertilizers. The use of fertilizers and pesticides is significantly reduced through sustainable practices such as crop rotation and permanent soil cover with diverse cover crops including legumes, which significantly reduces the need for fertilizers and pesticides. The use of fertilizers and pesticides is significantly reduced through sustainable practices such as crop rotation and permanent soil cover with diverse cover crops containing legumes, thereby lowering costs from 126 €/ha to 60 €/ha. At the same time, the CA system incurs additional costs for cover crops (110 €/ha), which contributes to soil health and nitrogen fixation in the long term.

The Conservation Agriculture system also offers potential savings in labor and machinery costs: Diesel costs are reduced from 112 €/ha to 42 €/ha through the introduction of direct seeding and reduced tillage. Labor requirements are also reduced, lowering personnel costs from 55 €/ha in the conventional system to 32 €/ha in the CA system.

These savings result in significantly lower variable costs in the CA system despite the additional costs for cover crop mixtures (382 €/ha compared to 485 €/ha). This is reflected in a higher gross margin: While this is 1,154.75 €/ha in the conventional system, it rises to 1,257.75 €/ha (+8.92 percent) in the first CA scenario and to 1,339.74 €/ha (+16.02 percent) in the second scenario with increased yield.

The savings in operating resources and the possibility of increased yields make it clear that Conservation Agriculture offers not only ecological advantages but also economic incentives – especially in combination with improved yield stability under extreme weather conditions such as drought and wet periods.

10. Utilize natural cycles

The ecological resilience of agricultural systems depends crucially on how agroecosystems – and especially soils – are managed: the less they are disturbed, the more continuously they are covered, and the more diverse the plants and roots that grow in them, the healthier they become. These principles are interlinked, reducing the use of external inputs, promoting biodiversity, improving water management, and maintaining the fertility and productivity of the agroecosystem.

10.1 The three interrelated principles of Conservation Agriculture

Sustainable soil management promotes biological processes that stabilize soil structure in the long term and increase resilience to environmental stressors. Earthworms, microbes, and fungi ensure stable aggregate formation, improve water infiltration, and increase nutrient availability.[16] Reduced mechanical tillage of the soil, the finely tuned interaction between soil particles, organic matter, and microbial communities remains intact.[17] Healthy soil has a distinct crumb structure that regulates both water and air balance. The activity of soil organisms creates stable macropores that conduct water deep into the soil and prevent waterlogging. Earthworms contribute significantly to soil aeration and the mixing of organic material, making the decomposition processes of plant residues more efficient. Studies show that minimally tilled soils have higher levels of organic matter and better-connected nutrient cycles in the long term.[18]

Year-round ground cover acts as a natural protective layer that protects the soil from erosion, evaporation, and extreme heat. Studies show that continuous ground cover can reduce soil temperature in summer by up to 33°C and reduce the erosion rate by up to 90 percent.[19] [20] It not only stabilizes soil life but also serves as a valuable source of carbon inputs into the soil, which contributes to the long-term enrichment of organic matter.[21] High organic matter improves the storage capacity for water and nutrients, which increases the soil‘s resistance to dry periods.[22] Mulch layers and root exudates support microbial life, which in turn improves nitrogen and phosphorus availability.[23] Especially in regions with low rainfall, continuous soil cover has a positive effect on water retention capacity and significantly reduces irrigation requirements.[24] Plant diversity is essential for a resilient agricultural system.

Compared to narrow crop rotations, broader cultivation spectra are less susceptible to pests, diseases and nutrient depletion. Studies show that diversified crop rotations can increase yields and significantly reduce the need for chemical pesticides.[25]

Different plant species interact with soil microbes, stabilize nutrient flows, and reduce the risk of diseases and pests. Crop rotations with nitrogen-fixing legumes promote soil fertility and thus reduce the need for synthetic fertilizers.[26]

Increased microbial diversity contributes to the formation of symbiotic networks in which plants can exchange nutrients in a targeted manner. These interactions between plants and microorganisms have long-term positive effects on soil fertility and significantly reduce nutrient loss through leaching.[27]

Diversely used soil remains ecologically active, promotes carbon storage, and adapts better to changing environmental conditions.[28] Deep-rooted plants support humus formation, promote microbial activity, and contribute to carbon storage through permanent ground cover and species-rich cover crops.[29] This also improves water absorption.

10.2 Promotion of biodiversity

Reducing mechanical soil disturbance and maintaining continuous soil cover with mulch or, better still, living vegetation provides habitats for a wide variety of species, especially soil-dwelling organisms, insects, and small mammals. Studies show that CA systems lead to a significant increase in soil biodiversity as they promote beneficial microorganisms, fungi, and arthropods. Soil cover through cover crops and mulch creates a microclimatic balance that supports the number and diversity of soil organisms. Pollinators, such as wild bees, benefit from the continuous vegetation cover and flowering catch crops, as they find year-round food sources and nesting opportunities. Avoiding plowing and cultivator tillage also protects ground-nesting pollinators and thus contributes to the long-term stability of ecosystem services in agriculture.[30]

Furthermore, CA systems have been shown to significantly increase bird populations in agricultural areas. Studies show that the number of bird species in CA farming systems is up to 29 percent higher than in conventionally farmed fields. Ground-nesting birds, such as skylarks and partridges, benefit from the low mechanical disturbance and continuous vegetation cover, which increases their nesting opportunities and survival rates. Individual density can increase by more than 300 percent in CA areas, as continuous ground cover provides more food sources and protection from predators.[31]

10.3 Positive influence on the water balance

Conservation Agriculture has been shown to have a positive impact on the water cycle and microclimate of agricultural land. Improving soil structure through minimal intervention, humus formation, and promotion of soil organisms significantly increases water infiltration and storage.[32] Soils with a high proportion of organic matter can store many times their own weight in water, which ensures a more stable water supply, especially during dry periods.[33] Studies show that water storage capacity can be significantly increased by raising the humus content.[34]

In addition, the promotion of stable soil aggregates improves the infiltration of precipitation water, resulting in less surface runoff and erosion.[35] This contributes to more water reaching deeper soil layers, promoting groundwater recharge and stabilizing the regional water regime. The combination of mulch cover and continuous soil cover also reduces the evaporation rate and prevents the upper soil layers from drying out, which also has a positive effect on the landscape water balance.[36] This leads to greater local cooling and helps to regenerate small-scale water cycles, which is particularly important in areas with increasing temperature peaks and droughts. This is of crucial importance.

The positive effects of sustainable soil management not only impact biodiversity and water management but also have a direct impact on the productivity of agricultural ecosystems. Healthy soil forms the basis for higher net primary production (NPP). NPP measures the rate at which plants produce biomass through photosynthesis and thus reflects the efficiency of carbon sequestration and overall soil fertility. High NPP indicates a productive and healthy ecosystem, while low NPP may indicate degradation processes such as soil erosion or nutrient loss. This primary production determines how much plant biomass is available for agricultural use and is therefore a key measure of the long-term productivity of agricultural land.

Studies show that higher microbiological diversity in the soil and better nutrient availability correlate directly with increased NPP in arable and grassland areas.[37] In particular, the presence of nitrogen-fixing bacteria, mycorrhizal fungi, and beneficial soil microbes increases the efficiency of plant nutrition and leads to better biomass production. At the same time, data from European agricultural land shows that soils with higher organic matter and more stable soil structures are more productive over longer growing seasons because they can store and provide water and nutrients more efficiently.[38]

Factors such as soil erosion, nutrient loss, and compaction can significantly reduce NPP, thereby jeopardizing long-term productivity. The implementation of conservational farming methods that protect the soil and promote its biological activity therefore plays a decisive role in securing the long-term performance of agroecosystems and ensuring sustainable yields. Measures such as minimal soil disturbance, continuous soil cover, and diverse crop rotations not only ensure higher soil fertility but also strengthen the adaptability of agricultural systems to climatic changes.

11. Political demands and recommendations for action

The EU‘s current Common Agricultural Policy (CAP), which is largely based on area-based subsidies that are largely independent of performance, is seriously inefficient despite the considerable financial resources involved. Every year, around €55 billion flows into European agriculture, of which over €6.3 billion in EU funds will be available in Germany until the end of the current CAP funding period. However, due to their low steering effect, these considerable investments do not lead to the resolution of the pressing economic, ecological, and social challenges. Conditions for receiving funds have recently been relaxed again. The loss of biodiversity, the decoupling of natural cycles, and the social and economic weakening of rural regions remain largely unaddressed. To meet these challenges, a reorientation of agricultural subsidies and policy is needed that focuses on the health of agricultural ecosystems – especially soils – and includes an intelligent mix of legal standards and targeted financial rewards. The following aspects of rewarding are particularly recommended for scaling up Conservation Agriculture:

→ Agricultural measures such as intercropping, minimally invasive sowing techniques, and the use of special equipment necessary for the transition to regenerative cultivation systems, should be given priority financial support. These cultivation practices not only promote soil health and the functioning of natural cycles but also reduce dependence on synthetic inputs such as chemical fertilizers and plant protection products.

→ Equally important are support programs, such as eco-schemes, which address the remuneration of soil cover and associated ecological services.[39] Such approaches not only contribute to improving soil fertility and water management but also support production-integrated pest and disease control. The long-term ecological benefits of these measures also strengthen the economic resilience of farms and offer added value for society.

→ The approach of results-oriented remuneration and alignment of European agricultural policy would offer the opportunity to give farmers the freedom to act to achieve the goal of improved soil quality. This would allow for the targeted promotion of soil regeneration, biodiversity, and adaptation to climate change. A central component of a results-oriented agricultural policy is the development of context-specific indicators and benchmarks that make the performance of farmers measurable and comparable. These indicators should be tailored to local and regional conditions and serve as the basis for simple, direct, and unbureaucratic payments. Possible indicators could include net primary production (NPP) and the degree of soil cover.[40] These can be evaluated with low error rates using remote sensing, and corresponding payments could help reduce bureaucratic effort. NPP as an indicator could be an effective lever for results-oriented agricultural support and enables a comprehensive assessment of the ecological health and productivity of agricultural land.

Appendix

Methodology: Comparative data for pesticide & nitrogen use

To be able to meaningfully compare the data from the 17 CA sample farms, we needed precise reference values that reflected both regional differences and specific farming methods. This information was essential to place the results from Conservation Agriculture (CA) in a meaningful context with conventional systems. For this purpose, we were able to draw data from a specialized farm advisory firm that provided representative application patterns for farms in the vicinity of our CA farms under investigation.

The data provided included average application patterns for farms that use either plow or mulch sowing methods. These patterns were created specifically for the four regions studied and the four crops considered and covered the three years of the study period. They included the average nitrogen application per hectare and detailed treatment patterns showing the active ingredients used and their application rates. In addition, the consulting firm provided an extensive and a less intensive application pattern for each region, representing farms that operate less intensively and thus use slightly less plant protection products. These extensive patterns were integrated into the analysis to create a broader basis for comparison and to evaluate the effects of CA in relation to both intensive and less intensive conventional systems. Based on this comprehensive data set, generic application patterns were developed that made it possible to compare the specific data of the CA farms precisely with the regional standards of conventional systems. This not only allowed for a regionalized comparison but also created a sound basis for analyzing the environmental impacts and efficiency differences of the various systems.

Compared to intensive conventional systems, the less intensive variant shows a slight reduction in environmental impact. The less intensive patterns exclude the last fungicide, insecticide, and growth regulator treatments, typically in April/May. The data from the farm advisory service suggests that savings in plant protection products are around three to five percent lower than with the intensive application patterns. Thus, the less intensive variant offers some relief for the environment and soil but remains heavily dependent on chemical herbicides and other conventional agents, in addition to intensive tillage and low soil cover.

The data was evaluated based on the four soil climate regions or clusters, which were statistically analyzed. The operational data of the CA farms studied was always compared with the region-specific patterns for pesticide and nitrogen use from the farm advisory service. A region-specific evaluation was carried out depending on the crop, and average values for pesticide and nitrogen use were calculated for each region. These average values were then weighted based on the sample size in the respective regions. Based on the differences between regions, crops, and the three years of the study, the differences were averaged and weighted to calculate an overall reduction in pesticide and nitrogen use for Germany. These aggregated results are presented in Fig. 4 of the study.

Methodology: Fuel analysis

To analyze the energy efficiency of different cultivation systems, three typical working methods—plowing, mulch seeding, and direct seeding—were examined. These represent different approaches to soil cultivation that are widely used in agricultural practice. While the plowing system requires intensive soil cultivation, involving steps such as stubble cultivation, plowing, harrowing, and sowing with a rotary harrow and seed drill, mulch seeding reduces soil disturbance. Here, plowing is replaced using a deep cultivator, while the other steps remain largely unchanged. Direct seeding, on the other hand, dispenses almost entirely with soil cultivation. Cover crops and main crops are sown directly with special direct seeding machines, accompanied by a single pass with the crop protection sprayer for chemical weed control. The following are the assumptions regarding the machines used in the KTBL calculator – a in Germany widely accepted calculator for fuel consumption:

The calculations were performed using the KTBL calculator and are based on uniform framework conditions to ensure reliable comparability of the methods. The modeling was based on a field size of five hectares and a farm-field distance of five kilometers. Uniform working widths were specified for the machines used: cultivators and seed drills had a working width of three meters, the spring tine harrow 4.5 meters, and the crop protection sprayer 21 meters. These standardized parameters enabled practical results that were not distorted by individual farm differences.

Soil management scenarios with associated working methods for calculating fuel consumption	
Scenario 1 (plow):	**Working width and power (kW)**
Stubble cultivators	3 m; 120 kW
Cultivators with wing share cultivators	3 m; 102 kW
Plowing with rotary adjustable plow, mounted	5 Share; 157 kW
Harrowing with spring tine harrow, mounted	4.5 m; 102 kW
Sowing wheat, field beans, peas, and soybeans with a rotary harrow and seed drill	3 m; 120 kW
Scenario 2 (mulch seeding)	
Stubble cultivators, flat, angled (30°)	3 m; 120 kW
Cultivators with wing share cultivators	3 m; 102 kW
Cultivators with deep cultivators/sub soiling	3 m; 157 kW
Harrowing with spring tine harrow, mounted	4.5 m; 102 kW
Sowing wheat, field beans, peas, and soybeans with a rotary harrow and seed drill	3 m; 120 kW
Scenario 3 (direct seeding)	
Sowing grass seed with a direct seeder	3 m; 102 kW
Plant protection sprayer, mounted	21 m; 3,000 l; 83 kW
Sowing wheat, field beans, peas, and soybeans with a rotary harrow and seed drill	3 m; 102 kW

Tabelle 3: Calculation of fuel consumption. Source: Board of Trustees for Technology and Construction in Agriculture e. V. (German: Kuratorium fur Technik und Bauwesen in der Landwirtschaft e. V. (KTBL))

Methodology: Soil samples

In recent years, technological advances have enabled new digital methods for measuring soil biodiversity and created the potential for automating the process. This allows for more comprehensive and scalable biodiversity assessments. These methods include community-level physiological profiling (CLPP) and environmental DNA (eDNA) metabarcoding. Community-level physiological profiling (CLPP) measures functional biodiversity by assessing the ability of soil organisms to utilize different carbon and nitrogen sources. This allows the diversity of organisms in the soil to be approximated.

Despite the low equipment requirements and its high potential for standardization, CLPP does not provide detailed information on individual species. However, it can offer valuable insights into the total number of soil organisms and complement other new methods. Since CLPP is often readily available, it could serve as a general indicator before more precise analyses are carried out.

The CLPP method developed by BIOTREX provides information on the practical relevance of functional soil biodiversity and soil health. For this purpose, soil samples were taken from six of the seventeen farms included in this study. In each case, pairs of fields with CA management and directly adjacent conventionally managed fields were examined to ensure that the soil and climatic conditions were comparable and that only the management method varied. The sampling period was August to September 2023.

Sampling was carried out in a grid based on the photosynthetic performance of the respective field. The test plots were divided into three yield regions to ensure a representative representation of the variability within the area. A total of 107 samples were analyzed within the six pairs, enabling a comprehensive comparison between CA and conventional systems.

Methodology: Spade test for earthworm counting

In addition to sampling for the evaluation of microbial activity, spade samples were taken at the same time for the visual counting of earthworms. This spade sample is a simple and practical method for evaluating the effects of different cultivation measures and documenting changes in soil life over time. It can help farmers optimize decisions on soil cultivation, crop rotation, and organic fertilization to promote healthy soils with high biological activity in the long term. A 20 x 20 cm and approx. 25 cm deep soil block was taken with a spade. This corresponded to the current standards for earthworm studies. The size corresponds approximately to the volume used in scientific studies for standardized earthworm counts. The soil block was carefully placed on a sheet of plastic to allow a better view of the soil structure. For the count, the soil was carefully broken up with the hands to capture all worms as completely as possible. The species distribution was not considered. The focus was purely on the number of earthworms in the sample.

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