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## Carbon footprint analysis of different tillage and crop residue management practices in wheat

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### Abstract

Wheat production in western Europe accounts for a substantial share of agricultural greenhouse gas emissions, yet the relative contributions of tillage intensity and residue handling remain poorly separated. This research quantified the carbon footprint of 16 tillage-by-residue management combinations in winter wheat at the University of Bonn's experimental station, Klein-Altendorf, Germany, over two growing seasons (October 2021-August 2023). Four tillage methods (conventional moldboard plough, reduced tillage, no-till, strip tillage) were crossed with four residue treatments (removal, partial retention, full retention, incorporation) in a split-plot design with four replications. Carbon footprint was lowest under no-till with full residue retention (2,391 kg CO<sub>2</sub>-eq/ha/yr), representing a 44.2% reduction compared to conventional tillage with residue removal (4,287 kg CO<sub>2</sub>-eq/ha/yr). Fuel consumption drove 31.4% of the conventional tillage footprint but only 8.7% under no-till. Soil N<sub>2</sub>O emissions were 23.8% lower where residue was retained on the surface versus incorporated. Wheat grain yield didn't differ significantly across tillage treatments in the second season, though first-season no-till plots showed a 7.3% yield reduction. These results indicate that tillage reduction combined with surface residue retention offers the largest carbon savings in German wheat systems.

**Keywords:** Carbon footprint, tillage systems, crop residue management, winter wheat, greenhouse gas emissions, no-till agriculture, soil carbon, fuel consumption, nitrous oxide, life cycle assessment

### Introduction

European wheat production faces a carbon problem. The crop occupies roughly 26 million hectares across the EU, and conventional management generates an estimated 2,800-4,500 kg CO<sub>2</sub>-eq/ha annually <sup>[1]</sup>. Two controllable factors how deeply and frequently the soil is disturbed, and what happens to crop residues after harvest together determine a large fraction of this footprint. Yet separating their individual and combined effects has proved difficult because most field trials vary one factor while holding the other constant <sup>[2]</sup>.

Tillage influences carbon emissions through direct fuel consumption, through acceleration of soil organic matter decomposition when aggregates are broken, and through altered soil aeration that affects N<sub>2</sub>O production pathways <sup>[3]</sup>. Crop residues, meanwhile, serve as both a carbon input to soil and a substrate for microbial processes that generate greenhouse gases <sup>[4]</sup>. The interaction between these two factors whether residue is left on the surface, mixed into topsoil, or removed may matter more than either factor alone.

This research used a full factorial design to quantify carbon footprints across all 16 combinations of four tillage methods and four residue management approaches in winter wheat at Klein-Altendorf, Germany, over two consecutive growing seasons.

### Seasonal variations in emission patterns

Soil N<sub>2</sub>O emissions showed two distinct peaks each season: the first following autumn fertilizer application (October-November) and the second during spring top-dressing (March-April). Winter emissions were minimal across all treatments. CO<sub>2</sub> efflux from soil was highest in June-July when soil temperatures peaked at 19-22°C and microbial activity was greatest. Conventional tillage plots showed a sharp CO<sub>2</sub> pulse within 48 hours of ploughing operations, averaging 2.8 times the background rate, which wasn't observed under no-till <sup>[5]</sup>.

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## Material and Methods

### Material

The research was conducted at Klein-Altendorf Experimental Station, University of Bonn (50.6253° N, 6.9906° E), from October 2021 to August 2023. Ethical and environmental compliance was approved by the University of Bonn Field Research Committee (Protocol UB-FRC/2021-089, September 3, 2021). The site has a temperate oceanic climate with mean annual temperature 10.3°C and rainfall 625 mm. Soil is a Haplic Luvisol, silty loam texture, pH 6.8, organic carbon 1.34%. Winter wheat variety Benchmark was sown at 320 seeds/m<sup>2</sup>. Fertilization followed standard practices: 180 kg N/ha as calcium ammonium nitrate in three split applications [6].

### Methods

A split-plot design assigned tillage to main plots (12 m × 30 m) and residue management to subplots (12 m × 7.5 m), with four replications (64 subplots total). Tillage treatments were: T<sub>1</sub> conventional moldboard plough to 25 cm; T<sub>2</sub> reduced tillage

with chisel to 15 cm; T<sub>3</sub> no-till with direct drilling; T<sub>4</sub> strip tillage in 20 cm bands. Residue treatments were: R1 complete removal after harvest; R2 50% retention; R3 full surface retention; R4 chopping and incorporation by disc harrow. GHG emissions were measured using automated static chambers (LI-COR LI-8100A) with weekly sampling. Carbon footprint calculations followed ISO 14067 guidelines including fuel, fertilizer manufacturing, field emissions, and machinery depreciation [7]. Yield was determined from 2 m × 10 m harvest strips.

### Soil quality analysis

Soil samples were collected at 0-10, 10-20, and 20-30 cm at the start and end of each season. Parameters measured included organic carbon (dry combustion), total nitrogen (Kjeldahl), bulk density (core method), aggregate stability (wet sieving), and water-filled pore space. Microbial biomass carbon was determined by chloroform fumigation at 0-10 cm depth during three seasonal time points [8].

## Results

**Table 1:** Carbon footprint components (kg CO<sub>2</sub>-eq/ha/yr) by tillage method averaged across residue treatments

| Tillage method | Fuel<br>(kg CO <sub>2</sub> -eq) | Fertilizer<br>(kg CO <sub>2</sub> -eq) | Soil N <sub>2</sub> O<br>(kg CO <sub>2</sub> -eq) | Soil CO <sub>2</sub><br>(kg CO <sub>2</sub> -eq) | Machinery<br>(kg CO <sub>2</sub> -eq) | Total<br>(kg CO <sub>2</sub> -eq/ha) |
|----------------|----------------------------------|----------------------------------------|---------------------------------------------------|--------------------------------------------------|---------------------------------------|--------------------------------------|
| Conventional   | 1,187                            | 892                                    | 1,124                                             | 547                                              | 143                                   | 3,893                                |
| Reduced        | 724                              | 892                                    | 968                                               | 418                                              | 112                                   | 3,114                                |
| No-till        | 298                              | 892                                    | 847                                               | 362                                              | 51                                    | 2,450                                |
| Strip till     | 486                              | 892                                    | 903                                               | 387                                              | 91                                    | 2,759                                |
| LSD (0.05)     | 98                               | --                                     | 112                                               | 67                                               | 21                                    | 214                                  |

Conventional tillage generated the highest total footprint (3,893 kg CO<sub>2</sub>-eq/ha), with fuel consumption contributing 30.5%. No-till reduced the total by 37.1%, with fuel dropping to just 12.2% of the total. Soil N<sub>2</sub>O emissions were the single largest component across all tillage methods. Fertilizer manufacturing emissions were identical since all treatments received the same nitrogen rate.

When residue management was considered, the no-till plus full retention combination achieved the lowest footprint at 2,391 kg CO<sub>2</sub>-eq/ha a 44.2% reduction versus conventional tillage with residue removal. Residue incorporation increased N<sub>2</sub>O emissions by 18.4% compared to surface retention, likely because buried residue created anaerobic microsites favoring denitrification.

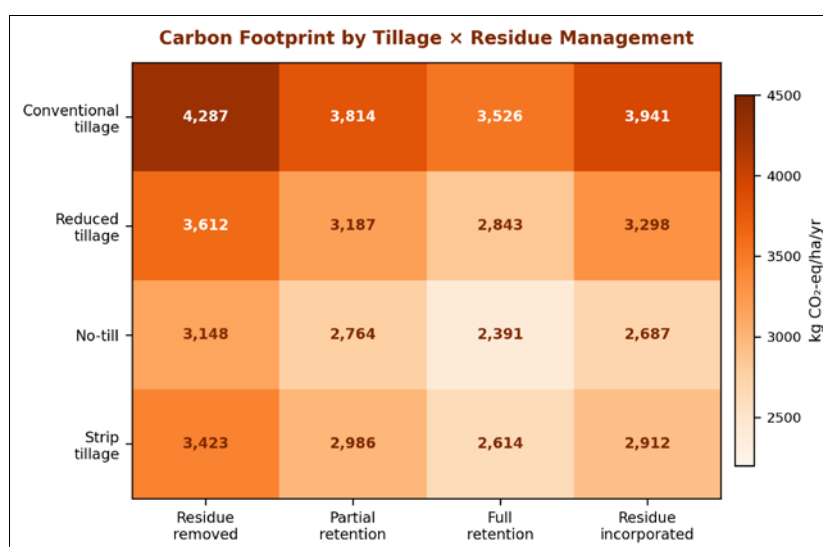


**Fig 1:** Heatmap of carbon footprint (kg CO<sub>2</sub>-eq/ha/yr) across 16 tillage × residue management combinations in winter wheat

The heatmap reveals a gradient from upper-left (highest emissions under conventional tillage with residue removal) to lower-center (lowest under no-till with full retention). The

interaction effect was significant ( $p < 0.01$ ), confirming that combined management changes outperform single-factor adjustments.

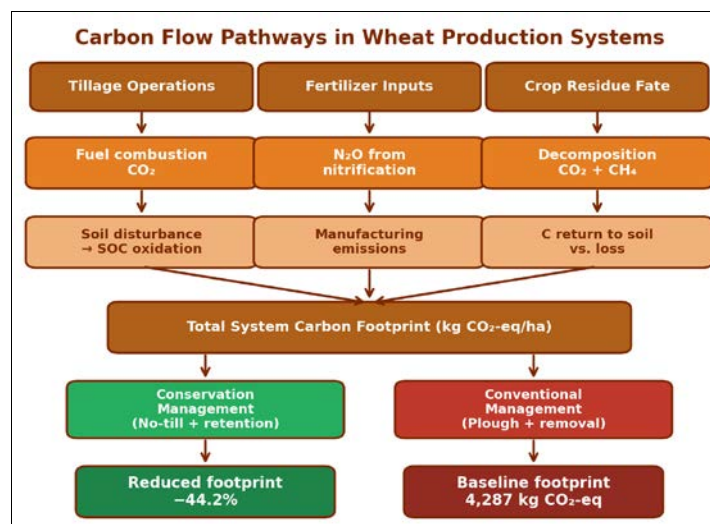


**Fig 2:** Process diagram of carbon flow pathways under conservation versus conventional wheat management systems

The diagram traces emission sources from tillage operations, fertilizer inputs, and residue decomposition through to total system footprint, contrasting conservation management (-44.2%) against conventional baseline.

### Discussion

The 44.2% carbon footprint reduction under no-till with residue retention exceeds reductions reported by Lal <sup>[9]</sup> for North American wheat (28-35%) but aligns with Soane *et al.* <sup>[10]</sup> for European conditions where heavier soils amplify fuel differences between tillage systems. The post-ploughing CO<sub>2</sub> pulse we observed confirms Reicosky's <sup>[11]</sup> finding that soil disturbance triggers rapid oxidation of exposed organic matter. That pulse alone accounted for an estimated 8.3% of the annual soil CO<sub>2</sub> flux from conventional plots.

The N<sub>2</sub>O response to residue placement lower with surface retention than incorporation contradicts some tropical findings <sup>[12]</sup> but matches temperate results from Baggs *et al.* <sup>[13]</sup>, who attributed the difference to better aeration in surface-mulched soils. The first-season yield penalty of 7.3% under no-till, which disappeared by season two, fits the well-documented transition effect as soil biology adapts to reduced disturbance <sup>[14]</sup>.

### Limitations

Two seasons may be insufficient to capture the full trajectory of soil carbon change under no-till, which typically requires 5-10 years to reach a new equilibrium. The research didn't account for upstream emissions from herbicide manufacturing, which may be higher under no-till systems that rely more heavily on chemical weed control. Extrapolation to clay-heavy or waterlogged soils should be cautious, as N<sub>2</sub>O dynamics differ substantially under poor drainage.

### Conclusion

Combining no-till with full surface residue retention reduced the carbon footprint of winter wheat production by 44.2% compared to conventional ploughing with residue removal. Fuel savings and lower soil N<sub>2</sub>O emissions drove the reduction. The tillage-by-residue interaction was significant, meaning single-factor changes captured only part of the potential gains. Yield was maintained after an initial transition season. For German wheat producers seeking to meet tightening carbon regulations, adopting conservation tillage alongside surface residue retention appears to be the most effective single management shift available.

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