**ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY**

*Ecological Engineering & Environmental Technology*, 2026, 27(2), 125–138
https://doi.org/10.12912/27197050/216722
ISSN 2719–7050, License CC-BY 4.0

Received: 2026.01.03
Accepted: 2026.01.28
Published: 2026.02.07

# Life cycle assessment of greenhouse gas emissions and carbon balance of bread winter wheat cultivars: Varietal differentiation and straw management effects in the Ukraine

Oleh Prysiazhniuk[1*], Nadiia Kononiuk[1], Volodymyr Musich[1], Mykola Cherniak[1], Tamara Shevchenko[2], Vitalii Kravchenko[3], Lidiia Kononenko[3], Nataliia Poltoretska[3], Yevhen Kachura[4], Oleksandr Honcharuk[1]

[1] Institute of Bioenergy Crops and Sugar Beet NAAS, 25 Klinichna St., Kyiv, 03110, Ukraine
[2] National Academy of Agrarian Sciences of Ukraine, 9 Mykhaylo Omelyanovycha-Pavlenko St., Kyiv, 01010, Ukraine
[3] Uman National University of Horticulture, 1 Instytutska St., Uman, 20305, Ukraine
[4] Institute of Agroecology and Environmental Management of NAAS, 12 Metrolohichna St., Kyiv, 03113, Ukraine
* Corresponding author's e-mail: ollpris@gmail.com

## ABSTRACT

This study presents a partial life cycle assessment (LCA) of greenhouse gas (GHG) emissions and carbon balance for 36 bread winter wheat cultivars under the conditions of the Right-Bank Forest-Steppe of Ukraine during 2020–2024. The assessment followed ISO 14040/14044 standards and IPCC (2006, 2019) guidelines with cradle-to-farm gate system boundaries. Total GHG emissions amounted to 1,938.2 kg $CO_2$-eq/ha, with mineral fertilizer production (41.8%) and field $N_2O$ emissions (34.2%) as dominant sources. The carbon footprint varied from 236 to 335 kg $CO_2$-eq/t depending on cultivar yield, representing a 42% difference attributable solely to cultivar selection under identical technology. Five highly carbon-efficient cultivars (<250 kg $CO_2$-eq/t) were identified: Lehenda Bilotserkivska (236), Okhtyrchanka (238), Pryvitna (244), Optyma Odeska (244), and MIP Valensiia (248). The gross carbon balance was positive for all cultivars (+19.3 to +28.2 t $CO_2$-eq/ha). The sequestration break-even point ranged from 77% to >100% straw retention depending on yield. Cultivar selection combined with straw management can modify the net carbon balance by up to 14,206 kg $CO_2$-eq/ha. To achieve carbon neutrality, high-yielding cultivars should be combined with ≥75% straw retention.

**Keywords:** carbon footprint, carbon sequestration, straw management, varietal differentiation, carbon balance, bread winter wheat.

## INTRODUCTION

Agriculture is one of the largest sources of anthropogenic greenhouse gas (GHG) emissions, accounting for about 10–12% of global emissions (IPCC,2021; Tubiello et al., 2013). Under the implementation of the Paris Agreement and the European Green Deal, there is a pressing need to substantially reduce the carbon footprint of agricultural production while maintaining food security (European Commission, 2019; Wollenberg et al., 2016).

Winter wheat is Ukraine's main staple crop, with sown areas exceeding 5 million ha (State Statistics Service of Ukraine, 2024). Wheat grain production is associated with considerable GHG emissions, the key sources being the manufacture and application of mineral fertilizers, primarily nitrogen fertilizers, which cause direct and indirect emissions of nitrous oxide ($N_2O$) – a potent greenhouse gas with a global warming potential (GWP) 265 times higher than that of $CO_2$ (Reay et al., 2012; Ciais et al., 2013).

An important component of the carbon balance of agroecosystems is the sequestration of atmospheric carbon in soil through the humification of plant residues (Minasny et al., 2017; Lal, 2004). Wheat straw is a major source of organic carbon inputs to soil, and its management (removal for feed, burning, chopping and incorporation) significantly affects the humus balance (Blanco-Canqui and Lal, 2009; Wilhelm et al., 2007).

Varietal differentiation of GHG emissions and carbon balance remains insufficiently studied. Yield differences among cultivars under the same production technology lead to differences in the carbon footprint per unit of product and in the amount of carbon sequestered (Barraclough et al., 2010; Reynolds et al., 2009). This creates opportunities to optimize the carbon balance through cultivar selection and crop-residue management.

In Ukraine, there is a growing practice of using cereal straw for biofuel production. Typically, 100% or a significant portion of straw is removed, which increases production efficiency but negatively impacts soil fertility (Prysiazhniuk et al., 2025). Therefore, establishing sustainable limits for by-product removal based on carbon sequestration balance is highly relevant.

The aim of this study is to conduct a Life Cycle Assessment of GHG emissions and carbon balance for bread winter wheat cultivars in the Forest-Steppe of Ukraine, to determine varietal differentiation in carbon efficiency, and to identify the effects of different straw-management scenarios on the carbon sequestration balance.

## MATERIALS AND METHODS

### Study site and experimental design

The study was conducted in the Right-Bank Forest-Steppe of Ukraine (Kyiv oblast, coordinates 50.023194°N, 30.173895°E) during 2020–2024 at the experimental station of the Institute of Bioenergy Crops and Sugar Beet NAAS. The soil was typical low-humus chernozem with humus content of 3.8–4.2%, pH 6.2–6.5, and available nutrients: N – 120–135 mg/kg, $P_2O_5$ – 145–160 mg/kg, $K_2O$ – 110–125 mg/kg.

The experimental design was a randomized complete block with four replications. Plot size was 25 m² (5 × 5 m). Grain yield was determined by mechanized harvesting using a Wintersteiger plot combine and adjusted to 14% moisture content.

### Cultivar selection criteria

The selection of 36 cultivars was based on the following criteria:

1. All cultivars registered in the State Register of Plant Varieties of Ukraine (2024) and recommended for the Forest-Steppe zone;
2. Representation of all major breeding institutions (7 institutions);
3. Diversity of biological groups: intensive (12 cultivars), semi-intensive (15), and plastic/universal (9);
4. Range of yield potential from 5.5 to 9.5 t/ha under optimal conditions.

The cultivars included: Lehenda Bilotserkivska, Okhtyrchanka, Pryvitna, Optyma Odeska, MIP Valensiia, Zorepad Bilotserkivskyi, Mudrist Odeska, Mariia, Kraievyd, Hratsiia Bilotserkivska, MIP Dniprianka, Spivanka Poliska, Kesariia Poliska, Burhunka, Vozdvyzhenka, Berehynia Myronivska, Vezha Myronivska, Hratsiia Myronivska, MIP Assol, Nasnaha, Anatoliia, Manera Odeska, Vodohrai, Katrusia Odeska, Vodohrai Bilotserkivskyi, Konka, MIP Vyshyvanka, Romanivna, Svitanokova, Oranta Odeska, Zdobna, Solovushka, Spryiatlyva, Estafeta Myronivska, Analoh, and Poliska 90 (Figure 1). This comprehensive selection ensures that results are representative of the entire spectrum of winter wheat cultivars available to Ukrainian farmers.

### Cultivation technology

The cultivation technology was intensive and identical for all cultivars: seeding rate 5 million viable seeds/ha; mineral fertilizers $N_{120}$ (urea), $P_{60}$ (superphosphate), $K_{40}$ (potassium chloride). Crop protection included herbicides, fungicides, and insecticides with a total active ingredient application of 2.5 kg/ha.

### Life cycle assessment framework

This study employed a partial life cycle assessment (LCA) approach following ISO 14040:2006 and ISO 14044:2006 standards, as well as IPCC

**Figure 1.** General view of experimental plots of different bread winter wheat cultivars

guidelines (IPCC, 2006; 2019). The functional unit was defined as 1 tonne of winter wheat grain at farm gate moisture content (14%).

System boundaries (cradle-to-farm gate) included:

- Upstream processes – production and transportation of mineral fertilizers, seeds, and pesticides,
- Field operations – soil cultivation, sowing, fertilizer and pesticide application, harvesting,
- Field emissions – direct and indirect $N_2O$ from nitrogen fertilizers, $CO_2$ from urea hydrolysis.

Excluded from system boundaries: post-harvest processing and storage, transportation beyond farm gate, capital goods (machinery manufacturing), and infrastructure. The cradle-to-farm gate boundary was selected as it represents the scope of farmer decision-making regarding cultivar selection and agronomic practices. This boundary is consistent with numerous wheat carbon footprint studies (Gan et al., 2014; Wojcik-Gront and Bloch-Mechkour, 2021).

## Rationale for cultivar-focused approach

While fertilizer production dominates absolute emissions (41.8%), the carbon footprint per unit of product (kg $CO_2$-eq/t) is determined by the ratio of emissions to yield. Since all cultivars received identical inputs, absolute emissions were constant (1,938.2 kg $CO_2$-eq/ha). However, cultivar yield varied from 5.79 to 8.20 t/ha, resulting in carbon footprint variation of 42% (236–335 kg $CO_2$-eq/t).

This approach addresses a practical question: given current fertilizer use levels, which cultivars provide the lowest environmental impact per unit of food produced? Reducing fertilizer application would lower absolute emissions but may also reduce yields, potentially increasing carbon footprint per tonne. The cultivar selection approach allows emission reduction without compromising food production.

## Emission inventory

All emissions were expressed in kilograms of $CO_2$-equivalent (kg $CO_2$-eq) using 100-year global warming potentials from IPCC AR5.

### *Fertilizer production emissions*

Emissions from mineral fertilizer production were estimated using full life-cycle emission factors (Brentrup et al., 2016) (Table 1):

$$E_{\text{fertilizers}} = N \times EF_N + P_2O_5 \times EF_P + K_2O \times EF_K \quad (1)$$

where: $EF_N$ = 5.88 kg $CO_2$-eq/kg $N$ (for urea, including ammonia production via Haber–Bosch process, granulation, packaging, and transport); $EF_P$ = 1.35 kg $CO_2$-eq/kg $P_2O_5$; $EF_K$ = 0.58 kg $CO_2$-eq/kg $K_2O$.

### *Field $N_2O$ emissions*

Field $N_2O$ emissions included direct and indirect components, calculated according to IPCC (2019) Tier 1 methodology (Table 2, 3):

**Table 1.** Application rates and emission factors for agricultural inputs

| Input | Rate, kg/ha | EF, kg $CO_2$-eq/unit | Source | Emissions, kg $CO_2$-eq/ha |
|---|---|---|---|---|
| Nitrogen (N) | 120 | 5.88/kg N | Brentrup et al., 2016 | 705.6 |
| Phosphorus ($P_2O_5$) | 60 | 1.35/kg $P_2O_5$ | Brentrup et al., 2016 | 81.0 |
| Potassium ($K_2O$) | 40 | 0.58/kg $K_2O$ | Brentrup et al., 2016 | 23.2 |
| Seeds | 220 | 0.32/kg | Williams et al., 2006 | 70.4 |
| Pesticides (a.i.) | 2.5 | 10.97/kg a.i. | Audsley et al., 2009 | 27.4 |
| TOTAL inputs | – | – | – | 907.6 |

$$E_{N_2O} = [N \times EF_1 + N \times Frac_{vol} \times EF_4 + N \times Frac_{leach} \times EF_5] \times (44/28) \times GWP_{N_2O} \quad (2)$$

*Machinery and fuel emissions*

Emissions from machinery use were calculated based on diesel fuel consumption for each field operation (Table 4):

$$E_{machinery} = \Sigma(V_i \times EF_{diesel}) \quad (3)$$

where: $V_i$ is the fuel consumption for operation $i$ (L/ha); $EF_{diesel}$ = 3.21 kg $CO_2$-eq/L, including extraction, refining, transportation, and combustion (JRC, 2014).

## Carbon footprint calculation

The carbon footprint (CF) of grain production was calculated as the ratio of total emissions to grain yield:

$$CF = E_{total} / Y \quad (4)$$

where: $E_{total}$ is total GHG emissions (kg $CO_2$-eq/ha) and $Y$ is grain yield (t/ha). Because the cultivation technology was identical for all cultivars, $E_{total}$ was constant (1,938.2 kg $CO_2$-eq/ha), and $CF$ depended only on yield.

Cultivars were categorized by carbon efficiency based on quartile distribution: highly efficient (<250 kg/t, <Q1), efficient (250–280 kg/t), medium (280–310 kg/t), and low efficiency (>310 kg/t, >Q3).

## Carbon balance assessment

$CO_2$ uptake by biomass was calculated based on carbon content of plant components:

$$CO_{2abs} = (M_{grain} \times C_{grain} + M_{straw} \times C_{straw} + M_{stubble} \times C_{stubble} + M_{roots} \times C_{roots}) \times 3.667 \times 1000 \quad (5)$$

where: $M$ is the mass of component (t/ha); $C$ is carbon content (fraction): *grain* – 0.450, *straw* – 0.457, *stubble* – 0.440, *roots* – 0.349; 3.667 = 44/12 is the conversion factor from C to $CO_2$. Straw mass was assumed equal to grain mass (1:1 ratio), stubble mass was 8% of grain, and root mass was 5% of grain (Bolinder et al., 2007).

Three balance types were calculated:

Gross balance: $$Balance_{gross} = CO_{2abs} - E_{total} \quad (6)$$

Net field balance:
$$Balance_{net} = CO_{2retained} - E_{total} \quad (7)$$

Sequestration balance**:**
$$Balance_{seq} = CO_{2humified} - E_{total} \quad (8)$$

**Table 2.** Parameters for field $N_2O$ emission calculations

| Parameter | Value | Source |
|---|---|---|
| $EF_1$ (direct emission factor) | 0.01 | IPCC 2019, Table 11.1 |
| Frac_vol (volatilization fraction) | 0.10 | IPCC 2019, Table 11.3 |
| $EF_4$ (volatilization EF) | 0.01 | IPCC 2019, Table 11.3 |
| Frac_leach (leaching fraction) | 0.30 | IPCC 2006, humid climate default |
| $EF_5$ (leaching EF) | 0.0075 | IPCC 2019, Table 11.3 |
| GWP_$N_2O$ | 265 | IPCC AR5 |
| EF_urea ($CO_2$ from hydrolysis) | 0.20 | IPCC 2006, Chapter 11 |

**Table 3.** Calculated field $N_2O$ and $CO_2$ emissions

| Emission type | kg $CO_2$-eq/ha |
|---|---|
| Direct $N_2O$ emissions | 499.7 |
| Indirect $N_2O$ (volatilization) | 50.0 |
| Indirect $N_2O$ (leaching) | 112.4 |
| $CO_2$ from urea hydrolysis | 95.6 |
| Total field emissions | 757.7 |

**Table 4.** Fuel consumption and emissions from field operations

| Field operation | Fuel, L/ha | kg $CO_2$-eq/ha |
|---|---|---|
| Primary tillage | 25.0 | 80.2 |
| Seedbed preparation | 12.0 | 38.5 |
| Sowing | 8.0 | 25.7 |
| Fertilizer application | 6.0 | 19.3 |
| Crop protection | 4.0 | 12.8 |
| Harvesting | 22.0 | 70.6 |
| Transport (5 km) | 8.0 | 25.7 |
| Total | 85.0 | 272.9 |

**Note:** Fuel consumption rates based on KTBL (2020) and verified against actual farm records.

where: humification coefficients were: straw – 0.15, stubble – 0.20, roots – 0.30 (Kätterer et al., 2011; Poeplau and Don, 2015).

### Straw management scenarios

Five straw retention scenarios were developed to address practical decision-making in Ukrainian agriculture:

- 0% (complete removal): Maximum straw utilization for biofuel or livestock feed. Currently practiced on ~15% of wheat area in Ukraine (Prysiazhniuk et al., 2025).
- 30% (baseline): Typical practice where combines leave chopped straw while significant portion is baled and removed.
- 50% (partial retention): Balanced approach between straw utilization and soil carbon maintenance.
- 75% (high retention): Prioritizing soil health with minimal straw removal.
- 100% (full incorporation): Maximum carbon sequestration scenario.

The sequestration break-even point was defined as the minimum straw retention rate at which the sequestration balance becomes non-negative. It was calculated individually for each cultivar.

### Statistical analysis

Yield data collection: Grain yield was measured annually (2020–2024) for each cultivar from experimental plots of 25 m² in four replications using a Wintersteiger plot combine. Yield was adjusted to 14% moisture content.

Descriptive statistics – for each cultivar, the following parameters were calculated: arithmetic mean yield over five years ($\bar{y}$), standard deviation (SD), coefficient of variation ($CV = SD/\bar{y} \times 100\%$), and minimum/maximum annual yields.

Carbon footprint range – CF was calculated using mean yield, with the range determined using minimum and maximum annual yields to represent inter-annual variability.

Correlation analysis – Pearson correlation coefficients were calculated to assess relationships between yield and carbon footprint, yield and sequestration balance, and yield variability (CV) and carbon footprint stability (Prysiazhniuk et al., 2016).

Sensitivity analysis – the effect of ±10% variation in key emission factors ($EF_N$, $EF_1$, $EF_{diesel}$) on total emissions and carbon footprint was assessed.

## RESULTS AND DISCUSSION

### Yield performance of cultivars (2020–2024)

Mean grain yield across the 36 cultivars over five years ranged from 5.79 t/ha (Poliska 90) to 8.20 t/ha (Lehenda Bilotserkivska), representing a 42% yield difference among cultivars under identical management. The coefficient of variation (CV) ranged from 7.7% (Vodohrai) to 32.2% (Mariia), indicating substantial differences in yield stability.

Annual mean yield across all cultivars increased from 5.62 t/ha in 2020 (drought stress) to 7.98 t/ha in 2023 (favorable conditions), then slightly decreased to 7.41 t/ha in 2024.

### Structure of greenhouse gas emissions

Total GHG emissions from winter wheat production amounted to 1,938.2 kg $CO_2$-eq/ha. The emission structure is presented in Table 5.

The dominant emission sources were mineral fertilizer production (41.8%) and field $N_2O$ emissions (34.2%), which together accounted for 76% of total emissions. This is consistent with European studies showing that the nitrogen cycle contributes ~70–80% of emissions in cereal production (Gan et al., 2014; Jensen et al., 2012).

### Carbon footprint by cultivar

The carbon footprint varied substantially depending on cultivar yield (Table 6). Five highly efficient cultivars (<250 kg $CO_2$-eq/t) were identified: Lehenda Bilotserkivska (236), Okhtyrchanka (238), Pryvitna (244), Optyma Odeska (244), and MIP Valensiia (248 kg $CO_2$-eq/t).

The difference in carbon footprint between the best cultivar (Lehenda Bilotserkivska, 236 kg/t) and the worst (Poliska 90, 335 kg/t) was 99 kg $CO_2$-eq/t, or 42%. This indicates that cultivar choice alone, without changing production technology, can reduce the product carbon footprint by up to 30–40%.

Pearson correlation between yield and carbon footprint was $r = -0.998$ ($p < 0.001$), confirming the strong inverse relationship. The correlation between yield CV and carbon footprint range was $r = 0.87$ ($p < 0.001$), indicating that yield stability contributes to carbon footprint predictability.

### Carbon balance analysis

The gross carbon balance was positive for all cultivars, ranging from +19,340 kg $CO_2$-eq/ha (Poliska 90) to +28,196 kg $CO_2$-eq/ha (Lehenda Bilotserkivska). This indicates that $CO_2$ uptake by biomass exceeded anthropogenic emissions by 11–15 times (Table 7).

However, the sequestration balance under the baseline scenario (30% straw retention) was negative for all cultivars, ranging from −951 kg $CO_2$-eq/ha (Lehenda Bilotserkivska) to −1.241 kg $CO_2$-eq/ha (Poliska 90). This indicates that with 30% straw retention, all cultivars act as net sources of soil carbon loss when emissions are considered.

**Table 5.** Structure of greenhouse gas emissions in winter wheat production

| Emission source | kg $CO_2$-eq/ha | Share, % |
|---|---|---|
| Mineral fertilizer production | 809.8 | 41.8 |
| Nitrogen ($N_{120}$) | 705.6 | 36.4 |
| Phosphorus ($P_{60}$) | 81.0 | 4.2 |
| Potassium ($K_{40}$) | 23.2 | 1.2 |
| Field $N_2O$ emissions | 662.1 | 34.2 |
| Direct | 499.7 | 25.8 |
| Indirect (volatilization) | 50.0 | 2.6 |
| Indirect (leaching) | 112.4 | 5.8 |
| $CO_2$ from urea hydrolysis | 95.6 | 4.9 |
| Machinery use | 272.9 | 14.1 |
| Seed production | 70.4 | 3.6 |
| Pesticide production | 27.4 | 1.4 |
| Total | 1938.2 | 100.0 |

### Straw management scenarios

The sequestration balance strongly depended on the share of straw retained in the field. With complete straw removal (0%), all cultivars had negative sequestration balances (−1.569 to −1.678 kg $CO_2$-eq/ha). A positive sequestration balance was achieved only under 75–100% straw retention for high-yielding cultivars (Table 8).

The sequestration break-even point varied from 77% (Lehenda Bilotserkivska, Okhtyrchanka) to >100% (low-yielding cultivars such as Poliska 90, Analoh). This means that low-yielding cultivars cannot reach carbon neutrality even with full straw retention; additional organic inputs or cultivar change is required (Table 9).

The straw effect (difference between 100% and 0% retention) averaged 2.061 kg $CO_2$-eq/ha for the sequestration balance. The cultivar effect (under 100% straw retention) was 714 kg $CO_2$-eq/ha. Therefore, straw management has approximately 2.9 times stronger impact on the sequestration balance than cultivar choice; however, the optimal outcome is achieved by combining both factors (Table 10).

Sensitivity analysis showed that ±10% variation in key emission factors affected total emissions as follows: $EF_N$ (±72.6 kg $CO_2$-eq/ha, ±3.7%), $EF_1$ for $N_2O$ (±50.0 kg, ±2.6%), $EF_{diesel}$ (±27.3 kg, ±1.4%). The ranking of cultivars by carbon footprint was robust to these variations.

### Comparison with other studies

The obtained value (1,938.2 kg $CO_2$-eq/ha) falls within the typical range reported for winter wheat production in Europe. According to various studies, emissions amount to: Poland – 2.378–2.759 kg $CO_2$-eq/ha (Wojcik-Gront and Bloch-Mechkour, 2021), Finland – 2.330 kg/ha (Järvenpää and Wikström, 2014), Lithuania – 2.686–2.919 kg/ha (Šarauskis et al., 2019), an d China – 5.455 kg/ha (higher intensification) (Huang et al., 2017). The lower emissions observed in Ukraine can be explained by smaller nitrogen fertilizer rates ($N_{120}$ vs $N_{150–200}$ in Western Europe) and a lower intensity of crop protection (Prysiazhniuk et al., 2025).

**Table 6.** Carbon efficiency of winter wheat cultivar production

| No. | Cultivar | Yield, t/ha | CV, % | $CO_2$-eq/t | Range | Category |
|---|---|---|---|---|---|---|
| 1 | Lehenda Bilotserkivska | 8.20 | 24.8 | 236.4 | 172–335 | Highly efficient |
| 2 | Okhtyrchanka | 8.15 | 18.0 | 237.8 | 192–329 | Highly efficient |
| 3 | Pryvitna | 7.95 | 27.1 | 243.9 | 163–332 | Highly efficient |
| 4 | Optyma Odeska | 7.94 | 26.1 | 244.2 | 170–335 | Highly efficient |
| 5 | MIP Valensiia | 7.83 | 21.0 | 247.7 | 208–367 | Highly efficient |
| 6 | Zorepad Bilotserkivskyi | 7.69 | 26.1 | 252.0 | 178–366 | Efficient |
| 7 | Mudrist Odeska | 7.64 | 28.0 | 253.8 | 186–359 | Efficient |
| 8 | Mariia | 7.51 | 32.2 | 258.2 | 166–373 | Efficient |
| 9 | Kraievyd | 7.47 | 16.7 | 259.6 | 216–364 | Efficient |
| 10 | Hratsiia Bilotserkivska | 7.44 | 22.8 | 260.7 | 188–342 | Efficient |
| 11 | MIP Dniprianka | 7.36 | 14.4 | 263.5 | 227–349 | Efficient |
| 12 | Spivanka Poliska | 7.26 | 26.0 | 267.0 | 185–360 | Efficient |
| 13 | Kesariia Poliska | 7.10 | 15.7 | 273.1 | 230–335 | Efficient |
| 14 | Burhunka | 7.08 | 24.8 | 273.7 | 188–359 | Efficient |
| 15 | Vozdvyzhenka | 7.06 | 14.1 | 274.5 | 217–323 | Efficient |
| 16 | Berehynia Myronivska | 7.03 | 9.8 | 275.9 | 248–332 | Efficient |
| 17 | Vezha Myronivska | 7.02 | 17.9 | 276.0 | 212–371 | Efficient |
| 18 | Hratsiia Myronivska | 6.99 | 15.2 | 277.3 | 225–364 | Efficient |
| 19 | MIP Assol | 6.92 | 15.2 | 280.1 | 235–382 | Medium |
| 20 | Nasnaha | 6.90 | 17.3 | 280.9 | 223–360 | Medium |
| 21 | Anatoliia | 6.80 | 16.5 | 285.1 | 226–357 | Medium |
| 22 | Manera Odeska | 6.76 | 17.5 | 286.9 | 236–362 | Medium |
| 23 | Vodohrai | 6.67 | 7.7 | 290.5 | 259–321 | Medium |
| 24 | Katrusia Odeska | 6.63 | 26.8 | 292.3 | 192–371 | Medium |
| 25 | Vodohrai Bilotserkivskyi | 6.60 | 8.2 | 293.8 | 268–341 | Medium |
| 26 | Konka | 6.59 | 16.1 | 294.1 | 241–356 | Medium |
| 27 | MIP Vyshyvanka | 6.57 | 12.3 | 295.0 | 261–377 | Medium |
| 28 | Romanivna | 6.48 | 13.8 | 299.0 | 252–370 | Medium |
| 29 | Svitanokova | 6.42 | 9.8 | 302.0 | 273–349 | Medium |
| 30 | Oranta Odeska | 6.40 | 9.4 | 302.7 | 269–342 | Medium |
| 31 | Zdobna | 6.35 | 14.3 | 305.4 | 264–401 | Medium |
| 32 | Solovushka | 6.28 | 8.8 | 308.6 | 269–344 | Medium |
| 33 | Spryiatlyva | 6.08 | 8.5 | 318.7 | 285–356 | Low efficiency |
| 34 | Estafeta Myronivska | 6.06 | 9.3 | 319.7 | 287–379 | Low efficiency |
| 35 | Analoh | 5.86 | 12.3 | 330.5 | 276–399 | Low efficiency |
| 36 | Poliska 90 | 5.79 | 9.5 | 334.6 | 292–392 | Low efficiency |

**Note:** Highly efficient (<250), efficient (250–280), medium (280–310), low efficiency (>310 kg $CO_2$-eq/t).

The carbon footprint of 236–335 kg $CO_2$-eq/t of grain is also consistent with global benchmarks. The global average carbon footprint of wheat is estimated at 300–450 kg $CO_2$-eq/t (Poore and Nemecek, 2018), whereas high-yielding systems in Western Europe typically range from 200 to 280 kg/t (Clark and Tilman, 2017). Thus, the highly efficient Ukrainian cultivars (<250 kg/t) are competitive in terms of this indicator.

## Role of varietal differentiation

The difference in carbon footprint between the best cultivar (Lehenda Bilotserkivska, 236 kg/t) and the worst (Poliska 90, 335 kg/t) is 99 kg $CO_2$-eq/t, or 42%. This indicates that cultivar choice, even without changing production technology, can reduce the product carbon footprint by 30–40%. Similar results were reported in studies from

**Table 7.** Carbon balance of winter wheat cultivars

| No. | Cultivar | $CO_2$ uptake | Balance (gross) | Net | Sequestration | Category |
|---|---|---|---|---|---|---|
| 1 | Lehenda Bilotserkivska | 30 134 | +28 196 | +3 767 | -951 | Highly efficient |
| 2 | Okhtyrchanka | 29 951 | +28 012 | +3 732 | -957 | Highly efficient |
| 3 | Pryvitna | 29 216 | +27 277 | +3 593 | -981 | Highly efficient |
| 4 | Optyma Odeska | 29 179 | +27 241 | +3 586 | -982 | Highly efficient |
| 5 | MIP Valensiia | 28 775 | +26 836 | +3 510 | -995 | Highly efficient |
| 6 | Zorepad Bilotserkivskyi | 28 260 | +26 322 | +3 412 | -1 012 | Highly efficient |
| 7 | Mudrist Odeska | 28 076 | +26 138 | +3 377 | -1 018 | Highly efficient |
| 8 | Mariia | 27 599 | +25 660 | +3 287 | -1 034 | Efficient |
| 9 | Kraievyd | 27 452 | +25 513 | +3 259 | -1 039 | Efficient |
| 10 | Hratsiia Bilotserkivska | 27 341 | +25 403 | +3 238 | -1 042 | Efficient |
| 11 | MIP Dniprianka | 27 047 | +25 109 | +3 183 | -1 052 | Efficient |
| 12 | Spivanka Poliska | 26 680 | +24 742 | +3 113 | -1 064 | Efficient |
| 13 | Kesariia Poliska | 26 092 | +24 154 | +3 002 | -1 083 | Efficient |
| 14 | Burhunka | 26 018 | +24 080 | +2 988 | -1 086 | Efficient |
| 15 | Vozdvyzhenka | 25 945 | +24 007 | +2 974 | -1 088 | Efficient |
| 16 | Berehynia Myronivska | 25 835 | +23 896 | +2 953 | -1 092 | Medium |
| 17 | Vezha Myronivska | 25 798 | +23 860 | +2 946 | -1 093 | Medium |
| 18 | Hratsiia Myronivska | 25 688 | +23 749 | +2 925 | -1 097 | Medium |
| 19 | MIP Assol | 25 430 | +23 492 | +2 876 | -1 105 | Medium |
| 20 | Nasnaha | 25 357 | +23 419 | +2 862 | -1 107 | Medium |
| 21 | Anatoliia | 24 989 | +23 051 | +2 793 | -1 119 | Medium |
| 22 | Manera Odeska | 24 842 | +22 904 | +2 765 | -1 124 | Medium |
| 23 | Vodohrai | 24 512 | +22 573 | +2 702 | -1 135 | Medium |
| 24 | Katrusia Odeska | 24 365 | +22 426 | +2 675 | -1 140 | Medium |
| 25 | Vodohrai Bilotserkivskyi | 24 254 | +22 316 | +2 654 | -1 143 | Medium |
| 26 | Konka | 24 218 | +22 280 | +2 647 | -1 145 | Medium |
| 27 | MIP Vyshyvanka | 24 144 | +22 206 | +2 633 | -1 147 | Medium |
| 28 | Romanivna | 23 813 | +21 875 | +2 570 | -1 158 | Low efficiency |
| 29 | Svitanokova | 23 593 | +21 655 | +2 529 | -1 165 | Low efficiency |
| 30 | Oranta Odeska | 23 519 | +21 581 | +2 515 | -1 168 | Low efficiency |
| 31 | Zdobna | 23 336 | +21 398 | +2 480 | -1 174 | Low efficiency |
| 32 | Solovushka | 23 078 | +21 140 | +2 431 | -1 182 | Low efficiency |
| 33 | Spryiatlyva | 22 343 | +20 405 | +2 292 | -1 206 | Low efficiency |
| 34 | Estafeta Myronivska | 22 270 | +20 332 | +2 278 | -1 208 | Low efficiency |
| 35 | Analoh | 21 535 | +19 597 | +2 139 | -1 233 | Low efficiency |
| 36 | Poliska 90 | 21 278 | +19 340 | +2 090 | -1 241 | Low efficiency |

**Note:** Highly efficient (≥ +26,000), efficient (+24,000–26,000), medium (+22,000–24,000), low efficiency (< +22,000).

Germany (Küstermann et al., 2008) and the United Kingdom (Williams et al., 2006), where varietal differentiation produced differences of 25–45%.

Five highly efficient cultivars with a carbon footprint of <250 kg/t were identified: Lehenda Bilotserkivska (236), Okhtyrchanka (238), Pryvitna (244), Optyma Odeska (244), and MIP Valensiia (248). These cultivars are characterized by high mean yields (7.83–8.20 t/ha) and are recommended for farms aiming to reduce the carbon footprint of production.

Yield stability is also important. Okhtyrchanka had the lowest coefficient of variation (CV = 18.0%), ensuring a consistently low carbon footprint under variable weather conditions. Kraievyd (CV = 16.7%) also showed high stability, although with a slightly higher mean carbon footprint (260 kg/t).

**Table 8.** Net balance (retained in the field – emissions) at different straw retention shares, kg $CO_2$-eq/ha

| № | Cultivar | 0% | 30% | 50% | 75% | 100% | Break-even point |
|---|---|---|---|---|---|---|---|
| 1 | Lehenda Bilotserkivska | -355 | +3 767 | +6 515 | +10 637 | +13 385 | 77% |
| 2 | Okhtyrchanka | -365 | +3 732 | +6 463 | +10 561 | +13 292 | 77% |
| 3 | Pryvitna | -403 | +3 593 | +6 257 | +10 254 | +12 918 | 80% |
| 4 | Optyma Odeska | -405 | +3 586 | +6 247 | +10 238 | +12 899 | 80% |
| 5 | MIP Valensiia | -427 | +3 510 | +6 134 | +10 070 | +12 694 | 81% |
| 6 | Zorepad Bilotserkivskyi | -454 | +3 412 | +5 989 | +9 855 | +12 432 | 83% |
| 7 | Mudrist Odeska | -463 | +3 377 | +5 938 | +9 778 | +12 339 | 84% |
| 8 | Mariia | -488 | +3 287 | +5 804 | +9 579 | +12 096 | 85% |
| 9 | Kraievyd | -496 | +3 259 | +5 762 | +9 518 | +12 021 | 86% |
| 10 | Hratsiia Bilotserkivska | -502 | +3 238 | +5 732 | +9 472 | +11 965 | 86% |
| 11 | MIP Dniprianka | -517 | +3 183 | +5 649 | +9 349 | +11 816 | 87% |
| 12 | Spivanka Poliska | -537 | +3 113 | +5 546 | +9 196 | +11 629 | 89% |
| 13 | Kesariia Poliska | -568 | +3 002 | +5 381 | +8 950 | +11 330 | 91% |
| 14 | Burhunka | -571 | +2 988 | +5 360 | +8 920 | +11 292 | 92% |
| 15 | Vozdvyzhenka | -575 | +2 974 | +5 340 | +8 889 | +11 255 | 92% |
| 16 | Berehynia Myronivska | -581 | +2 953 | +5 309 | +8 843 | +11 199 | 92% |
| 17 | Vezha Myronivska | -583 | +2 946 | +5 299 | +8 828 | +11 180 | 92% |
| 18 | Hratsiia Myronivska | -589 | +2 925 | +5 268 | +8 782 | +11 124 | 93% |
| 19 | MIP Assol | -602 | +2 876 | +5 196 | +8 674 | +10 993 | 94% |
| 20 | Nasnaha | -606 | +2 862 | +5 175 | +8 644 | +10 956 | 94% |
| 21 | Anatoliia | -625 | +2 793 | +5 072 | +8 490 | +10 769 | 96% |
| 22 | Manera Odeska | -633 | +2 765 | +5 031 | +8 429 | +10 694 | 97% |
| 23 | Vodohrai | -651 | +2 702 | +4 938 | +8 291 | +10 526 | 98% |
| 24 | Katrusia Odeska | -658 | +2 675 | +4 897 | +8 229 | +10 451 | 99% |
| 25 | Vodohrai Bilotserkivskyi | -664 | +2 654 | +4 866 | +8 183 | +10 395 | 99% |
| 26 | Konka | -666 | +2 647 | +4 855 | +8 168 | +10 377 | 100% |
| 27 | MIP Vyshyvanka | -670 | +2 633 | +4 835 | +8 137 | +10 339 | 100% |
| 28 | Romanivna | -687 | +2 570 | +4 742 | +7 999 | +10 171 | >100% |
| 29 | Svitanokova | -699 | +2 529 | +4 680 | +7 907 | +10 059 | >100% |
| 30 | Oranta Odeska | -703 | +2 515 | +4 659 | +7 877 | +10 022 | >100% |
| 31 | Zdobna | -712 | +2 480 | +4 608 | +7 800 | +9 928 | >100% |
| 32 | Solovushka | -726 | +2 431 | +4 536 | +7 693 | +9 797 | >100% |
| 33 | Spryiatlyva | -764 | +2 292 | +4 330 | +7 386 | +9 424 | >100% |
| 34 | Estafeta Myronivska | -768 | +2 278 | +4 309 | +7 355 | +9 386 | >100% |
| 35 | Analoh | -807 | +2 139 | +4 103 | +7 049 | +9 012 | >100% |
| 36 | Poliska 90 | -820 | +2 090 | +4 031 | +6 941 | +8 882 | >100% |

## Straw management as a sequestration tool

The results demonstrate the critical role of straw management in the carbon balance. With complete straw removal (0%), all cultivars had negative sequestration balances (−1.569…−1.678 kg $CO_2$-eq/ha), i.e., they acted as net sources of soil carbon losses. A positive sequestration balance was achieved only under 75–100% straw retention for high-yielding cultivars and was not achieved for low-yielding ones (requiring >100%).

The sequestration break-even point – the minimum straw fraction required for a zero balance – varied from 77% (Lehenda Bilotserkivska, Okhtyrchanka) to >100% (Poliska 90, Zolotokolosa). This means that low-yielding cultivars cannot reach carbon neutrality even with full straw retention; additional organic inputs or a change of cultivar is required.

The straw effect (difference between 100% and 0% retention) averaged 11,678 kg $CO_2$-eq/

**Table 9.** Sequestration balance (humification – emissions), kg $CO_2$-eq/ha

| № | Cultivar | 0% | 30% | 50% | 75% | 100% | Break-even point |
|---|---|---|---|---|---|---|---|
| 1 | Lehenda Bilotserkivska | -1 569 | -951 | -539 | +80 | +492 | 77% |
| 2 | Okhtyrchanka | -1 571 | -957 | -547 | +67 | +477 | 77% |
| 3 | Pryvitna | -1 580 | -981 | -581 | +18 | +418 | 80% |
| 4 | Optyma Odeska | -1 581 | -982 | -583 | +16 | +415 | 80% |
| 5 | MIP Valensiia | -1 586 | -995 | -602 | -11 | +382 | 81% |
| 6 | Zorepad Bilotserkivskyi | -1 592 | -1 012 | -626 | -46 | +341 | 83% |
| 7 | Mudrist Odeska | -1 594 | -1 018 | -634 | -58 | +326 | 84% |
| 8 | Mariia | -1 600 | -1 034 | -656 | -90 | +287 | 85% |
| 9 | Kraievyd | -1 602 | -1 039 | -663 | -100 | +276 | 86% |
| 10 | Hratsiia Bilotserkivska | -1 603 | -1 042 | -668 | -107 | +267 | 86% |
| 11 | MIP Dniprianka | -1 607 | -1 052 | -682 | -127 | +243 | 87% |
| 12 | Spivanka Poliska | -1 611 | -1 064 | -699 | -152 | +213 | 89% |
| 13 | Kesariia Poliska | -1 619 | -1 083 | -726 | -191 | +166 | 91% |
| 14 | Burhunka | -1 620 | -1 086 | -730 | -196 | +160 | 92% |
| 15 | Vozdvyzhenka | -1 620 | -1 088 | -733 | -201 | +154 | 92% |
| 16 | Berehynia Myronivska | -1 622 | -1 092 | -738 | -208 | +145 | 92% |
| 17 | Vezha Myronivska | -1 622 | -1 093 | -740 | -211 | +142 | 92% |
| 18 | Hratsiia Myronivska | -1 624 | -1 097 | -745 | -218 | +133 | 93% |
| 19 | MIP Assol | -1 627 | -1 105 | -757 | -235 | +113 | 94% |
| 20 | Nasnaha | -1 628 | -1 107 | -760 | -240 | +107 | 94% |
| 21 | Anatoliia | -1 632 | -1 119 | -778 | -265 | +77 | 96% |
| 22 | Manera Odeska | -1 634 | -1 124 | -784 | -275 | +65 | 97% |
| 23 | Vodohrai | -1 638 | -1 135 | -800 | -297 | +39 | 98% |
| 24 | Katrusia Odeska | -1 640 | -1 140 | -807 | -307 | +27 | 99% |
| 25 | Vodohrai Bilotserkivskyi | -1 641 | -1 143 | -812 | -314 | +18 | 99% |
| 26 | Konka | -1 642 | -1 145 | -813 | -316 | +15 | 100% |
| 27 | MIP Vyshyvanka | -1 642 | -1 147 | -817 | -321 | +9 | 100% |
| 28 | Romanivna | -1 647 | -1 158 | -832 | -344 | -18 | >100% |
| 29 | Svitanokova | -1 649 | -1 165 | -842 | -358 | -36 | >100% |
| 30 | Oranta Odeska | -1 650 | -1 168 | -846 | -363 | -42 | >100% |
| 31 | Zdobna | -1 652 | -1 174 | -854 | -376 | -56 | >100% |
| 32 | Solovushka | -1 656 | -1 182 | -866 | -393 | -77 | >100% |
| 33 | Spryiatlyva | -1 665 | -1 206 | -900 | -442 | -136 | >100% |
| 34 | Estafeta Myronivska | -1 665 | -1 208 | -904 | -447 | -142 | >100% |
| 35 | Analoh | -1 674 | -1 233 | -938 | -496 | -202 | >100% |
| 36 | Poliska 90 | -1 678 | -1 241 | -950 | -513 | -222 | >100% |

ha for the net balance. The cultivar effect (under 100% straw retention) was 4.504 kg $CO_2$-eq/ha. Therefore, straw management has roughly a two-fold stronger impact on the carbon balance than cultivar choice; however, the best outcome is achieved by combining both factors.

## Practical recommendations

To reduce the carbon footprint of wheat grain production, it is recommended to: use highly efficient cultivars (Lehenda Bilotserkivska, Okhtyrchanka, Pryvitna, Optyma Odeska, MIP Valensiia); retain at least 75% of straw in the field to achieve a positive sequestration balance; and, if straw retention is not feasible, compensate with organic fertilizers.

The combination "Lehenda Bilotserkivska + 100% straw" provides the best result: net balance +13,385 kg $CO_2$-eq/ha, sequestration +492 kg $CO_2$-eq/ha. The combination "Poliska 90 + 0%

**Table 10.** Gross balance

| № | Cultivar | Uptake | Emissions | Gross balance | Ratio |
|---|---|---|---|---|---|
| 1 | Lehenda Bilotserkivska | 30 134 | 1 938 | +28 196 | 15.5x |
| 2 | Okhtyrchanka | 29 951 | 1 938 | +28 012 | 15.5x |
| 3 | Pryvitna | 29 216 | 1 938 | +27 277 | 15.1x |
| 4 | Optyma Odeska | 29 179 | 1 938 | +27 241 | 15.1x |
| 5 | MIP Valensiia | 28 775 | 1 938 | +26 836 | 14.8x |
| 6 | Zorepad Bilotserkivskyi | 28 260 | 1 938 | +26 322 | 14.6x |
| 7 | Mudrist Odeska | 28 076 | 1 938 | +26 138 | 14.5x |
| 8 | Mariia | 27 599 | 1 938 | +25 660 | 14.2x |
| 9 | Kraievyd | 27 452 | 1 938 | +25 513 | 14.2x |
| 10 | Hratsiia Bilotserkivska | 27 341 | 1 938 | +25 403 | 14.1x |
| 11 | MIP Dniprianka | 27 047 | 1 938 | +25 109 | 14.0x |
| 12 | Spivanka Poliska | 26 680 | 1 938 | +24 742 | 13.8x |
| 13 | Kesariia Poliska | 26 092 | 1 938 | +24 154 | 13.5x |
| 14 | Burhunka | 26 018 | 1 938 | +24 080 | 13.4x |
| 15 | Vozdvyzhenka | 25 945 | 1 938 | +24 007 | 13.4x |
| 16 | Berehynia Myronivska | 25 835 | 1 938 | +23 896 | 13.3x |
| 17 | Vezha Myronivska | 25 798 | 1 938 | +23 860 | 13.3x |
| 18 | Hratsiia Myronivska | 25 688 | 1 938 | +23 749 | 13.3x |
| 19 | MIP Assol | 25 430 | 1 938 | +23 492 | 13.1x |
| 20 | Nasnaha | 25 357 | 1 938 | +23 419 | 13.1x |
| 21 | Anatoliia | 24 989 | 1 938 | +23 051 | 12.9x |
| 22 | Manera Odeska | 24 842 | 1 938 | +22 904 | 12.8x |
| 23 | Vodohrai | 24 512 | 1 938 | +22 573 | 12.6x |
| 24 | Katrusia Odeska | 24 365 | 1 938 | +22 426 | 12.6x |
| 25 | Vodohrai Bilotserkivskyi | 24 254 | 1 938 | +22 316 | 12.5x |
| 26 | Konka | 24 218 | 1 938 | +22 280 | 12.5x |
| 27 | MIP Vyshyvanka | 24 144 | 1 938 | +22 206 | 12.5x |
| 28 | Romanivna | 23 813 | 1 938 | +21 875 | 12.3x |
| 29 | Svitanokova | 23 593 | 1 938 | +21 655 | 12.2x |
| 30 | Oranta Odeska | 23 519 | 1 938 | +21 581 | 12.1x |
| 31 | Zdobna | 23 336 | 1 938 | +21 398 | 12.0x |
| 32 | Solovushka | 23 078 | 1 938 | +21 140 | 11.9x |
| 33 | Spryiatlyva | 22 343 | 1 938 | +20 405 | 11.5x |
| 34 | Estafeta Myronivska | 22 270 | 1 938 | +20 332 | 11.5x |
| 35 | Analoh | 21 535 | 1 938 | +19 597 | 11.1x |
| 36 | Poliska 90 | 21 278 | 1 938 | +19 340 | 11.0x |

straw" is the worst: net balance −820 kg $CO_2$-eq/ha, sequestration −1.678 kg $CO_2$-eq/ha. The difference between the extreme combinations exceeds 14 t $CO_2$-eq/ha.

### Limitations and future research

This study has several limitations: (1) system boundaries excluded post-harvest processing and long-distance transportation; (2) $N_2O$ emissions used IPCC Tier 1 default factors rather than site-specific measurements. Future research should include direct soil carbon monitoring and field measurements of GHG fluxes.

## CONCLUSIONS

Total greenhouse gas emissions from winter wheat production under the conditions of the

Right-Bank Forest-Steppe of Ukraine amounted to 1,938.2 kg $CO_2$-eq/ha. The dominant sources were mineral fertilizer production (41.8%) and field $N_2O$ emissions (34.2%), which together accounted for 76% of total emissions.

The carbon footprint of grain production varied from 236 to 335 kg $CO_2$-eq/t depending on cultivar yield. Five highly efficient cultivars (<250 kg/t) were identified: Lehenda Bilotserkivska (236), Okhtyrchanka (238), Pryvitna (244), Optyma Odeska (244), and MIP Valensiia (248).

The gross carbon balance was positive for all cultivars (+19.3…+28.2 t $CO_2$-eq/ha), indicating that $CO_2$ uptake exceeded anthropogenic emissions. However, the sequestration balance under the baseline scenario (30% straw) was negative for all cultivars (−951…−1.241 kg/ha).

The sequestration break-even point (zero humification balance) ranged from 77% straw retention (high-yielding cultivars) to >100% (low-yielding cultivars). Only with 75–100% straw retained did high-yielding cultivars achieve a positive sequestration balance.

Cultivar choice and straw management can change the net field balance by 14,206 kg $CO_2$-eq/ha and the sequestration balance by 2.170 kg/ha. The straw effect (100% vs 0%) was 2.6 times greater than the cultivar effect; nevertheless, the optimal outcome is achieved by combining both factors.

To achieve carbon neutrality in wheat production, it is recommended to: use highly efficient cultivars (Lehenda Bilotserkivska, Okhtyrchanka, Pryvitna), retain at least 75% of straw in the field, and, when straw retention is not possible, compensate with organic fertilizers.

## REFERENCES


1. Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G. (2009). *Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use.* Cranfield University, UK.
2. Barraclough, P.B., Howarth, J.R., Jones, J., Lopez-Bellido, R., Parmar, S., Shepherd, C.E., Hawkesford, M.J. (2010). Nitrogen efficiency of wheat: Genotypic and environmental variation. *Journal of Experimental Botany*. *61*, 2933–2949. https://doi.org/10.1093/jxb/erq116
3. Blanco-Canqui, H., Lal, R. (2009). Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Sciences*. *28*, 139–163. https://doi.org/10.1080/07352680902776519
4. Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A., VandenBygaart, A.J. (2007). An approach for estimating net primary productivity and annual carbon inputs to soil. *Agriculture, Ecosystems & Environment*. *118*, 29–42. https://doi.org/10.1016/j.agee.2006.08.013
5. Brentrup, F., Hoxha, A., Christensen, B. (2016). Carbon footprint analysis of mineral fertilizer production in Europe and other world regions. *10th International Conference on Life Cycle Assessment of Food.* Dublin. 482–490.
6. Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S., Thornton, P. (2013). Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis*. IPCC. P. 465–570. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter06_FINAL.pdf
7. Clark, M., Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems. *Nature*. *548*, 229–232. https://doi.org/10.1038/nature22976
8. European Commission. (2019). The European Green Deal. COM 640 final. Brussels. 2019. 24 p. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%253A2019%253A640%253AFIN
9. Gan, Y., Liang, C., Chai, Q., Lemke, R.L., Campbell, C.A., Zentner, R.P. (2014). Improving farming practices reduces the carbon footprint of spring wheat production. *Nature Communications*. *5*, 5012. https://doi.org/10.1038/ncomms6012
10. Huang, X., Chen, C., Qian, H., Deng, S., Zhang, Y. (2017). Quantification for carbon footprint of agricultural inputs of grains cultivation in China. *Journal of Cleaner Production*. *141*, 1375–1383. https://doi.org/10.1016/j.jclepro.2016.09.134
11. IPCC. (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: *Agriculture, Forestry and Other Land Use*. IGES, Japan. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/
12. IPCC. (2019). Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/
13. IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report. *Cambridge University Press*. 2391. https://doi.org/10.1017/9781009157896

14. ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework.
15. ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines.
16. Järvenpää, M., Wikström, M. (2014). Carbon footprint of grain crops in Finnish cultivation. MTT Report 126. *Jokioinen, 45*. https://jukuri.luke.fi/handle/10024/481588
17. Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, B.J.R., Morrison, M.J. (2012). Legumes for mitigation of climate change. *Agronomy for Sustainable Development*. *32*, 443–479. https://doi.org/10.1007/s13593-011-0056-7
18. JRC (2014). Well-to-wheels analysis of future automotive fuels and powertrains. Joint Research Centre, European Commission.
19. Kätterer, T., Bolinder, M.A., Andrén, O., Kirchmann, H., Menichetti, L. (2011). Roots contribute more to refractory soil organic matter than above-ground crop residues. *Agriculture, Ecosystems & Environment*. *141*, 184–192. https://doi.org/10.1016/j.agee.2011.03.029
20. KTBL (2020). Betriebsplanung Landwirtschaft 2020/21. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Germany
21. Küstermann, B., Kainz, M., Hülsbergen, K. J. (2008). Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. *Renewable Agriculture and Food Systems*, *23*, 38–52. https://doi.org/10.1017/S1742170507002062
22. Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*. *123*, 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032
23. Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002
24. Poeplau, C., Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, *200*, 33–41. https://doi.org/10.1016/j.agee.2014.10.024
25. Poore, J., Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*, 987–992. https://doi.org/10.1126/science.aaq0216
26. Prysiazhniuk, O. I., Karazhbei, H. M., Leshchuk, N. V., Tsyba, S. V., Mazhuha, K. M., Brovkin, V. V., Symonenko, V. A., Maslechkin, V. V. (2016). Statistical analysis of agronomic research data package Statistica 10. Guidelines. Kyiv: Nilan-Ltd.
27. Prysiazhniuk O., Kononiuk N., Cherniak M., Musich V., Kachura Y., Prytula O., Voievoda L., Honcharuk O. (2025). Agroecological aspects of zonal application of fertilizers and pesticides in wheat cultivation in the Forest-Steppe of Ukraine. *Ecological Engineering & Environmental Technology*, *26*(5), 146–162. https://doi.org/10.12912/27197050/203075
28. Reay, D.S., Davidson, E.A., Smith, K.A., Smith, P., Melillo, J.M., Dentener, F., Crutzen, P.J. (2012). Global agriculture and nitrous oxide emissions. *Nature Climate Change*, *2*, 410–416. https://doi.org/10.1038/nclimate1458
29. Reynolds, M., Foulkes, M.J., Slafer, G.A., Berry, P., Parry, M.A.J., Snape, J.W., Angus, W.J. (2009). Raising yield potential of wheat. *Journal of Experimental Botany*, *60*, 1899–1918. https://doi.org/10.1093/jxb/erp016
30. Šarauskis, E., Masilionytė, L., Juknevičius, D., Buragienė, S., Kriaučiūnienė, Z. (2019). Energy use efficiency, GHG emissions, and cost-effectiveness of organic and sustainable fertilisation. *Energy*, *172*, 1137–1149. https://doi.org/10.1016/j.energy.2018.10.143
31. Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B*. *363*, 789–813. https://doi.org/10.1098/rstb.2007.2184
32. State Statistics Service of Ukraine. (2024). Crop Production of Ukraine 2023: Statistical Collection. Kyiv. https://www.ukrstat.gov.ua/druk/publicat/kat_e/2024/zb/09/zb_rur_2023.pdf
33. Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., Smith, P. (2013). The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters*, 8. 015009. https://doi.org/10.1088/1748-9326/8/1/015009
34. Wilhelm, W. W., Johnson, J. M. F., Karlen, D. L., Lightle, D. T. (2007). Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal*, *99*, 1665–1667. https://doi.org/10.2134/agronj2006.0218
35. Williams, A. G., Audsley, E., Sandars, D. L. (2006). Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Defra Research Project IS0205. Bedford. 2006. 97. https://www.silsoe.

cranfield.ac.uk/PartnersandCustomers/ResearchReports/IS0205_3959_FRP.pdf

36. Wojcik-Gront, E., Bloch-Mechkour, A. (2021). Carbon footprint of winter wheat production in Poland. *Environmental Science and Pollution Research*, *28*, 25351–25358. https://doi.org/10.1007/s11356-021-12486-9
37. Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander, B.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S., Campbell, B.M. (2016). Reducing emissions from agriculture to meet the 2 °C target. *Global Change Biology*, *22*, 3859–3864. https://doi.org/10.1111/gcb.13340