scientific data

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European multi-trial data set on carbon and nitrogen isotope ratios of winter wheat spanning 170 years

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Long-term and multi-site datasets are essential for understanding crop responses to environmental variability and management practices, yet such data remain scarce, particularly for physiological indicators. Here, we present a harmonized dataset of analyses of stable carbon (i.e., $\delta^{13}C$ values) and nitrogen (i.e. $\delta^{15}N$ values) isotope ratios from winter wheat samples collected across ten long-term and short-term field trials in Europe. The dataset spans over 170 years (1850–2024) and includes sites in Switzerland, France, Germany, Denmark, and the United Kingdom. Samples originate from experiments encompassing unfertilized controls, mineral and organic nitrogen fertilization at multiple rates, and contrasting management systems, including conventional and organic practices. Grain samples were available for all selected years, with straw samples included when available. In addition to isotope ratios, the dataset provides harmonized management information, including sowing and harvest dates, nitrogen inputs, and yield data. Technical validation confirmed that management records and isotope ratios are agronomically and physiologically plausible and internally consistent across sites and years. This dataset offers a unique resource for investigating long-term (genotype by) environment by management interactions, benchmarking crop models, and conducting comparative analyses of carbon and nitrogen dynamics in European agroecosystems.

Background & Summary

Global food demand is increasing[1,2] while relying on a handful of arable crops, such as maize, rice, or wheat[3]. Despite their global importance, long-term, harmonized datasets capturing crop physiological responses across diverse environments and management regimes remain scarce. Simultaneously, climate change has a major impact on these crops and threatens crop yields on a global scale[4,5]. Especially extreme events, such as cold, heat, or drought stress, are known to influence the performance and yield of crops[6–10], and are prone to increase under future climates[11]. Furthermore, crop performance is shaped not only by interactions between crop (or genotype; G) and environment (E), but also by management (M), including fertilization regimes, soil treatment, sowing, and harvest timing. A better understanding of these overarching interactions, also referred to as crop (or genotype) by environment by management interaction (GxExM), is essential for improving stress resilience in cropping systems and for parametrizing, validating, or benchmarking crop and ecosystem models across contrasting conditions[12,13].

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However, these interactions are complex and therefore require harmonized long-term, multi-site datasets that capture environmental variability and management intensities[14]. One of the most important factors regarding the management is the fertilization, or more specifically, the amount of nitrogen applied[15].

Analyses of carbon (C) and nitrogen (N) stable isotopic ratios (expressed as $\delta^{13}C$ and $\delta^{15}N$ values on the VPDB and AIR-N_2 scales) of the plant material offer integrative indicators of plant physiological responses, or stressors, to environmental and management conditions[16]. Variation of $\delta^{13}C$ values reflects changes in stomatal regulation and carbon assimilation, making it a valuable proxy for water use efficiency and drought stress[17]. $\delta^{15}N$ values can provide insights into nitrogen uptake dynamics, fertilizer source partitioning, and microbial interactions, and are particularly informative for tracing nitrogen inputs and management intensity. Information on stable carbon and nitrogen isotopic ratios of plant material thus enables the assessment of stress responses and resource-use strategies across varying G × E × M contexts, providing opportunities for physiological, agronomic, and ecological investigations across sites and years[18,19]. Stable isotope analyses of archived crops from these specific trials have been previously conducted on smaller scales. Fraser *et al.*[20] determined the stable carbon and nitrogen isotope ratios of cereal grains from Broadbalk (Rothamsted), Askov, and Bad Lauchstädt to establish baseline isotope ratios under controlled nutrient regimes. These empirical baselines were subsequently utilized by Bogaard *et al.*[21] to define nitrogen isotope thresholds representing low ($\delta^{15}N < 3‰$), medium ($3‰ \leq \delta^{15}N \leq 6‰$), and high ($\delta^{15}N > 6‰$) manuring rates in archaeological crop reconstructions. While those studies demonstrated the utility of crop archives for reconstructing historical and prehistoric management, they relied on targeted sample subsets. The continuous, high-density records from Broadbalk, Askov, and Bad Lauchstädt in our dataset build upon these precedents, extending over multi-decadal to centennial scales to provide robust, long-term baselines under documented, stable management regimes.

Long-term, multi-site agricultural experiments spanning multiple decades are rare, due to the substantial logistical, financial, and institutional commitments required. However, several long-term experiments have been established in Europe decades ago, covering various management strategies or fertilization levels, and hence provide a unique source of historical data. We present a harmonized dataset comprising ten winter wheat fertilization trials distributed across Europe, with observations extending back to 1850. Thus, this dataset represents one of the longest continuous historical records currently available of crop stable C and N isotope ratios directly originating from controlled agronomic trials. We selected samples to represent a gradient in N application in each experiment, if available, with a control treatment with no N application. Furthermore, we sought to cover an extended range of genotypes, including several trials across multiple years and, in selected cases, replicates. Overall, the dataset comprises information from 1491 samples and thus provides a comprehensive resource for investigating G × E × M interactions in long-term cropping systems focusing on winter wheat. It is meant to support model development, cross-site meta-analyses, and benchmarking of crop and biogeochemical models.

Methods

Analysis of isotope ratios and data harmonization. All samples were prepared and analyzed for C and N isotope ratios at ETH Zurich to ensure analytical consistency across experiments and years. Grain samples were finely ground using a ball mill (MM 200, Retsch, Haan, D) prior to analysis. Subsamples (2.3-2.5 mg) were weighed into Sn capsules (Saentis Analytical, Teufen, CH) for the determination of the C and N isotope ratios. Measurement of C and N isotope ratios was performed using an elemental analyzer (Flash EA 1112 Series elemental analyzer (Thermo Italy, former CE Instruments, Rhodano, I) coupled to a Delta^{plus}XP mass spectrometer (Finnigan MAT, Bremen, D)[22,23]. The measurement of the C (% C) and N (% N) content of the samples was performed simultaneously using the same analytical setup, thereby allowing the calculation of the carbon-to-nitrogen (C:N) ratio of the samples. $\delta^{13}C$ and $\delta^{15}N$ values are reported in per mill (‰) relative to international standards (VPDB for carbon and AIR-N_2 for nitrogen). Samples, blanks, and (laboratory) standard materials were positioned according to the Identical-Treatment principle in a measurement series that followed the scheme described by[24]. Post-run off-line calculations (blank-, offset-, and drift-corrections) were performed according to[24] to allow an assignment of the final δ values of the samples on the V-PDB and AIR-N_2 scales. Laboratory standards were regularly calibrated against international reference materials provided by the International Atomic Energy Agency (IAEA; Vienna, Austria). The long-term precision of our quality control standard (tyrosine) for $\delta^{13}C$ and $\delta^{15}N$ measurements is 0.03 ‰ and 0.07 ‰, respectively. Straw samples were treated equally. However, nitrogen concentration in most straw samples was insufficient to determine $\delta^{15}N$ at the applied sample mass reliably, and $\delta^{15}N$ values for straw are therefore not reported.

Management information, including sowing dates, harvest dates, yields, and nitrogen inputs, was compiled from original experimental records for each trial and harmonized across trials to ensure consistency within the dataset. All nitrogen inputs were converted to a common unit (kg ha^{-1} yr^{-1}), distinguishing between mineral and organic sources where available. Dates were standardized to a uniform format (YYYYMMDD), and yield data were converted to t ha^{-1} dry matter to facilitate cross-site and long-term comparisons. Any inconsistencies encountered during harmonization were resolved by consulting original documentation where possible. Missing information was retained as explicit NA entries to preserve transparency and avoid introducing assumptions. We used the ERA5-Land post-processed dataset to calculate the average temperature in Figure 1. This dataset is freely available and can additionally be used in combination with this data[25].

Detailed information about the (long-term) experiments. Isotope analyses and metadata harmonization of all experiments described later followed the procedures described in the Methods section.

Askov long-term field experiment - Askov (DK). The Askov-LTE, initiated in 1894, is located at Askov Experimental Station, South of Jutland (55.47° N, 9.12° E; 63 m above sea level (m asl)). The soil classifies as a sandy loam (Typic Hapludalf, fine loamy, mixed, mesic). The experiment includes four fields (blocks) that

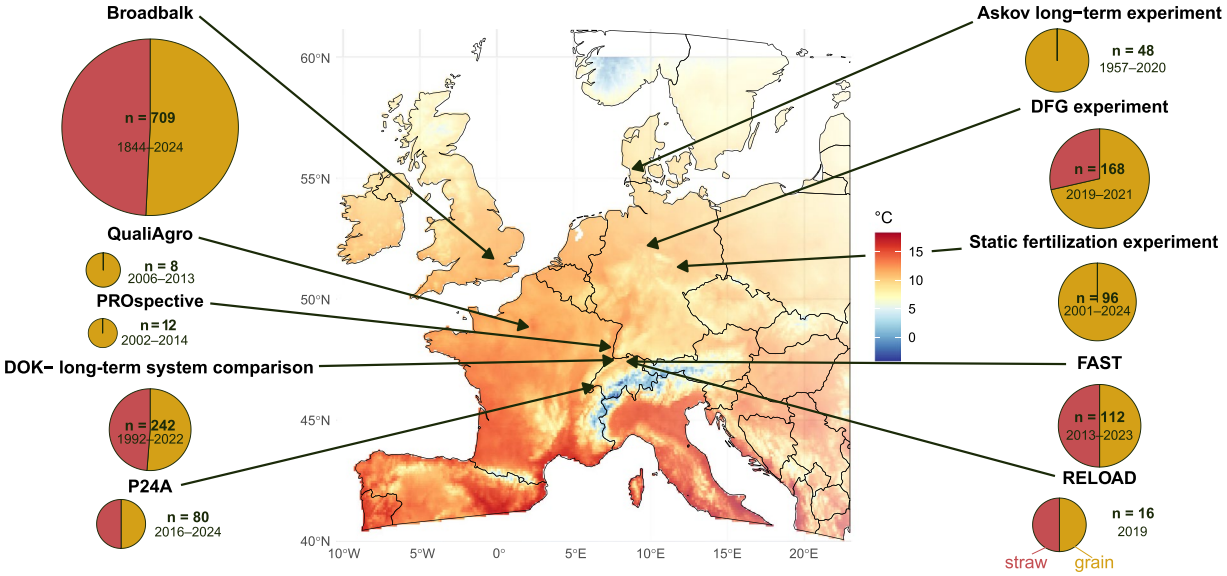


Fig. 1 Locations of the experiments combined in this dataset. The map represents the average temperature between 2011 and 2024. The size of the pie plots represents the number of available samples (also mentioned as n = # samples), and the colors indicate the ratio of grain (orange) to straw (red) samples per experiment. The duration during which samples were available is indicated as the year of the first and last sample. The Broadbalk, DOK, FAST, RELOAD experiments are represented by the largest number of samples and an almost 50:50 ratio of grain to straw samples. The Askov long-term experiment, QualiAgro, PROspective, and the Static Fertilization Experiment provide only grain samples.

were grown in a rotation of root crops (replaced by silage maize in 2005), spring cereals (barley since 1932), grass-clover, and autumn-sown cereals (winter wheat since 1932). Each field carries one crop in a given year. For all treatments, soil pH is kept in the range 5.5 to 6.5 using Mg-enriched lime. The nutrient treatments include different levels of N, P and K in mineral fertilizers (0, 1/2, 1, 1 1/2 NPK). During 1949–1972, winter wheat received 70 kg N ha^{-1} yr^{-1} in 1 NPK; during 1973–2006, the rate was 96 kg N ha^{-1}; in 2006 this was raised to 150 kg N ha^{-1} [26,27].

The present study rests on analysis of winter wheat grain samples pooled across the four fields. Ten periods each covering 4-year intervals were included, starting in 1957, 1977, 1981, 1985, 1989, 1993, 1997, 2001, 2005, 2009, and 2013. The year 2020 was also included as an individual sampling year. Detailed information on crop varieties, sowing and harvest dates can be found in a separate table (*Askov_detailed_sowing_harvest_variety_info.csv*).

Broadbalk Wheat Experiment- Rothamsted (UK). The Broadbalk wheat experiment is the world's oldest continuously running long-term winter wheat experiment. It was established in 1843 at the Rothamsted Research Station in the United Kingdom (51.81° N, -0.37° E; 130 m asl)[28]. The experiment was designed to investigate the long-term effects of organic manures and inorganic fertilizers, including nitrogen (N) and phosphorus (P), on winter wheat yield. The soil of the Broadbalk experiment is classified as a chromic Luvisol[29]. Over its history, the experiment has undergone changes in varieties and management practices, reflecting the development of modern wheat production systems.

For the present dataset, samples from three N fertilization treatments (0, 48, and 144 kg N ha^{-1} yr^{-1}) were selected at five-year intervals for the period from 1850 to 1965. For the period from 1968 to 2024, annual samples were included from four N fertilization levels (0, 48, 144, and 192 kg N ha^{-1} yr^{-1}). Grain samples were available throughout the sampling period, while straw samples were included when preserved material was available. Corresponding yield data[30,31,31] were included where recorded and harmonized with other metdadata[32,33] as described in the Methods section.

DOK-Langzeit-Systemvergleich - Therwil (CH). The DOK long-term field trial is located in Therwil, Switzerland (47.50° N, 7.54° E; 308 m asl)[34]. The experiment was established in 1978 to compare biodynamic (D), bioorganic (O), and conventional (K) agricultural cropping systems[35]. The predominant soil type at the site is classified as a haplic Luvisol, with a mean clay content of 15.7% and a sand content of 11.7%[36].

The experiment comprises eight treatments, including two fertilization levels within each of the biodynamic (D1, D2), bioorganic (O1, O2), and conventional systems receiving manure and mineral fertilizers (K1, K2). In addition, an unfertilized control (N0) and a conventional treatment receiving only mineral fertilizers (M2) are included[37]. Winter wheat varieties have changed over the years and are reported in the dataset accordingly.

For the present dataset, samples from the unfertilized control (N0), the mineral-fertilized conventional treatment (M2), and the high-input conventional manure treatment (K2) were selected. These treatments were sampled for 21 individual years between 1992 and 2022 (1992, 1993, 1995-2001, 2005-2007, 2009, 2010, 2012, 2013, 2015, 2017-2019, and 2022), using one replicate per treatment. In addition, all available treatments and replicates

were included for the years 2003 and 2020 to assess heterogeneity across experimental plots and to increase the range of fertilization applications. Isotope ratios of the grain samples were analyzed for all selected years, and straw samples were included for all years except 2010 and 2015.

Farming System and Tillage Experiment (FAST) - Rümlang (CH). The Farming System and Tillage (FAST) experiment is located near Zürich, Switzerland (47.44° N, 8.53° E; 485 m asl). The soil type is classified as a calcareous Cambisol, with an average soil organic carbon content of 1.4%, and a texture comprising 23% clay, 34% silt, and 43% sand[38]. The FAST experiment consists of two adjacent fields established in 2009 and 2010, respectively, following the same crop rotation but offset by one year. Both fields include treatments combining intensive tillage (mouldboard ploughing) and no-tillage/shallow tillage management under conventional and organic farming systems, each having four replicates per experiment. Nitrogen fertilization differed between farming systems, with average total N inputs of 121 kg N_{tot} ha^{-1} yr^{-1} applied predominantly through cattle slurry and few organic commercial fertilizers under organic management, and 92 kg N_{tot} ha^{-1} yr^{-1} in mineral form under conventional management[39]. Within each farming system, fertilization is applied at full and half rates of the recommended N input since the second crop rotation (2016 and 2017).

For the present dataset, samples were selected from the tilled treatments only, including conventional and organic management systems at both full and half fertilization rates, resulting in four treatments. These treatments were sampled for eight individual years (2013, 2014, 2016, 2017, 2019, 2020, 2022, and 2023), using one replicate per treatment. Except for the years 2019 and 2020, all four available replicates were analyzed.

Resilience of organic and conventional production systems to drought (RELOAD) - part of FAST. The Resilience of organic and conventional production systems to drought (RELOAD) project was conducted on the FAST trial. Additionally, one year of drought-stressed samples from the RELOAD project has been added. The samples were collected in 2019 for the tilled organic and conventional management with the full fertilization rate applied. All experimental properties are equivalent to those of the FAST trials, except that an artificial drought stress treatment was applied with rain-out shelters[40].

DFG Experiment for Modern Wheat Variety Testing - Ruthe (DE). Field trials were conducted at the research station of Leibniz University Hannover in Ruthe, Germany (52.25° N, 9.12° E; 70 m asl). The experiment, funded by the Deutsche Forschungsgemeinschaft (DFG), was carried out over three winter wheat growing seasons (2018–2019, 2019–2020, and 2020–2021) to assess the breeding progress in Germany[41]. Four winter wheat genotypes were grown during the first season, and eight genotypes were included in each of the subsequent two seasons[42].

The experimental design comprised two N fertilization levels (176 and 220 kg N ha^{-1} yr^{-1}), combined with two sowing dates and different N application timings. For the present dataset, samples were selected from the early sowing treatment with split N application at both fertilization levels. Grain samples were analyzed for all three growing seasons, whereas straw samples were available and analyzed only for the 2020–2021 season.

P24A - Changins (CH). The P24A long-term field experiment is located at the Swiss Research Station of Agroscope in Changins, Switzerland (46.40° N, 6.24° E; 442 m asl). The experiment was established in 1976 and is conducted on a soil classified as a calcaric Cambisol. The P24A experiment comprises six main organic amendment treatments: no organic amendment (Min), green manure (GM), straw (Str), manure with 35 t ha^{-1} (Ma35) and 70 t ha^{-1} every three years (Ma70), and 60 m^3 ha^{-1} slurry every three years (Slu). In addition, each main treatment includes four mineral N fertilization sub-treatments: 0 N (A), recommended N minus 40 kg N ha^{-1} (B), recommended N (C), and recommended N plus 40 kg N ha^{-1} (D)[43].

For the present dataset, samples from the mineral-only treatment (Min) were selected, including all four mineral N sub-treatments (A-D) and four replicates per treatment for two years (2018 and 2022) to be able to check for field heterogeneity. However, in the remaining two years (2016 and 2024), only one replicate was measured due to the labour-intensive sample preparation and time constraints. The C and N isotope ratios and the corresponding elemental contents of the grain and straw samples were analyzed for the years 2016, 2018, 2022, and 2024, following the procedures described in the Methods section.

PROspective - Colmar (FR). The PROspective trial is located at Colmar, northeastern France (48.05° N ; 7.32° E; 200 m asl) on the experimental station of France's National Research Institute for Agriculture, Food and Environment's (INRAE) experimental station in Colmar[44]. The experiment was established in 2000 and is still ongoing on a soil classified as Calcisol derived from loess. It investigates the long-term agronomic and environmental effects of repeated applications of organic waste products. The crop rotation prior to 2020 comprised grain maize, winter wheat, sugar beet, and spring barley[45].

For the present dataset, winter wheat samples were selected from the years 2002, 2006, 2010, and 2014, representing three fertilization treatments: unfertilized control, organic fertilization applied every second year at 170 kg N ha^{-1} yr^{-1}, and mineral fertilization at 120 kg N ha^{-1} yr^{-1}. The C and N isotope ratios and the corresponding elemental contents of the grain samples were analyzed when available.

QualiAgro - Orgeval (FR). The QualiAgro long-term experiment is located near Orgeval, France (48.90° N, 1.97° E; 177 m asl), and was established in 1998. The experiment is managed by INRAE and investigates, as the PROspective trial, the long-term agronomic and environmental effects of repeated applications of organic waste products. The trial was conducted under conventional cropping systems until 2013, with winter wheat as the main crop. This site is situated on a Haplic Luvisol developed on loess in the Paris Basin, representative of the region's fertile agricultural soils[45].

For the present dataset, winter wheat samples were selected from four years (2006, 2009, 2011, and 2013), representing two mineral N fertilization treatments: TEM N- (minimal mineral fertilization) and TEM N+ (optimal mineral fertilization). The C and N isotope ratios and the corresponding elemental contents of the grain samples were analyzed, as well as the yield and metadata were harmonized following the procedures described in the Methods section.

Static Fertilization Experiment - Bad Lauchstädt (DE). The Static Fertilization Experiment is located in Bad Lauchstädt, Germany (51.39° N, 11.87° E; 118 m asl). The experiment was initiated in 1902 and investigates the effects of organic and mineral fertilization on crop performance[46]. Three levels of organic fertilizer are applied: no application, 20 t ha^{-1}, and 30 t ha^{-1} every second year. Within these organic treatments, six mineral fertilization treatments are applied: control (no mineral), NPK, NK, NP, N, and PK. The crop rotation includes sugar beet, summer barley, potato, and winter wheat until 2014, and from then on silage maize, summer barley, silage maize, and winter wheat, all represented annually in the trial[47].

For the present dataset, four treatments were selected: the control (Var. 18), NPK without organic fertilization (Var. 13), 30 t ha^{-1} organic fertilizer every second year with no mineral fertilization (Var. 6), and 30 t ha^{-1} organic fertilizer every second year combined with NPK mineral fertilization (Var. 1). Grain samples were analyzed, yield (dry matter) and meta data were harmonized.

Summary of Included Experiments. The dataset includes winter wheat samples from ten long-term and short-term experiments across Europe (Switzerland, France, Germany, Denmark, and the United Kingdom), spanning 1850–2024. Treatments cover unfertilized controls, mineral and organic fertilization at multiple rates, and management variations such as conventional/organic systems. Grain samples were available for all selected growing periods (i.e., harvest years), and straw samples were added whenever available. Measurements of $\delta^{13}C$ and $\delta^{15}N$ values were carried out for all analyzed grain samples. Replication varies by site and year, typically from one to four replicates per treatment, and detailed metadata are link each sample to its site, year, treatment, and replicate.

Data Records

The dataset is openly available through Zenodo[48] and is provided under an open license. All scripts used for data processing and technical validation are available in a public Git repository (https://github.com/ftschurr/long-term_dataset_validation), enabling transparency and reproducibility of the validation steps described in this manuscript.

The dataset is available as two comma-separated values (CSV) files. The primary file contains management information, results of isotope analyses, C and N concentration, and C:N ratio data for all samples, while a secondary file provides corresponding yield data when available. Both files use consistent unique identifiers (UID) to allow unambiguous linkage between information on management, isotopic compositions, C:N, and yield records. The main data file (*winter_wheat_isotopes_management.csv*) contains one row per sample and includes information on experimental site (longitude, latitude, and elevation), year, fertilization treatment (total, organic, and mineral N input) and defined comparable class (treatment_level), crop material (straw or grain), C and N isotope ratios (given as $\delta^{13}C$ and $\delta^{15}N$ values), C and N concentration, C to N ratio, variety, previous grown crop, sowing and harvest date (see Table 1). Missing values are encoded as NA.

The yield data file (*winter_wheat_yield.csv*) contains grain and straw yield (both as dry matter) information associated with the samples in the main dataset (Table 1). Yield records are linked to the main dataset via unique identifiers. Yield values are reported in tonnes per hectare (dry matter t ha^{-1}). When yield data were not available for a given sample or year, entries are retained as missing values (NA) to preserve the original structure of the long-term experiments. Yield values must be cited with the corresponding publication mentioned in the yield data file if provided. If an entry in the *reference_to_cite* column is provided, the yield data were already published (see Table 2), which applies to the following datasets:[30,31,42,49].

Together, these files provide a harmonized and structured representation of information on long-term winter wheat management, C and N isotope ratios, and yield data across ten European trials, enabling reuse for agronomic, ecological, and modeling applications.

Technical Validation

Meta Data. The temporal distribution of samples shows that the majority of observations originate from the 1960s onward, with additional shorter-duration experiments contributing data primarily in more recent decades (Figure 2a). Across trials, control treatments without N application were sampled whenever available, resulting in nearly 300 observations with zero N input (Fig. 2b). Reported N inputs were cross-checked against documented treatment levels for each experiment and compared with published fertilization ranges for the wheat trials. N inputs span from 0 to 225 kg ha^{-1} yr^{-1}, which is consistent with expected agronomic practices. Missing values were retained as explicit NA entries to ensure transparency and facilitate informed reuse.

Sowing and harvest dates were systematically evaluated to assess consistency and plausibility across trials and years. Sowing and harvest dates fall within agronomically realistic windows for winter wheat cultivation in each European location (Fig. 2c,d), with temporal variability reflecting known regional and historical management differences. Only in the Broadbalk experiment, sowing took place very late in several years (December to February), and correspondingly, a late harvest date can be observed.

Yield data were analyzed separately for grain and straw. Given the wide range of nitrogen treatments across experiments, considerable yield variability is expected and observed. Reported grain yields reach up to 10 t ha^{-1}, compatible with high-input winter wheat systems (Fig. 2e,f). Yield values from the Broadbalk experiment, the trial with the oldest samples, cluster toward the lower end of the distribution, reflecting the use of older varieties

Variable name	unit	description
location		Name of the site location
trial_ID		Abbreviation of the trial
trial_name		Name of the experimental trial
year		Harvest year of this sample
UID		Unique sample identifier
material		Either grain or straw to define the material of the sample
id_local		Name of the treatment in the naming convention of the original trial
rep		Replication number
treatment_level		Given name for each N application to compare within and between experiments
N_tot_input	$kgNha^{-1}$	Total applied N for the corresponding cropping season
N_min	kg N ha^{-1}	Applied mineral N for the corresponding cropping season
N_org	kg N ha^{-1}	Applied organic N for the corresponding cropping season
lat	decimal degrees	Latitude of the trial
lon	decimal degrees	Longitude of the trial
elevation	meter above sea level	Elevation of the trial
sowing_date	YYYYMMDD	Date when sowing took place
harvest_date	YYYYMMDD	Date when harvest took place
variety		Name of the variety cultivated
previous_crop		Name of the crop cultivated in the previous to the sample
d13C	‰	Carbon isotope ratios
d15N	‰	Nitrogen isotope ratios
C_content	%	Carbon concentration of the sample
N_content	%	Nitrogen concentration of the sample
C_N_ratio		Ratio of carbon to nitrogen content
responsible_person		Contact to the PI of this data point
comments		Additional comments if required

Table 1. Description of variables in the main dataset (*winter_wheat_isotopes_management.csv*), including site metadata, management treatments, nitrogen inputs, crop variety, sampling dates, and C and N isotope ratios (listed as $\delta^{13}C$ and $\delta^{15}N$ values) of grain and straw samples.

Variable name	unit	description
location		Name of the site location
trial_ID		Abbreviation of the location
trial_name		Name of the experimental trial
year		Harvest year of this sample
UID		Unique sample identifier
material		Either grain or straw to define the material of the sample
yield_t_ha	dry matter tonnes per ha	Grain or straw yield
responsible_person		Contact to the PI of this data point
reference_to_cite		Publication to be cited if this data point is used

Table 2. Description of variables included in the winter wheat yield dataset (*winter_wheat_yield.csv*). The table lists all recorded metadata fields, their units, and brief explanations to facilitate data interpretation and reuse.

and historical management conditions. This pattern is consistent with documented breeding progress and yield improvements since the mid-19th century.

Overall, these validation steps confirm that management and yield records are internally consistent, agronomically plausible, and appropriate for investigating genotype (or crop) × environment × management (G × E × M) interactions across multiple trials and more than a century of agricultural experimentation.

Isotope Data. The measured $\delta^{13}C$ values were evaluated against published reference ranges for winter wheat grain and straw and fall within the expected range for a C3 crop[50–52]. $\delta^{13}C$ values show coherent clustering within individual trials and across years, consistent with known variation in carbon assimilation driven by environmental conditions and management. No implausible values or visual outliers were identified (Fig. 3c,d). Grain $\delta^{15}N$ values generally fell within expected ranges for mineral- and organically fertilized wheat (Fig. 3e,f). However, 33 grain samples from the Broadbalk experiment exhibited very high $\delta^{15}N$ values (>11‰). These samples all originated from fertilized treatments after 1980, whereas the control treatment remained unaffected. In that year, a ^{15}N tracer experiment was conducted at Broadbalk[53], likely resulting in a residual ^{15}N enrichment in the soil that persisted

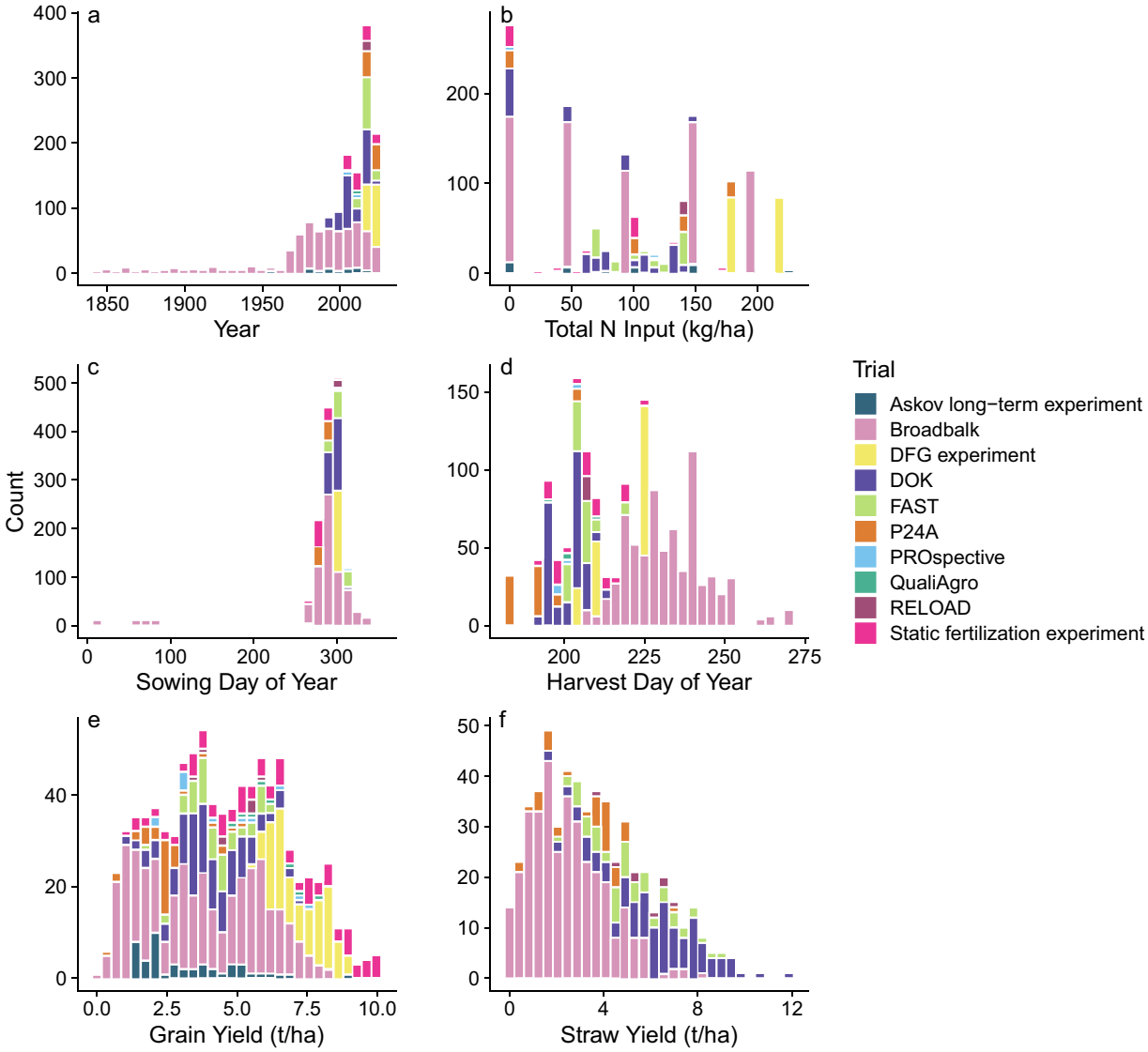


Fig. 2 Histograms showing the temporal distribution of samples over the years (**a**), total N input (kg ha^{-1} yr^{-1}; **b**), sowing dates (**c**), harvest dates (**d**), grain yield (t ha^{-1}; **e**), and straw yield (t ha^{-1}; **f**). Colors indicate the different experiments included in the dataset.

in subsequent years. To avoid bias introduced by this legacy effect, all grain δ^{15}N values exceeding the maximum observed prior to the ^{15}N labeling experiment (11‰) were excluded from the dataset. Excluded observations are explicitly documented in the *comments* column of the *winter_wheat_isotopes_management.csv* file.

Most straw samples could not be used for δ^{15}N analysis due to very low %N values at the applied sample mass. Straw δ^{15}N values were therefore only retained when signal quality met analytical thresholds. Specifically, measurements with a signal IRMS N_2 peak amplitude(m/z 28) greater than 800 mV were considered reliable and are reported in the dataset. However, to be able to retrieve a reliable value for the C:N ratio and N concentration, we lowered the amplitude threshold to 500 mV because control measurements confirmed that this threshold still yielded reliable results. After these quality-control steps, no further visual outliers were detected. δ^{13}C and δ^{15}N values cluster by trial with variability that can be attributed to year, fertilization intensity, and, where applicable, genotype. This confirms that the determination of the C and N isotopic compositions are internally consistent, physiologically meaningful, and suitable for cross-site and long-term analyses of genotype × environment × management interactions.

Usage Notes

The dataset provides a harmonized, multi-year collection of winter wheat management, yield, and analyses of C and N isotope ratios from long-term and modern experiments across Europe. It is suitable for a wide range of applications in agronomy, plant physiology, and crop modeling. Potential uses of the dataset include quantitative analyses of genotype (or crop) × environment × management (G × E × M) interactions across multiple decades, as well as the calibration and validation of process-based crop growth models under diverse

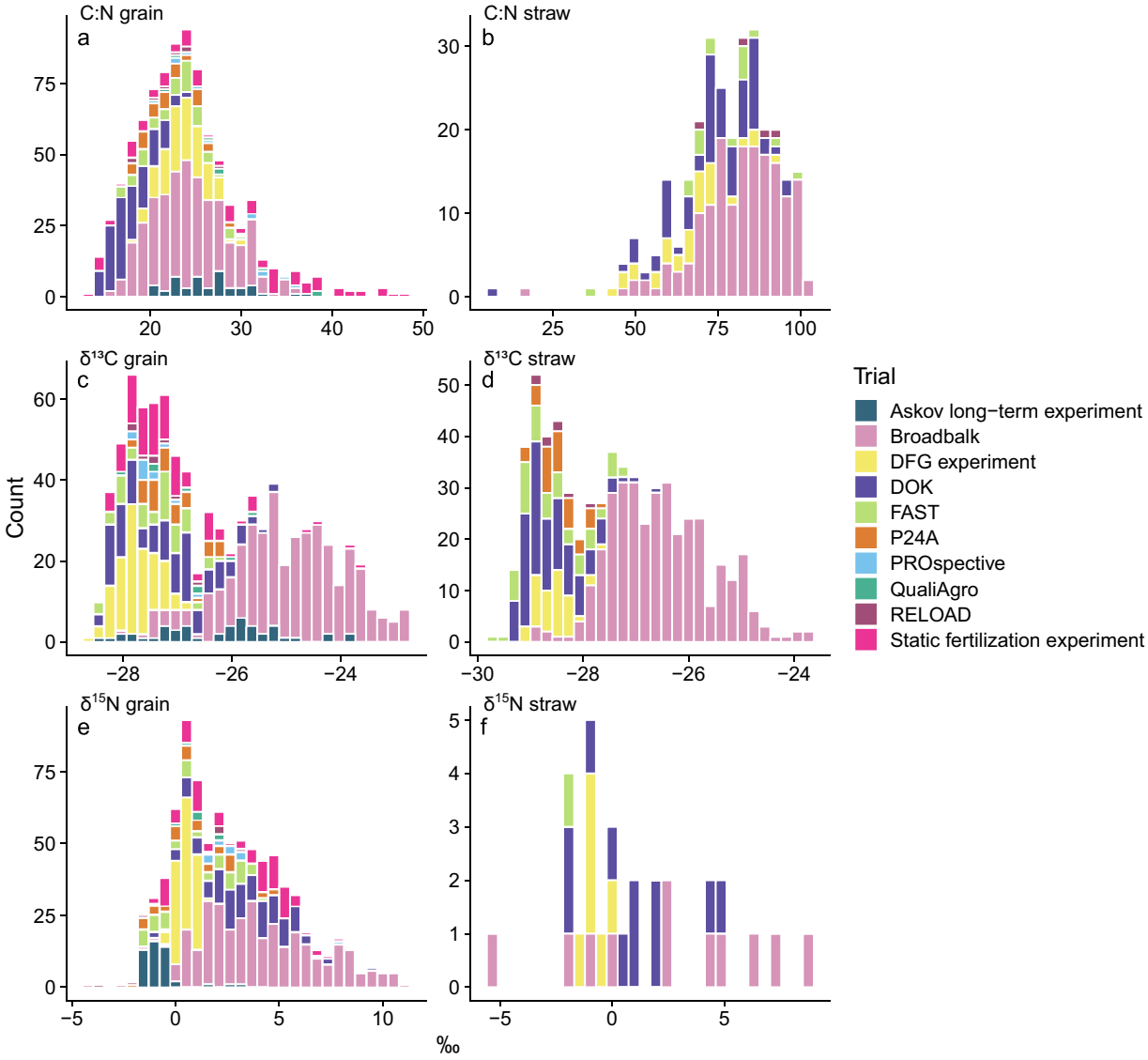


Fig. 3 Histograms showing the C:N ratio of the grain (**a**) and straw (**b**) samples, δ^{13}C values of the grain (‰; **c**) and straw (‰; **d**) samples, and δ^{15}N values of the grain (‰;**e**) and straw (‰; **f**) samples. Colors indicate the different experiments included in the dataset.

fertilization regimes, climatic conditions, and management practices. The analyses of C and N isotope ratios enable physiological investigations of winter wheat responses to environmental and management drivers, with C isotope ratios serving as an integrative proxy for water-use efficiency and N isotope ratios providing insights into nitrogen uptake and source dynamics. In addition, the long temporal coverage and multi-site structure of the dataset support meta-analyses and long-term trend studies addressing fertilization strategies, yield trends, and environmental responses across contrasting agroecosystems.

Potential limitations of this dataset are that not all experiments included in it provide complete observations for every year, treatment, or replicate. Missing values are retained as explicit NA entries to ensure transparency. Straw samples are not available for all years or experiments, and δ^{15}N analyses in straw are limited due to low nitrogen concentrations in the analyzed material. Although management information and isotope analyses were harmonized across trials, management practices, varieties, and experimental protocols differ among the trials and over time. For organic fertilization, applications during the corresponding growing season are reported. However, effects from previous years or crops can affect the performance of the reported winter wheat seasons. These differences should be considered when combining data for meta-analyses or model-based applications. The dataset is restricted to winter wheat, and caution is advised when extrapolating findings to other crop species or agroecological regions not covered in this dataset.

Researchers are encouraged to cite both the dataset DOI and the original experiments when reusing this dataset. Detailed metadata, including site coordinates, N inputs, and sowing and harvest dates, are provided to facilitate reproducible analyses.

Data availability

The dataset is openly available through Zenodo (https://doi.org/10.5281/zenodo.19201634).

Code availability

Code to reproduce the technical validation is available at: https://github.com/ftschurr/long-term_dataset_validation.

Received: 9 April 2026; Accepted: 5 October 2026;
Published: xx xx xxxx

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Acknowledgements

We thank Annika Ackermann for her diligent work in this project, taking care of all IRMS-isotope analyses. We also thank Daniela Prando da Silva, Kuei-Jr Liao, Alena Pavlačková, Hugo de Sousa Côrtes, and Yuzhuo Pang for their immense help in preparing the samples for the IRMS analyses.The Askov long-term field experiment, including archived samples and datasets, is maintained and funded by the Department of Agroecology, Aarhus University. The NyMarkmodel project was funded by the Ministry of Green Transition.The Broadbalk Wheat experiment, including archived samples and datasets, is part of the Rothamsted Long-Term Experiments - National Bioscience Research Infrastructure (RLTE-NBRI) funded by the UK Research and Innovation – Biotechnology and Biological Sciences Research Council (UKRI-BBSRC) under award BBS/E/RH/23NB0007 (2023-2028). The RLTE-NBRI is also supported by the Lawes Agricultural Trust.DFG wheat was supported by Deutsche Forschungsgemeinschaft (DFG, Project number 419973621). We gratefully acknowledge Prof. Dr. Hartmut Stützel and Kathrin Rolf for their support in the field experiment and Dr. Ina Pinker and Constantin Schmidt for their assistance in sample preparation.The Agroscope experiments (DOK, FAST, P24A), including field work, sample and data management, are maintained and financed by Agroscope as part of the Swiss Federal Office of Agriculture. The DOK experiment is co-financed and co-managed by Agroscope and The Research Institute of Organic Agriculture (FiBL). The RELOAD project was funded by the Mercator Research Program of the ETH Zurich World Food System Center, the ETH Zurich Foundation, and Agroscope. Within the framework of P24A, the MaCaN project (grant number 215490) was financed by the Swiss National Science Foundation.The QualiAgro and PROspective field experiments are part of the SOERE-PRO (network of long-term experiments dedicated to the study of impacts of organic waste product recycling) integrated as a service of

the 'Investment in the Future' infrastructure AnaEE-France, overseen by the French National Research Agency (ANR-11-INBS-0001). The QualiAgro experiment was founded and is still supported by INRAE and Veolia. The PROspective experiment is supported by INRAE and SMRA68.Flavian Tschurr has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI), directed from the project NextGenCarbon (grant number 101184989).

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Competing interests

The authors declare no competing interests.

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