Harmonized European Union subnational crop statistics can reveal climate impacts and crop cultivation shifts

Giulia Ronchetti, Luigi Nisini Scacchiafichi, Lorenzo Seguini, Iacopo Cerrani, and Marijn van der Velde

European Commission, Joint Research Centre (JRC), 21027 Ispra (VA), Italy

Correspondence: Giulia Ronchetti (giulia.ronchetti89@gmail.com) and Marijn van der Velde (marijn.van-der-velde@ec.europa.eu)

Abstract. The availability of coherent time series of crop statistics is essential to better analyze the past, understand the present, and predict future trends in yield, area, and production. Importantly, such data also underpin assessments and subsequent policy actions that can shape future food systems that are more resilient in the face of climate change and sustainable in terms of resource use efficiency. In the European Union (EU), there currently is no legal obligation for EU countries to provide subnational crop statistics. Yet, such data could improve in-season crop forecasts, climate change impacts and adaption need assessments, and evaluation of agri-environmental schemes. The dataset described in this paper includes a harmonized collection of subnational crop statistics on area, production, and yield, collected for the EU from National Statistical Institutes (NSIs) and the Eurostat REGIO database – subnational crop statistics voluntarily contributed by EU countries. The crops considered are wheat (including soft and durum wheat), barley (including winter and spring barley), grain maize, sunflower and sugar beet. All data is harmonized towards the hierarchical structure of the Eurostat legend, and the regional classification of NUTS (Nomenclature of Territorial Units for Statistics) version 2016, to provide coherent time series. A total of 344282 records is presented here (115974 for wheat, 122705 for barley, 35274 for grain maize, 34916 for sugar beet, and 35413 for sunflower) for a total of 961 regions in 27 EU countries. Statistics are reported from 1975 to 2020, with a median time spans range of 21 years. A flagging system details for each data record information on data sources, processing steps, and quality checking results. This includes consistency checks between reported values for area, yield and production, identification of null values, missing and calculated data, information on crop legend matching, and NUTS versioning. We illustrate the value of this dataset by analyzing impacts on crops and production zone shifts in Europe due to climatic and economic factors. Recommendations and future developments of collecting subnational statistics at EU level are briefly discussed. The dataset is accessible with ECAS login at https://doi.org/10.2905/685949ff-56de-4646-a8df-844b5bb5f835 (Ronchetti et al., 2023b).

1   Introduction

Coherent statistics on yield, area, and production, feeds the fields of food system analysis, food security assessments (Mueller et al., 2012), and food economics, to name a few. While good quality national level crop statistics are – as a rule of thumb - available (but not always), for most countries around the world (see FAOSTAT), subnational crop statistics generally are not. Yet, coherent subnational crop statistics on yield, area, and production, are increasingly in demand by businesses, market

analysts, policymakers, scientists, and economists. Among the main application fields that rely on subnational crop statistics, remote sensing-based analysis and crop model estimations play a major role. To name a few, Blickensdörfer et al. make use of area crop statistics as independent dataset to assess the accuracy of crop type maps derived from a combination of satellite imagery; similarly, in d'Andrimont et al. (2021) and Becker-Reshef et al. (2023) crop maps are compared to official subnational statistics to validate results. The major global agricultural monitoring systems (Fritz et al., 2019) rely on well consolidated time series of crop statistics to develop estimation models for providing crop yield forecasts (Schauberger et al., 2020), but many other studies are available in the literature where crop statistical datasets are used to calibrate and validate crop models performances from local to global level (Paudel et al., 2022; Kern et al., 2018; Neumann and Smith, 2018; Kowalik et al., 2014).

Subnational statistics are published by National Statistical Institutes (NSIs) and/or Other National Authorities (ONAs) for each respective country. These subnational statistics can often be obtained through dedicated websites (e.g., United States Department of Agriculture - USDA). Several public international organizations (e.g., Eurostat and FAOSTAT) or inter-agency platforms (e.g., Agricultural Market Information System - AMIS) provide access to harmonized datasets that include statistical information on area, production and yield for the most relevant crops at national level for many countries (AMIS). Crop statistics are also provided by universities or research institutes. For instance, in 2008, Monfreda et al. (2008) provided global gridded data on harvested area and yields of 175 distinct crops around the year 2000 based on national and subnational level census statistics and a global cropland dataset. Recently, Iizumi and Sakai (2020) developed a hybrid dataset for crop yields based on agricultural census statistics and satellite remote sensing to fill temporal and spatial gaps. To support climate impact analysis, Anderson et al. (2023) published a dataset with 100-year time series of subnational wheat and maize crop statistics from global breadbaskets (Anderson et al., 2022).

Yet, despite their importance, a complete and harmonized collection of subnational crop statistics for countries in the European Union (EU) currently does not exist. A new EU framework regulation governing the collection of Statistics on Agricultural Inputs and Outputs (SAIO) will apply from 1st January, 2025. The collection of subnational crop statistics will become legally binding (European Parliament, EPRS). This new regulation should improve the availability and quality of subnational statistics at EU-level considerably. Currently, Eurostat (Eurostat, 2020) receives subnational statistics from Member States (MS) and reports these in the regional database (Eurostat, b), the data provision relies on voluntary contributions, contains gaps, and does not consider changes in regional administrative boundaries through time. By assessing Eurostat regional crop statistics for the years 2016, 2017 and 2018 we found that an extended use of this dataset can be limited by some inconsistencies, such as: i) it does not contain yield data, ii) it does not report statistics for spring barley; iii) it includes records of outdated NUTS classifications (i.e. version 2006, 2010 and 2013); iv) there is an incoherent use of zero and null values for crop record entries without data; and v) aggregated production values are not coherent with the national production values published in the national database (Eurostat, b) for many combinations of countries and crops. In addition, NSIs annually provide subnational crop statistics, accounting for regional variations but also accommodating specific characteristics and needs of each individual country. A further challenge is the mapping between the different crop names, terminology, and classifications, used in the various countries. As an example, the Austrian statistical service (Statistics Austria), distinguishes spring soft wheat, winter soft

wheat, spring durum wheat, and winter durum wheat, while the National Statistical Institute of Bulgaria (Republic of Bulgaria) only reports figures for total wheat, without any specifications on variety. In Spain, the Ministry of Agriculture, Fisheries and Food (MAPA), provides crop statistics on area and yield with a distinction between irrigated and non-irrigated crops.

Furthermore, from a historical and geographical point of view, the EU has changed over the years. The number of MS has changed over time, and within each country, there have been variations in terms of local subdivisions. The EU-wide Nomenclature of Territorial Units for Statistics (NUTS) includes several spatial levels for each country and has been managed by Eurostat under a series of agreements with the MS (Eurostat, 2018). These NUTS classifications can undergo changes over time (e.g. a regional unit can be merged with another region or divided, creating new regions in the process (Eurostat, c). For example, in the NUTS 2016 classification, some NUTS 2 regions in France have been recoded with respect to the NUTS 2013 classification (Eurostat, 2015b) (i.e., FR42 turned into FRF1); in Poland, a new region (i.e., PL92) has been introduced as an aggregation of regions; in Hungary, region HU10 has been split into two new regions (i.e., HU11 and HU12). These variations could compromise the completeness of statistical time series; therefore, the reporting of crop statistics requires a spatial reference system that is spatially consistent through time.

Given these considerations, the need for a homogeneous dataset of crop statistics that can consider and solve local variations, both from a geographical and agronomical point of view, and that is as extensive as possible, so that it can be considered as a reference for EU, becomes evident. The dataset presented in this paper is a harmonized set of subnational crop statistics for the EU (in the current composition, including 27 countries). Statistical values include information on area, yield and production, for the major crops cultivated in EU (Avitabile et al., 2023). In particular, the crops considered here are: wheat (including soft and durum wheat), barley (including winter and spring barley), grain maize, sugar beet and sunflower. According to Eurostat data, in the last three years these crops jointly accounted for 50% of the arable land in the EU (Eurostat, b). The harmonization follows the hierarchical structure of the Eurostat legend and is harmonized towards the administrative classification of NUTS 2016, to provide a consistent and complete dataset. The length of the time series varies by crop and subnational unit. A flagging system details information on data sources, data processing steps, and data quality. This dataset may define a benchmark for subnational crop statistics in the EU, and can be used in agro-economic and agro-environmental studies as a reference for model calibration and validation purposes.

The aim of this paper is to describe all the different steps involved in the generation of the dataset. Data collection and data processing are detailed in Section 2, while Section 3 focuses on the structure of the dataset. The value of the dataset is illustrated by mapping the lowest and highest yielding years, and by calculating shifts in crop production zones in Section 4. The paper closes with some general considerations and future perspectives on collecting subnational crop statistics in the EU.

2 Methods

The procedure to generate a harmonized dataset of subnational crop statistics of the EU consists of three main steps, namely i) data collection; ii) data harmonization; iii) data post-processing. The complete workflow is schematically shown in Figure 1.
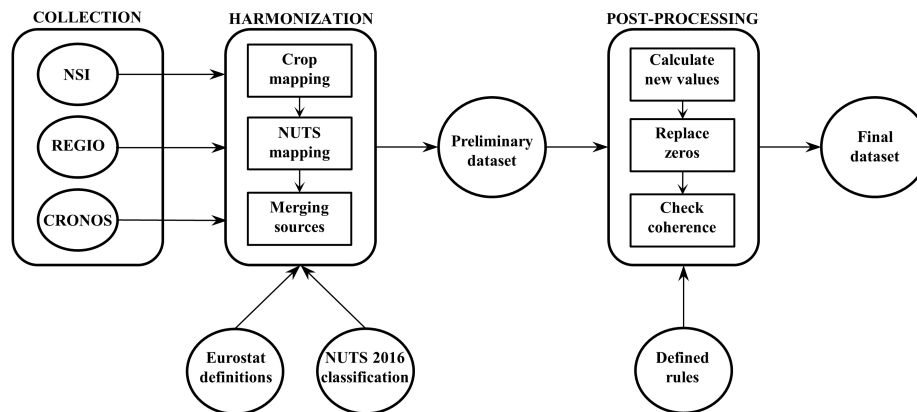
Figure 1. Workflow for generating the harmonized dataset of subnational crop statistics.

2.1 Data collection

The collection of statistics on area, production, and yield for the crops considered in this dataset includes the querying of different statistical sources, and the extraction of the required information, as far as existing and available. Data are first collected in any provided format (i.e., text files, documents, spreadsheets, etc..), and then converted into a compatible format to be ingested into a database. The length of statistical time series can vary depending on crops, countries and data sources, but overall statistics cover the period from 1975 to 2020. The latest data were collected in July 2022, accounting to 219472 records for the crops included in this dataset. The main statistical sources investigated for the data collection are the following:

– Subnational statistics from NSIs and ONAs responsible for agricultural statistics (Eurostat, a): this set of agricultural statistical time series is obtained by directly downloading statistics from the official national websites, or by contacting the different NSIs or national authorities, which provide crop statistics on area, production, and yield at the lowest administrative level available (e.g. NUTS 3). The complete list of all the involved NSIs and national authorities is reported in Table 1, together with the administrative level at which the statistics are provided. From here on, this dataset is identified with the name "NSI".

– EUROSTAT regional database (*Tables apro_cpnhr and apro_cpnhr_h*, Eurostat (b)): this source consists of a database, providing figures for a list of agricultural commodities available for EU Member States and some neighboring countries. Data are provided at subnational level, namely NUTS 1 and NUTS 2 level. From here on, this dataset is identified with the name "REGIO".

– EUROSTAT national database (*Tables apro_cpnh1 and apro_cpnh1_h*, Eurostat (b)): this source consists of a database, providing figures for a list of agricultural commodities available for EU Member States and some neighboring countries. Data are provided at national level, namely NUTS 0 level. From here on, this dataset is identified with the name "CRONOS".

Table 1. National source and administrative level provided of the statistics collected in the EU Member States.

Country code	Country	Administrative level	National source
AT	Austria	NUTS 2	Statistics Austria
BE	Belgium	NUTS 2	STATBEL, Belgian statistical office
BG	Bulgaria	NUTS 2	National Statistical Institute
CY	Cyprus	NUTS 0	National Statistical Service
CZ	Czechia	NUTS 3	Czech Statistical Office
DE	Germany	NUTS 3	Federal and state statistical offices
DK	Denmark	NUTS 3	Statistics Denmark
EE	Estonia	County	Statistics Estonia
EL	Greece	NUTS 3	Hellenic Statistical Authority
ES	Spain	NUTS 3	Ministry of Agriculture, Fisheries and Food
FI	Finland	County	Natural Resources Institute Finland
FR	France	NUTS 3	Agreste, Statistical Services for Ministry of Agriculture
HR	Croatia	NUTS 2	Croatian Bureau of Statistics
HU	Hungary	NUTS 3	Hungarian Central Statistical Office
IE	Ireland	NUTS 3	Central Statistics Office
IT	Italy	NUTS 3	Italian National Institute of Statistics
LT	Lithuania	NUTS 3	Official Statistics Portal
LU	Luxembourg	NUTS 0	National Institute of Statistics and Economic Studies
LV	Latvia	NUTS 3	Official Statistics of Latvia
MT	Malta	NUTS 0	National Statistics Office
NL	Netherlands	NUTS 2	Statistics Netherlands
PL	Poland	NUTS 2	Statistics Poland
PT	Portugal	NUTS 2	Statistics Portugal
RO	Romania	NUTS 3	National Institute for Statistics
SE	Sweden	NUTS 3	Statistics Sweden
SI	Slovenia	NUTS 3	Republic of Slovenia Statistical Office
SK	Slovakia	NUTS 3	National Institute for Statistics

2.2 Data harmonization

The set of regional data on crop statistics collected from EUROSTAT and NSIs is very heterogeneous. As mentioned before, the administrative level at which statistics are provided (i.e., NUTS 1, NUTS 2 or NUTS 3) varies among the different sources, and even within the same source, as the several statistical offices from the Member States often produce regional statistics disaggregated at different administrative levels and levels for publication can change over the years. Moreover, the definitions

of crops are sometimes differing between national statistical services and over the years, and crop/varieties have to be properly assigned to match reference terminology. Therefore, the statistical data collected are processed to make them comparable to the European standards used for crop definitions and administrative units. These standards follow the convention in terms of both aggregated name and crop definition provided by Eurostat (Eurostat, 2020). The target crops selected for this dataset are listed in Table 2, while the selected reference layer for the administrative division is the Nomenclature of Territorial Units for Statistics (NUTS), version 2016 (Eurostat, 2018). Moreover, the units of measure of the collected data can vary according to the different data sources, although the standard rules suggest reporting area statistics in hectares (ha), production in tons (t) and yield in tons per hectares ($t \times ha^{-1}$). A harmonization procedure has been developed to map collected statistics to

Table 2. Eurostat definitions for the crops included in the dataset.

Crop Name	Eurostat Code	Eurostat label	Definition
Total wheat	C1100	Wheat and spelt	Common wheat (*Triticum aestivum L. emend. Fiori et Paol.*), spelt (*Triticum spelta L.*), einkorn wheat (*Triticum monococcum L.*) and durum wheat (*Triticum durum Desf.*). Cereal grains harvested just before maturity
Soft wheat	C1110	Common wheat and spelt	Common wheat (*Triticum aestivum L. emend. Fiori et Paol.*), spelt (*Triticum spelta L.*), einkorn wheat (*Triticum monococcum L.*). Cereal grains harvested just before maturity
Durum wheat	C1120	Durum wheat	Durum wheat (*Triticum durum Desf.*). Cereal grains harvested just before maturity
Total barley	C1300	Barley	Barley (*Hordeum vulgare L.*). Cereal grains harvested just before maturity
Winter barley	C1310	Winter barley	Barley (*Hordeum vulgare L.*) sown before or during winter. Cereal grains harvested just before maturity
Spring barley	C1320	Spring barley	Barley (*Hordeum vulgare L.*) sown in the spring. Cereal grains harvested just before maturity
Grain maize	C1500	Grain maize and corn-cob-mix	Maize (*Zea mays L.*) harvested for grain, as seed or as corn-cob-mix.
Sugar beet	R2000	Sugar beet (excluding seed)	Sugar beet (*Beta vulgaris L.*) intended for the sugar industry, alcohol production or renewable energy production.
Sunflower	I1120	Sunflower seed	Sunflower (*Helianthus annuus L.*) harvested as dry grains.

the reference hierarchy and to merge the different data sources. This procedure is fully detailed in Cerrani et al. (2023), and consists of three main steps:

1. Crop mapping and transformation: all crop legend classes in use by the EU Member States are mapped to match Eurostat crop legend hierarchy. Original crop classes and their mapping values per country are included as tables in the data documentation available along with the dataset (see 3.1). Any value that needed crop harmonization after the collection is marked with a proper flag.

2. NUTS mapping and transformation: any region that was affected by a NUTS version update through time is aggregated or disaggregated to coherently match NUTS version 2016 region subdivision. An algorithm was developed to compare two administrative units belonging to different NUTS versioning, and determine the regions that are equal; those which have changed only the region identifier but not their geometry; and those which have changed both geometry and identifier, providing also the weight to recompute statistics to the target layer. Any value that needed region harmonization after the collection is marked with a proper flag;

3. Data sources merging: crop and NUTS mapping and transformation are applied independently to each collected dataset. The final dataset is then generated by merging the data from the various sources from the NSIs and the Eurostat databases. The merging procedure ranks sources and first gives priority to the most recently collected data, then to data directly collected from NSIs, and finally to the regional data reported in the Eurostat database, particularly for the cases of crop statistics not reported by the NSIs. In this phase, units of measure are also homogenized, to be consistent with each other. The final dataset provides area values in hectares (ha), production values in tons (t), as well as yield values in tons per hectare ($t \times ha^{-1}$).

2.3 Data post-processing

After data harmonization, a post-processing procedure is required in order to complete the dataset with possible newly calculated values and to verify data consistency. In particular, data post-processing focuses on i) calculation of new values starting from the existing ones, both as a combination of variables and as an aggregation of crops; ii) recognition and replacement of null or erroneously zero values; iii) assessment of coherence between variables and, whenever possible, between aggregated crops.

2.3.1 Calculate new values

Whenever a value is missing in the dataset, a dedicated procedure tries to derive the missing value from the existing ones, through the application of simple rules. The newly calculated value can be retrieved either as a combination of variables, by exploiting the relationship between area, production, and yield values, or, in the specific case of total wheat and total barley, as an aggregation between soft and durum wheat, or between winter and spring barley, respectively. Any newly calculated value is marked with a proper flag, and, in the newly calculated record, the source is set according to the source used to calculate the new data (i.e., if both data records are from either NSIs or Eurostat then the data source for the calculated value is set accordingly, otherwise it is set as Mixed sources).

To derive a new value as a combination of variables, the formulas reported in Eq. 1, Eq. 2, and Eq. 3 are implemented in the

160 data post-processing procedure:

$$Y = \frac{P}{A} \tag{1}$$

where Y is the newly calculated value of yield in $t \times ha^{-1}$, P is the existing value of production in t, A is the existing value of area in ha, $P \geq 0$ and $A > 0$.

$$A = \frac{P}{Y} \tag{2}$$

165 where A is the newly calculated value of area in ha, P is the existing value of production in t, Y is the existing value of yield in $t \times ha^{-1}$, $P \geq 0$ and $Y > 0$.

$$P = A \times Y \tag{3}$$

where P is the newly calculated value of production in t, A is the existing value of area in ha, Y is the existing value of yield in $t \times ha^{-1}$, $A \geq 0$ and $Y \geq 0$.

170 The formulas reported in Eq. 1, Eq. 2, and Eq. 3 can be also applied to replace a value equal to zero or a null value. If two out of three variables have positive values and the third one is zero or null, a new value is calculated for the third variable by means of the same equations. Moreover, if two out of three variables are zeros and the third one is null, the value for the third variable is turned into zero as well; conversely, if two out of three variables are null and the third one is equal to zero, the value for the third variable is converted in a null value.

175 To derive a new value of total wheat or/and total barley as an aggregation of crops, the formulas reported in Eq. 4, Eq. 5, and Eq. 6 are implemented in the data post-processing procedure:

$$A_{total} = A_{crop1} + A_{crop2} \tag{4}$$

where A_{total} is the newly calculated value of area in ha for total wheat (barley), A_{crop1} is the existing value of area in ha for soft wheat (winter barley), A_{crop2} is the existing value of area in ha for durum wheat (spring barley), $A_{crop1} > 0$, and
180 $A_{crop2} > 0$.

$$P_{total} = P_{crop1} + P_{crop2} \tag{5}$$

where P_{total} is the newly calculated value of production in t for total wheat (barley), P_{crop1} is the existing value of production in t for soft wheat (winter barley), P_{crop2} is the existing value of production in t for durum wheat (spring barley), $P_{crop1} > 0$, and $P_{crop2} > 0$.

185 $$Y_{total} = \frac{P_{total}}{A_{total}} \tag{6}$$

where Y_{total} is the newly calculated value of yield in $t \times ha^{-1}$ for total wheat (barley), P_{total} is the value of production in t for total wheat (barley), A_{total} is value of area in ha for total wheat (barley), $P_{total} \geq 0$, and $A_{total} > 0$. If P_{total} is not available, then the new value for yield is derived as an area-weighted average of yields. Specifically, the formula reported in Eq. 7 is applied:

$$Y_{total} = \frac{Y_{crop1} \times A_{crop1} + Y_{crop2} \times A_{crop2}}{A_{total}} \tag{7}$$

where Y_{total} is the newly calculated value of yield in $t \times ha^{-1}$ for total wheat (barley), Y_{crop1} is the existing value of yield in $t \times ha^{-1}$ for soft wheat (winter barley), A_{crop1} is the existing value of area in ha for soft wheat (winter barley), Y_{crop2} is the existing value of yield in $t \times ha^{-1}$ for durum wheat (spring barley), A_{crop2} is the existing value of area in ha for durum wheat (spring barley), A_{total} is value of area in ha for total wheat (barley), $Y_{crop1} \geq 0$, $Y_{crop2} \geq 0$, $A_{crop1} \geq 0$, $A_{crop2} \geq 0$, and $A_{total} > 0$.

2.3.2 Identify and replace zero with null

A dedicated procedure was developed also to identify and replace any value equal to zero that causes inconsistencies. In principle, the values of area, production and yield must be consistent with each other. Gross errors, e.g. area values equal to zero associated with positive yield values or positive production values, are detected and flagged, to provide the end-users the possibility to easily manage them. In particular, all zero values are checked and transformed into a null value should the variables disagree. Any value originally equal to zero that is replaced with a null value, is marked with a proper flag.

2.3.3 Check coherence

Finally, data quality control is carried out by calculating the coherence between the three variables. The threshold value for determining an inconsistency between the data is set at 1%. The coherence between statistics of area, production and yield for a given region and year is verified by applying the formula in Eq. 8:

$$|P - (A \times Y)| \leq 0.01 \times P \tag{8}$$

where P is the value of production in t, A is the value of area in ha, Y is the value of yield in $t \times ha^{-1}$. Whenever the condition is met or not, a proper flag is provided. Of course, the coherence check can only be applied if none of the three variables is missing or null. The coherence between variables is calculated for all the crops included in the dataset.

Moreover, an additional coherence check is provided exclusively for statistics regarding crops wheat and barley. Since statistics for total wheat (barley) are derived by aggregation, the coherence between the statistics of the crops involved in the aggregation is also verified. In particular, the formulas reported in Eq. 9, Eq. 10, and Eq. 11 are applied. For these controls, the threshold value for determining an inconsistency between the data is also set at 1%.

$$|A_{total} - (A_{crop1} + A_{crop2})| \leq 0.01 \times A_{total} \tag{9}$$

where A_{total} is the value of area in ha for total wheat (barley), A_{crop1} is the value of area in ha for soft wheat (winter barley), A_{crop2} is the value of area in ha for durum wheat (spring barley). Whenever the condition is met or not, a proper flag is

provided. The coherence can only be checked if none of the three values is missing or null.

$$|P_{total} - (P_{crop1} + P_{crop2})| \leq 0.01 \times P_{total} \tag{10}$$

where P_{total} is the value of production in t for total wheat (barley), P_{crop1} is the value of production in t for soft wheat (winter barley), P_{crop2} is the value of production in t for durum wheat (spring barley). Whenever the condition is met or not, a proper flag is provided. The coherence can only be checked if none of the three values is missing or null.

$$|Y_{total} - \frac{Y_{crop1} \times A_{crop1} + Y_{crop2} \times A_{crop2}}{A_{total}}| \leq 0.01 \times Y_{total} \tag{11}$$

where Y_{total} is the value of yield in $t \times ha^{-1}$ for total wheat (barley), Y_{crop1} is the value of yield in $t \times ha^{-1}$ for soft wheat (winter barley), A_{crop1} is the value of area in ha for soft wheat (winter barley), Y_{crop2} is the value of yield in $t \times ha^{-1}$ for durum wheat (spring barley), A_{crop2} is the existing value of area in ha for durum wheat (spring barley), A_{total} is the value of area in ha for total wheat (barley), and $A_{total} > 0$. Whenever the condition is met or not, a proper flag is provided. The coherence can only be checked if none of the values is missing or null.

3 Subnational crop statistics dataset

The final dataset consists of 344282 records, including 115974 records for wheat, 122705 records for barley, 35274 records for grain maize, 34916 records for sugar beet, and 35413 records for sunflower, covering 961 regions and 46 years, namely from 1975 to 2020. Table 3 presents the number of records for each crop and variable, as well as the length of each time series. In addition, details regarding the number of records for each crop and variable, the reported administrative level, and the length of each time series according to countries are summarized in Appendix A.

Table 3. Number of records and length of time series for each crop included in the dataset.

Crop	First year	Last year	# records Area	# records Production	# records Yield
Total wheat	1975	2020	13638	11368	11361
Soft wheat	1975	2020	14339	14201	19308
Durum wheat	1986	2020	10609	10575	10575
Total barley	1975	2020	14544	13799	13774
Winter barley	1975	2020	11617	11448	16796
Spring barley	1975	2020	12039	11878	16810
Grain maize	1975	2020	11777	11749	11748
Sugar beet	1975	2020	10345	9981	14590
Sunflower	1975	2020	11948	11765	11700

3.1 Structure of the dataset

The current version of the subnational crop statistics dataset is composed of 13 fields, including information on region, crop, year, variable, value, source, and some additional flags. The following information can be found in the dataset:

- REGION: the code of the administrative unit which the value refers to. Administrative unit codes are based on the Eurostat classification of NUTS 2016;

- CROP_NAME: the name of the crop which the value refers to. Crop names follow the Eurostat definition (Table 2, Eurostat, 2020);

- YEAR: the year which the value refers to. Years range from 1975 to 2020, according to data availability;

- VARIABLE: the variable which the value refers to. Specifically, the variables are Area, Production and Yield. In this dataset, the variable Area refers to area of harvesting, although not all the data sources distinguish between area of sowing and harvesting;

- VALUE: the harmonized subnational statistics value;

- UoM: the unit of measure for the specific value. Units of measure depend on the respective variable: Area in hectares (ha), Production in tons (t), and Yield in tons per hectares $t \times ha^{-1}$;

- SOURCE: the data source of the value. Data sources are NSI, Eurostat, or Mixed (i.e., when a value is calculated from a combination of values derived from both NSI and Eurostat);

- CALCULATED_R: flagging system, reporting if a value has been derived from a NUTS version different from NUTS 2016, by means of NUTS mapping and transformation procedure (Section 2.2);

- CALCULATED_C: flagging system, reporting if a value has been derived from a combination of crops to match Eurostat definitions, by means of crop mapping and transformation procedure (Section 2.2);

- CALCULATED_V: flagging system, reporting if a value, that originally was missing or null or zero, has been calculated during the post-processing phase, by means of the Equations presented in Section 2.3.1;

- ZERO_AS_NULL: flagging system, reporting if a value of zero has been turned into a null value during the post-processing phase because of any inconsistencies, as described in Section 2.3.2;

- COHERENCE_APY: flagging system, reporting if there is agreement among values of Area, Production and Yield for the same region, crop and year, according to the rule defined in Eq. 8;

- COHERENCE_CROP: flagging system, reporting if there is agreement among values of Total wheat (Total barley), Soft wheat (Winter barley), and Durum wheat (Spring barley) for the same region, variable and year, according to the rules defined in Eq.9, Eq.10, and Eq.11.

3.2 Flagging system

A total of six flags are reported together with the data, representing additional information on data processing and data quality.
This flagging system can help the users of this dataset to have a clear knowledge of the originality and the level of processing
underlying the values they are dealing with, as well as to verify the reliability of the data. The flags *CALCULATED_R*, *CALCU-
LATED_C*, *CALCULATED_V*, and *ZERO_AS_NULL* are set as *Yes* or left blank, depending on whether the specific condition is
met or not. The flags about coherence, namely *COHERENCE_APY*, and *COHERENCE_CROP* are set as *Yes* or *No*, depending
on whether coherence is verified or not, and left blank when it is not possible to evaluate coherence due to missing or null
values, as described in Section 2.3.3. Maps in Figure 2 represent regions whose values were derived from a transformation of
NUTS and/or crops. The need of deriving values from a transformation of regions arises from two main reasons: data sources
providing values according to a different NUTS version classification prior to version 2016, and/or data sources providing val-
ues according to their own internal administrative subdivision. The former is the case of regions in Ireland, Italy, and Poland,
where the less recent crop statistics values were updated to match NUTS classification version 2016, as data sources originally
provided them according to a different NUTS versioning. The latter is the case of regions in Denmark, Estonia, and Finland,
whose NSIs report crop statistics values using their own internal administrative units (e.g., county) not compliant (i.e., Estonia)
or only partially compliant (i.e., Denmark and Finland) with NUTS classification. Finally, crop statistics values for Greece
were derived from a NUTS transformation, as regions in Greece have deeply changed after NUTS classification version 2010
but also NSI reports detailed crop statistics for small islands that need to be grouped to match the NUTS classification in use.

As regards values calculated from a transformation of crops, wheat and grain maize have required the highest number of
transformations. Most NSIs reports statistics for wheat with a distinction between winter and spring varieties, and for maize
with details about seeds and corn-cob mix and/or about irrigation. The map of Figure 2b shows that most countries required
computing a transformation of crops only for one crop (i.e. soft wheat), while in France and Romania we derived values for
two crops (i.e. soft and durum wheat). Only in Austria, almost all crops (i.e. total wheat, soft wheat, durum wheat and grain
maize) required to be harmonized with Eurostat crop definitions. Also, not all the data sources reported clear and coherent
details how they account for corn-cob mix in their publications. In Figure 3, maps show the shares of records with verified
coherence among variables for each region and crop, as well as the maps of Figure 4 and 5 display the shares of records with
verified coherence for total wheat and total barley, respectively. The shares of records with verified coherence among variables
and/or crops are computed by comparing the number of coherent records (i.e. Yes flags in the coherence columns) with the
total number of records in the time series for each crop and region. A share close to 100% means that coherence is verified in
all the reported records, while a share close to 0% represents very few records with verified coherence in the time series.

Main causes that can affect coherence among variables are to be attributed to the distinction between sown and harvested
area. It is not always known if area values refer to sown or harvested area, since only a few statistical sources either publish
both values or clearly mention values they refer to. The nature of statistical collection often results in sown area being reported,
as it is derived from aggregated area values from the farmers' applications for the Common Agricultural Policy that are done at
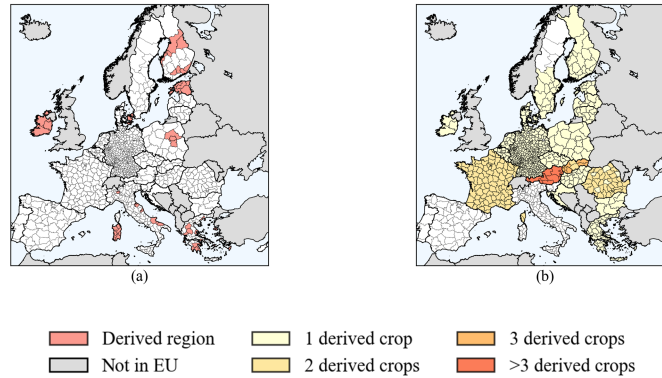
Figure 2. Regions whose the reported values were derived from a transformation of NUTS (a) and/or crops (b) for at least one crop included in this dataset.

the start of the season and not updated. However, such information is especially important during heavy impacts where sown area may have been strongly reduced and this can result in inconsistencies with production and yield data.

From the maps of Figure 3 it is evident that coherence rate among variables is very high for all regions and crops with a few exceptions, including Germany and Finland. For Germany, the low coherence rate is due to the fact that time series of variable
300   yield are more complete and longer than the ones of area and production, therefore coherence checks can be computed only for few records. Differently, for Finland, the coherence check rule is not verified in the northernmost regions with low agricultural activity where crop statistics are affected by approximation errors.

As regarding coherence among total, soft and durum wheat (Figure 4), coherence rate values differ from country to country and mostly depend from the availability of durum wheat statistics. Coherence rates are high for regions in southern Europe,
305   where most durum wheat is produced, and in regions where the production of durum wheat is absent, while rates are low in regions where time series of durum wheat statistics are discontinuous or rarely published. Similarly, coherence rates among total, winter and spring barley vary from country to country, as some NSIs do not provide distinct statistics for winter and spring wheat, as for the case of Romania and Bulgaria. Finally, in Germany, coherence rates of yield are lower than the ones of area and production, because of the different lengths of these time series preventing to apply the coherence checks formula
310   (Eq. 11).
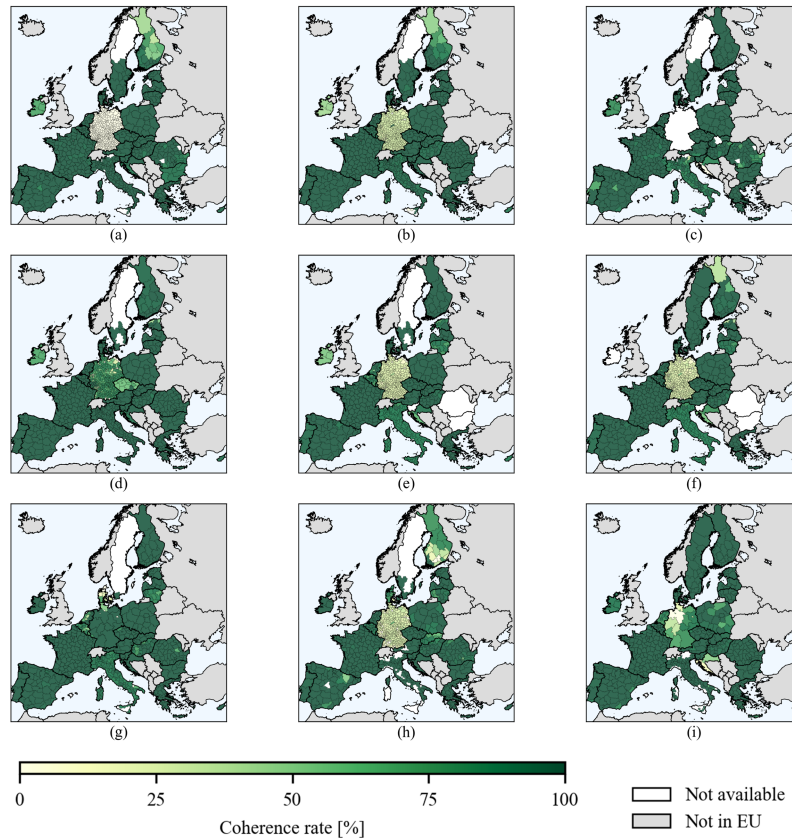
Figure 3. The shares of records with verified coherence among area, production and yield variables for each region and crop: a) Total wheat, b) Soft wheat, c) Durum wheat, d) Total barley, e) Winter barley, f) Spring barley, g) Grain maize, h) Sugar beet, i) Sunflower.

4   Discussion

4.1   Potential uses of this dataset

In order to highlight the novelty and significance of this dataset, some potential uses are presented below and discussed. The reported analyses exploit the major strengths of this dataset, including the fine spatial resolution of data, the length, completeness and coherence of time series.

4.1.1   Lowest and highest yielding years

Crop statistics included in this dataset cover a long time range, from 1975 to 2020, to allow time series analysis. In this study, we performed a simple analysis, selecting for each region and crop the year when the lowest and highest yield values occurred. Results for soft wheat, grain maize, and sugar beet are reported in Figure 6. No detrending procedure was computed on yield
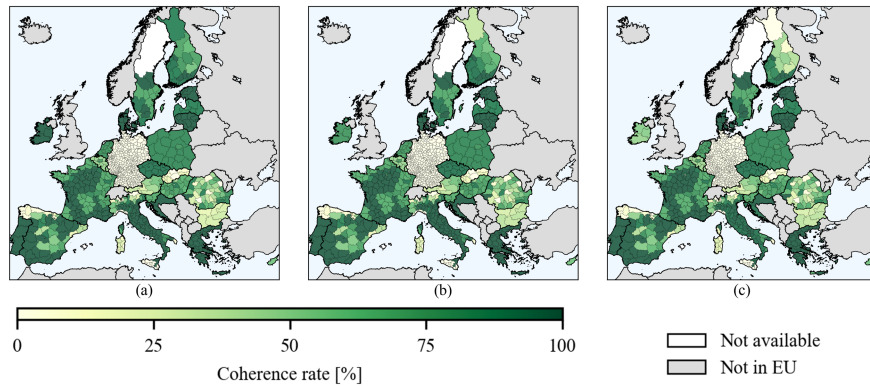
Figure 4. The shares of records with verified coherence among total, soft and durum wheat for each region and variable: a) Area, b) Production, c) Yield.
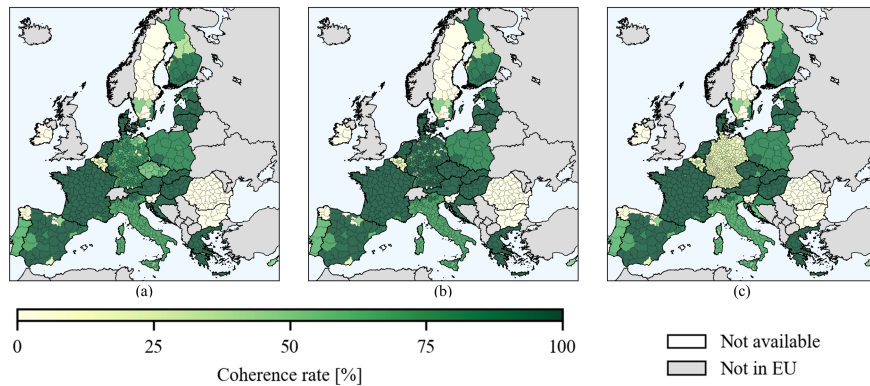
Figure 5. The shares of records with verified coherence among total, winter and spring barley for each region and variable: a) Area, b) Production, c) Yield.

values. Therefore, in regions where an important trend component related to the improvement of agro-management practices exists (García-Condado et al., 2019; Ceglar et al., 2016; Finger, 2010), the highest yield values were observed (Figure 6 right) in the most recent years (i.e. from 2016 to 2020), while the lowest yield values were registered at the beginning of the time series, mostly in the early 2000s (Figure 6 left). This is particularly evident in eastern and northeastern EU countries, including Bulgaria, Romania, Hungary, Slovakia, Poland and Lithuania. In the other MS, improvements in agronomic techniques and management practices have less impact on crop yields (Ronchetti et al., 2023a), which are more dependent on climate and weather conditions within the season. Trend effects on yield values are low, and in these countries inter-annual variability of yields is high. Yet, the years when the highest and lowest yield values occurred are heterogeneous, vary from region to region and cover the whole time range. The maps on the left of Figure 6 can also reveal extreme years, whose unfavourable conditions

have affected crops and led to low yield values. The most outstanding is year 2016 in France for soft wheat (Figure 6a), when a combination of factors caused the most severe yield loss in over half a century in one of the leading wheat-producing regions of Europe (Nóia Júnior et al., 2023; Ben-Ari et al., 2018). This exceptional yield decline is well depicted in the map, with dark red colours extending throughout the north-easternmost administrative units of France. Similarly, in 2018 a severe summer drought affected summer crops yields in central and eastern Europe (Beillouin et al., 2020; Webber et al., 2020). As a consequence, 2018 resulted the year when the lowest yield values for grain maize occurred in Germany and Belgium, as represented in Figure 6c. Furthermore, these maps show that the distribution of yields does not necessarily follow national boundaries, but often there are clusters of regions with similar behaviour in neighbouring states. Weather conditions, soil types, agronomic practices, but also historical factors, have determined clusters of agricultural regions that do not coincide with national borders (Guth and Smędzik-Ambroży, 2020; Guiomar et al., 2018; Reiff et al., 2018). Regions in Poland are the most evident case: western regions tend to uniform with eastern German regions, whereas eastern Polish regions create an agronomic cluster with the Baltics.

4.1.2 Crop production zones and shifts

In this dataset, crop statistics are reported at the finest spatial detail available, namely subnational administrative distribution. This allows to perform analyses and comparisons within each country and assess the inter-country spatial distribution of crop production. Figure 7 shows the spatial distribution of crop production centroids within each country in the time period 2000 - 2020. To produce the map, we first selected production statistics for the period of interest and compute the average for each subnational unit, then we extracted geometric centroids for each subnational unit, finally crop production centroids for each country were calculated as the weighted aggregation of subnational centroids using production averages as weights. The resulting map represents the spatial distribution of the production for each crop in the different countries. In some countries, including central and northeastern Europe (e.g. Czechia, Slovakia, Poland, Lithuania, Latvia, Estonia) production centroids for the different crops are located in the same area, roughly corresponding to the geometric centroids of the country. This can suggest that all subnational units almost equally concur to national crop production and there are few regions providing a greater contribute (Joint Research Centre, 2023; Lennert and Farkas, 2020; Rega et al., 2020; López-Lozano et al., 2015). In Finland, Denmark, Sweden and Austria, the map points out the presence of agricultural active regions, as production centroids are centred in a small area that do not correspond to the geometric centroids (Peltonen-Sainio and Jauhiainen, 2020; Jørgensen et al., 2019; Piikki and Söderström, 2019; Stürmer et al., 2013). In the remaining parts of these countries, agriculture activities are limited by mountains, forests and non-favourable climatic conditions. Finally, in wide and/or north-south oriented European countries, including Spain, France, Italy, Germany, and Romania, crop production centroids are widespread over the country with crops located in their most productive regions in each country (Ballot et al., 2022; Schmitt et al., 2022; d'Andrimont et al., 2021; Ribeiro et al., 2020). As an example, in Italy, the durum wheat centroid is located in the south, while grain maize centroid is located in the north in the middle of Pianura Padana; in Spain, all crops centroids are distributed around Castilla y Leon region, with the exception of durum wheat centroid which is shifted in the south close to Andalusia region; in France,
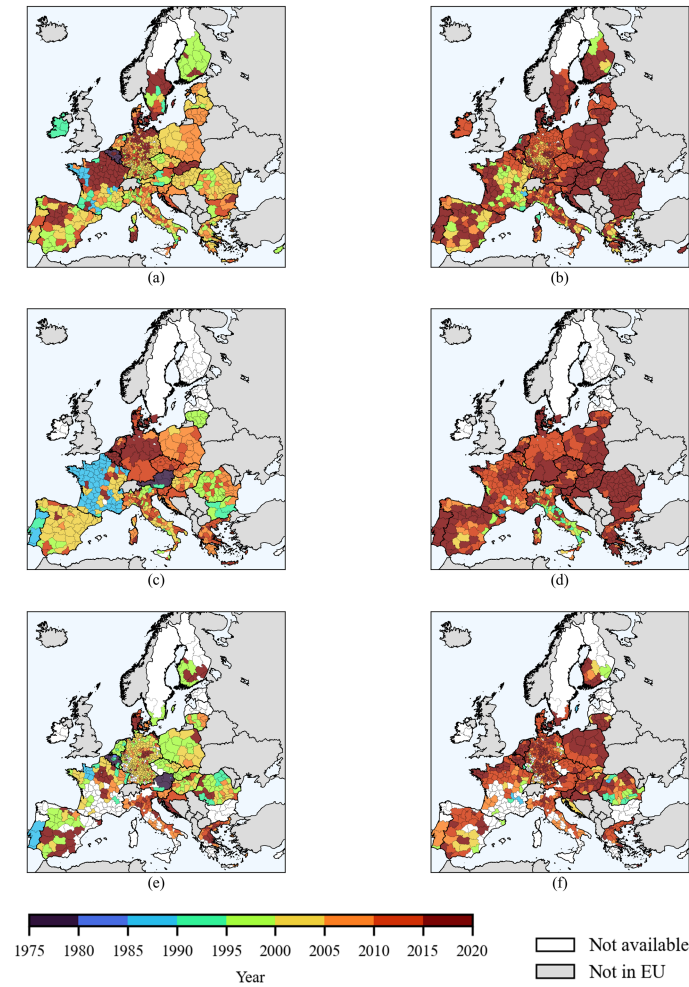
Figure 6. Years when the lowest (left) and the highest (right) yield values occurred for each region for crop *Soft wheat* (a, b), *Grain maize* (c, d), *Sugar beet* (e, f).

centroids for soft wheat, barley and sugar beet are located in the north-east part of the country, while centroids for grain maize, sunflower and durum wheat are placed in western/southwestern regions.

By exploiting both the fine spatial resolution of data and the length and completeness of time series, we performed an analysis on the distribution of crop production zones in the EU and their evolution and changes in time. First, we divided the dataset in two parts: the first one including statistics from 2000 to 2009, the second one with statistics from 2010 to 2019. Then, following the approach above, we calculated the average production in both time periods and computed crop production centroids for the EU for both time periods, as weighted average of each regional centroid, using crop production averages as weights. Finally, we compared the two centroids and generated the displacement vectors as the difference between crop production centroids of the
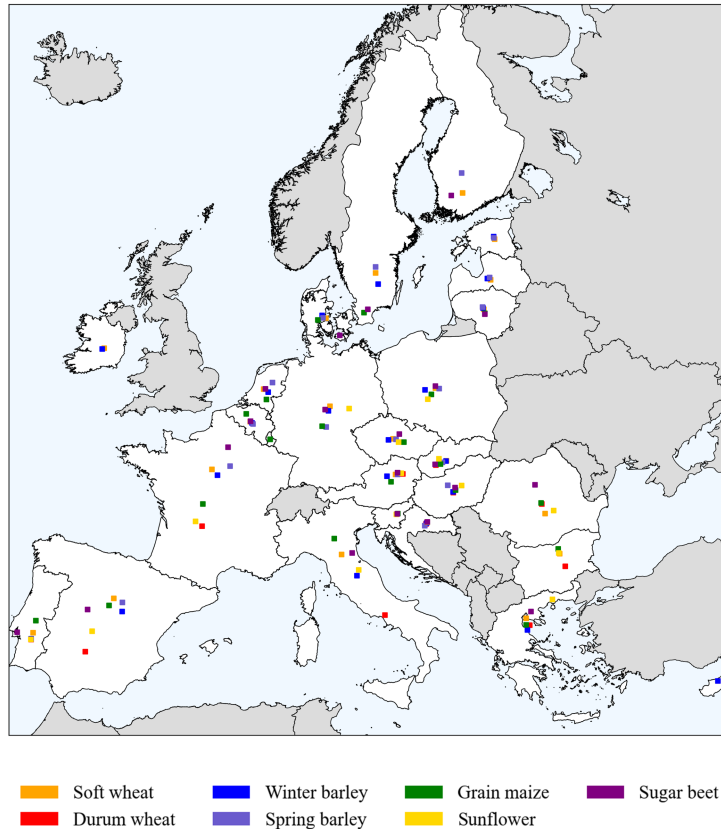
Figure 7. Spatial representation of crop production centroids within each country in the time period 2000 - 2020.

370   second and first time period. Results are displayed in the polar plot of Figure 8. These vectors represent the shift of production
in EU in a 10 years time frame for each crop. Overall, the prevalent directions of vectors are from northwest to east, testifying
an increasing contribution of northern and eastern EU MS to European agricultural production. The lowest shifts (i.e. rate equal
to 5 km per year) are reported for spring barley, winter barley and sugar beet, mostly northward. The greatest displacements
are observed for sunflower, followed by durum wheat, grain maize and soft wheat. For sunflower, the production shift follows

375   a rate of 25 km per year, in the eastern direction, due to continuously growing production in Romania, Hungary and Bulgaria.
These countries jointly accounted for 70% of the total European sunflower production in 2019 while in 2009 for almost 53%.
Likewise, the vector for soft wheat points towards an eastern direction, at a rate of 10 km per year. For soft wheat, an increasing
contribution of eastern and north-eastern European states, such as Romania and Poland, but also the Baltics, is highlighted.
Similarly, Sloat et al. (2020) found a northward migration for wheat in Eastern European countries. The production centroids of

380   grain maize and durum wheat are also displaced by nearly 10 km per year but northeastward. These crops, typically cultivated
in southern Europe, including Spain, Italy and France, are expanding more and more northeastward. Climate change is one

of the causes of these shifts. Ceglar et al. (2019) pointed out that agro-climate zones are migrating northward and that the migrating rate is accelerating due to climate change. Crop production may shift northward because of larger suitability and more favourable climate conditions, while in southern Europe adverse conditions may affect crop production. In this scenario,

385 southern regions, including the Mediterranean area, may lose suitability to grow specific crops in favor of northern European regions (Ceglar et al., 2019; Fontana et al., 2015). Ceglar et al. observed a migration velocity of agro-climate zones northward of 100 km per 10 years solely using agro-metereological indicators, while we find results comparable in magnitude through the analysis of crop statistics for grain maize and durum wheat. In addition, we show production shifts not mediated by climate but rather by economic opportunity, largely in eastern Europe, as illustrated by the high eastward shift rate of sunflower production.

390 Hence, the completeness of subnational crop statistics presented here can be of help to reveal changes in agricultural cultivation zones due to various concurring factors with subsequent crop production impacts.
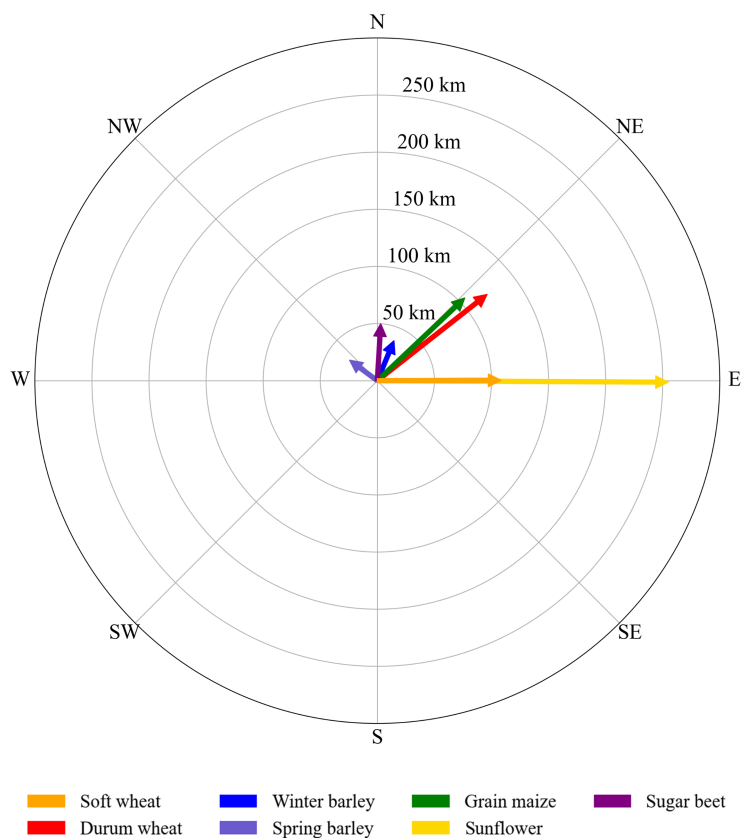
Figure 8. Displacement vectors representing the shifts of production centroids for each crop in EU, from the first to the second decade of the 2000s

4.2 Outlook and recommendations

In SAIO, MS will have to report crop statistics on area and production before 30th September the year after (N+1). Guidance is given on how the reporting should be done, e.g. in terms of clean, dry weight of grains at the standard market humidity level in the country (Eurostat, 2015a). National standard humidity level needs to be reported too for possible recalculations to standardized EU values. For sugar beet, MS will have to provide data on the sugar content of the harvested production. SAIO will improve subnational crop statistics in the EU considerably. A few practical recommendations have been identified during the progress of this study, which we list here and should improve the reporting and use of future statistics:

1. *Mapping to a common legend.* There is no integral publication available on how MS match their national crop legends in national languages in their reporting to the harmonized Eurostat crop legend (Eurostat, 2020). While several newer MS have adopted their national reporting to the Eurostat crop legend, older MS have not. Since all MS must go through this exercise, this information should exist and the availability of such a document would be very valuable. We provide such a (re-engineered) list in the ancillary file Mapping_eurostat_legend.xlsx, included in our data repository (see Section 5).

2. *Adherence to the latest NUTS version.* In reporting to Eurostat, MS should use the latest and most up to date NUTS version.

3. *Clarity on reported data values.* In SAIO, clarity has been created on the definition of area, and sown area is the area data that will be collected, and this is often sourced from the farm holding declarations in the MS IACS (Integrated Administration and Control System). We find that incoherence between area, production, and yield often arises from the fact that NSIs use harvested areas to calculate production and yield. In cases with those inconsistencies, the sown area is then not updated. Therefore, depending on the methodology MS use to calculate harvested production, clarity should be provided on whether harvested area is used as part of the calculation.

4. *Sharing common parameters.* Reporting and using of unequivocal standards on humidity, and if relevant on oil and sugar content.

5. *Updating past statistical data values.* In the creation of this dataset, we also identified inconsistencies with respect to past statistics on area, production, and yield. MS should go through an effort to update the past statistical time series available at Eurostat. While SAIO will cover data from 2025 and onward, ideally, such an update would be an integrated exercise since the availability of such time series will underpin our capacity to improve the assessment and forecasting of the impact of extreme weather. Such information is essential for global forecasting systems, as the case of the European Commission's Joint Research Centre (EC-JRC) MARS (Monitoring Agricultural Resources) Crop Yield Forecasting System (MCYFS, Van der Velde et al. (2019)).

6. *Promoting the use of automated data flows.* While sourcing and reporting of crop statistics from MS to Eurostat has significantly improved in the last years, with standardized online forms facilitating this, ample room exist for use of automated data flows. For instance, if each MS keeps a registry with a database of national and subnational crop statistics

following standardized metadata, an application programming interface (API) could automatically source this informa­tion from NSIs websites. This would improve the transparency and timeliness of reporting of crop statistics considerably, including for national and preliminary statistics.

5 Data availability

The harmonized dataset of subnational crop statistics presented in this paper is available for download at https://doi.org/10.2905/685949ff-56de-4646-a8df-844b5bb5f835 (Ronchetti et al., 2023b), accessible with ECAS login. The data publication includes ancillary documentation along with the dataset to provide users with useful information for a deep understand­ing of the dataset and which can be found here: https://agri4cast.jrc.ec.europa.eu/DataPortal/Resource_Files/SupportFiles/36/Allmetadata.zip. The whole publication contains the following files:

 – AllCrops_subnstats_2023.csv: crop statistics dataset stored in CSV format. The complete list of attributes and fields included in the dataset are reported in Section 3;

 – ResourceInfo.pdf: document reporting a description of the whole data publication;

 – Regional db Structure and Flagging system.pdf: document reporting a description of the structure of the dataset and details of the associated flagging system;

 – Summary of algorithm for disaggregation.pdf: document reporting a short summary of the procedures used for data harmonization;

 – Mapping_eurostat_legend.xlsx: excel file, including a set of tables reporting original crop classes in original language and their mapping to the common Eurostat legend (Table 2) per country;

 – Country_fiches.zip: compressed files containing a set of tables with summary statistics per MS and crop, as well as Supplementary Figures mapping the number of records across the EU, the length of time series, for each of the area, yield, and production crop statistics for each MS.

6 Conclusions

This data paper presents a subnational dataset of crop statistics for major crops in EU. The dataset includes harmonized subnational crop statistics on area, production, and yield, collected for the EU from National Statistical Institutes and the Eurostat REGIO database. Crop statistics are available for soft, durum, and total wheat, winter, spring, and total barley, grain maize, sunflower, and sugar beet, for a total of 344282 reported values. A dedicated flagging system has been set for the dataset, to provide users with more information on data quality and coherence.

The dataset requires frequent activities dedicated to maintaining and updating it, including efforts to provide complete time

series at the finest available subnational level and for an increasing number of crops. Nonetheless, at the time being, this dataset can be considered as a benchmark for subnational crop statistics in Europe, and can serve as a reference for setting methodologies and indicators, including calibration and validation of agronomic models and crop yield forecasting systems, and many research studies will benefit of it. Among the potential uses of this dataset, in this paper we presented the effects of climate change on crop production by analyzing crop statistics only.

455

Appendix A: Overview of data records

Number of records included in the dataset, length of time series and reported administrative level for each crop.

Table A1. Number of records included in the dataset, length of time series and reported administrative level for crop *Total wheat*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1975	2020	351	352	351
BE	NUTS 2	1975	2020	466	469	465
BG	NUTS 2	1991	2020	180	180	180
CY	NUTS 0	1987	2020	34	34	34
CZ	NUTS 3	1998	2020	322	322	322
DE	NUTS 3	1999	2020	2198	0	0
DK	NUTS 3	2006	2020	165	165	165
EE	NUTS 3	2004	2020	85	85	85
EL	NUTS 3	1998	2019	1047	1047	1047
ES	NUTS 3	1998	2020	1069	1066	1066
FI	NUTS 3	1998	2020	352	334	333
FR	NUTS 3	1989	2020	2615	2606	2606
HR	NUTS 2	2008	2020	26	26	26
HU	NUTS 3	1996	2020	490	490	490
IE	NUTS 2	1990	2020	93	63	63
IT	NUTS 3	1995	2020	1922	1919	1919
LT	NUTS 3	2000	2020	209	209	209
LU	NUTS 0	1975	2020	46	46	46
LV	NUTS 3	2000	2018	95	95	95
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	1994	2020	324	324	324
PL	NUTS 2	1999	2020	369	369	369
PT	NUTS 2	1986	2020	245	245	245
RO	NUTS 3	1998	2020	469	456	455
SE	NUTS 3	2000	2020	327	327	327
SI	NUTS 2	2007	2020	28	28	28
SK	NUTS 3	2007	2018	90	90	90

Table A2. Number of records included in the dataset, length of time series and reported administrative level for crop *Soft wheat*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1995	2020	234	234	234
BE	NUTS 2	1975	2020	439	438	438
BG	NUTS 2	1995	2020	65	65	65
CY	NUTS 0	2000	2020	21	21	21
CZ	NUTS 3	1998	2020	322	322	322
DE	NUTS 3	1999	2020	1956	1868	6973
DK	NUTS 3	2006	2020	165	165	165
EE	NUTS 3	2004	2020	85	85	85
EL	NUTS 3	1998	2019	1047	1047	1047
ES	NUTS 3	1998	2020	1108	1108	1108
FI	NUTS 3	1998	2020	353	334	334
FR	NUTS 3	1989	2020	3028	3028	3028
HR	NUTS 2	2008	2020	26	26	26
HU	NUTS 3	2002	2020	380	380	380
IE	NUTS 2	1990	2020	93	63	63
IT	NUTS 3	1995	2020	2325	2325	2328
LT	NUTS 3	2000	2020	209	209	209
LU	NUTS 0	1975	2020	46	46	46
LV	NUTS 3	1997	2018	110	110	110
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	1994	2020	324	324	324
PL	NUTS 2	2003	2020	301	301	301
PT	NUTS 2	1986	2020	245	245	245
RO	NUTS 3	1998	2020	955	954	954
SE	NUTS 3	1990	2020	437	438	437
SI	NUTS 2	2007	2020	28	28	28
SK	NUTS 3	2017	2018	16	16	16

Table A3. Number of records included in the dataset, length of time series and reported administrative level for crop *Durum wheat*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1995	2020	171	172	171
BE	NUTS 2	2000	2020	227	227	227
BG	NUTS 2	1998	2020	60	60	60
CY	NUTS 0	1987	2020	34	34	34
CZ	NUTS 3	2000	2020	294	294	294
DE	-	-	-	-	-	-
DK	NUTS 3	2006	2020	165	165	165
EE	NUTS 3	2004	2020	85	85	85
EL	NUTS 3	1998	2019	1047	1047	1047
ES	NUTS 3	1998	2020	735	732	732
FI	NUTS 3	2000	2020	324	324	324
FR	NUTS 3	1989	2020	2615	2608	2608
HR	NUTS 2	2008	2020	26	26	26
HU	NUTS 3	1998	2020	397	397	399
IE	NUTS 2	1990	2020	93	84	84
IT	NUTS 3	1995	2020	2344	2341	2341
LT	NUTS 3	2000	2020	209	209	209
LU	NUTS 0	2000	2020	21	21	21
LV	NUTS 3	2000	2018	95	95	95
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	2000	2020	252	252	252
PL	NUTS 2	2003	2020	301	301	301
PT	NUTS 2	1986	2020	245	245	245
RO	NUTS 3	1998	2020	469	456	455
SE	NUTS 3	2000	2020	327	327	327
SI	NUTS 2	2000	2020	42	42	42
SK	NUTS 3	2017	2018	10	10	10

Table A4. Number of records included in the dataset, length of time series and reported administrative level for crop *Total barley*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1975	2020	413	413	413
BE	NUTS 2	1975	2020	468	470	446
BG	NUTS 2	1991	2020	180	180	180
CY	NUTS 0	1987	2020	34	34	34
CZ	NUTS 3	1998	2020	322	322	322
DE	NUTS 3	1999	2020	2207	1491	1491
DK	NUTS 3	2006	2020	165	165	165
EE	NUTS 3	2004	2020	83	84	83
EL	NUTS 3	1998	2019	1047	1047	1047
ES	NUTS 3	1998	2020	1008	1008	1008
FI	NUTS 3	1998	2020	354	354	354
FR	NUTS 3	1989	2020	3027	3027	3027
HR	NUTS 2	2008	2020	26	26	26
HU	NUTS 3	1996	2020	492	492	492
IE	NUTS 2	1990	2020	93	63	63
IT	NUTS 3	2000	2020	2122	2121	2121
LT	NUTS 3	2000	2020	208	208	208
LU	NUTS 0	1975	2020	46	46	46
LV	NUTS 3	1997	2018	110	110	110
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	1994	2020	323	323	323
PL	NUTS 2	1999	2020	365	365	365
PT	NUTS 2	1986	2020	245	245	245
RO	NUTS 3	1998	2020	957	956	956
SE	NUTS 3	1995	2020	104	104	104
SI	NUTS 2	2007	2020	28	28	28
SK	NUTS 3	2007	2018	96	96	96

Table A5. Number of records included in the dataset, length of time series and reported administrative level for crop *Winter barley*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1975	2020	413	413	413
BE	NUTS 2	2009	2020	126	126	125
BG	-	-	-	-	-	-
CY	NUTS 0	2004	2020	17	17	17
CZ	NUTS 3	1998	2020	322	322	322
DE	NUTS 3	1999	2020	1752	1624	7075
DK	NUTS 3	2006	2020	165	165	165
EE	NUTS 3	2004	2020	77	72	72
EL	NUTS 3	1998	2019	1047	1047	1047
ES	NUTS 3	1998	2020	901	902	901
FI	NUTS 3	2000	2020	314	314	314
FR	NUTS 3	1989	2020	3027	3027	3027
HR	NUTS 2	2008	2020	26	26	26
HU	NUTS 3	1996	2020	492	492	492
IE	NUTS 2	2000	2020	63	33	33
IT	NUTS 3	2005	2020	1512	1512	1409
LT	NUTS 3	2000	2020	208	208	210
LU	NUTS 0	1975	2020	46	46	46
LV	NUTS 3	1997	2018	110	110	110
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	1994	2020	323	323	323
PL	NUTS 2	2003	2020	301	301	301
PT	NUTS 2	1999	2020	154	147	147
RO	-	-	-	-	-	-
SE	NUTS 3	1995	2020	104	104	104
SI	-	-	-	-	-	-
SK	NUTS 3	2007	2018	96	96	96

Table A6. Number of records included in the dataset, length of time series and reported administrative level for crop *Spring barley*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1975	2020	414	414	414
BE	NUTS 2	2009	2020	120	120	120
BG	-	-	-	-	-	-
CY	NUTS 0	2004	2020	17	17	17
CZ	NUTS 3	1998	2020	322	322	322
DE	NUTS 3	1999	2020	1678	1525	6558
DK	NUTS 3	2006	2020	165	165	165
EE	NUTS 3	2004	2020	81	81	81
EL	NUTS 3	1998	2019	1047	1047	1047
ES	NUTS 3	1998	2020	956	955	955
FI	NUTS 3	1999	2020	328	328	328
FR	NUTS 3	1989	2020	2993	2993	2993
HR	NUTS 2	2008	2020	26	26	26
HU	NUTS 3	1996	2020	492	492	492
IE	-	-	-	-	-	-
IT	NUTS 3	2005	2020	1512	1512	1409
LT	NUTS 3	2000	2020	208	208	210
LU	NUTS 0	1975	2020	46	46	46
LV	NUTS 3	1997	2018	110	110	110
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	1994	2020	324	324	324
PL	NUTS 2	2003	2020	301	301	301
PT	NUTS 2	1999	2020	154	147	147
RO	-	-	-	-	-	-
SE	NUTS 3	1990	2020	628	628	628
SI	-	-	-	-	-	-
SK	NUTS 3	2007	2018	96	96	96

Table A7. Number of records included in the dataset, length of time series and reported administrative level for crop *Grain maize*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1975	2020	414	414	414
BE	NUTS 2	2011	2020	106	106	106
BG	NUTS 2	1991	2020	180	180	180
CY	NUTS 0	2000	2020	21	21	21
CZ	NUTS 3	2005	2020	219	219	219
DE	NUTS 1	2010	2020	149	131	131
DK	NUTS 3	2011	2020	110	110	110
EE	NUTS 3	2000	2020	105	105	105
EL	NUTS 3	2009	2019	563	563	563
ES	NUTS 3	1998	2020	1163	1157	1157
FI	NUTS 3	2000	2020	399	399	399
FR	NUTS 3	1989	2020	3026	3026	3026
HR	NUTS 2	2005	2020	32	32	32
HU	NUTS 3	1996	2020	492	492	492
IE	NUTS 2	2000	2020	63	63	63
IT	NUTS 3	1995	2020	2569	2566	2564
LT	NUTS 3	2000	2020	209	209	210
LU	NUTS 0	2000	2020	21	21	21
LV	NUTS 3	2000	2020	126	126	126
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	2008	2020	156	156	156
PL	NUTS 2	2003	2020	301	301	301
PT	NUTS 2	1986	2020	245	245	245
RO	NUTS 3	1998	2020	955	954	954
SE	NUTS 3	2007	2020	10	10	10
SI	NUTS 2	2007	2020	28	28	28
SK	NUTS 3	2007	2018	94	94	94

Table A8. Number of records included in the dataset, length of time series and reported administrative level for crop *Sugar beet*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1975	2020	279	279	279
BE	NUTS 2	1975	2020	468	470	441
BG	NUTS 2	2008	2020	78	78	78
CY	NUTS 0	2000	2020	21	21	21
CZ	NUTS 3	1998	2020	270	270	270
DE	NUTS 3	1999	2020	1733	1432	6051
DK	NUTS 3	2006	2020	157	159	159
EE	NUTS 3	1998	2020	115	115	115
EL	NUTS 3	2009	2019	562	562	562
ES	NUTS 3	1998	2020	490	486	486
FI	NUTS 3	1998	2020	282	228	228
FR	NUTS 3	1989	2020	2398	2397	2397
HR	NUTS 2	2005	2020	18	18	18
HU	NUTS 3	1996	2020	460	461	460
IE	NUTS 2	2007	2020	42	42	42
IT	NUTS 3	2006	2020	507	507	507
LT	NUTS 3	1998	2020	186	184	184
LU	NUTS 0	1975	2020	46	46	46
LV	NUTS 3	2008	2020	78	78	78
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	1994	2020	324	324	324
PL	NUTS 2	1999	2020	369	368	369
PT	NUTS 2	1986	2020	245	245	245
RO	NUTS 3	1990	2020	916	910	908
SE	NUTS 3	1990	2020	132	132	132
SI	NUTS 2	2007	2020	28	28	28
SK	NUTS 3	1997	2018	120	120	141

Table A9. Number of records included in the dataset, length of time series and reported administrative level for crop *Sunflower*.

Country	NUTS level	First year	Last year	# records Area	# records Production	# records Yield
AT	NUTS 2	1975	2020	311	311	310
BE	NUTS 2	1975	2020	462	462	462
BG	NUTS 2	1991	2020	180	180	180
CY	NUTS 0	2000	2020	21	21	21
CZ	NUTS 3	2005	2020	140	140	140
DE	NUTS 1	1988	2020	405	271	257
DK	NUTS 3	2000	2020	231	231	231
EE	NUTS 3	2000	2020	105	105	105
EL	NUTS 3	2009	2019	562	562	562
ES	NUTS 3	1998	2020	877	875	874
FI	NUTS 3	1990	2020	589	589	589
FR	NUTS 3	1989	2020	2917	2916	2916
HR	NUTS 2	2005	2019	20	20	20
HU	NUTS 3	1996	2020	492	492	492
IE	NUTS 2	1999	2020	60	66	60
IT	NUTS 3	2006	2020	1063	1059	1059
LT	NUTS 3	2000	2020	210	210	210
LU	NUTS 0	2010	2020	11	11	11
LV	NUTS 3	2000	2020	126	126	126
MT	NUTS 0	2000	2020	21	21	21
NL	NUTS 2	1975	2020	540	492	454
PL	NUTS 2	1999	2020	372	372	368
PT	NUTS 2	1986	2020	245	245	245
RO	NUTS 3	1998	2020	891	890	890
SE	NUTS 3	1975	2020	966	966	966
SI	NUTS 2	2007	2020	28	28	28
SK	NUTS 3	1995	2018	103	104	103

Author contributions. GR drafted the manuscript, created figures, processed and analyzed the data. GR, LNS, LS and IC collected data, performed data harmonization and defined post-processing rules. MvdV provided guidance and reviewed the manuscript. All the authors provided comments and suggestions on the paper.

Competing interests. The contact authors have declared that none of the authors has any competing interests.

Acknowledgements. The authors would like to acknowledge Steven Hoek and Hendrik Boogaard from Wageningen Environmental Research (WENR), and many colleagues, including Sara García-Condado, and Raul López-Lozano, who contributed to setting definitions and collecting data statistics over the years.

References

AMIS: AMIS Market Database, https://app.amis-outlook.org/#/market-database/supply-and-demand-overview, online, last access: 24 August 2023.

Anderson, W., Baethgen, W., Capitanio, F., Ciais, P., Cook, B. I., da Cunha, C. G., Goddard, L., Schauberger, B., Sonder, K., Podestá, G., van der Velde, M., and You, L.: Twentieth Century Crop Statistics, 1900-2017., https://sedac.ciesin.columbia.edu/data/set/food-twentieth-century-crop-statistics-1900-2017, online, last access: 24 August 2023, 2022.

Anderson, W., Baethgen, W., Capitanio, F., Ciais, P., Cook, B. I., da Cunha, C. G., Goddard, L., Schauberger, B., Sonder, K., Podestá, G., van der Velde, M., and You, L.: Climate variability and simultaneous breadbasket yield shocks as observed in long-term yield records, Agricultural and Forest Meteorology, 331, 109 321, https://doi.org/10.1016/j.agrformet.2023.109321, 2023.

Avitabile, V., Baldoni, E., Baruth, B., Bausano, G., Boysen-Urban, K., Caldeira, C., Camia, A., Cazzaniga, N., Ceccherini, G., Laurentis, V. D., Doerner, H., Giuntoli, J., Gras, M., Garcia, J. G., Gurria, P., Hassegawa, M., JasineviČius, G., Jonsson, R., Konrad, C., Kupschus, S., Notte, A. L., M'barek, R., Mannini, A., Migliavacca, M., Mubareka, S., Patani, S., Pilli, R., Rebours, C., Ronchetti, G., Ronzon, T., Rougieoux, P., Sala, S., Lopez, J. S., Mengual, E. S., Sinkko, T., Sturm, V., Leeuwen, M. V., Vasilakopoulos, P., Verkerk, P. J., Virtanen, J., Winker, H., and Zulian, G.: Biomass production, supply, uses and flows in the European Union. Integrated assessment., Technical Report, Luxembourg, https://doi.org/10.2760/811744, JRC132358, 2023.

Ballot, R., Guilpart, N., and Jeuffroy, M.-H.: The first map of dominant crop sequences in the European Union over 2012–2018, Earth System Science Data Discussions, 2022, 1–26, https://doi.org/10.5194/essd-2022-300, 2022.

Becker-Reshef, I., Barker, B., Whitcraft, A., Oliva, P., Mobley, K., Justice, C., and Sahajpal, R.: Crop Type Maps for Operational Global Agricultural Monitoring, Scientific Data, 10, 172, 2023.

Beillouin, D., Schauberger, B., Bastos, A., Ciais, P., and Makowski, D.: Impact of extreme weather conditions on European crop production in 2018, Philosophical Transactions of the Royal Society B, 375, 20190 510, 2020.

Ben-Ari, T., Boé, J., Ciais, P., Lecerf, R., Van der Velde, M., and Makowski, D.: Causes and implications of the unforeseen 2016 extreme yield loss in the breadbasket of France, Nature communications, 9, 1627, 2018.

Blickensdörfer, L., Schwieder, M., Pflugmacher, D., Nendel, C., Erasmi, S., and Hostert, P.: Mapping of crop types and crop sequences with combined time series of Sentinel-1, Sentinel-2 and Landsat 8 data for Germany, Remote sensing of environment, 269, 112 831, 2022.

Ceglar, A., Toreti, A., Lecerf, R., Van der Velde, M., and Dentener, F.: Impact of meteorological drivers on regional inter-annual crop yield variability in France, Agricultural and Forest Meteorology, 216, 58–67, https://doi.org/10.1016/j.agrformet.2015.10.004, 2016.

Ceglar, A., Zampieri, M., Toreti, A., and Dentener, F.: Observed northward migration of agro-climate zones in Europe will further accelerate under climate change, Earth's Future, 7, 1088–1101, 2019.

Cerrani, I., Ronchetti, G., Nisini Scacchiafichi, L., López Lozano, R., and Van der Velde, M.: Algorithm for the disaggregation of crop area statistics in the MARS crop yield forecasting system, Ispra: European Commission, 2023.

d'Andrimont, R., Verhegghen, A., Lemoine, G., Kempeneers, P., Meroni, M., and Van der Velde, M.: From parcel to continental scale–A first European crop type map based on Sentinel-1 and LUCAS Copernicus in-situ observations, Remote sensing of environment, 266, 112 708, 2021.

European Parliament, EPRS: Statistics on agricultural input and output (SAIO), https://www.europarl.europa.eu/legislative-train/theme-agriculture-and-rural-development-agri/file-saio, online, last access: 28 August 2023.

Eurostat: European Statistical System (ESS), https://ec.europa.eu/eurostat/web/european-statistical-system, online, last access: 25 July 2023, a.

Eurostat: Database, https://ec.europa.eu/eurostat/web/main/data/database, online, last access: 31 January 2023, b.

505 Eurostat: History of NUTS, https://ec.europa.eu/eurostat/web/nuts/history, online, last access: 31 January 2023, c.

Eurostat: Strategy for agricultural statistics for 2020 and beyond, Crop statistics working group, 2015a.

Eurostat: Regions in the European Union. Nomenclature of territorial units for statistics NUTS 2013/EU-28, 2015b.

Eurostat: Regions in the European Union, edition 2018, Nomenclature of territorial units for statistics -NUTS 2016/EU-28., https://doi.org/10.2785/475524, 2018.

510 Eurostat: Annual crop statistics handbook, Crop statistics working group, 2020.

FAOSTAT: Crops and livestock products, https://www.fao.org/faostat/en/data/QCL, online, last access: 31 January 2023.

Finger, R.: Evidence of slowing yield growth–the example of Swiss cereal yields, Food Policy, 35, 175–182, 2010.

Fontana, G., Toreti, A., Ceglar, A., and De Sanctis, G.: Early heat waves over Italy and their impacts on durum wheat yields, Natural Hazards and Earth System Sciences, 15, 1631–1637, https://doi.org/10.5194/nhess-15-1631-2015, 2015.

515 Fritz, S., See, L., Bayas, J. C. L., Waldner, F., Jacques, D., Becker-Reshef, I., Whitcraft, A., Baruth, B., Bonifacio, R., Crutchfield, J., et al.: A comparison of global agricultural monitoring systems and current gaps, Agricultural systems, 168, 258–272, 2019.

García-Condado, S., López-Lozano, R., Panarello, L., Cerrani, I., Nisini, L., Zucchini, A., Van der Velde, M., and Baruth, B.: Assessing lignocellulosic biomass production from crop residues in the European Union: Modelling, analysis of the current scenario and drivers of interannual variability, GCB Bioenergy, 11, 809–831, 2019.

520 Guiomar, N., Godinho, S., Pinto-Correia, T., Almeida, M., Bartolini, F., Bezák, P., Biró, M., Bjørkhaug, H., Bojnec, Š., Brunori, G., et al.: Typology and distribution of small farms in Europe: Towards a better picture, Land use policy, 75, 784–798, 2018.

Guth, M. and Smędzik-Ambroży, K.: Economic resources versus the efficiency of different types of agricultural production in regions of the European union, Economic Research-Ekonomska Istraživanja, 33, 1036–1051, https://doi.org/10.1080/1331677X.2019.1585270, 2020.

Iizumi, T. and Sakai, T.: The global dataset of historical yields for major crops 1981–2016, Scientific Data, 7, 97, 2020.

525 Joint Research Centre: JRC MARS Bulletin – Crop monitoring in Europe, https://joint-research-centre.ec.europa.eu/monitoring-agricultural-resources-mars/jrc-mars-bulletin_en, online, last access: 24 August 2023, 2023.

Jørgensen, L. N., Kudsk, P., and Ørum, J. E.: Links between pesticide use pattern and crop production in Denmark with special reference to winter wheat, Crop Protection, 119, 147–157, 2019.

Kern, A., Barcza, Z., Marjanović, H., Árendás, T., Fodor, N., Bónis, P., Bognár, P., and Lichtenberger, J.: Statistical modelling of crop yield in Central Europe using climate data and remote sensing vegetation indices, Agricultural and Forest Meteorology, 260, 300–320, 2018.

530 Kowalik, W., Dabrowska-Zielinska, K., Meroni, M., Raczka, T. U., and de Wit, A.: Yield estimation using SPOT-VEGETATION products: A case study of wheat in European countries, International Journal of Applied Earth Observation and Geoinformation, 32, 228–239, 2014.

Lennert, J. and Farkas, J. Z.: Transformation of agriculture in Hungary in the period 1990-2020, Studia, 56, 33–72, 2020.

López-Lozano, R., Duveiller, G., Seguini, L., Meroni, M., García-Condado, S., Hooker, J., Leo, O., and Baruth, B.: Towards regional grain yield forecasting with 1 km-resolution EO biophysical products: Strengths and limitations at pan-European level, Agricultural and Forest Meteorology, 206, 12–32, 2015.

MAPA: Ministery of Agriculture, Fisheries and Food, https://www.mapa.gob.es/en/default.aspx, online, last access: 31 January 2023.

Monfreda, C., Ramankutty, N., and Foley, J. A.: Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000, Global biogeochemical cycles, 22, 2008.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., and Foley, J. A.: Closing yield gaps through nutrient and water management, Nature, 490, 254–257, 2012.

Neumann, M. and Smith, P.: Carbon uptake by European agricultural land is variable, and in many regions could be increased: Evidence from remote sensing, yield statistics and models of potential productivity, Science of The Total Environment, 643, 902–911, 2018.

Nóia Júnior, R. d. S., Deswarte, J.-C., Cohan, J.-P., Martre, P., van Der Velde, M., Lecerf, R., Webber, H., Ewert, F., Ruane, A. C., Slafer, G. A., et al.: The extreme 2016 wheat yield failure in France, Global Change Biology, 29, 3130–3146, 2023.

Paudel, D., Boogaard, H., de Wit, A., van der Velde, M., Claverie, M., Nisini, L., Janssen, S., Osinga, S., and Athanasiadis, I. N.: Machine learning for regional crop yield forecasting in Europe, Field Crops Research, 276, 108 377, 2022.

Peltonen-Sainio, P. and Jauhiainen, L.: Large zonal and temporal shifts in crops and cultivars coincide with warmer growing seasons in Finland, Regional Environmental Change, 20, 1–13, 2020.

Piikki, K. and Söderström, M.: Digital soil mapping of arable land in Sweden–Validation of performance at multiple scales, Geoderma, 352, 342–350, 2019.

Rega, C., Short, C., Pérez-Soba, M., and Paracchini, M. L.: A classification of European agricultural land using an energy-based intensity indicator and detailed crop description, Landscape and urban planning, 198, 103 793, 2020.

Reiff, M., Ivanicova, Z., and Surmanova, K.: Cluster analysis of selected world development indicators in the fields of agriculture and the food industry in European Union countries, Agricultural Economics, 64, 197–205, 2018.

Republic of Bulgaria: National Statistical Institute, https://www.nsi.bg/en, online, last access: 31 January 2023.

Ribeiro, A. F. S., Russo, A., Gouveia, C. M., Páscoa, P., and Zscheischler, J.: Risk of crop failure due to compound dry and hot extremes estimated with nested copulas, Biogeosciences, 17, 4815–4830, 2020.

Ronchetti, G., Manfron, G., Weissteiner, C. J., Seguini, L., Scacchiafichi, L. N., Panarello, L., and Baruth, B.: Remote sensing crop group-specific indicators to support regional yield forecasting in Europe, Computers and Electronics in Agriculture, 205, 107 633, 2023a.

Ronchetti, G., Nisini Scacchiafichi, L., Seguini, L., Cerrani, I., and van der Velde, M.: Harmonized European Union subnational crop statistics., https://doi.org/10.2905/685949ff-56de-4646-a8df-844b5bb5f835, [Dataset], 2023b.

Schauberger, B., Jägermeyr, J., and Gornott, C.: A systematic review of local to regional yield forecasting approaches and frequently used data resources, European Journal of Agronomy, 120, 126 153, 2020.

Schmitt, J., Offermann, F., Söder, M., Frühauf, C., and Finger, R.: Extreme weather events cause significant crop yield losses at the farm level in German agriculture, Food Policy, 112, 102 359, 2022.

Sloat, L. L., Davis, S. J., Gerber, J. S., Moore, F. C., Ray, D. K., West, P. C., and Mueller, N. D.: Climate adaptation by crop migration, Nature Communications, 11, https://doi.org/10.1038/s41467-020-15076-4, 2020.

Statistics Austria: The National Statistical System, https://www.statistik.at/en/about-us/organisation/the-national-statistical-system, online, last access: 31 January 2023.

Stürmer, B., Schmidt, J., Schmid, E., and Sinabell, F.: Implications of agricultural bioenergy crop production in a land constrained economy– The example of Austria, Land Use Policy, 30, 570–581, 2013.

Van der Velde, M., van Diepen, C., and Baruth, B.: The European crop monitoring and yield forecasting system: Celebrating 25 years of JRC MARS Bulletins, 2019.

Webber, H., Lischeid, G., Sommer, M., Finger, R., Nendel, C., Gaiser, T., and Ewert, F.: No perfect storm for crop yield failure in Germany, Environmental Research Letters, 15, 104 012, 2020.