BIKE

BIOFUELS PRODUCTION
AT LOW - ILUC RISK
FOR EUROPEAN SUSTAINABLE
BIOECONOMY

D 2.1

Productivity increases that can result in additional feedstock for European biomass crop options

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LIST OF ACRONYMS

CEEC	Central- and Eastern European countries
SOM	soil organic matter
SOC	soil organic carbon
BIKE	Biofuels Production at low – ILUC Risk for European Sustainable Bioeconomy
NUTS	Nomenclature of territorial units for statistics
AEZ	Agro-ecological Zones
GAEZ	Global Agro-ecological Zones
RCPs	Representative Concentration Pathways
RED	Renewable Energy Directive
ILUC	Indirect Land Use Change
GHG	Green House Gas
CAP	Common Agricultural Policy
ILUC	Indirect Land Use Change

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Executive summary

This report presents the results from Task 2.1 in the BIKE project. This task follows the Commission Delegated Regulation (EU) 2019/807 which defines 'additional feedstock' as 'the additional amount of a food and feed crop produced in a clearly delineated area compared to the dynamic yield baseline and that is the direct result of applying an additionality measure'. The work involves the following components:

1) A comparative review and a statistical based analysis for the baseline of relevant crops produced in European land (national and NUTS2 levels) and being suitable for biofuel production. The crops included in the analysis are cereals (soft wheat, barley, and maize), sugar (sugar beet) and oil (oilseed rape, sunflower). Ethiopian mustard, castor, sweet sorghum, lignocellulosic perennial grasses and Short Rotation Forestry are also assessed in WP2 and the results are presented in Deliverable 2.2.

2) An overview of crop management practices and their associated input requirements and evaluation of their potential to increase productivity for the understudy crops in the different agroecological zones (AEZ) in Europe.

3) Estimation of yield increases, calculated against the reference of five-year average reported yields over the period of 2015-2020, to have representative figures across a variety of climatic conditions, crop varieties, etc. The projection for yield increases by 2025 also consider potential changes in management practices. Projections of attainable crop yield based on the Global Agroecological Zones model (GAEZ v4.0) include climate conditions for four Representative Concentration Pathways (RCPs) until 2040. These results are complemented by a simple statistical analysis which extrapolates future yields of selected crops to 2030 and compares them with the relevant dynamic yield baseline as defined by the Commission Implementing Regulation (EU) 2022/996.

Part of the contents of this deliverable is overlapping with the information recently published in a review paper:

Panoutsou, C., Giarola, S., Ibrahim, D., Verzandvoort, S., Elbersen, B., Sandford, C., Malins, C., Politi, M., Vourliotakis, G., Zita, V. E., Vásáry, V., Alexopoulou, E., Salimbeni, A. & Chiaramonti, D. (2022), Opportunities for Low Indirect Land Use Biomass for Biofuels in Europe. 1 May 2022, In: Applied Sciences (Switzerland). 12, 9, 4623.

The above paper is based on the content presented in D2.1 (this report) and D2.2 and these were written simultaneously with the review paper.

1. Introduction

1.1. Why low ILUC-risk feedstock?

The Renewable Energy Directive (REDII)[1] takes a targeted approach to reduce Indirect Land Use Change (ILUC) impacts associated with conventional biofuels[2], bioliquids and biomass fuels[3]. Since ILUC emissions cannot be measured with the level of precision required to be included in the European Union Greenhouse Gas (GHG) emission calculation methodology, it keeps the approach of having a limit on the amount of crop-based biofuels, bioliquids, and biomass fuels consumed in transport that can be considered when calculating the national overall share of renewable energy, as well as the sectoral share in transport. After the 31st of December 2023 biofuels, bioliquids and biomass fuels produced from food or feed crops 'for which a significant expansion of the production area into land with high carbon stock is observed'[4] (so called high ILUC-risk feedstocks) will gradually decrease to zero by 2030. In this context, the Directive also sets national limits at Member States' 2019 levels for the period 2021-2023. Member States will still be able to import and use fuels affected by the limits, but they will not be able to consider them as renewable energy or count them for their renewable energy targets.

The Directive also introduces another exemption from the limits placed on biofuels, thereby allowing them to continue contributing to the 14% renewable energy target; this exemption applies when they have been certified as **low ILUC-risk**. These will therefore represent **one of the main options to maintain current shares and further develop the sustainable biofuels market potential in Europe from 2023 onwards, especially in sectors with limited short-term alternatives as aviation, heavy duty and maritime.**

The **low ILUC-risk status** is so far defined by the Commission Delegated Regulation (EU) 2019/807 of 13 March 2019[5] supplementing Directive (EU) 2018/2001. This states that **low ILUC-risk** biofuels, bioliquids and biomass fuels are those '**that are produced under circumstances that avoid ILUC effects, by virtue of having been cultivated on unused, abandoned or severely degraded land or emanating from crops which benefited from improved agricultural practices'** [6,7].

This definition intersects with a wide range of agricultural practices, business models, and land use decision-making, such that the low ILUC-risk concept could be influential far beyond the narrow scope of negating high ILUC-risk status. Indeed, the adoption of biomass production methods compatible with low ILUC-risk aims will necessarily form a critical component of any future sustainable bioenergy system (as well as agricultural systems more broadly) – in the EU

[1] https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii
[2] "Biofuels" as defined in RED.
[3] "Biomass fuels" is a new term introduced in REDII, for gaseous and solid fuels produced from biomass.
[4] https://ec.europa.eu/transparency/regdoc/rep/3/2019/EN/C-2019-2055-F1-EN-ANNEX-1-PART-1.PDF
[5] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0807
[6] https://ec.europa.eu/energy/sites/ener/files/documents/2_en_act_part1_v3.pdf
[7] https://ec.europa.eu/transparency/regdoc/rep/1/2019/EN/COM-2019-142-F1-EN-MAIN-PART-1.PDF

and beyond[8]. Indeed, the availability of sustainable biofuel has been identified as particularly relevant to sectors with limited short-term alternatives, namely aviation, heavy-duty long-haul road transport, and maritime. Low ILUC-risk production may therefore represent an **important option to maintain and develop the sustainable biofuels market potential in Europe**.

In this context, a detailed assessment of both low ILUC-risk pathways (i.e., unused land and increased productivity) will add value to the policy discussion and provide some foundation to analyses of EU renewables targets and its future energy mix.

1.2.Added value from BIKE

The BIKE project[9] aims to develop scientifically robust evidence for low ILUC-risk biofuels. The work is organised around two value chain types, meeting the criteria for additionality as introduced above: i) cultivation in unused[10], abandoned[11] or severely degraded[12] land; and ii) productivity increases from improved agricultural practices.

The aim of the Deliverable 2.1 **is to present an approach on how to use available statistics at NUTS2 level to: i) construct baselines for food and feed crops produced on European land and being suitable for advanced biofuel production, ii) estimate 'additional' yield increases with potential changes in crop management practices.** The crops included in the analysis are cereals (wheat, barley, maize), sugar (sugarbeet) and oil (rapeseed, sunflower).

The analysis follows the Commission Delegated Regulation (EU) 2019/807. '**Additional feedstock' is defined as the additional amount of a food and feed crop produced in a clearly delineated area compared to the dynamic yield baseline and that is the direct result of applying an additionality measure**.

The findings of the work performed so far will be discussed, validated, and updated with stakeholders from EUROSTAT, statistical officers, industries and relevant associations.

[8] These issues are explored in other outputs from the BIKE consortium – for instance deliverable D5.1 on the policy and institutional frameworks surrounding low ILUC-risk opportunities.

[9] https://www.bike-biofuels.eu/

[10] 'unused land' means areas which, for a consecutive period of at least 5 years before the start of cultivation of the feedstock used for the production of biofuels, bioliquids and biomass fuels, were neither used for the cultivation of food and feed crops, other energy crops nor any substantial amount of fodder for grazing animals;

[11] 'abandoned land' means unused land, which was used in the past for the cultivation of food and feed crops but where the cultivation of food and feed crops was stopped due to biophysical or socioeconomic constraints;

[12] 'Severely degraded land' means land that, for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded.

2. Approach

The approach combined available, open access statistical data series and modelling to:

- construct yield baselines using open-access statistical datasets from EUROSTAT;
- analyse baseline yields at European Agroecological Zones[13], national and regional (NUTS2) levels (see Section 2.2 and Section 3);
- calculate the yield increment that could be identified as additional in each region following the European Commission's methodological approach (see Section 2.3 and Section 3);
- understand opportunities for improved crop management practices (see Sections 4 and 5);
- estimate the potential for yield increases (see Section 2.4, Section 5, and Section 6).

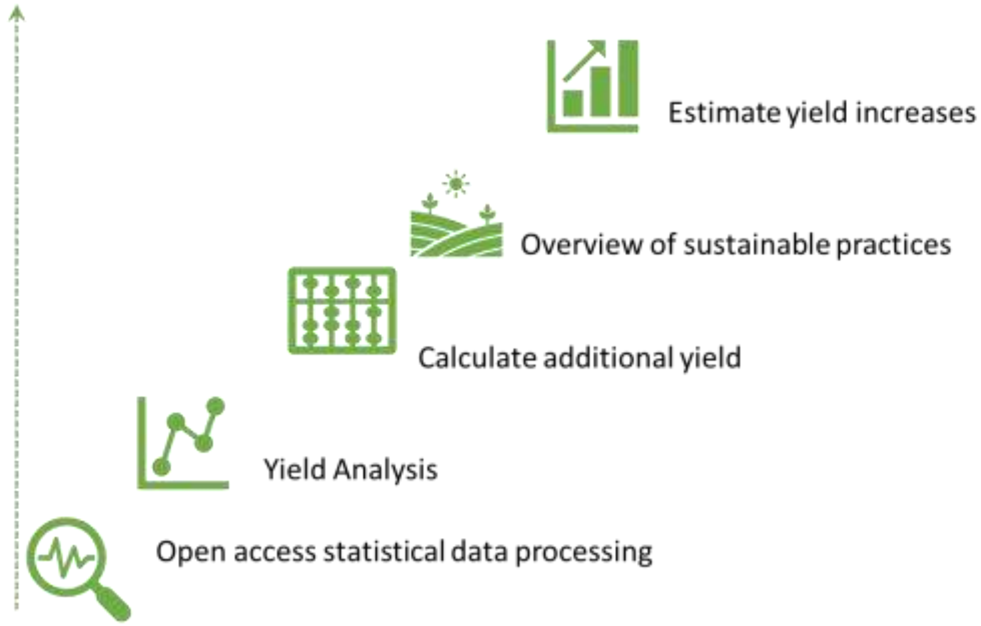

Figure 1: Approach for the calculation of additional yields and future yield increases in conventional crops for advanced biofuels

2.1. Open access statistical data processing

Some of the investigations presented in this report are based on "simple" statistical analysis of open-access historical data, while other parts require more intensive modelling to explore counterfactual and future scenarios. The latter will be introduced below in Section 2.4; for the former, the data source is Eurostat's apro_cpshr[14], which spans the period 2000-2021. Variables of interest for the analysis in BIKE are productive area (AR, units of ha) and the production

[13] European Agro-Ecological Zones- AEZ (A: Atlantic, C&B: Continental and Boreal, M: Mediterranean)

[14] https://ec.europa.eu/eurostat/databrowser/view/APRO_CPSHR/default/table?lang=en

(YI_HU_EU, units of t) for each crop and area in the dataset. Crop yield is calculated as the ratio of production over area, as these datasets are better populated than Eurostat's dataset for yield.

Crops: From the available crops, we filter down to those relevant to BIKE – these have already been mentioned in the previous section. Each crop or crop category is associated with a standard code (e.g., barley is C1300); a list of these codes is provided in an annex.

Areas: Countries in the dataset include all the EU plus some other European and peripheral countries like Armenia and Turkey; these are listed in an annex. To make the visualisations more accessible we restrict focus to EU countries plus the UK.

Data processing: The three elements of data processing are: cleaning raw data; calculating variables of interest; and visualisation of the results. Scripts for these are written in Python, with some graphing of additional yields done in Excel.

Cleaning pipeline: Cleaning consists of transforming the data into a format more useful for subsequent calculations, eliminating datapoints which appear to be erroneous to prevent them from skewing results, and dealing with gaps in the record. Specifically, the steps are: pivoting the panel dataset into an annual format; dropping duplicated entries[15]; flagging values that appear to be rounded to a lower level of precision (for manual follow-up); automatically eliminating erroneous data-points identified from jumps in time-series; eliminating erroneous data-points which have been identified by manually checking peculiar results; merging and filling records whose NUTS2 identifier codes have changed over time; and filling missing yield data with appropriate proxy values.

Data filling: The data-filling routine just mentioned identifies where gaps in the yield data for one crop may be filled by values for similar crop categories, to arrive at a reasonable approximation. For example, a country may not report the required data for the crop "winter wheat"; however, if it does report data for the more general "wheat" category, then we use this to infer the "winter wheat" trends. As can be verified by looking at countries which report both crop categories, this provides a useful and decently accurate proxy. The virtue of this whole procedure is to allow yield trends to be compared between countries on a common (and limited) set of crops, with maximum specificity where specific data exist, but without throwing away useful data from the parent categories. However, by using one crop category as a stand-in for another, we naturally sacrifice accuracy, and so any detailed investigation of a particular country or sub-national district should be done on the un-filled dataset.

Validation: As a check, we compare the post-processing EUROSTAT data with national data from FAOSTAT. This serves a dual purpose of validating our data cleaning and calculations and flagging any inherent discrepancies between the datasets (including difference in crop category terminology in different countries). We find that the results from analysing both datasets are extremely similar, which increases confidence in our analysis pipeline when applied to sub-national data.

[15] I.e., cases in which two or more regional labels are associated with identical data, including cases where the regional label is also repeated.

2.2. Baseline yield analysis

For biomass projects which seek to produce additional (i.e., low ILUC-risk certifiable) material by enhancing crop yields, the European Commission's implementing regulation on certification schemes[16] requires the calculation of a crop yield baseline. The work in BIKE first performed a comparative review, and following that, calculated crop baselines based on a mixture of local statistics to set the initial yield level, and global trends to fix the average background yield variation over time.

In the first step, a review was done of observed crop yields at regional level between 2000 and 2020. For this we made an inventory of yield statistics for EU member states and the UK at regional level (combined NUTS-units at levels 0-3 according to availability) over the period 1990-2020, derived from reported annual yield data in EU, national and regional data sources. This was done for wheat, (spring/ winter) barley and grain maize in the group of starch crops, for oil seed rape (OSR) in the group of oil crops and for sugarbeet.

Data from the Eurostat, the European Joint Research Centre (JRC) and national statistical sources were collected and combined to maximise the temporal and regional coverage of the annual yield data for each crop at regional level in all regions of importance for these crops (see Annex I Inventory of available yield statistics for wheat, barley, maize, OSR and sugarbeet). Trends in yields of the five crops are shown only for regions for which at least three years with reported yields were available in the periods 2000-2009 and 2010-2020.

Following, we used the Commission's implementing regulation mentioned above, to calculate the "dynamic yield baseline" for a particular crop at a given farm. The work is constructed in two stages:

- First, the crop yield for the previous three years is averaged at national and district level (NUTS2) to give a starting point[17].
- Second, future yields are linearly extrapolated according to the global average yield growth for that crop. The slope values are explicitly specified in the Regulation's Annex for a handful of crops[18].

This report examines the statistics of national and sub-national areas, firstly to explore the spread in average yields, both geographically and over the dataset's 20-year span, and secondly to construct relevant yield baselines and analyse their variability.

[16] European Commission Implementing Regulation (EU) 2022/996.

[17] The IR method excludes outliers – they suggest (but do not prescribe) to exclude points that differ by more than 30%. (The calculation is not unambiguously defined; we take it to mean any of the three points that that differs more than 30% from the three-point mean.)

[18] Namely: barley, maize, oil palm fruit, rapeseed, soybeans, sugar beet, sugar cane, sunflower seed, wheat. For other crops considered in this report, the yield slopes have been calculated afresh based on FAOSTAT data from 1998-2017.

2.3. 'Additional' yield calculations

2.3.1. Yield impact of additionality measures

The Commission's implementing regulation[19] sets out the procedure for calculating the amount of additional crop harvest that can be certified as low ILUC-risk. This requires comparing a farm's achieved yields with the dynamic yield baseline introduced in Section 2.2. The Commission Implementing Regulation (EU) 2022/996 states that:

> *After implementation of the additionality measure, the economic operator shall determine the volume of low ILUC risk biomass that can be claimed by comparing the actual crop yield achieved on the delineated plot with the dynamic yield baseline. The auditor must verify in the annual audit that the volume of additional biomass achieved is in line with the projections in the management plan, and seek justification if there are discrepancies of more than 20% compared to the estimates in the management plan[20].*

The yield increment above the dynamic yield baseline that can be certified as additional will therefore be a function of both the success of the additionality measure and of other external factors that affect the yield in a given year (e.g., good weather, other changes in management practices). If the additionality measure is successful and the year is otherwise average, the amount of material that can potentially be certified as low ILUC-risk should be close to the amount predicted in the management plan. If the additionality measure is successful and the growing conditions are also unusually favourable then the amount of material that can potentially be certified as low ILUC-risk could be significantly above the amount predicted by the management plan. On the other hand, if yields are suppressed in a given year for reasons beyond the control of the project (for instance bad weather results in a poor harvest) this will reduce the quantity of material that can be certified as low ILUC-risk even if the additionality measure is successful. If the yield achieved in a given year is at or below the calculated baseline then no material can be certified as low ILUC risk (though there is no additional penalty for falling below the baseline: one cannot have negative additional material).

If the quantity of biomass that is produced above the dynamic yield baseline departs by more than 20% from above the level expected in the management plan, this must be justified to the auditor – the BIKE Handbook for low ILUC-risk certification (deliverable D1.2) states that, "The economic operator must justify large deviations from the expected yield. The auditor must flag any justified or unjustified deviations in the annual audit report." In the case of delivered yield significantly higher than expected by the management plan, it is unclear how the amount of material certified would be affected. For example, if the calculated quantity of additional material was twice the expectation in the management plan and this was justified by reference to good weather, it is unclear whether that whole quantity of material would be certified as low ILUC risk, or only 60% of it (i.e. the expected amount plus an additional 20% only).

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[19] Ibid. Footnote 16.

[20] The management plan must include an "estimate of the additional biomass yield per year, with reference to the dynamic yield baseline for the delineated plot."

2.3.2. National above-baseline yield

Several analyses in this report rely on past statistical data from EU datasets for forecasting yield growth. This leads us to depart from the Commission definitions in two ways that influence the interpretation of our results.

(i) Low ILUC-risk certification is legislated to apply at the level of a single farm, or a cluster of similar farms. Similarly, the initialisation of the dynamic yield baseline is supposed to be based on historical farm records.

In the statistical analyses of the present work, we rely on EU datasets which are organised at the national and the NUTS2 level, and we hence construct yield baselines at scales far greater than envisioned by the legislation. Our results should therefore be interpreted as applying to a "typical" farm in each region. Of course, there may be significant variation within a region, especially in those that span a large geographical area and/or which straddle distinct bio-physical and socio-economic zones; in such cases, the average values presented here may provide limited insight for a given farm, but variability at the farm level is beyond the scope of this report.

(ii) As stated above, all crop production above the dynamic baseline will be regarded as additional, provided that it is broadly consistent with the expectations laid out in the management plan. The Commission Implementing Regulation states that it should be shown that the extra yield is the 'direct result of applying an additionality measure', but the rules do not require this to be actively demonstrated – rather, the certifier confirms that an additionality measure has been implemented and it is then assumed that if yields are increased in line with expectations that this is a result of the measure.

However, the investigations in this report are focussed on broad historical and geographical trends, that is, the quantitative tasks of calculating yield baselines, projecting above-baseline production, and pinpointing which regions appear most promising for yield growth (and hence would be good candidates for additional production as defined by RED II). Results in this work about "additional" yield, therefore, should be understood to merely concern potential above-baseline yield; other criteria which would have to be satisfied for low ILUC-risk certification, such as the demonstration of additionality measures, are neglected.

2.3.3. Yield slope variation

This section introduces an issue that will be highlighted and investigated further in Sections 3 and 6. In Section 2.2, it was stated that the slope of the yield baseline for a particular crop is set by the global average yield slope. Consider now a hypothetical country or a sub-national district for which historical records show a yield slope that is greater than the global average. This above-average performance has by definition occurred in the absence of any incentives from the low ILUC-risk system, which even now is yet to become fully active.

Should this performance continue, a typical farmer who successfully applies for low ILUC-risk certification may be able to claim additional production without great exertion, since farms in their region would anyway be generating above-baseline material. We invoke the term "tailwind additionality" to convey the advantage these farmers get from background trends. Conversely, farmers in areas with low background yield growth may struggle to achieve certifiable additional material, regardless of their efforts, and experience "headwind additionality".

2.4. Modelling for yield increases

The Global Agro-Ecological Zones (GAEZ) v4 modelling framework developed jointly by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) provides global information on crop suitability, constraints and production potentials for a large number of crops (Fischer et al. 2021). Moreover, estimates of crop yield are available for current climates as well as climate prediction derived from several climate models. The information provided in GAEZ is organized in six themes: (1) land and water resources, (2) agro-climatic resources, (3) agro-climatic potential yield, (4) suitability and attainable yield, (5) actual yields and production, and (6) yield and production gaps. Within the framework of BIKE, the information on the potential and attainable yields provided by GAEZ are used in this study to indicate if additional biomass production would still be possible.

2.4.1. Data retrieved from GAEZ

We retrieved information from the GAEZ portal on crop yields consisting of three data layers: irrigated potential yield, rainfed potential yield and attainable yield. The first data layer "irrigated potential yield" represents the absolute yield ceiling for a given crop under the given climatic conditions, unconstrained by availability of nutrients and water and under the absence of pest & disease and competition by weeds. The second data layer "rainfed potential yield" represents the absolute yield ceiling when only water is a limiting factor. Finally, the third layer represents the "attainable yield" which is the highest yield which can be obtained in practice given a number of local yield reducing factors such as slope, soil fertility, pest & disease, frost risk, etc. These yield limiting factors are often based on expert assessment of the impact of such factors on yield and are combined a so-called "suitability rating". Average attainable yield for a given GAEZ cell is then calculated by averaging over the different land units within that cell and their suitability type, assuming that the most suitable land will be used first.

All data retrieved from GAEZ for BIKE was based on the high input scenario. This scenario was selected assuming that most European agricultural systems will fall into this category. The GAEZ definition of "high input scenario" describes that "Under a high level of input (advanced management assumption), the farming system is mainly market oriented. Commercial production is a management objective." This is generally the case in Europe.

We obtained several data layers for 4 different crops (grain maize, barley, wheat and oilseed-rape). First of all, we downloaded for the period 1981- 2010 the irrigated potential yield, the rainfed potential yield and attainable yield. Next, we obtained the attainable yield for all climate models, Representative Concentration Pathways (RCPs) and the periods 2011-2040. For each time period and RCP, the average attainable yield was computed by averaging over the climate model outputs. For this study we consider the period 2011-2040. Table 1 provides an example of the list of data layers for attainable yield for maize. Finally, we retrieved one additional layer from the GAEZ database which represents the percentage of available cropland per grid cell.

Table 1: Example of the data layers for attainable yield obtained from GAEZ for future climates for maize. Each row represents a unique combination of time-period, climate model and RCP.

Time Period	Climate Model	RCP	Crop	Water Supply	Input Level	CO2 Fertilization
2011-2040	NorESM1-M	RCP8.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	NorESM1-M	RCP6.0	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	NorESM1-M	RCP4.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	NorESM1-M	RCP2.6	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	MIROC-ESM-CHEM	RCP8.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	MIROC-ESM-CHEM	RCP6.0	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	MIROC-ESM-CHEM	RCP4.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	MIROC-ESM-CHEM	RCP2.6	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	IPSL-CM5A-LR	RCP8.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	IPSL-CM5A-LR	RCP6.0	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	IPSL-CM5A-LR	RCP4.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	IPSL-CM5A-LR	RCP2.6	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	HadGEM2-ES	RCP8.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	HadGEM2-ES	RCP6.0	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	HadGEM2-ES	RCP4.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	HadGEM2-ES	RCP2.6	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	GFDL-ESM2M	RCP8.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	GFDL-ESM2M	RCP6.0	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	GFDL-ESM2M	RCP4.5	Maize	Rainfed	High	With CO2 Fertilization
2011-2040	GFDL-ESM2M	RCP2.6	Maize	Rainfed	High	With CO2 Fertilization

For sugarbeet, reported yield in Eurostat and national statistics is in 'fresh yield', including water, sugar and pulp. In GAEZ, the yield of sugar beet is expressed as 'sugar yield' in dry matter. In order to compare reported yield to the various types of yield generated in GAEZ, the values from GAEZ have been converted to fresh weight. This was done by using a factor of 0.10 for the dry matter that can be used from fresh yield for biomass applications.

2.4.2. Aggregation of GAEZ data layers

The reported crop yields obtained from Eurostat or national statistical offices are provided at the level of administrative regions. As a baseline for the estimated crop yield in future periods in GAEZ we considered reported yields over the period 2015-2020. For all crops, the level of the administrative region for which the reported yields were available varied per country. For example, in Germany the reported yields were only available at NUTS1 level, while reported yields for France were available at the NUTS3 level. For example, Figure 2 shows the rainfed potential yield for maize for the historical period 1981-2010 overlayed with the statistical regions for which the corresponding reported yields are available.

Aggregation of the GAEZ layers was done specifically for each crop given the available statistical regions. Each layer with statistical regions was rasterized towards a grid that corresponds exactly with the grid of the GAEZ database (Figure 3). Next the weighted average crop yield was computed for each region by multiplying each cell with the percentage of cropland in that cell, summing the weighted yields over the entire region and finally dividing by the sum of weights for that region. This procedure ensures that cells with little cropland receive little weight in the aggregation procedure and thus have little impact on the regional average yield. This procedure was applied on regions, crops and data layers, except that for the climate scenarios, the attainable yield was first averaged over the different climate models in order to obtain an ensemble average.

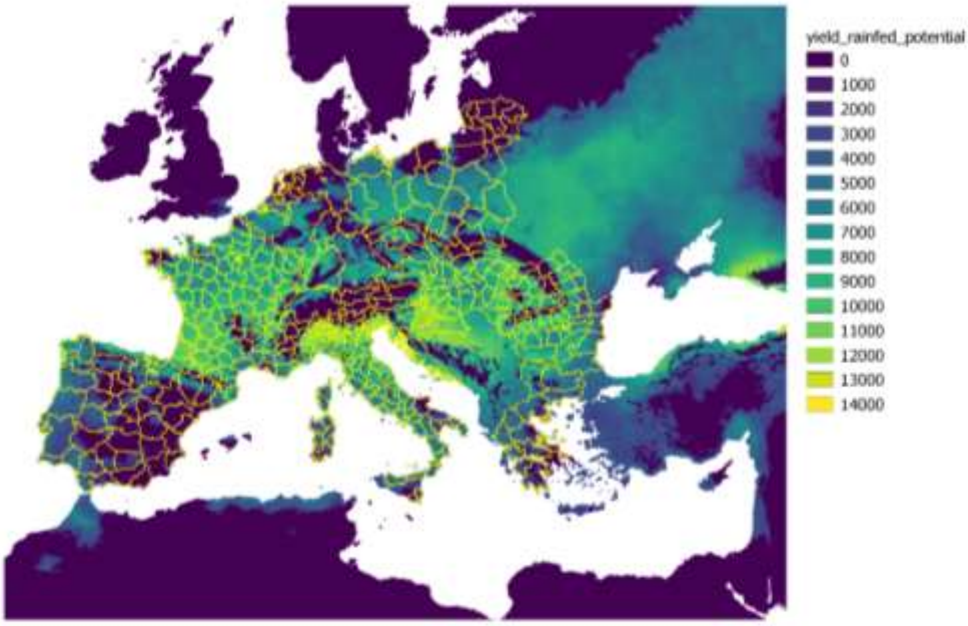


Figure 2: Rainfed potential yield (kg/ha) for grain maize over Europe for the period 1981-2010 and boundaries of administrative regions for which reported crop yields are available.

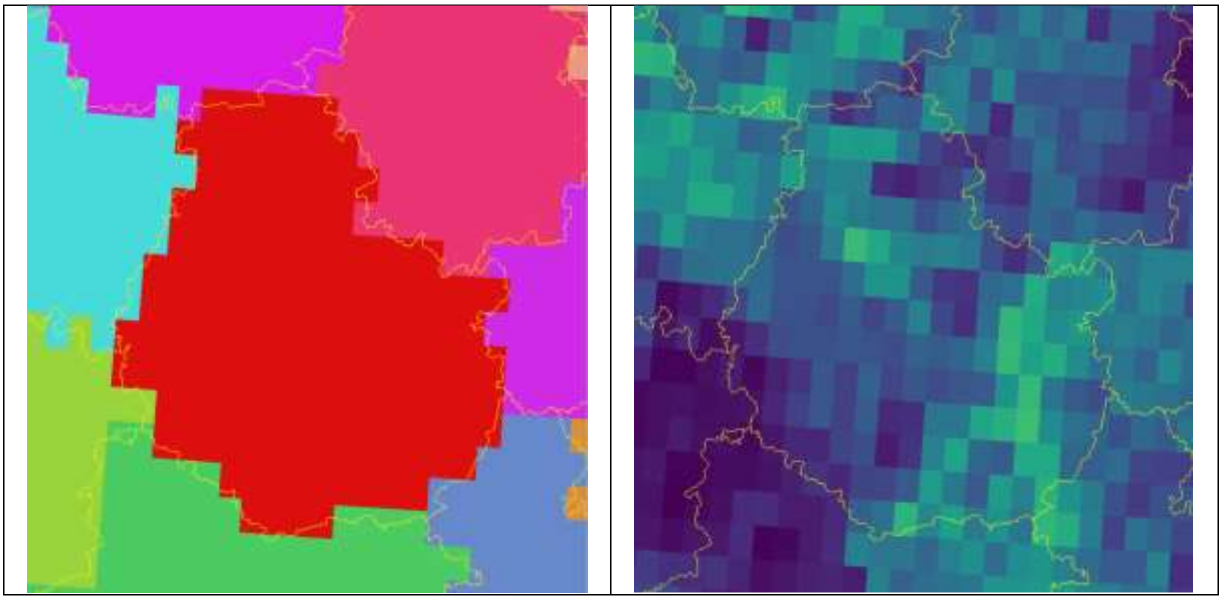


Figure 3: Example showing the aggregation inputs for region FR261 (Côte-D'or) showing the rasterized polygon on the GAEZ raster grid (left, in red) and the percentage of cropland within each raster cell for the same region (right). Percentage cropland ranges from zero (dark blue) to 69 percent (greenish).

2.4.3. Measures for potential additional yield

Several measures for the potential to produce additional yield for the crops considered were derived by comparing variables of potential and attainable yield extracted from the GAEZ model and reported yield (Table 2). The measures are listed together with the indication they give on the potential to obtain additional yield.

Table 2: Variables of reported potential and attainable crop yield. Sources: Eurostat or national statistical offices for reported yield; GAEZ v4.0 for potential and attainable yield.

Variable (unit)	Description
Reported yield (t/ha.y)	Reported yield in NUTS-regions (levels 2,3 of higher) for the period 2015-2020
Irrigated potential yield (t/ha.y)	Maximum crop yield under given climate conditions (period 1981-2010) without constraints
Rainfed potential yield (t/ha.y)	Maximum crop yield under given climate conditions (period 1981-2010), where only water is limiting
Attainable yield (t/ha.y)	Highest obtainable yield in practice under climate conditions of 1981-2010 and yield reducing conditions
Attainable yield in RCP2.6, 4.5, 6.0 and 8.5 (t/ha.y)	Attainable yield in the period 2011-2040 under climate conditions of RCPs, averaged over climate models
Average attainable yield over RCPs	Attainable yield in the period 2011-2040, averaged over RCPs and climate models

Table 3: Measures of potential for additional yield, derived from reported, potential and attainable crop yield.

Measure	Indication
Attainable yield - Reported yield	Potential for additional yield under improved management or environment under present climate conditions
Attainable yield averaged over RCPs – Reported yield	Potential for additional yield under future climate conditions
Attainable yield – Attainable yield averaged over RCPs	Impact of climate change on attainable yield
Irrigated potential yield – reported yield	Yield gap under irrigation
Rainfed potential yield – reported yield	Yield gap without irrigation

3. Observed and baseline yields for traditional crops in Europe

3.1. Introduction

Exploring the development of observed yields from conventional annual crops over the past decades allows to identify regions in Europe where yields have increased, thereby reducing the gap with attainable levels. This would give indications on observed and baseline yields and respective regions where additional biomass production might still be possible.

This section presents a comparative review of the observed yields and a statistical based analysis for the baseline of relevant crops produced in European land (national and NUTS2 levels) and being suitable for biofuel production. The crops included in the analysis are cereals[21] (soft wheat, barley, maize), sugar (sugarbeet) and oil (oilseed rape, sunflower). The results from the comparative review are presented and discussed at agroecological zone[22], while the statistical based analysis national and district (NUTS2) levels.

The baseline data of crop yields presented in maps are average values of yield in NUTS regions over the period 2015-2020, and average values in agroecological zones over the period 2010-2020. Changes in baseline yield are presented as relative changes in yield (in %) between the periods 2000-2009 and 2010-2020.

Table 4: Time period and spatial level of data collection and analysis on crop yields.

	Comparative review	Statistical based analysis
Time period(s)	2015-2020 (baseline) 2000-2009 vs 2010-2020 (change in yield)	2000-2020
Spatial level	NUTS regions (levels 0-3) agroecological zones	National and district (NUTS levels 0 and 2)

3.2. Cereals

More than half of cereals grown in the EU are wheat. The remaining 50% is composed of maize (grain and forage), and barley, each representing about one third. The last third includes cereals grown in smaller quantities such as rye, oats, and spelt.

[21] The EUROSTAT dataset distinguishes between some summer-grown and winter-grown cereals – e.g. for soft wheat and barley. Though data exists for both growing seasons, here we restrict attention to the winter season as this is more relevant to biofuel feedstock production.

[22] European Agro-Ecological Zones- AEZ (A: Atlantic, C&B: Continental and Boreal, M: Mediterranean)

Below we report trends in annual crop yield for cereal crops in all regions of the EU and UK. An overview of the cereal crop yield data collected at the level of countries is given in Annex IV.

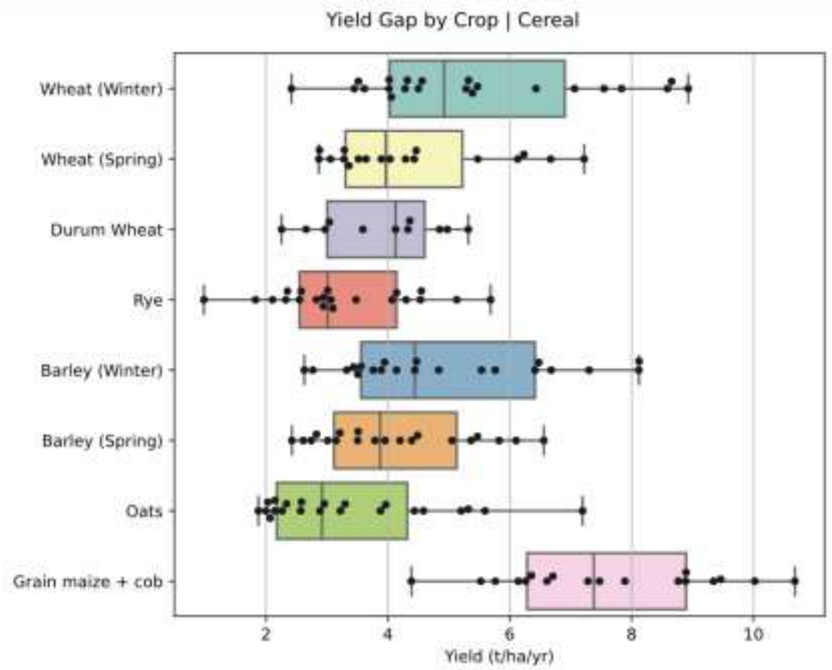


Figure 4: Average yields for cereals In EU27+UK in the period 2000-2020; each dot represents a country; colours are for presentation.

Figure 4 is provided as background context for cereal crops. Here, it is simply to illustrate how typical yields differ between crops, as indicated by the vertical median lines; it is also evident that all crops exhibit a widespread in yields, with top-performing countries achieving over twice the median yield.

3.2.1. Soft wheat

Crop yield review in European regions and agro-ecological zones

Observed yields for soft wheat between 2015-2020 showed large variations between countries in the EU, with low values in the southern Mediterranean, central and eastern Europe, and northern Sweden. The highest yields of soft wheat were observed in Ireland, the UK, northern France, Benelux, and Germany. In Belgium and southern Denmark there are even soft wheat yields of around 10 ton per hectare.

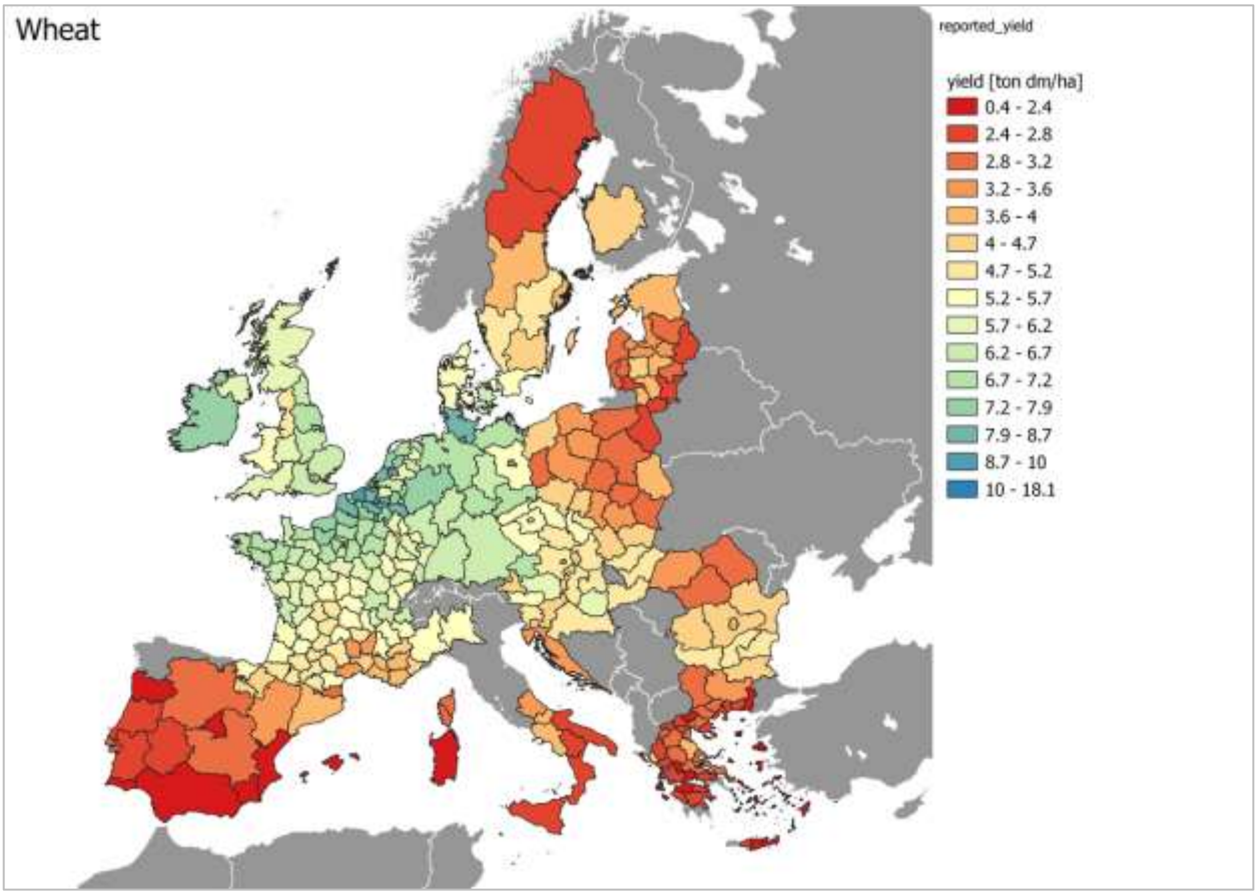


Figure 5: Observed yield (2015-2020) of soft wheat. Source data: national statistics and regional data from Eurostat and JRC.

Observed yield 2010-2020 in agro- ecological zones

The observed average yield of soft wheat over the period 2010-2020 in agro- ecological zones as recorded for regions at NUTS-levels 1-3 is shown in Figure 5. The highest values are found in the Atlantic agro- ecological zones), with yields up to 9.4 t/ha.y. The Mediterranean South zone is characterized by the lowest average yield of soft wheat in this period, with values between 1.2 and 3.8 t/ha.y. Spain, Italy and Greece have regions in this range of soft wheat yields in this agro-ecological zone. Standard deviations to illustrate the yield variation within the zones, are between 0.6 (for zones ALS, BOR and PAN) and 2.0 t/ha.y (for zone LUS).

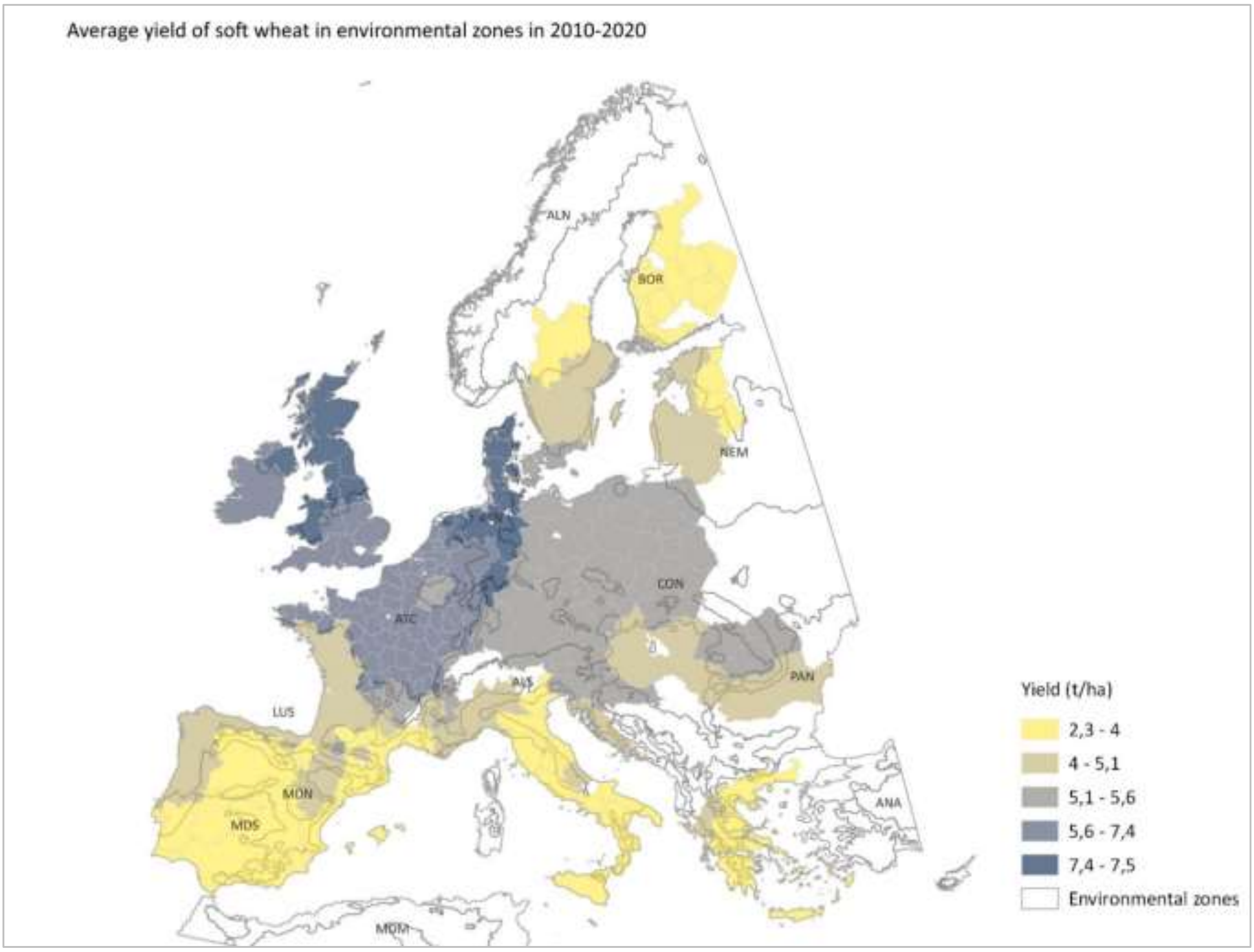


Figure 6: Observed yield (2010-2020) of soft wheat in agro- ecological zones in Europe. Source data: observations for 287 regions from national statistics and regional data from Eurostat and JRC. No observations available for agro- ecological zone Alpine North.

Changes in yield 2000-2009 versus 2010-2020

The yield of soft wheat has increased by more than 10% in central and eastern Europe and in some regions in southern European countries and southern Sweden in the period 2010-2020 in comparison to the period 2000-2009 (Figure 6). Yield remained stable in large parts of the UK, France and Germany. Decreases in yield over 10% were found amongst others in northern Finland, Denmark, Spain and Greece.

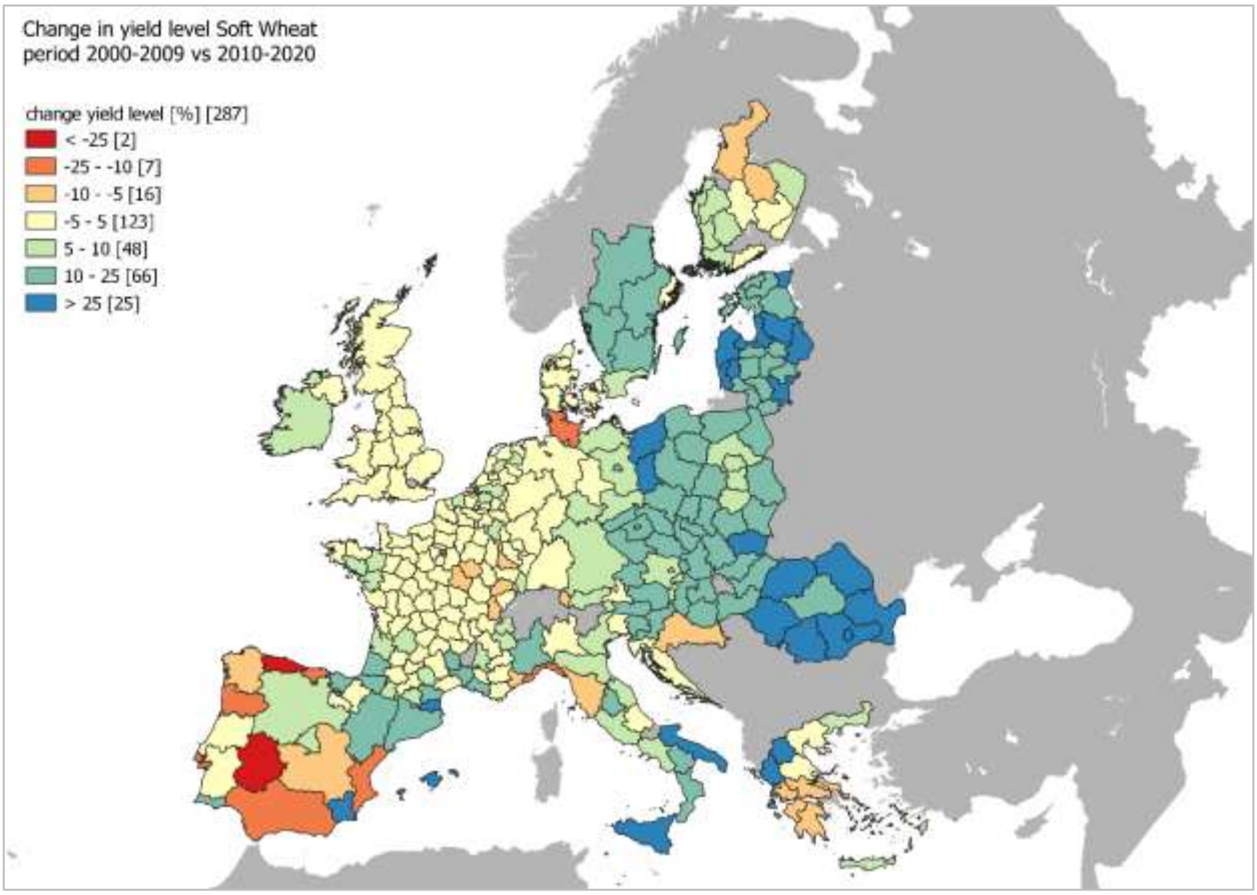


Figure 7: Relative change in yield of soft wheat (in %) in the period 2010-2020 compared to the period 2000-2009. Numbers of regions in each class indicated between [].

Management improvements are likely to have driven the higher wheat yields, especially in the CEEC where the increasing uptake of CAP payments made this possible. The large increase in yield levels in Spain, Northern Greece and southern Italy may be partly caused by an increase in irrigation area.

Changes in yield in agro- ecological zones

Changes in yield of soft wheat in the period 2010-2020 versus 2000-2009 differ between agro-ecological zones. Figure 7 shows that a relatively large share of NUTS-regions has undergone positive changes in wheat yield in the Continental, Nemoral and Pannonic-Pontic agro- ecological zones. Regions with decreases in yield of wheat to more than 10% are mostly found in the agro-ecological zones Mediterranean South and Lusitanian.

Baseline[23] yield analysis at national level

Figure 8 below provides the baseline yield trends for soft wheat (winter) for each country during the period 2000-2020 (we use country codes for brevity; these are listed for reference in an annex). The yield slope is common to all countries, and is explicitly stated in the Implementing Regulation; and all slope values considered are tabulated in a new annex in this document (Annex II). The only thing that is country-dependent is the initialisation point for the yield baseline, which, as described in Section 2.2, is calculated from the previous three years of yield data for the country-crop combination in question.

[23] Baseline yield is here referring to the technical REDII definition, as discussed in section 3.2.2.

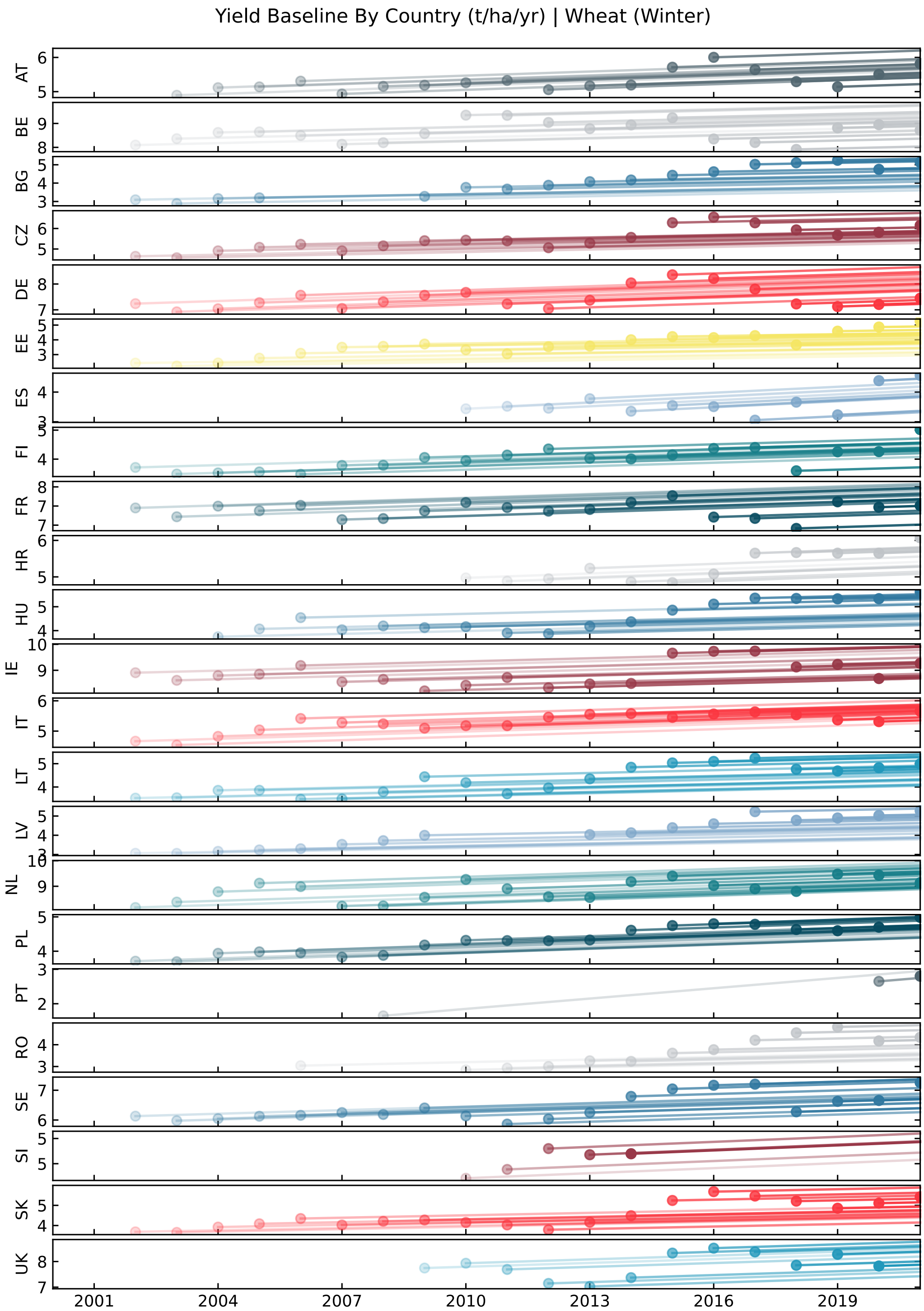


Figure 8: Baseline yield trend for calculating additional winter wheat production at the national level, for large EU countries + UK. Points indicate initial yield calculated on the previous three years' data, where available; lines are extrapolated using the FAOSTAT global average yield growth for the crop in question.

As is evident from comparing the panels in Figure 8, the exact timing of when to initialise the yield baseline can have a significant effect. Initialising right after three poor years of harvest will of course result in a lower baseline than certification that happens right after three good years, with consequences for the amount of above-baseline material that could be recognised thereafter. This figure highlights the degree of variability and shows that major benefits would accrue if it were possible to choose the right moment to initialise.

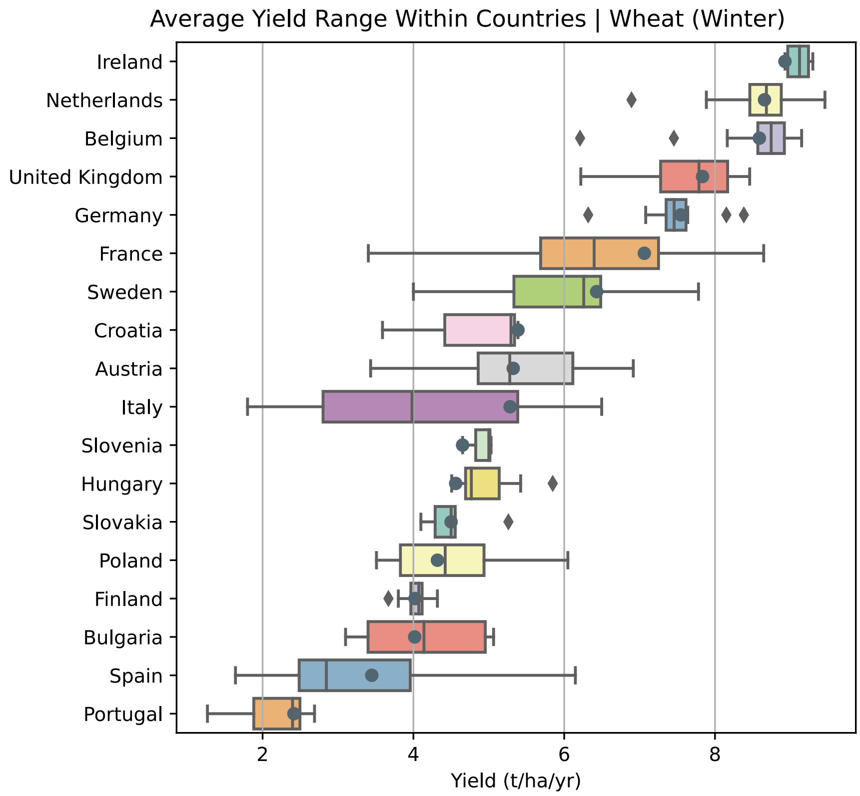
Moreover, we can identify two broad types of yield evolution: countries such as Bulgaria and Latvia have steadily increasing initialisation points, such that their yield baselines get higher each year; other countries, such as Austria and Ireland, witness more fluctuation in the baseline initialisation. Indeed, these fluctuations appear to be somewhat correlated between countries (meaning that the peaks and troughs fall roughly in the same years), suggesting that these countries ‘productivity may have been sensitive to some common weather event – for instance the European heat wave of 2006.

Average yield analysis at NUTS2 level

The national-level analysis shown above underscores how the timing of the initialisation point impacts the yield baseline, with ramifications for the amount of additional material that could be claimed under a low ILUC-risk system. We can also explore variability at more granular spatial scales (ignoring the time dimension for the moment), by comparing average yields for different districs to a single country. Districts which appear to underperform compared to their neighbours will have lower yield baselines, and there is much potential for exploring why this is the case. The figure below presents a first step in the analysis, by identifying which countries have large spreads in wheat yields – i.e. where some districts significantly outperform others in the same country.

In

Figure 9, the median of the district yields is shown as a vertical line, and the surrounding-coloured



boxes show the interquartile range. Whiskers represent the full range of district yields, with outliers shown as diamonds.

Figure 9: Box-plot of district yields in each country for winter soft wheat. Countries are sorted by national yield averaged 2000-20 (blue dots), with the highest at the top of the figure. Colours are for presentation.

Figure 9 can be read in a similar way to Figure 4, except now we consider the variation of average yields within countries for a single crop. It should primarily be thought of as a diagnostic tool, where we use the available data to identify countries with high geographical yield variability.

However, the statistics are not sufficient to *definitively* characterise country yields at the sub-national level. This is because countries have different numbers of districts, and different rates of reporting for each district: so while a low spread may indicate that yields are fairly uniform throughout the country (which is interesting), it may also indicate that the crop is grown in a small area of the country, or there is a low rate of data reporting. On the other hand, we can be more certain that a country with a high spread in yields actually has high variation in productivity among its various districts. These high-spread countries are candidates for follow-up investigation of yield gaps.

A final comment about the data used in

Figure 9, and in similar plots that we will meet for other crops. We would expect the blue dot, which shows the national average yield for each country, to be somewhere in the middle of each box plot; yet there are several cases (e.g. Ireland and Croatia) where it is observed at one extreme end of the range. This is mathematically dubious, as the average of a collection of numbers must of course lie between the two extrema; this points to limitations in the underlying dataset, where national-level values have been submitted which are not compatible with the sub-national district values. Unfortunately at this level of analysis there is little recourse to solving the issue, which anyway occurs only in a small subset of observations; and so here we simply highlight the issue and move on.

Yield slope analysis at national level

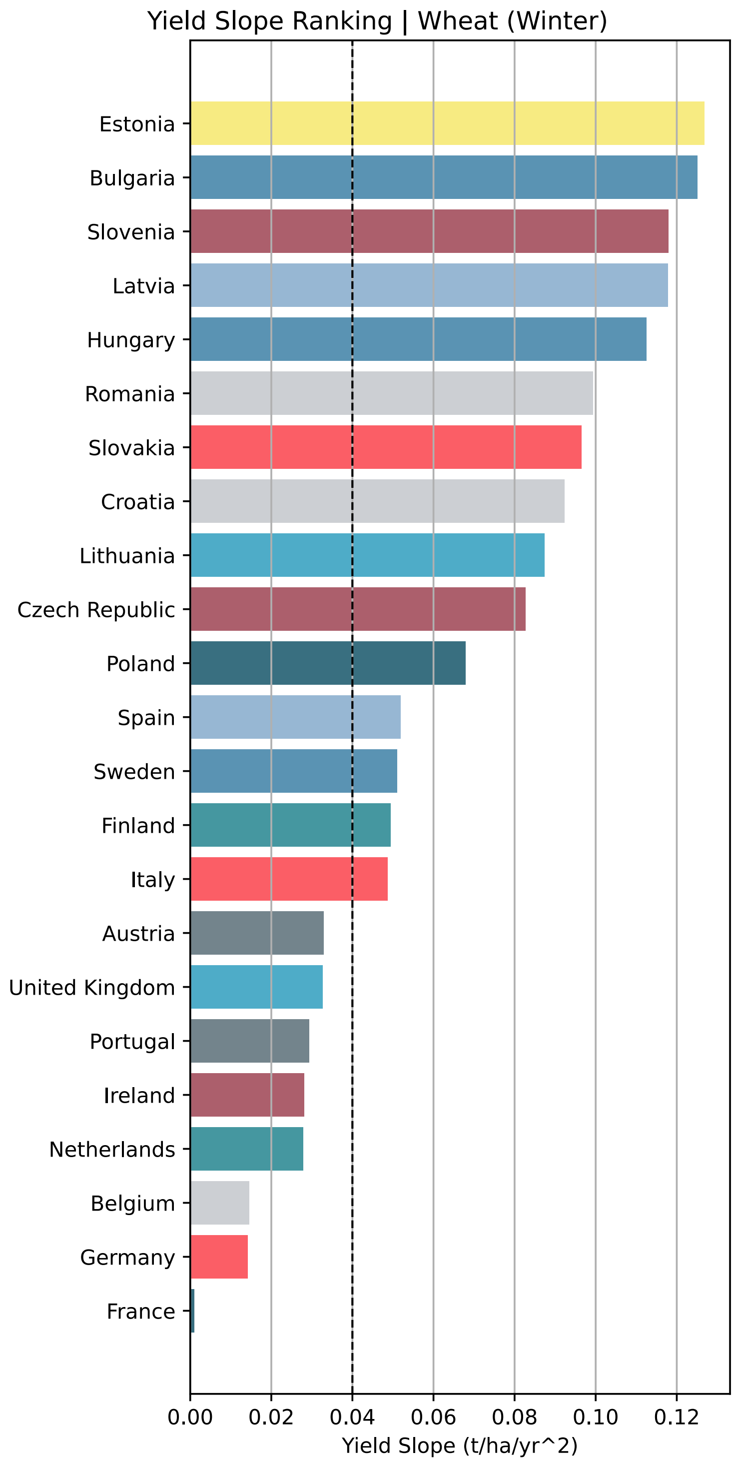


Figure 10: Country-level yield slopes for the period 2000-20 for the crop indicated. Countries are ordered according to their yield slope, with those at the top of the figure exhibiting high yield growth. The black dashed line is the FAOSTAT global average.

The two previous sections investigated how the baseline may be affected by variability in yield values – first at the national level and then at the NUTS2 level. The purpose of this section is to investigate the yield *trend* – that is, how yields are changing over time in different countries. This is quantified as the slope of the linearised yield time-series, measured in t/ha/yr2 and calculated over the period 2000-20; in plain terms, it is simply how much the yield grows on average in a given year.

The graph in Figure 10 shows the yield slope for winter wheat, for all countries with sufficient data. Countries appearing at the top of the figure have faster-growing yields than those at the bottom. The vertical dashed line indicates the FAOSTAT global average. Countries with yield slopes greater than this line may be able to produce additional biomass (as defined by REDII) with greater ease once other criteria have been satisfied. Naturally, it is possible to repeat this analysis at the NUTS2 level, but these plots have not been included.

The sections that follow repeat the analysis for different crops. Commentary will be limited to instances where there are new observations: otherwise, only the graphs will be shown.

3.2.2. Barley

Crop yield review in European regions and agro-ecological zones

The observed yields for barley between 2015-2020 show large variations between regions, with low values in practically the whole Mediterranean, central and eastern Europe and Baltics and northern Sweden. The highest yields of barley were observed in Ireland, the UK, northern France, Benelux and Germany. Also for Barley Belgium and southern Denmark have the highest levels.

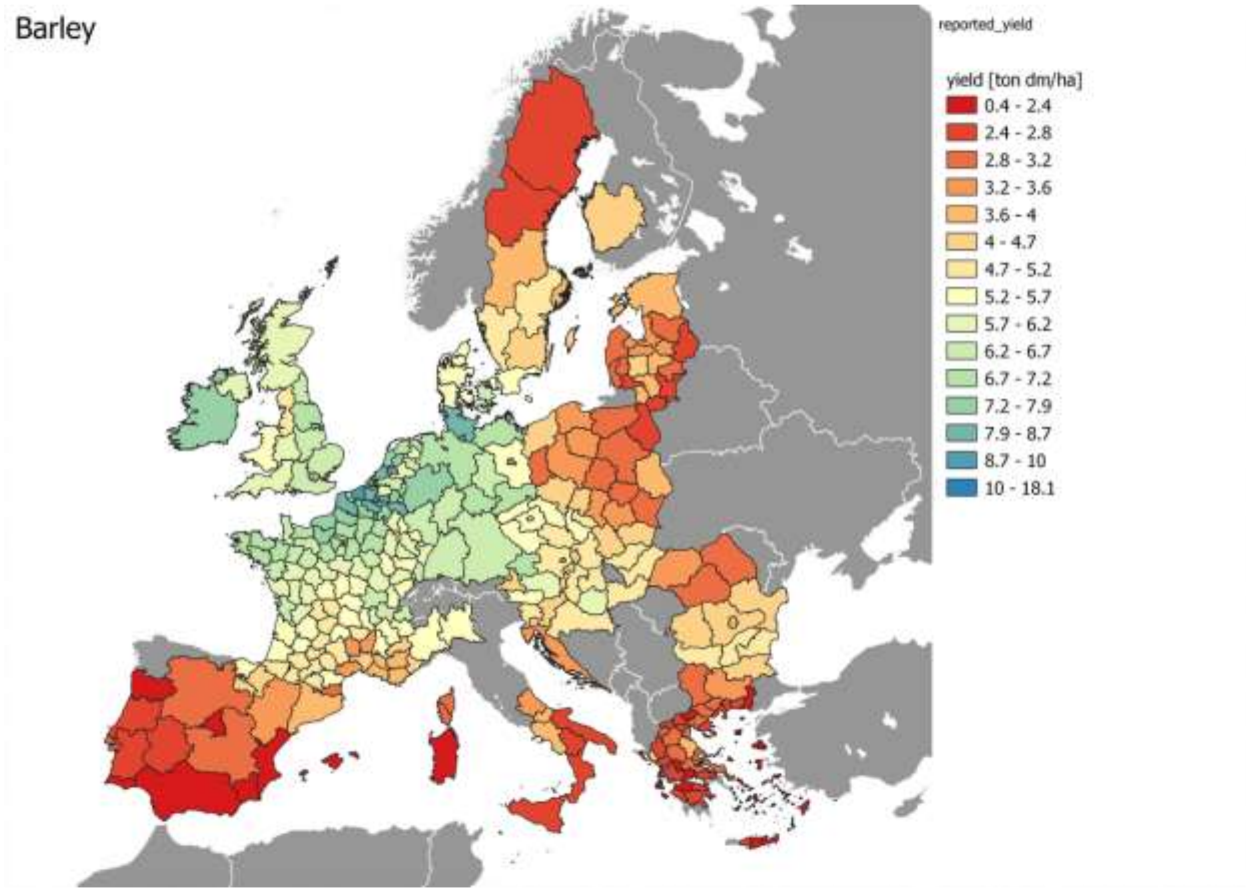


Figure 11: Observed yield (2015-2020) of barley. Source data: national statistics and regional data from Eurostat.

Observed yield 2010-2020 in agro- ecological zones

The observed average yield of barley over the period 2015-2020 in agro- ecological zones as recorded for regions at NUTS-levels 1-3 is shown in Figure 11. The highest values are found in the Atlantic agro- ecological zones (ATC and ATN), with yields up to 8.5 t/ha.y. Regions with yields in this range are found in the UK and Ireland, Denmark, the Benelux, France and the northern part of Portugal.

The lowest average yield for barley is observed in the agro- ecological zones Mediterranean South (MDS), Alpine North (ALN), Boreal (BOR) and Nemoral (NEM), with values between 2.4 and 5.7 t/ha.y. The regions with lower values of barley yields are in the Scandinavian and Baltic countries, Spain, Italy and Greece. Standard deviations are between 0.4 (for zone PAN) and 1.5 (for zones LUS and CON) indicating towards the largest yield differences occuring in this AEZ.

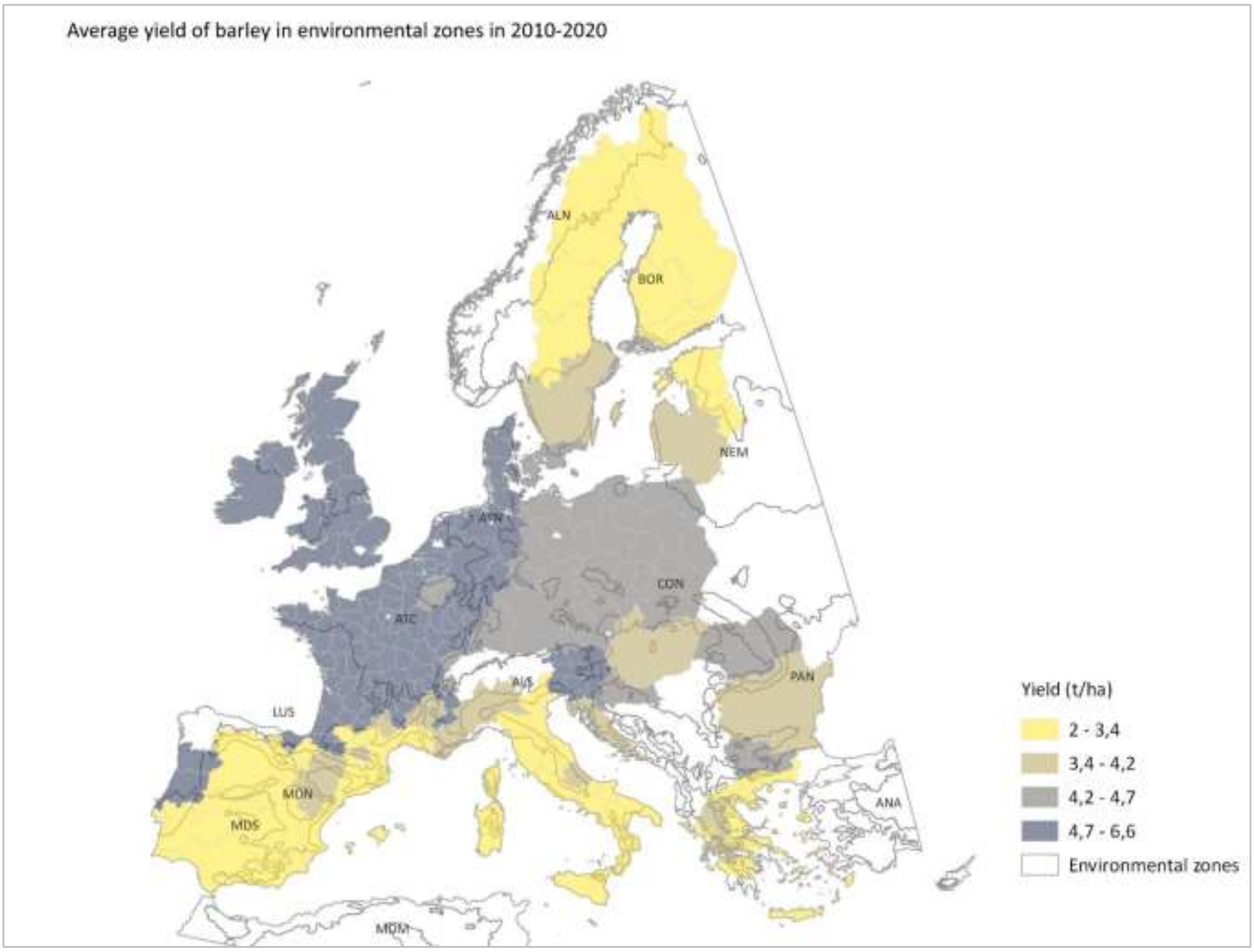


Figure 12: Observed yield (2010-2020) of barley in agro- ecological zones in Europe. Source data: observations for 312 regions from national statistics and regional data from Eurostat.

Changes in yield 2000-2009 versus 2010-2020

In the period 2010-2020 large increases in yield of barley (>25%) were found compared to the period 2000-2009 in statistics for Central- and Eastern-European countries, and moderate increases (5-25%) in Ireland, Germany, The Netherlands, regions in Spain and France and Sweden and Finland. Only a few regions in Portugal, Spain and Greece and France showed negative changes in yield. The region with a -30% change in yield of barley in Denmark showed a decrease in average yield from 5.4 to 7.7 t/ha.y between the periods.

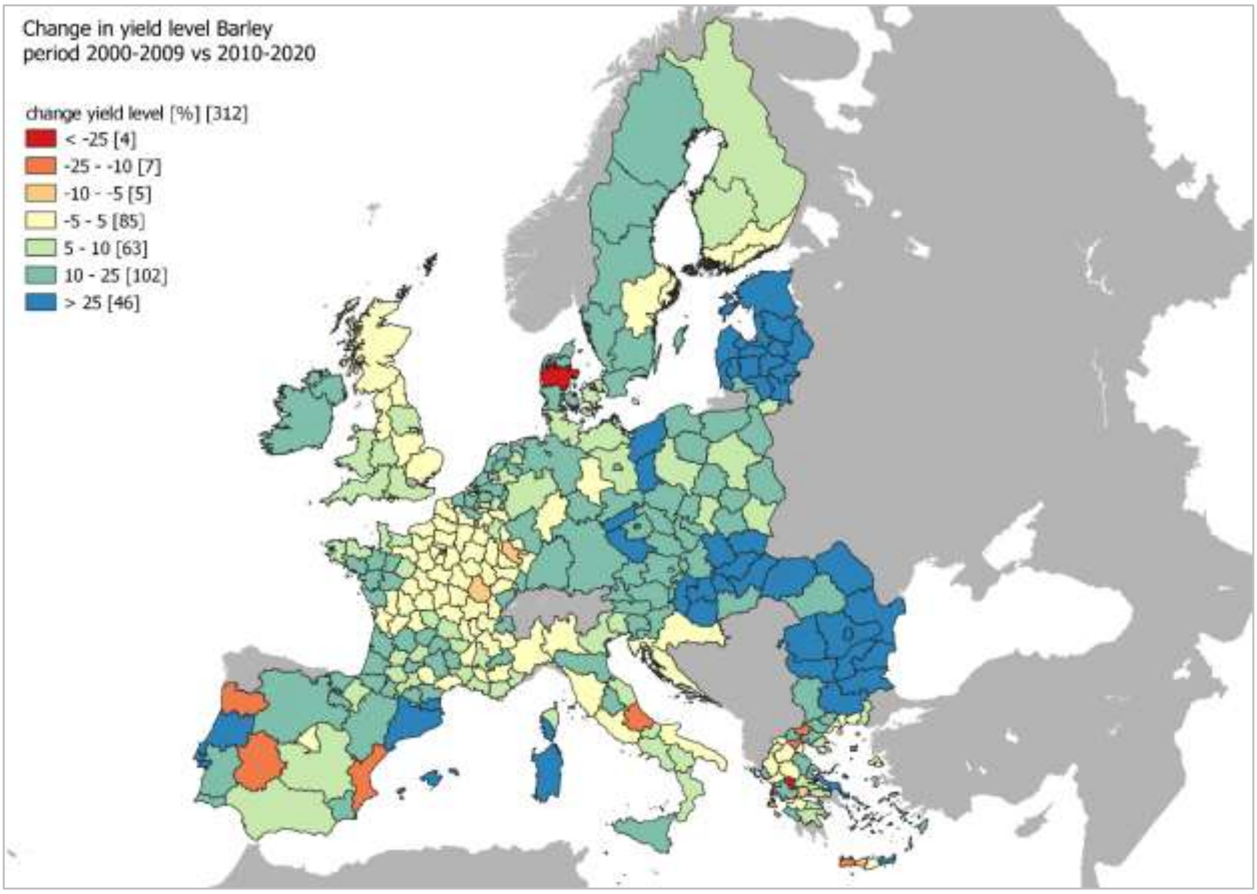


Figure 13: Change in yield of barley (in %) in the period 2010-2020 compared to the period 2000-2009. Numbers of regions in each class indicated between [].

Like with soft wheat, management improvements are likely to have driven the higher wheat yields increases in the CEEC where the CAP payments made improvements in management possible since entry in the EC as of 2000 onwards. The large increae in yield levels in certain regions in Spain, Portugal, Italy and Greece while at the same time also having regions where yields strongly decline may be related to increases in irrigation area in a selection of regions.

Changes in yield in agro- ecological zones

Most regions - relative to the total number of regions considered - with increases in yield of barley >10% in the period 2010-2020 compared to the period 2000-2009 are found in the Pannonic-Pontic agro- ecological zone (all 18 regions), the Nemoral, Continental and Alpine South agro-ecological zones. Regions where the yield of barley decreased by more than 10% are mostly seen in the zones Mediterranean South and Mediterranean mountains.

Baseline yield analysis at national level

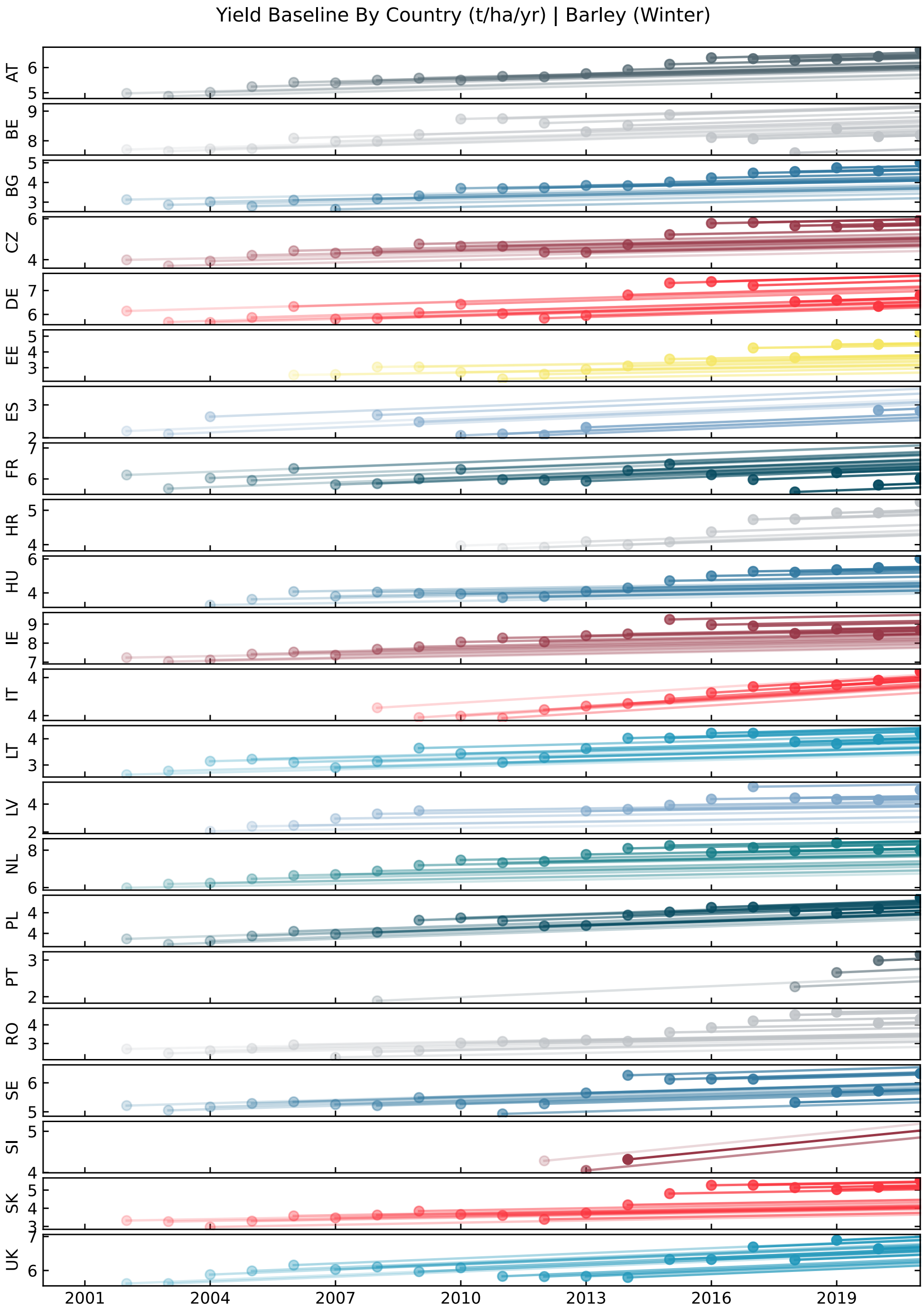


Figure 14: Baseline yield trend for calculating additional barley production at the national level, for large EU countries + UK. Points indicate initial yield calculated on the previous three years' data, where available; lines are extrapolated using the FAOSTAT global average yield growth for the crop in question.

Average yield analysis at NUTS2 level

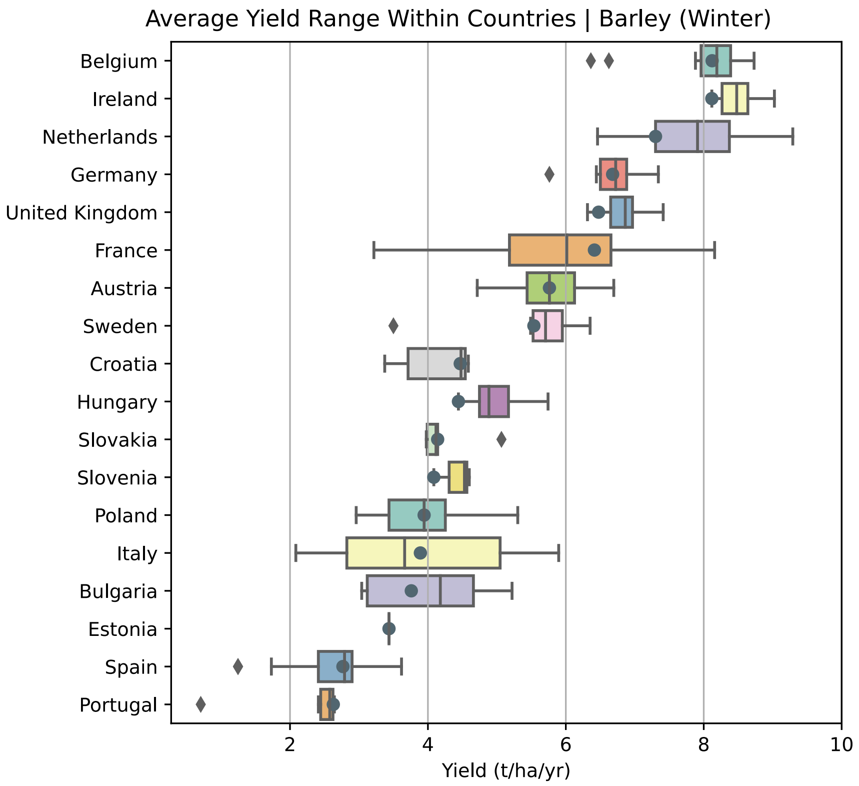


Figure 15: Box-plot of district yields in each country for winter barley Countries are sorted by national yield averaged 2000-20 (blue dots), with the highest at the top of the figure.

Yield slope analysis at national level

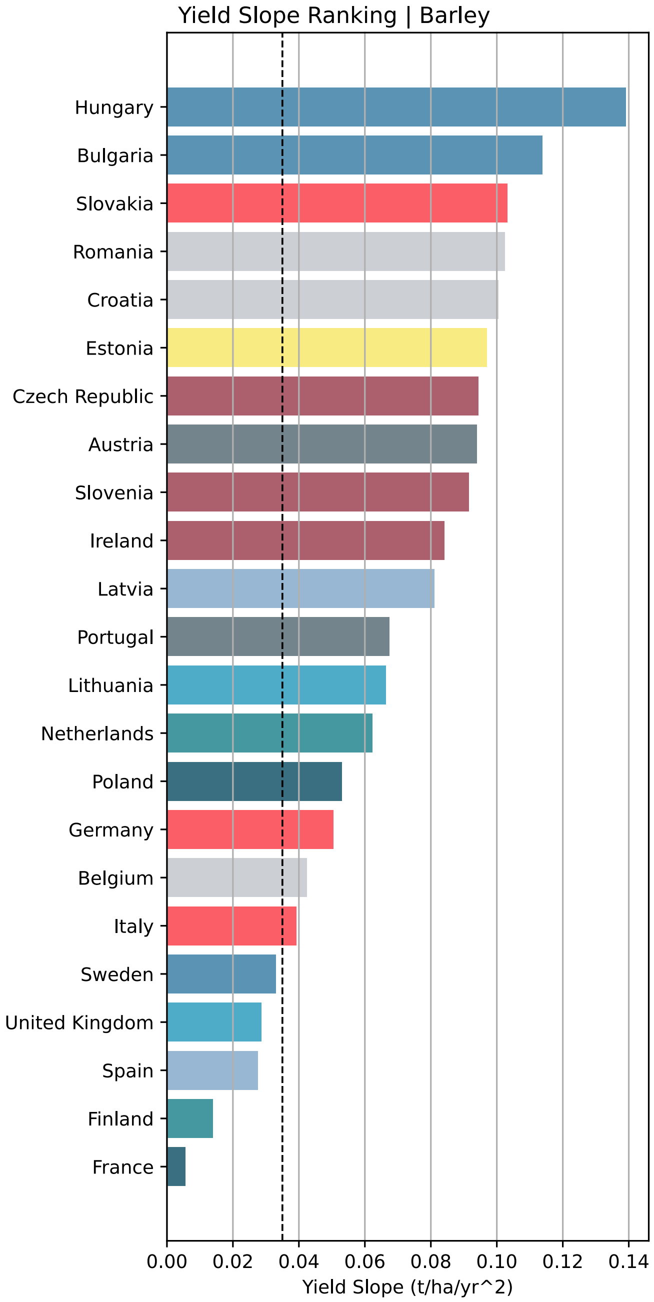


Figure 16: Country-level yield slopes for the period 2000-20 for the crop indicated. Countries are ordered according to their yield slope, with those at the top of the figure exhibiting high yield growth. The black dashed line is the FAOSTAT global average.

3.2.3. Grain maize

Crop yield review in European regions and agro-ecological zones

The observed yields of grain maize between 2015 and 2020 showed large variations over Europe (Figure 17). The high values in southern Mediterranean countries can be explained by the application of irrigation. Distribution of the crop shows a climatological limit; no observations were found for countries in northern Europe, except for The Netherlands. Maize is a tropical (C4 carbon fixation) crop and needs relatively high temperature and a sufficiently long growing season, hence the Atlantic central and Continental zones determine the climatological boundary. In regions with high summer temperatures, like in the Mediterranean and Continental zones, can produce very high yields, provided the crop obtains enough water.

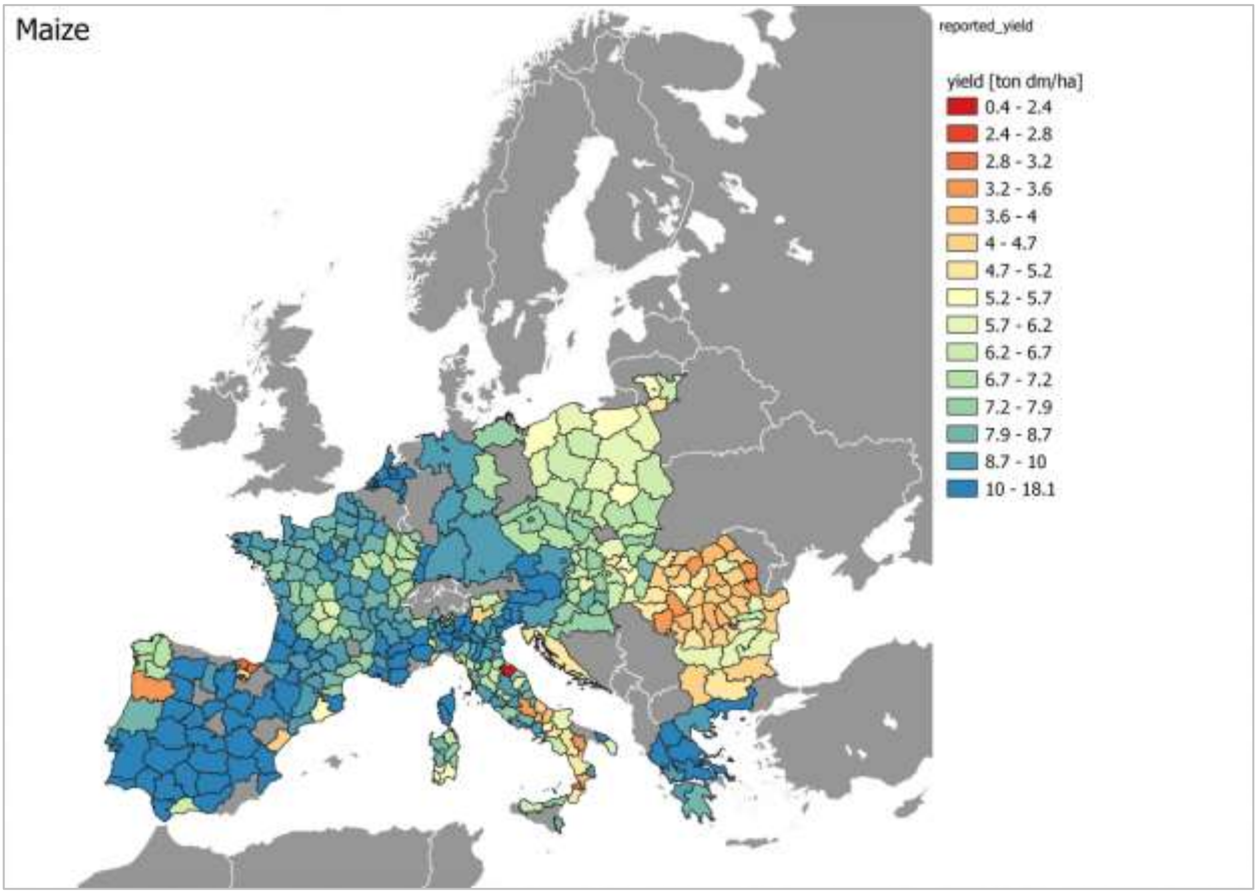


Figure 17: Observed yield (2015-2020) of grain maize. Source data: national statistics and regional data from Eurostat.

Observed yield 2010-2020 in agro- ecological zones

The observed average yield of grain maize over the period 2010-2020 in agro- ecological zones as recorded for regions at NUTS1-3 levels is shown in Figure 17. The highest values (>9 t/ha.y) are found in the agro- ecological zones Atlantic North (ATN). The high values (7-9 t/ha.y) in the Mediterranean agro- ecological zones, observed in Spain, France, Italy and Greece, are surprising because water stress may reduce maize growth and yield. The high yields can be explained by high irrigation levels for grain maize in these southern regions.

Regions with low baseline yields for grain maize (<6 t/ha.y) are found in the Pannonic-Pontic, Nemoral (NEM) and continental agro- ecological zones (resp. 5.4 t/ha.y, 6.0 and 6.4 t/ha.y on average for the regions in these zones).

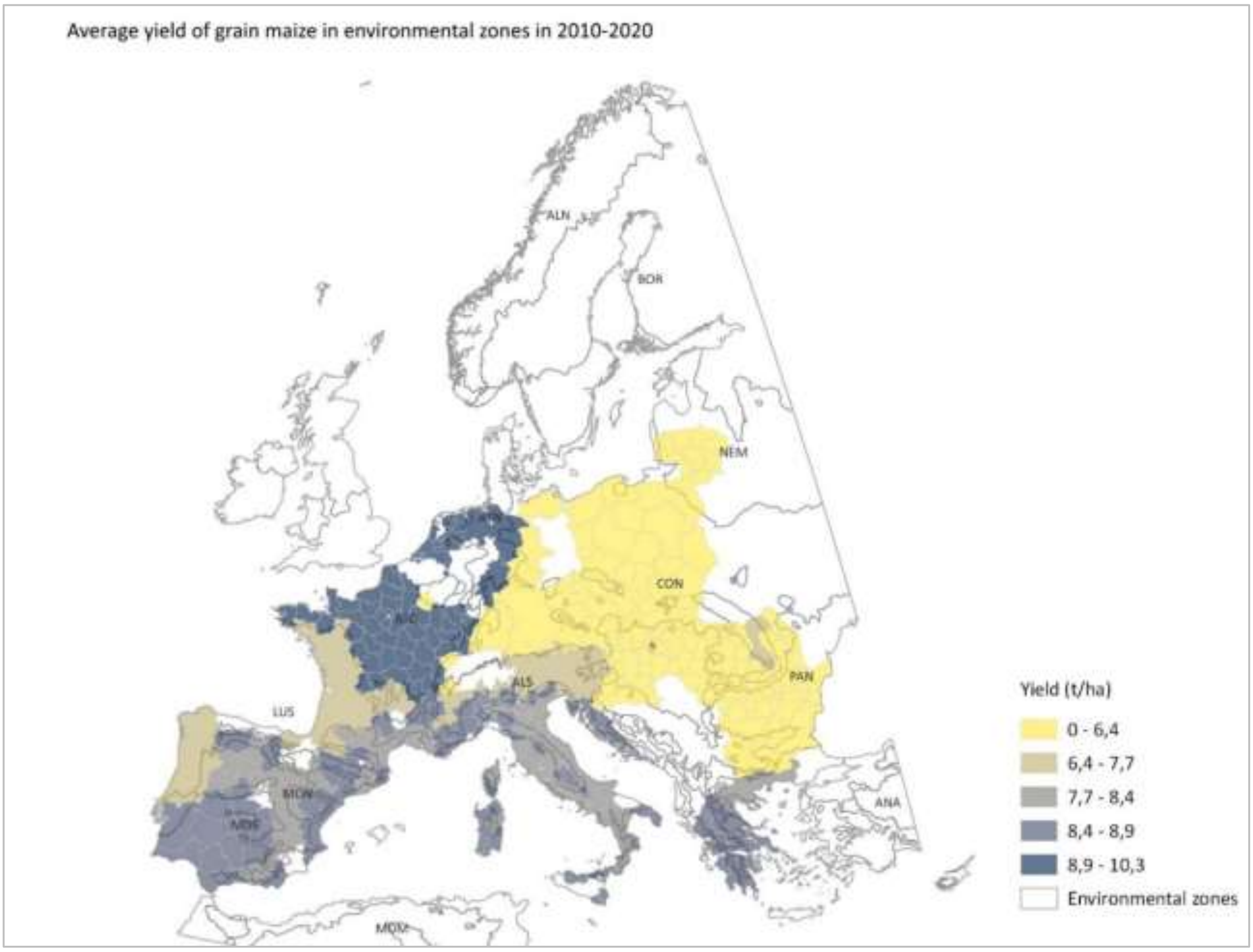


Figure 18: Observed yield (2010-2020) of grain maize in agro- ecological zones in Europe. Source data: observations for 389 regions from national statistics and regional data from Eurostat.

Changes in yield 2000-2009 versus 2010-2020

Increases in the yield of grain maize to more than 25% in the period 2010-2020 compared to 2000-2009 were observed in Bulgaria, Romania, Hungary, Lithuania and in Portugal and Spain. Large decreases in the yield of grain maize (>25%) were only observed for a few regions, mostly located in Italy.

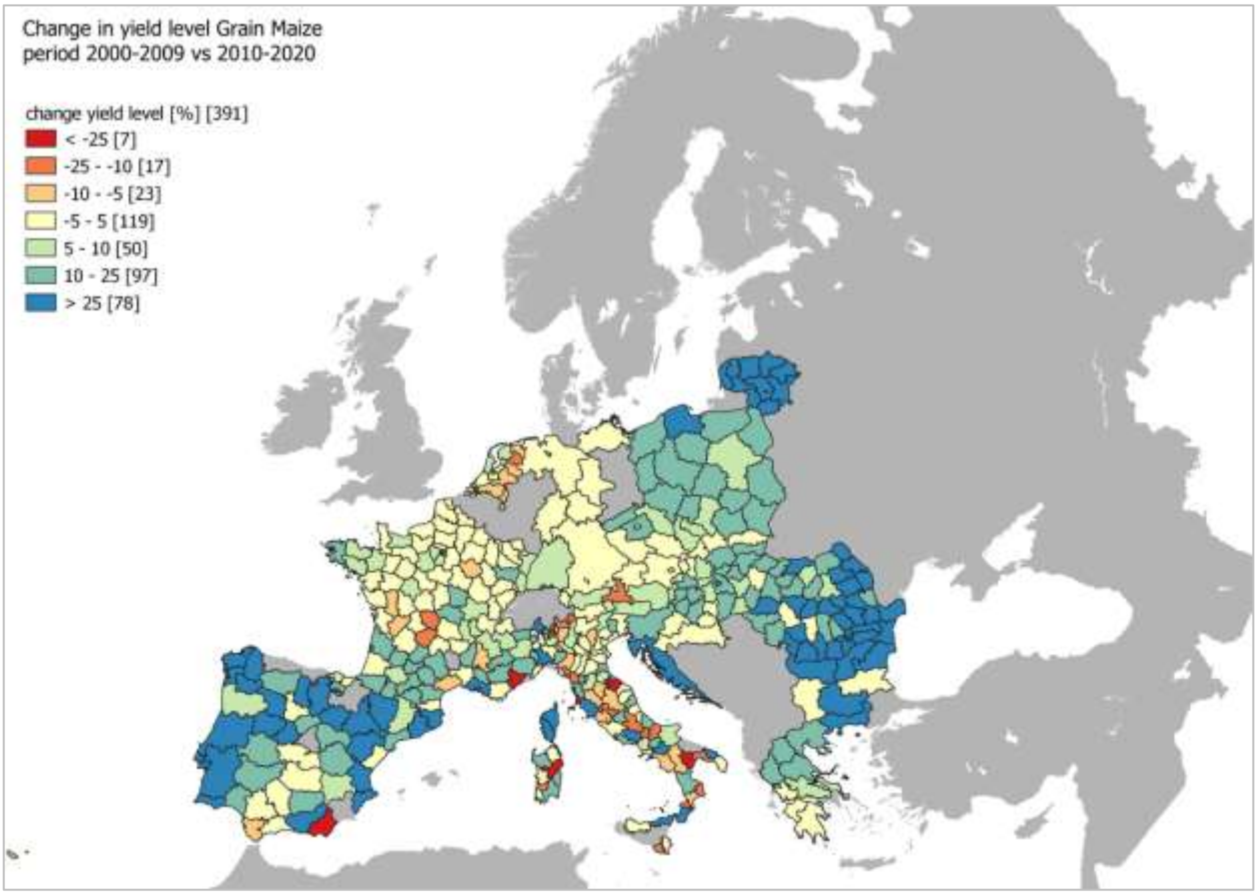


Figure 19: Change in yield of grain maize (in %) in the period 2010-2020 compared to the period 2000-2009. Numbers of regions in each class indicated between [].

Like for the soft wheat and barley, large yield increases are likely to be related to improved management and increases in irrigation area.

Changes in yield in agro- ecological zones

More than 50% of the regions (152 in total) in agro- ecological zones Pannonic-Pontic, Continental and Mediterranean mountains were characterized by increases of more than 10% in the yield of grain maize in the period 2010-2020 compared to 2000-2009. For the Nemoral zone this was also the case, but in this zone yields of grain maize were reported for only 10 regions. There are fewer regions with negative changes in yield (19 in total). These are located in the Mediterranean and Atlantic zones.

Baseline yield analysis at national level

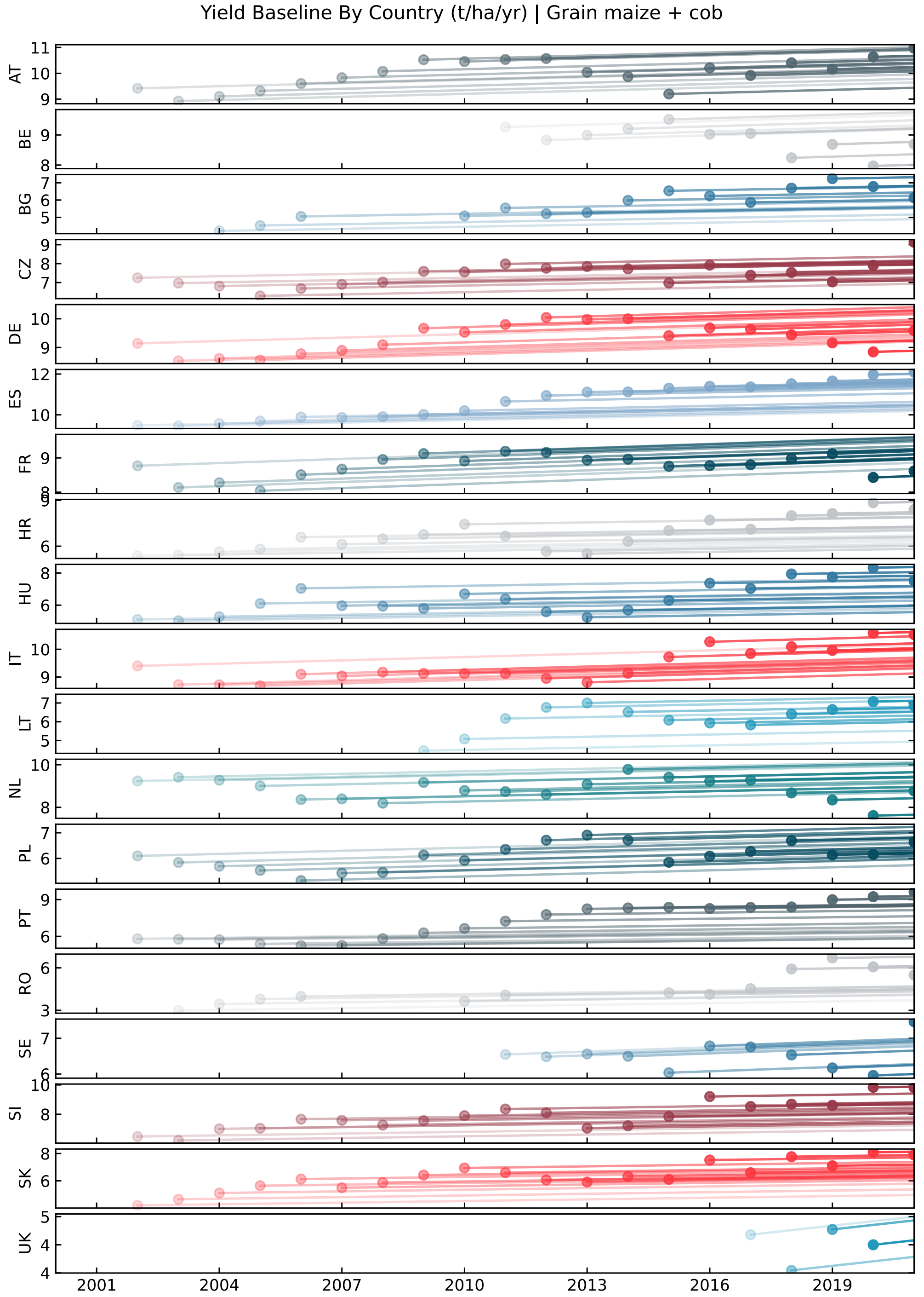


Figure 20: Baseline yield trend for calculating additional grain maize production at the national level, for large EU countries + UK. Points indicate initial yield calculated on the previous three years' data, where available; lines are extrapolated using the FAOSTAT global average yield growth for the crop in question.

Average yield analysis at NUTS2 level

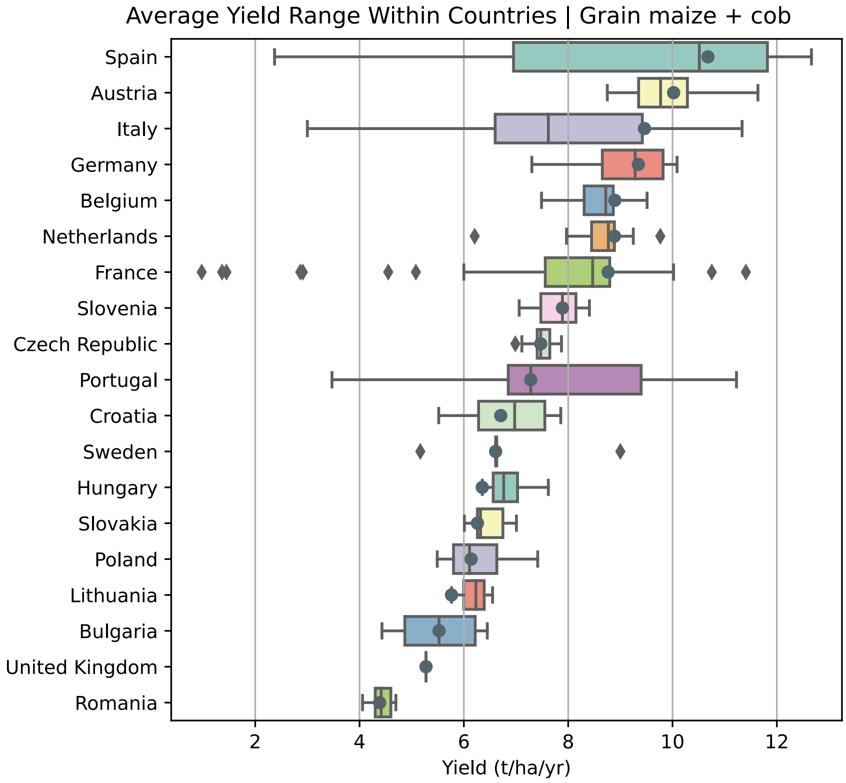


Figure 21: Box-plot of district yields in each country for grain maize. Countries are sorted by national yield averaged 2000-20 (blue dots), with the highest at the top of the figure.

Yield slope analysis at national level

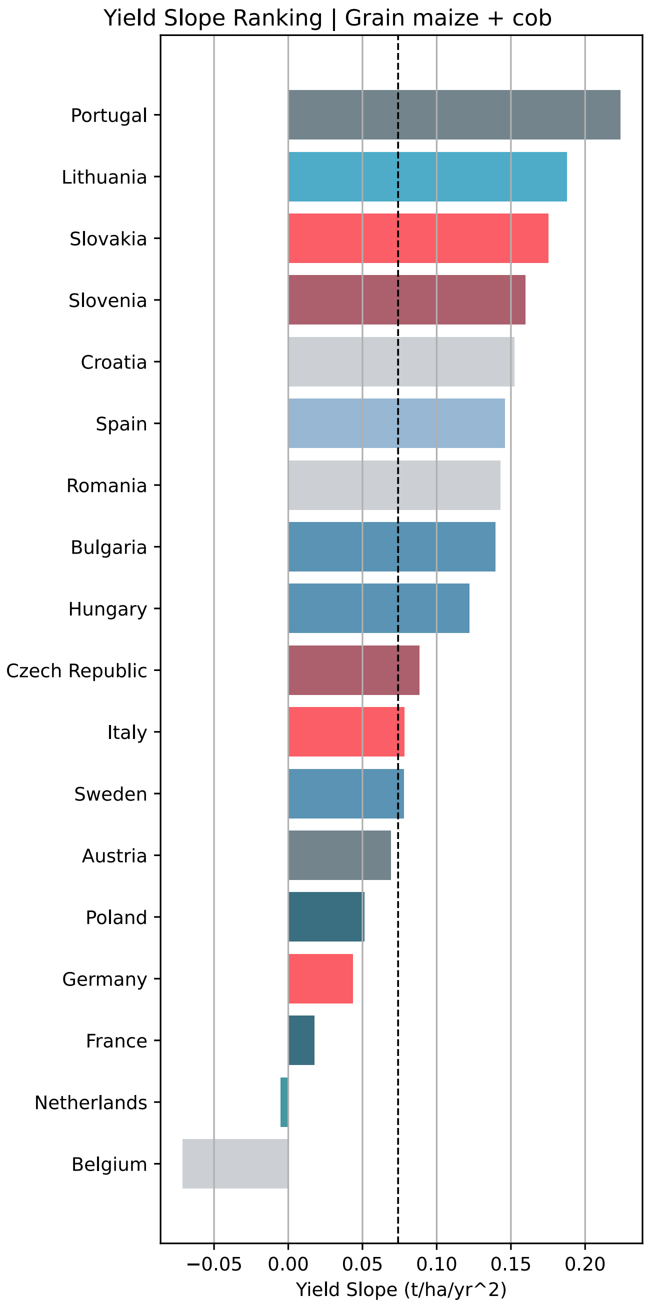


Figure 22: Country-level yield slopes for the period 2000-20 for the crop indicated. Countries are ordered according to their yield slope, with those at the top of the figure exhibiting high yield growth. The black dashed line is the FAOSTAT global average.

3.3. Oil crops

Today, lipids are needed to produce biobased substitutes in the hard-to-abate transport sectors of heavy duty, maritime, and aviation, namely, hydrotreated vegetable oil (HVO), the biobased hydrocarbon fuel substituting diesel, and hydrotreated esters and fatty acid (HEFA), the biobased jet fuel. Until 2030–2035 is it estimated the HEFA will be the dominant type of renewable jet fuel, whereas lignocellulosic biofuels and eFuels will emerge at large scale only afterwards.

Rapeseed is already used to produce biodiesel, and there is also interest from the chemical industry for the use of rapeseed HEAR to produce ‘green’ chemicals. Rapeseed is also considered an effective break crop in cereal rotation because it results in higher-yielding cereal crops and weed control.

Sunflower is a well-established oilseed crop for food, feed, lubricants, pharmaceuticals, biofuels and cosmetics in the Mediterranean agroecological zone.

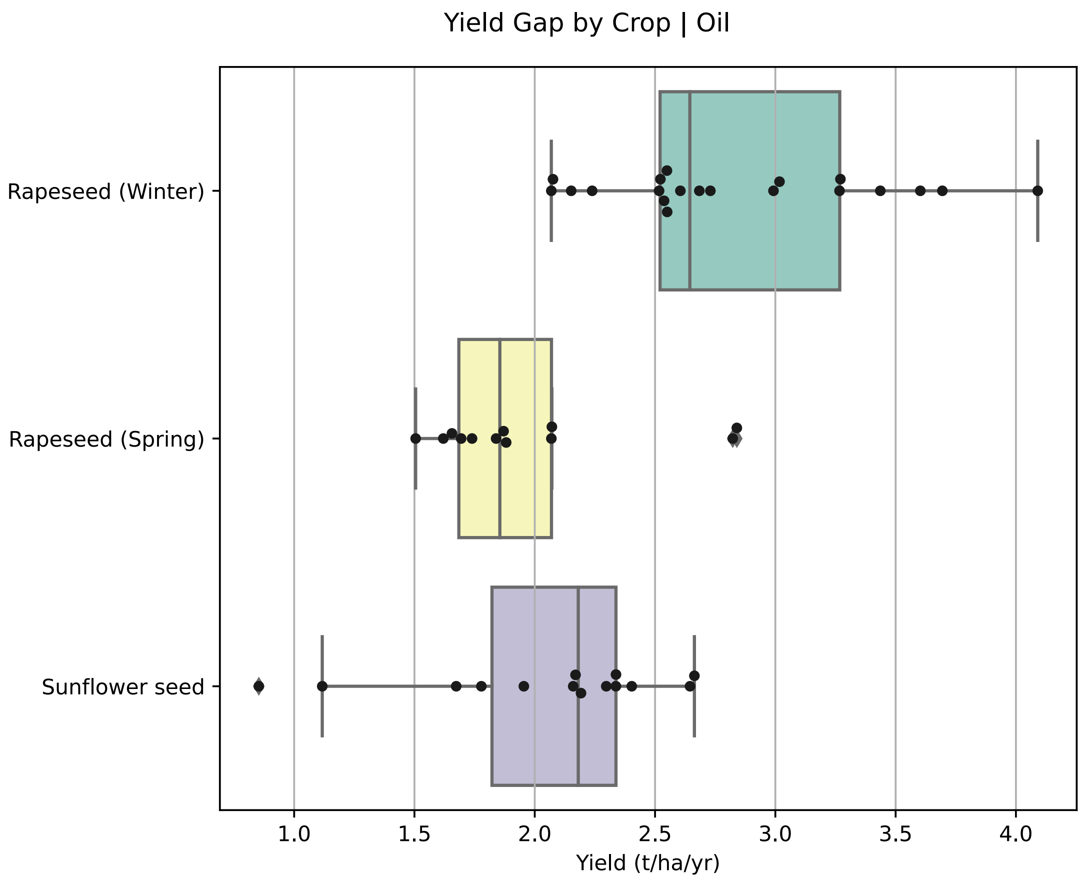


Figure 23: Average yields for oil crops In EU27 and UK over 2000-2020.

3.3.1. Rapeseed

Crop yield review in European regions and agro-ecological zones

Observed yields of oilseed rape in the period 2015-2020 were largest in north western Europe, with values up to 4.2 t/ha. The lowest values were observed in the southern and eastern Mediterranean countries (<2 t/ha).

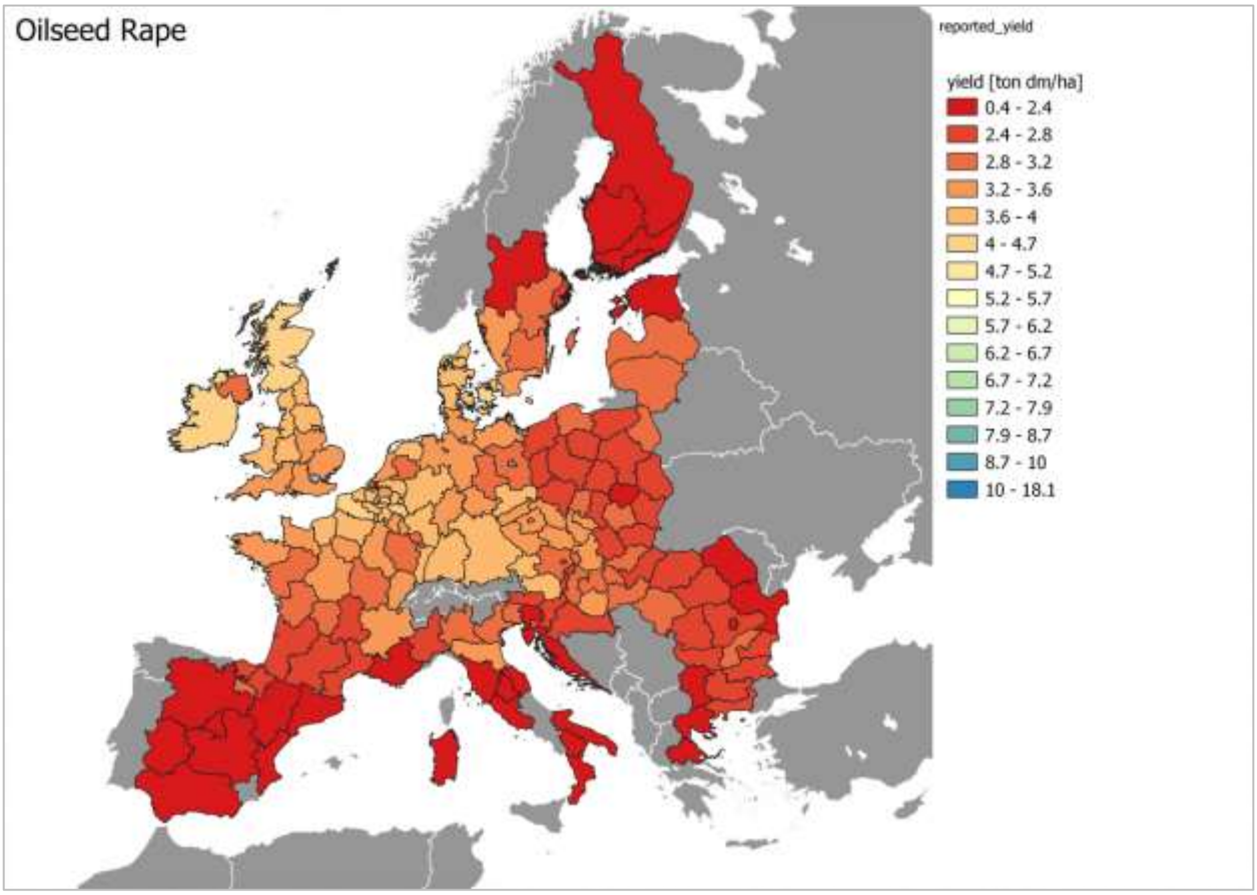


Figure 24: Observed yield (2015-2020) of oilseed rape. Source data: national statistics and regional data from Eurostat.

Observed yield 2010-2020 in agro- ecological zones

Observed yields of oilseed rape in the period 2010-2020 are highest in the Atlantic agro- ecological zones, with values up to 4.1 t/ha.y (note that the figure displays average yield per sone). The lowest yields were recorded in the Boreal and zone and Mediterranean South, with values down to 0.9 t/ha.y.

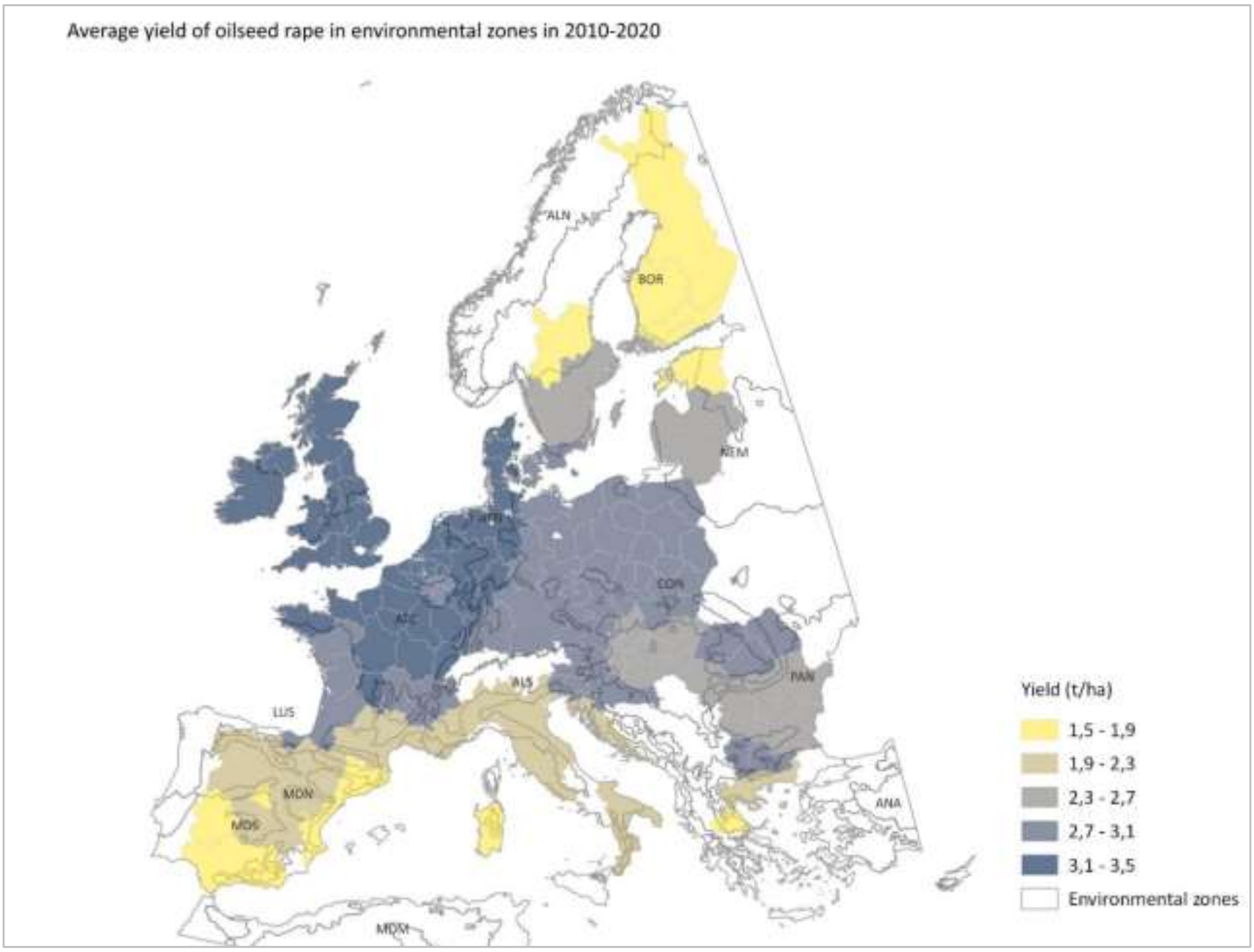


Figure 25: Observed yield (2010-2020) of oilseed rape in agro- ecological zones in Europe. Source data: observations for 166 regions from national statistics and regional data from Eurostat.

Changes in yield 2000-20009 versus 2010-2020

The yield of oilseed rape increased by more than 10% in 88 regions spread over Europe, with increased over 25% observed in Spain, Italy, central and eastern European countries and Belgium. Decreases in yield of more than 10% were observed in only 9 regions out of the 166.

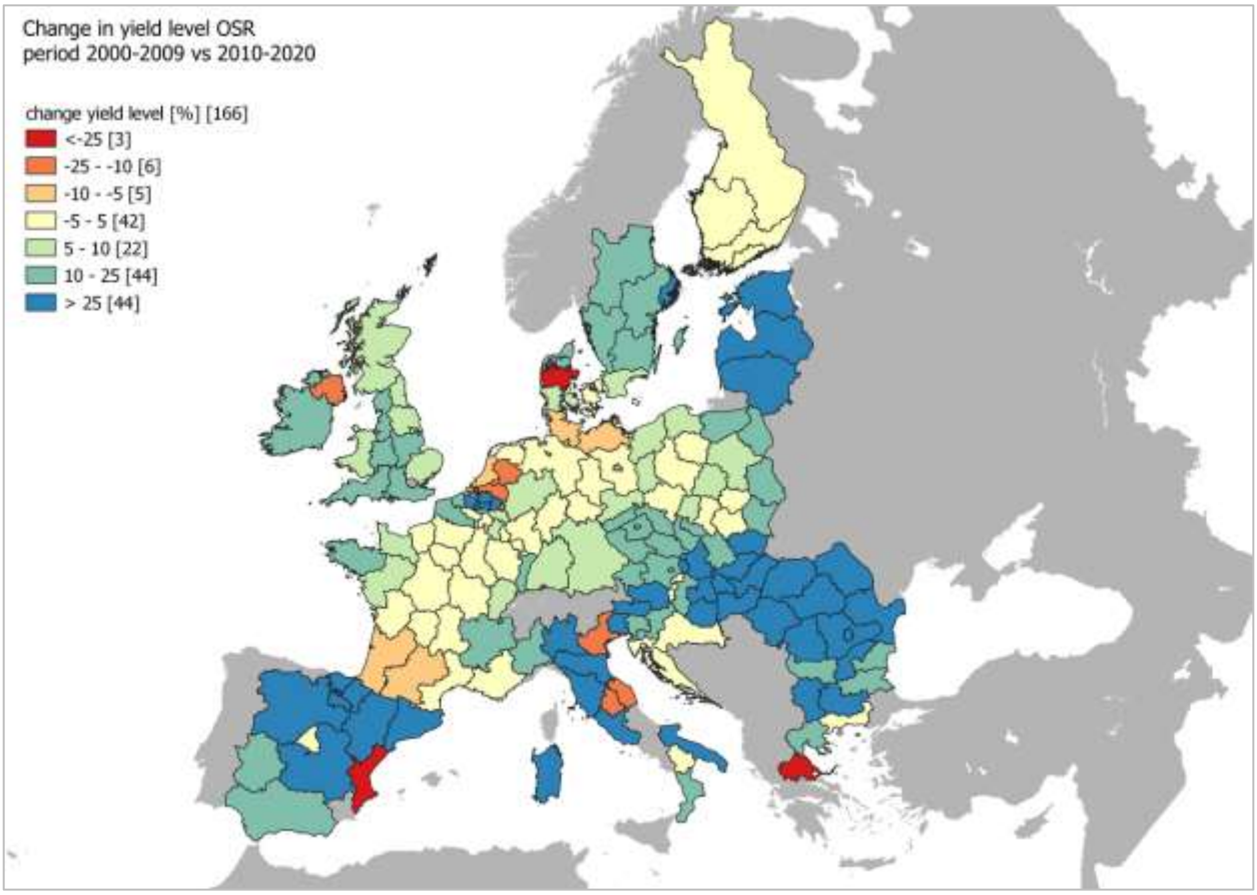


Figure 26: Relative change in yield of oilseed rape (in %) in the period 2010-2020 compared to the period 2000-2009. Numbers of regions in each class indicated between [].

Changes in yield in agro- ecological zones

Most regions with increases in yield of oilseed rape to more than 10% between 2010-2020 compared to 2000-2009 are located in the Pannonic-Pontic agro- ecological zone, relative to total numbers of regions (19 out of 20 regions with observations). In absolute numbers, most regions with increases >10% are in the Continental agro- ecological zone (21 regions out of 47). In only 9 regions, the yield of oilseed rape has decreased by more than 10% between the periods. These are located in the Mediterranean and Atlantic North zones.

Baseline yield analysis at national level

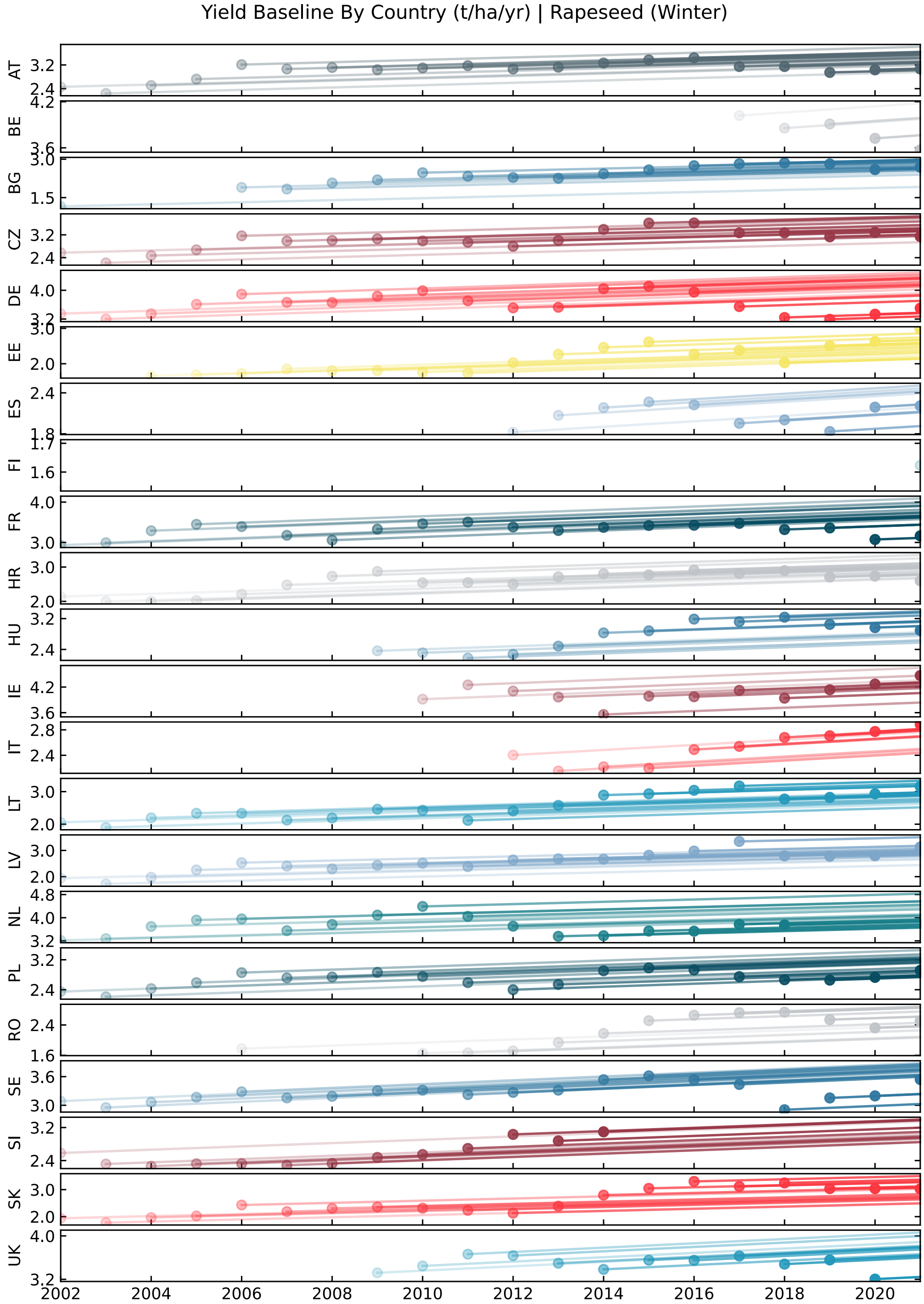


Figure 27: Baseline yield trend for calculating additional winter rapeseed production at the national level, for large EU countries + UK. Points indicate initial yield calculated on the previous three years' data, where available; lines are extrapolated using the FAOSTAT global average yield growth for the crop in question.

Average yield analysis at NUTS2 level

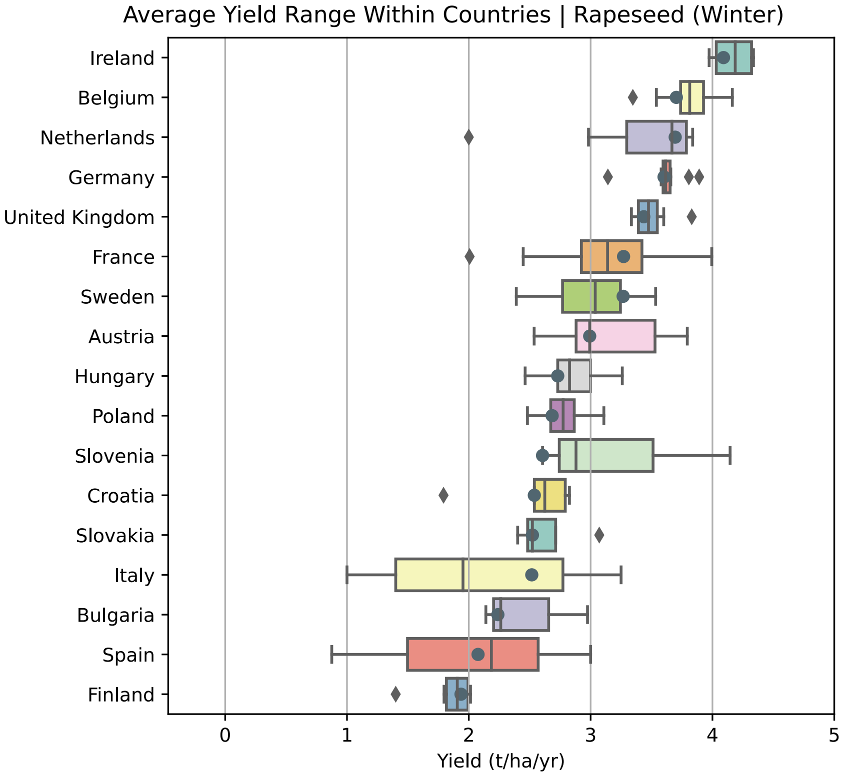


Figure 28: Box-plot of district yields in each country for winter rapeseed. Countries are sorted by national yield averaged 2000-20 (blue dots), with the highest at the top of the figure. The median of the district yields is shown as a vertical line, and the surround

Yield slope analysis at national level

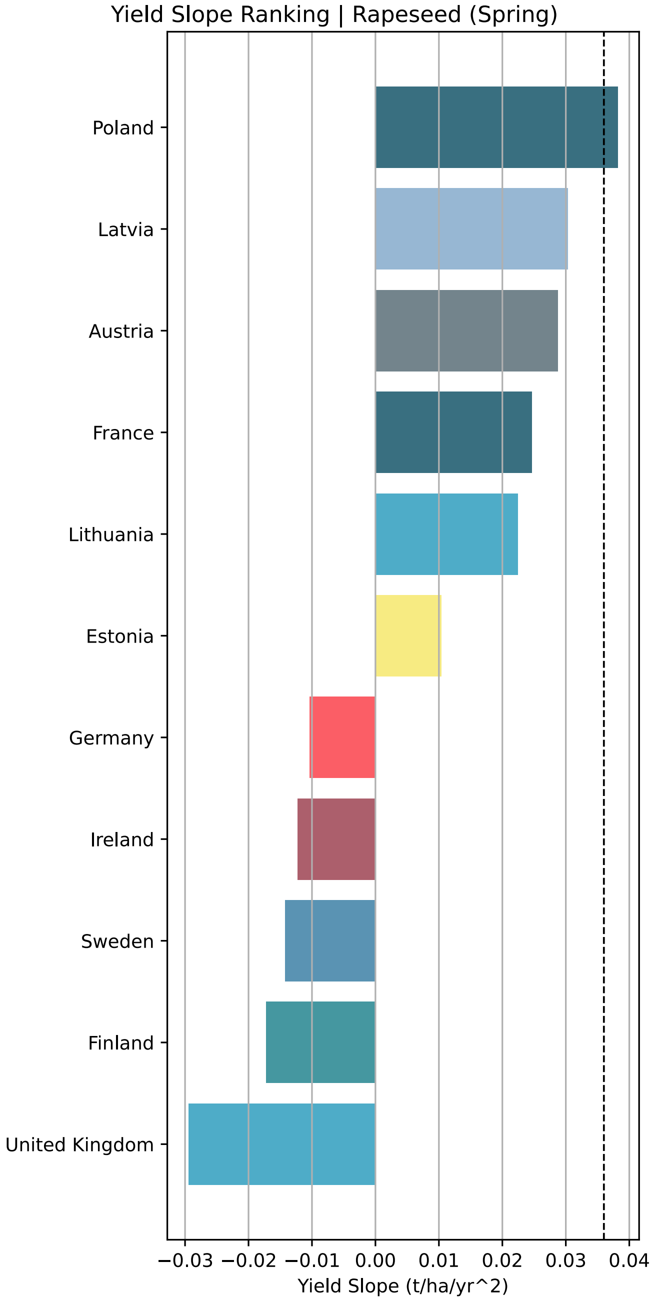


Figure 29: Country-level yield slopes for the period 2000-20 for the crop indicated. Countries are ordered according to their yield slope, with those at the top of the figure exhibiting high yield growth. The black dashed line is the FAOSTAT global average.

3.3.2. Sunflower

Baseline yield analysis at national level

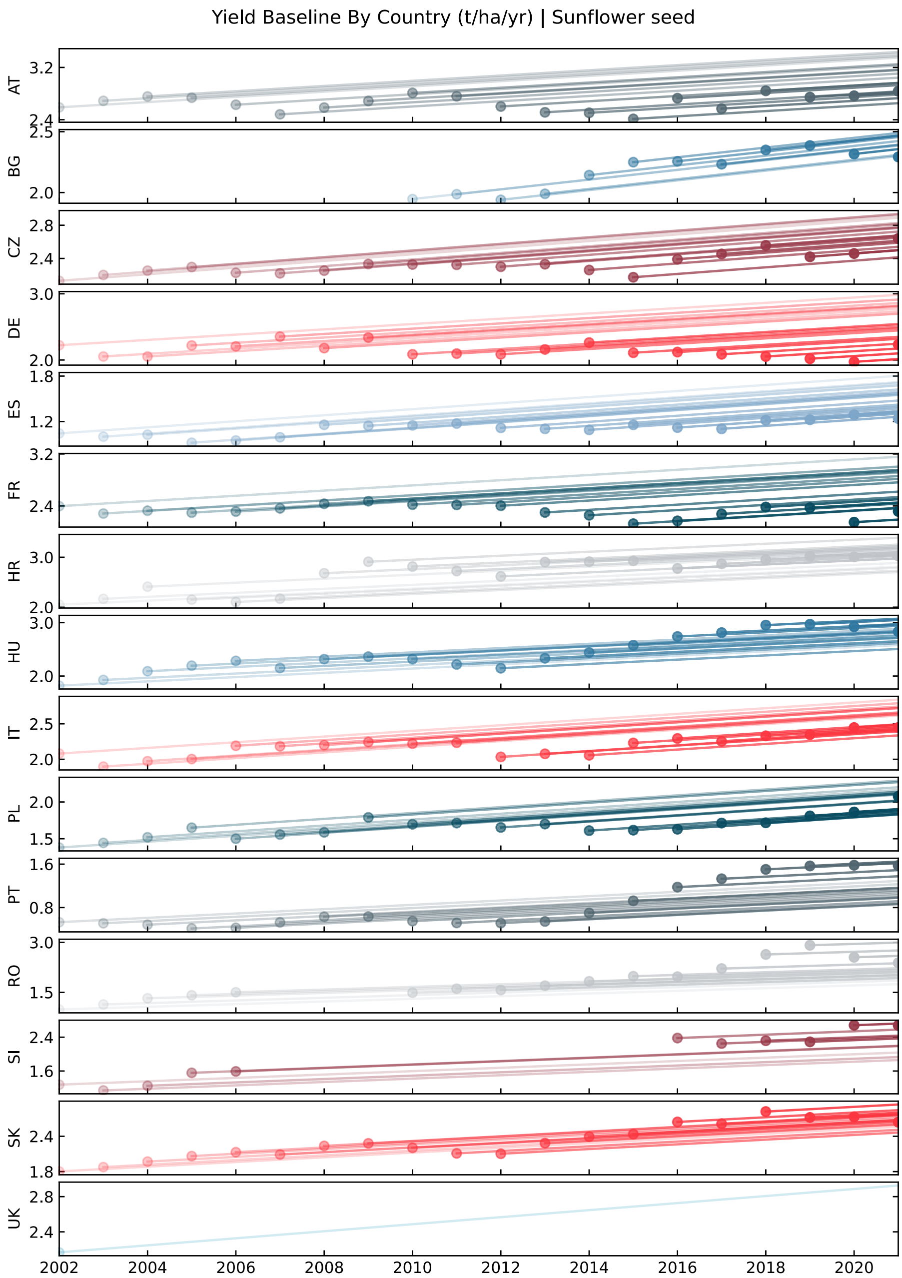


Figure 30: Baseline yield trend for calculating additional sunflower production at the national level, for large EU countries + UK. Points indicate initial yield calculated on the previous three years' data, where available; lines are extrapolated using the FAOSTAT global average yield growth for the crop in question.

Average yield analysis at NUTS2 level

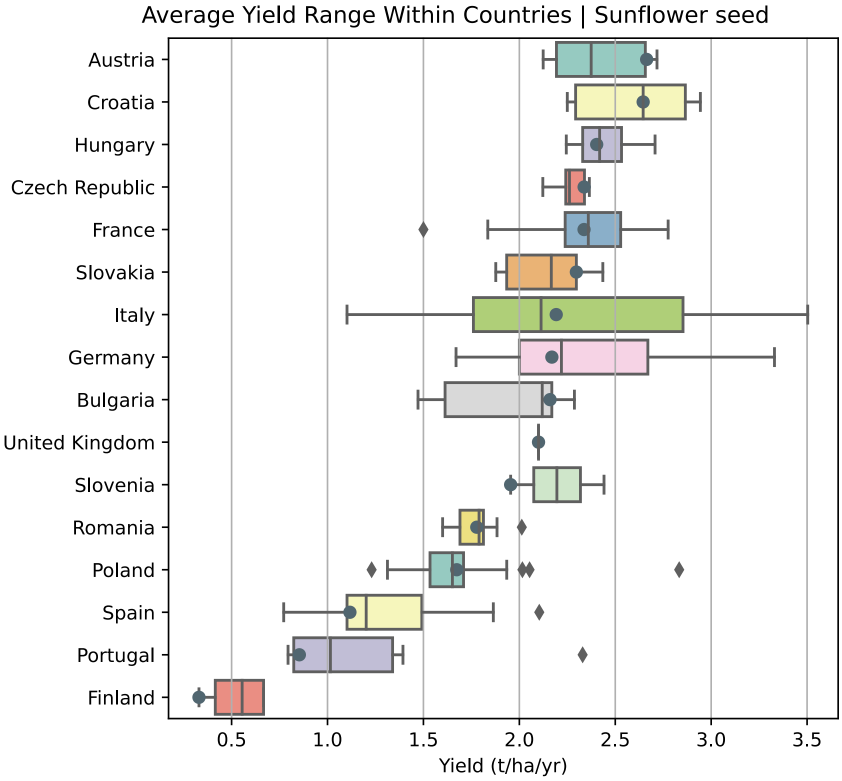


Figure 31: Box-plot of district yields in each country for sunflower. Countries are sorted by national yield averaged 2000-20 (blue dots), with the highest at the top of the figure.

Yield slope analysis at national level

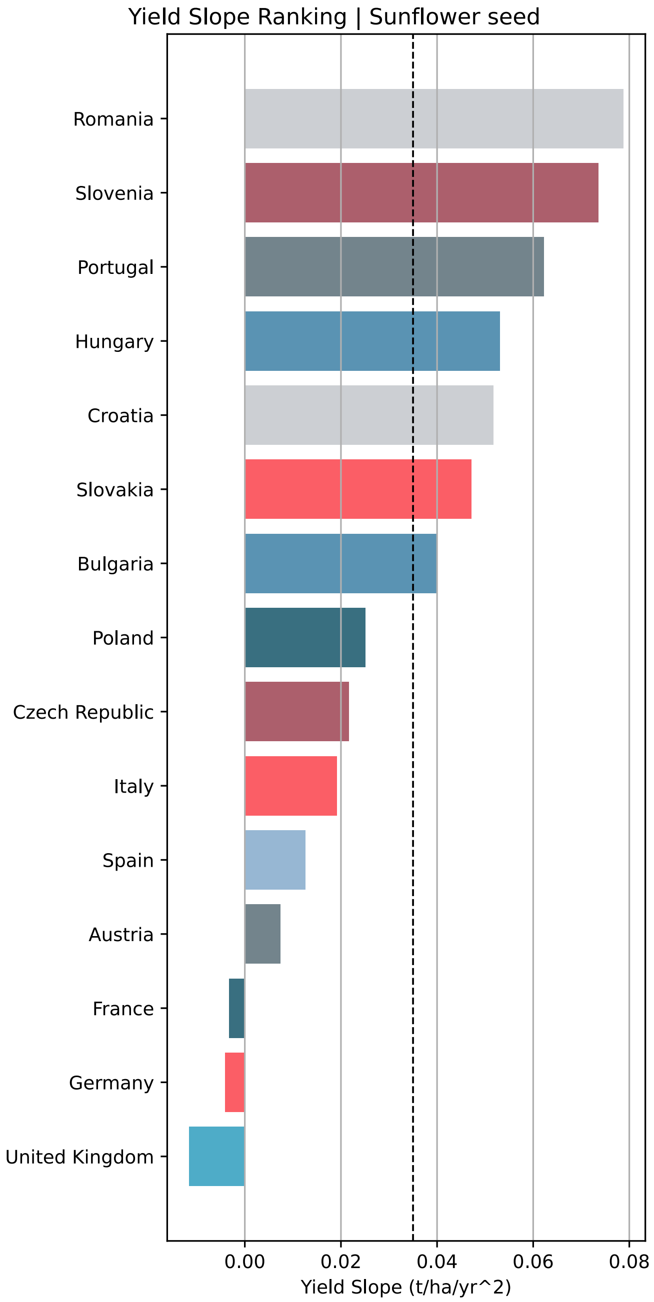


Figure 32: Country-level yield slopes for the period 2000-20 for the crop indicated. Countries are ordered according to their yield slope, with those at the top of the figure exhibiting high yield growth. The black dashed line is the FAOSTAT global average.

3.4. Sugarbeet

Crop yield review in European regions and agro-ecological zones

The observed yields for sugar beet (in fresh weight) between 2015 and 2020 range from 8 to 98 t/ha (Figure 33), with the highest values found in France, Belgium, Netherlands and Germany, and the lowest in Romania, Hungary, Finland and some regions in Italy. The map also shows that in many regions, no reports on sugar beet are available, or sugar beet is not cultivated.

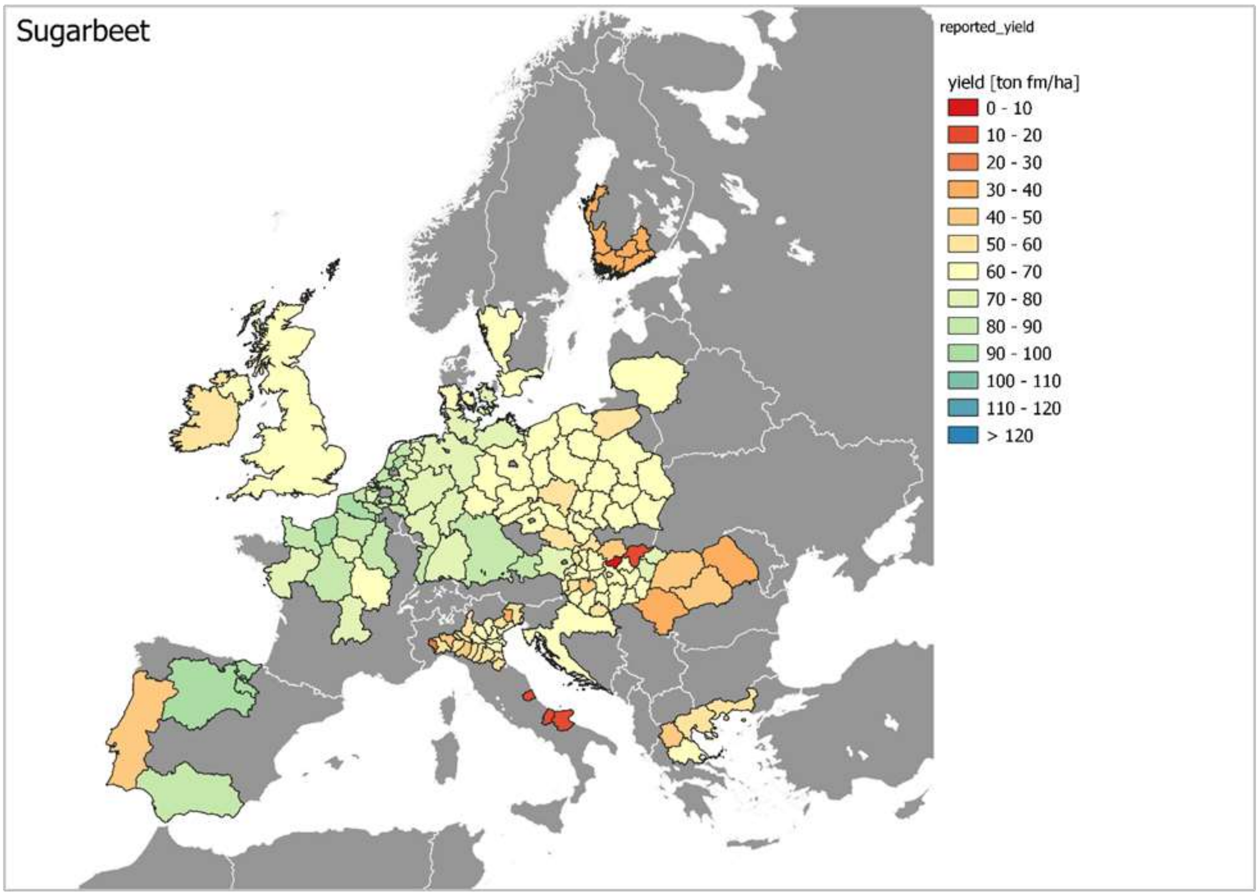


Figure 33: Observed yield (2015-2020) of sugar beet (in fresh weight). Source data: national statistics and regional data from Eurostat.

Observed yield 2010-2020 in environmental zones

The observed average yield of sugar beet over the period 2010-2020 in environmental zones as recorded for regions at NUTS-levels 0-3 is shown in **Error! Reference source not found.**. Average yields are highest in northwestern Europe, in the environmental zones Atlantic Central and Atlantic North, with average values above 70 t/ha. The lowest values (<40 t/ha) are found in the Boreal zone. The variation in yield within zones is highest in the southern part of Europe in the environmental zones Mediterranean North and Pannonian, with values of the standard deviation near 15 t/ha.

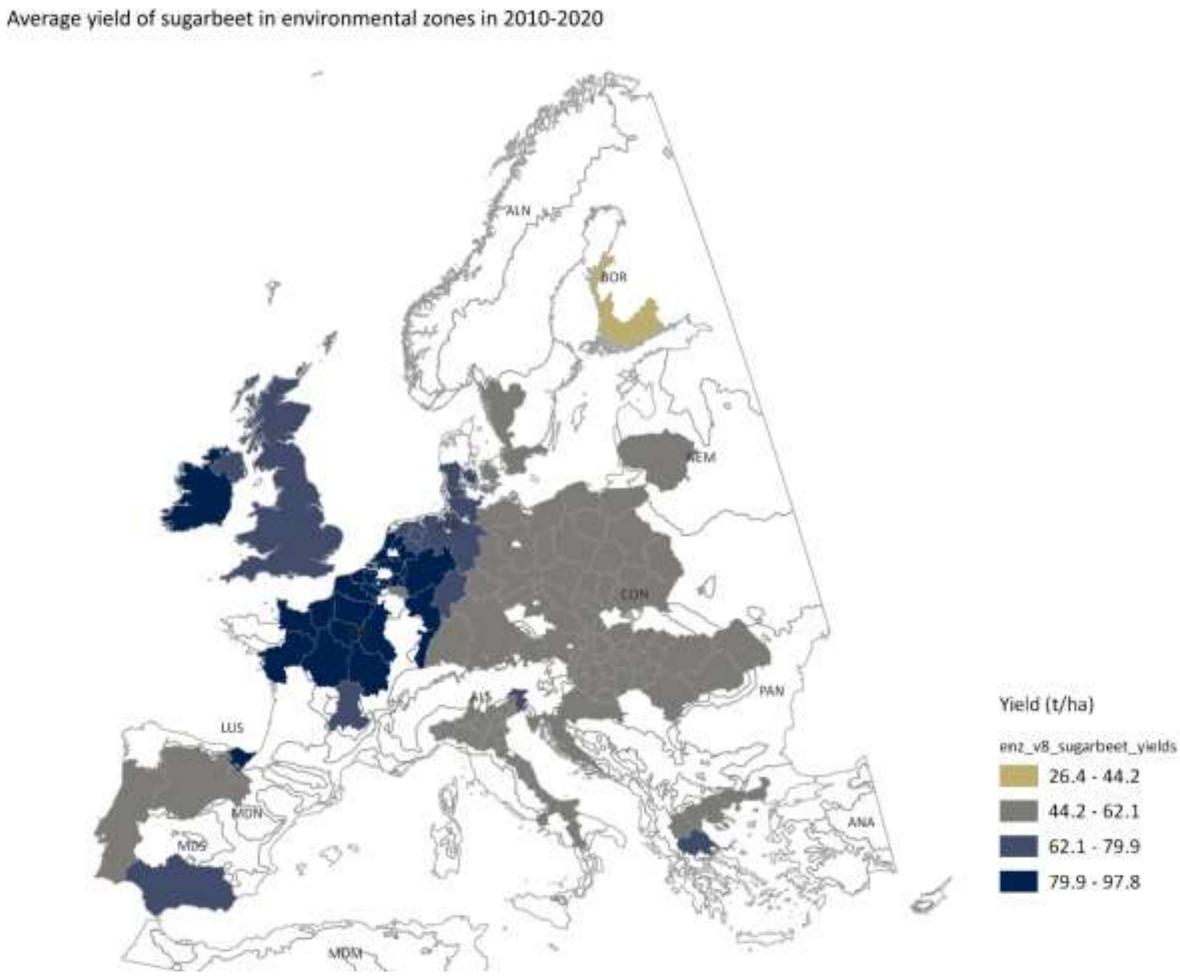


Figure 34: Observed yield (2010-2020) of sugar beet (fresh weight) in environmental zones in Europe. Source data: observations for 152 regions from national statistics and regional data from Eurostat.

Changes in yield 2000-2009 versus 2010-2020

In the period 2010-2020 the yield of sugar beet increased by 10-25% compared to the period 2000-2009 in 58 regions in northwestern Europe, notably in the UK, Ireland and Germany. Increases by more than 25% compared to the period 2000-2009 were reported for Poland, the Czech Republic, Romania, Hungary and Croatia (Figure 35). Decreases in yield of sugar beet were reported for a few regions in Greece, Italy and for Portugal.

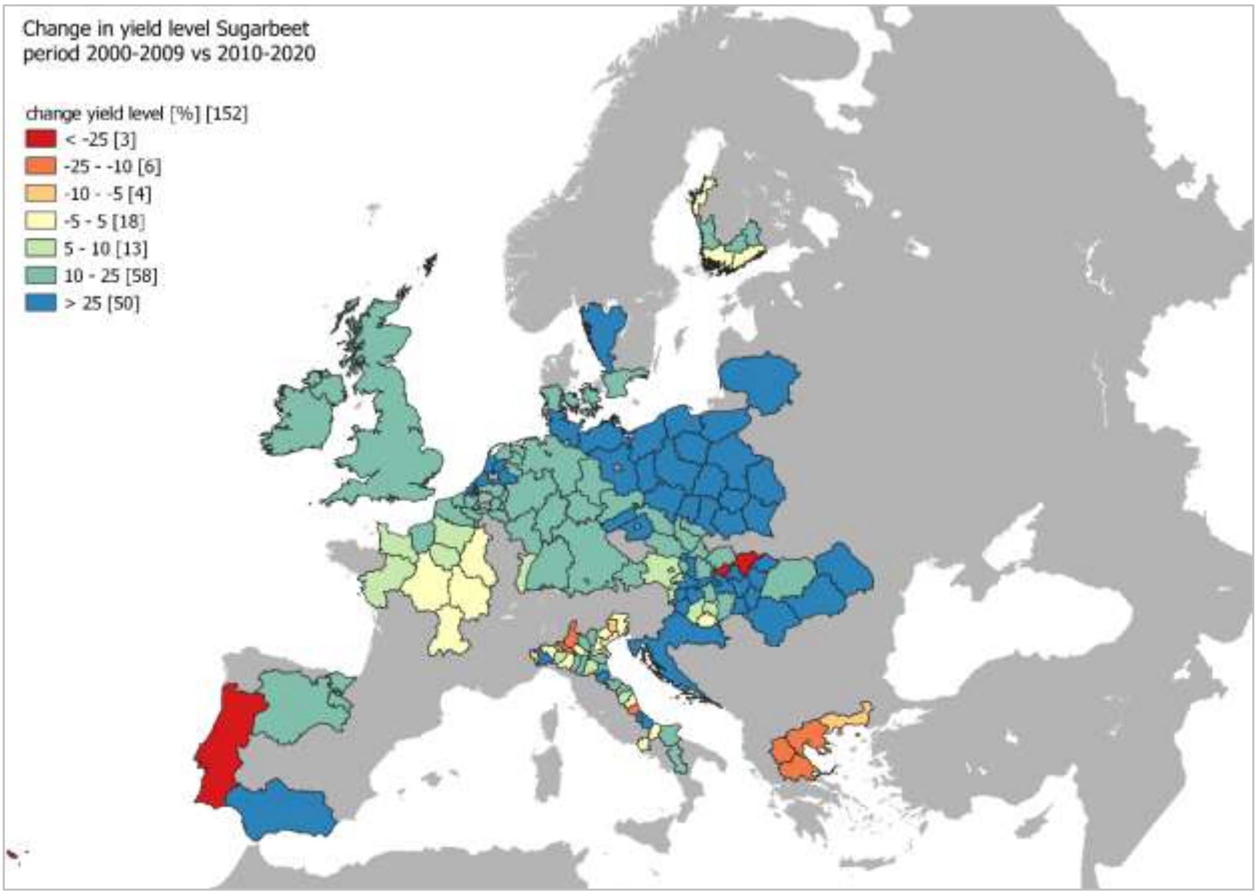


Figure 35: Change in yield of sugar beet (in %) in the period 2010-2020 compared to the period 2000-2009. Numbers of regions in each class indicated between [].

Baseline yield analysis at national level

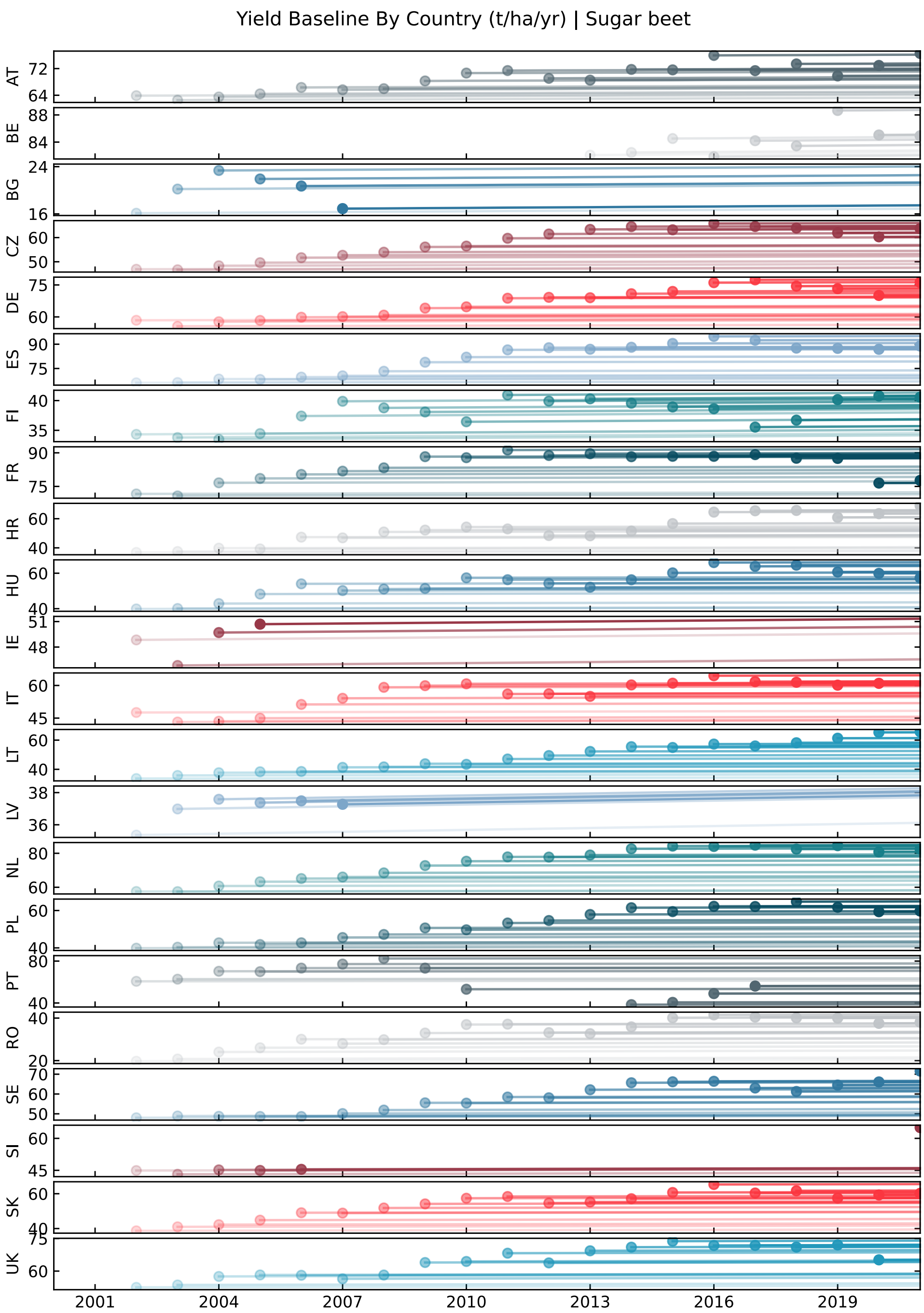


Figure 36: Baseline yield trend for calculating additional sugarbeet production at the national level, for large EU countries + UK. Points indicate initial yield calculated on the previous three years' data, where available; lines are extrapolated using the FAOSTAT global average yield growth for the crop in question.

Average yield analysis at NUTS2 level

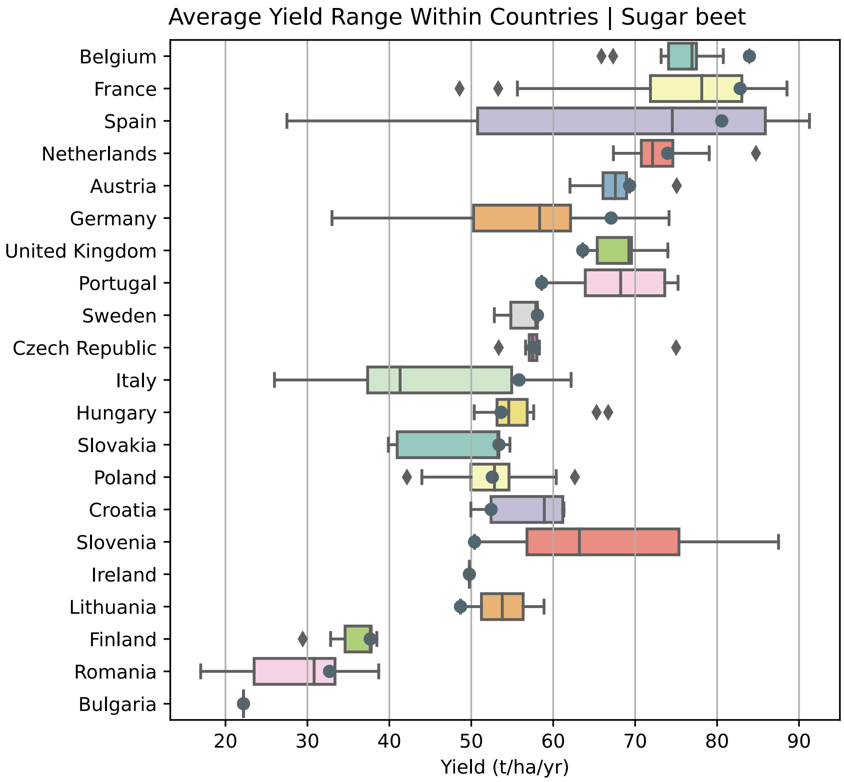


Figure 37: Box-plot of district yields in each country for sugarbeet. Countries are sorted by national yield averaged 2000-20 (blue dots), with the highest at the top of the figure. The median of the district yields is shown as a vertical line, and the surround

Yield slope analysis at national level

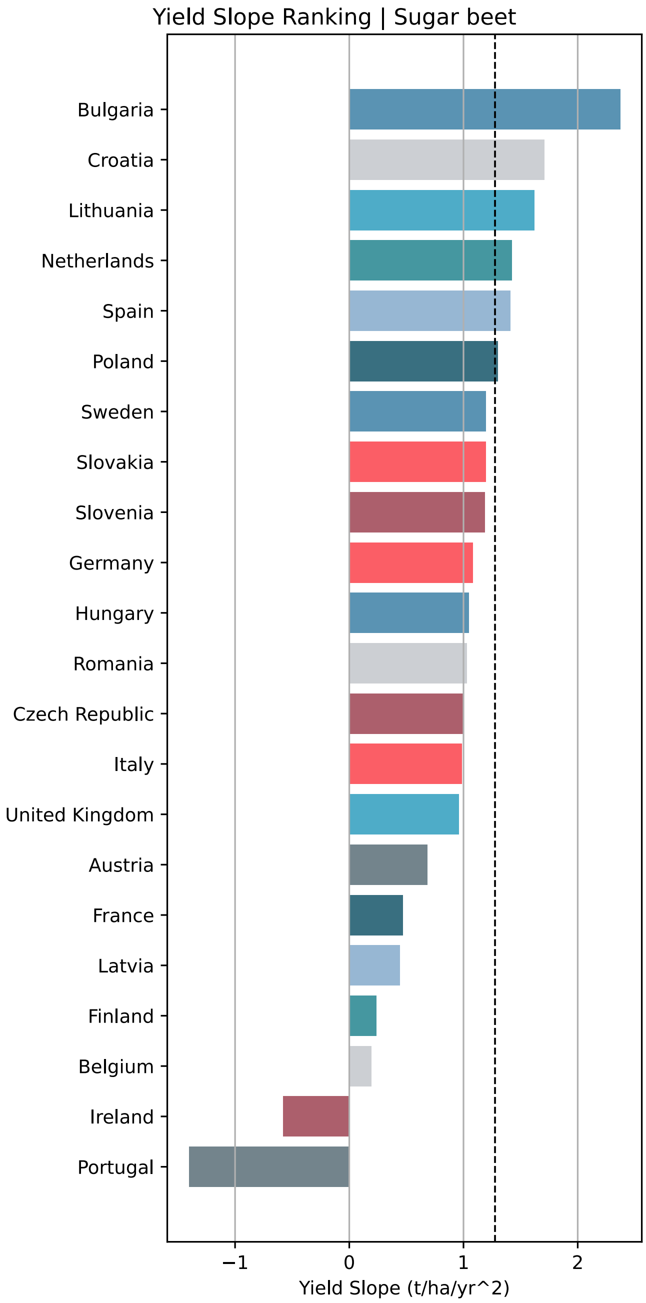


Figure 38: Country-level yield slopes for the period 2000-20 for the crop indicated. Countries are ordered according to their yield slope, with those at the top of the figure exhibiting high yield growth. The black dashed line is the FAOSTAT global average.

4. Overview of crop management practices

This section provides an overview of crop management practices and their associated input requirements, and the next section (Section 5) evaluates their potential to increase productivity for the understudy crops in the different agroecological zones (AEZ) in Europe.

The work has been published in an open access article:

Panoutsou, C., Giarola, S., Ibrahim, D., Verzandvoort, S., Elbersen, B., Sandford, C., Malins, C., Politi, M., Vourliotakis, G., Zita, V. E., Vásáry, V., Alexopoulou, E., Salimbeni, A. & Chiaramonti, D. (2022), Opportunities for Low Indirect Land Use Biomass for Biofuels in Europe. 1 May 2022, In: Applied Sciences (Switzerland). 12, 9, 4623. https://www.mdpi.com/2076-3417/12/9/4623

4.1. Introduction

The low ILUC-risk status for feedstocks involves the cultivation of crops that meet additional conditions and can be produced through smart, sustainable, and low input agricultural practices, which in return are expected to contribute to climate change mitigation and soil quality [28]. These include carbon sequestration through carbon farming. The term 'carbon farming' refers to land practices in agriculture and forestry leading to the storage of carbon from the atmosphere in biomass, organic matter, soils, and vegetation. Carbon farming is one of the mechanisms for the removal of carbon from the atmosphere that are proposed in the EU Communication on Sustainable Carbon Cycles [29]. Such practices include, among others, intercropping, cover crops, rotational cropping, and soil enrichment with biochar [30,31] that improve soil carbon stocks, organic fertilization, agroforestry that stores carbon in vegetation [32–34], and restoration of degraded land with perennial crops.

4.2. Management practices

Five types of practices that support biomass production, carbon storage, and soil quality are addressed in this review, based on their occurrence in policy instruments of the EU. Each of these will now be discussed in turn.

Intercropping refers to a crop grown amidst a main crop or in between the planting rows of that main crop and intended to be harvested or to be supportive to the harvest of the main crop[24].

Cover cropping refers to a crop grown in between two main crop seasons[25]. A review of meta-studies on soil improving cropping systems reported that intercropping, mixed crops, and cover crops can increase yields[26]. Effects on nutrient cycling and resilience to stress were less clear.

[24] Soilcare project glossary. Available online: https://www.soilcare-project.eu/resources/glossary

[25] Blanco-Canqui, H.; Shaver, T.M.; Lindquist, J.L.; Shapiro, C.A.; Elmore, R.W.; Francis, C.A.; Hergert, G.W. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. Agron. J. 2015, 107, 2449–2474. https://doi.org/10.2134/agronj15.0086.

[26] Van Delden, H.; Fleskens, L.; Muro, M.; Tugran, T.; Vanhout, R.; Baartman, J.; Nunes, J.P.; Vanermen, I.; Salputra, G.; Verzandvoort, S.; et al. Report on the Potential for Applying Soil-Improving CS across Europe; Deliverable 6.2 from the EU SoilCare Project, Grant Agreement 677407; 2021; European Commission, Brussels, Belgium 224p. Available online: https://www.soilcare-project.eu/downloads/public-documents/soilcare-reports-and-deliverables/433-report-43-d6-2-report-on-the-potential-for-applying-sics-across-europe-riks-full/file

Legume cover crops could be a substitute for N-fertilisers, whereas other cover crops could decrease loss of N by leaching. The input of carbon to soils from cover crops depends on the biomass yield of the crop, which is determined by the species, time of seeding, winter hardiness, and availability of water. Cover crops were reported to increase the soil organic matter content compared to fallow soils.

Data indicate that cover crops reduce soil penetration resistance by 0 to 29%. Cover crops also improve wet aggregate stability by 0 to 95% and cumulative infiltration by 0 to 190% but have insignificant impacts on bulk density, dry aggregate stability, saturated hydraulic conductivity, unsaturated hydraulic conductivity, and plant available water. The soils under the cover crop can be warmer in winter and colder in spring, summer, and autumn. Daytime soil temperature decreased by an average 2 °C, whereas night-time soil temperature increased by 1 °C, which also can induce changes in the soil organic carbon concentration.

Ten-year field trials using cover crops showed that the observed improvement in soil hydraulic function could be based on a more compensated distribution among macro to micropores, reducing soil compaction and increasing soil water retention and crop available water. The result could be less prone to runoff and drainage losses, compensating for the water competition[27].

Rotational cropping refers to the temporal alternation of different crop types (mown vs. lifted, monocots vs. dicots, annual vs. perennial) on a piece of farmland.

Crop rotation is the practice of growing a series of different types of crops in the same area in sequential seasons. Crop rotation gives various nutrients to the soil and replenishes nitrogen, for example, through the use of green manure, legumes, or cover crops in sequence with cereals and other crops. Crop rotation also helps to battle against erosion. Rotating crops helps to improve soil stability by alternating between crops with deep roots and those with shallow roots. Crop rotations can help prevent the accumulation of crop-specific pests and reduce the risk of pests developing resistance to ingredients used for crop protection. Diverse crop rotations have the potential to deliver organic carbon to the soil derived from harvest residues, root residues, and root exudates. The effect is mainly determined by the amount and composition of the harvest residues.

Crop rotation achieved higher yields, less weed pressure, and higher soil C and N content in Poland in spring wheat[28] and in spring barley[29].

Data of 30 long-term experiments collected from thirteen case study sites in Europe show that crop rotation had a positive effect on soil organic matter (SOM) content and yield and positively influenced earthworm numbers. Overall, crop rotation had little impact on soil pH and aggregate stability[30].

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[27] Aronsson, H.; Hansen, E.M.; Thomsen, I.K.; Liu, J.; Øgaard, A.F.; Kankanen, H.; Ulen, B. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. *J. Soil Water Conserv.* 2016, *71*, 41–55

[28] Woźniak, A.; Soroka, M. Effect of crop rotation and tillage system on the weed infestation and yield of spring wheat and on soil properties. Appl. Ecol. Environ. Res. 2018, 16, 3087–3096

[29] Woźniak, A.; Nowak, A.; Haliniarz, M.; Gawęda, D. Yield and Economic Results of Spring Barley Grown in Crop Rotation and in Monoculture. Pol. J. Environ. Stud. 2019, 28, 2441–2448

[30] Bai, Z.; Caspari, T.; Gonzalez, M.R.; Batjes, N.H.; Mäder, P.; Bünemann, E.K.; de Goede, R.; Brussaard, L.; Xu, M.; Ferreira, C.S.S.; et al. Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. *Agric. Ecosyst. Environ.* 2018, *265*, 1–7

Farmers in Finland are worried about wet conditions in winter, more frequent heavy rains, and wet conditions during the harvest periods, which affect crop yields, nutrient leaching, and erosion. In response, specific crop rotations, including the use of deep–rooted crops (i.e., clover and oilseed), have been proposed by local scientists[31]. In Italy, adopting 2 or 3 year crop rotations (based on winter wheat and tomato) under future conditions led to an increase in soil organic carbon (SOC) by approximately 10% of the SOC content of the current system that is based on continuous wheat[32].

Agroforestry involves land-use systems and practices where woody perennials are deliberately integrated with crops and/or animals on parcels with the same land management, without the intention to establish a permanent forest stand. The trees may be arranged as single stems, in rows or in groups, and grazing may also take place inside parcels (silvoarable agroforestry, Silvo pastoralism, grazed or intercropped orchards) or on the limits between parcels (hedges, tree lines). The standing stock of carbon aboveground is usually greater than the equivalent land use without trees, and plant-ing trees may also increase soil carbon sequestration[33] [34] [35]. Root systems of inter-cropped trees enable input of carbon to deeper soil layers compared to crops.

Review studies of agroforestry systems reduced surface runoff and soil, SOC, and nutrient losses by average values of 58%, 65%, 9%, and 50%, respectively. They also lowered herbicide, pesticide, and other pollutant losses by 49% on average. However, Mupepele et al. (2021)[36] called for a caution: only a few studies provide results based on strong evidence, and more detailed reporting on effects of agroforestry on soil quality aspects is needed. However, results from available studies do show that agro-forestry can lead to benefits on biodiversity[37] [38].

Soil enrichment can be achieved with biochar. The application of biochar produced from biowastes to soils could be a very good way to reduce demand for fertilisers (cutting dependency, costs, and pollution), sequester carbon, and enable relatively cheap and lasting amelioration of degraded land and sustainable and improved agriculture[39]. The pyrolysis process produces biochar as well as two additional materials, syngas and bio-oil, that may have commercial value as energy sources. Biochars differ depending on the feedstock, temperature, and residence time and have been effective tools of waste management, soil remediation, and may also offer

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[31] Huttunen, I.; Lehtonen, H.; Huttunen, M.; Piirainen, V.; Korppoo, M.; Veijalainen, N.; Viitasalo, M.; Vehviläinen, B. Effects of climate change and agricultural adaptation on nutrient loading from Finnish catchments to the Baltic Sea. *Sci. Total Environ.* **2015**, *529*, 168–181.

[32] Ventrella, D.; Giglio, L.; Charfeddine, M.; Lopez, R.; Castellini, M.; Sollitto, D.; Castrignanò, A.; Fornaro, F. Cli-mate change impact on crop rotations of winter durum wheat and tomato in southern Italy: Yield analysis and soil fertility. Ital. J. Agron. 2012, 7, e15.

[33] Brahma, B.; Pathak, K.; Lal, R.; Kurmi, B.; Das, M.; Nath, P.C.; Nath, A.J.; Das, A.K. Ecosystem carbon sequestra-tion through restoration of degraded lands in Northeast India. Land Degrad. Dev. 2018, 29, 15–25.

[34] Feliciano, D.; Ledo, A.; Hillier, J.; Nayak, D.R. Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agric. Ecosyst. Environ. 2018, 254, 117–129.

[35] Shi, L.; Feng, W.; Xu, J.; Kuzyakov, Y. Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degrad. Dev. 2018, 29, 3886–3897. https://doi.org/10.1002/ldr.3136.

[36] Mupepele, A.-C.; Keller, M.; Dormann, C.F. European agroforestry has no unequivocal effect on biodiversity: A time-cumulative meta-analysis. BMC Ecol. Evol. 2021, 21, 193. https://doi.org/10.1186/s12862-021-01911-9.

[37] Burgess, P.J.; Rosati, A. Advances in European agroforestry: Results from the AGFORWARD project. Agrofor. Syst. 2018, 92, 801–810. https://doi.org/10.1007/s10457-018-0261-3.

[38] Quinkenstein, A.; Wöllecke, J.; Böhm, C.; Grünewald, H.; Freese, D.; Schneider, B.U.; Hüttl, R.F. Ecological benefits of the alley cropping agroforestry system in sensitive regions of Europe. Environ. Sci. Policy 2009, 12, 1112–1121. https://doi.org/10.1016/j.envsci.2009.08.008.

[39] Barrow, C.J. Biochar: Potential for countering land degradation and for improving agriculture. Appl. Geogr. 2012, 34, 21–28.

mitigation of GHG emissions through carbon sequestration[40]. Due to the large variability of biochar, one type of biochar may not be suitable for all growing conditions and crops.

Table 5: Biomass crops, yields for the European Agro-Ecological Zones-AEZ (A: Atlantic, C&B: Continental and Boreal, M: Mediterranean) and opportunities for low ILUC-risk through sustainable agricultural practices [intercropping (I), cover cropping (CC), rotation (R), agroforestry (AF), biochar (B)].

		Agricultural Practices	**Average Baseline Yields (t/ha) Seeds for cereals, maize and oil crops and t/ha beets for sugarbeet per AEZ (standard deviation between ())**		
			A	C and B	M
Cereals & maize	Soft wheat	I, CC, R	7.2 (1.5)[41]	6.2 (1.5)[42]	3.6 (1.5)[43]
	Barley	I, CC, R	6.8 (1.2)[44]	4.5 (1.5)[45]	3.5 (1.3)[46]
	Grain & forage maize	I, CC, R	8.8 (1.4)[47]	5.9 (1.8)[48]	8.9 (2.7)[49]
Oil	Rapeseed	I, CC, R, B	4.5	4	3
	Sunflower	I, CC, R, B	3.5	4	2.5

[40] Lehmann, J.; Joseph, S. (Eds.) Biochar for Environmental Management: Science, Technology and Implementation; Routledge: London, UK, 2015.
[41] Agro-ecological zones ATC and ATN, 273 observations for the period 2015-2018.
[42] Agro-ecological zone CON (no observations for BOR), 94 observations for the period 2015-2018.
[43] Agro-ecological zones MDM, MDN and MDS, 167 observations for the period 2015-2018.
[44] Agro-ecological zones ATC and ATN, 278 observations for the period 2015-2020.
[45] Agro-ecological zones CON and BOR, 192 observations for the period 2015-2020.
[46] Agro-ecological zones MDM, MDN and MDS, 144 observations for the period 2015-2020.
[47] Agro-ecological zones ATC and ATN, 60 observations for the period 2015-2029.
[48] Agro-ecological zone CON (no observations for BOR), 53 observations for the period 2015-2019.
[49] Agro-ecological zones MDM, MDN and MDS, 157 observations for the period 2015-2029.

5. Estimated yield increases towards 2030 and further

The yield increase of the understudy crops has been estimated based on the meta-data analysis and information published from the projects noted in Table 1. For cereals and oilseed rape estimates are based on projections from the Global Agro-ecological Zones (GAEZ v4.0) (Fischer et al., 2021).

- Crop yield increases due to already foreseen genetic crop improvements in the varieties used is 10% between 2020 and 2030. This calculates an increase of 1% annually and is in line with the EU Agricultural Outlook, which presents the respective yield increases for cereals in Europe (agricultural-outlook-2020-report_en.pdf (europa.eu).
- The low and high increase rate because of the application of one or multiple sustainable agricultural practices (e.g., intercropping and biochar, etc.) is calculated as an average of 15% and 25%, respectively, between 2020 and 2030 based on the findings from BIO4A project.

The meta-analysis of effects of agricultural management practices in arable cropping in the SoilCare project[50] gave the following quantified effects for yield of crops:

- effect measure: relative change= factor -1
- Factor = treatment_data/control_data

Average values of relative change in yield as a result of crop management practices are reported below.

- Maize (40 cases, 6 practices): 0.56
- Spring wheat (16 cases, 2 practices): 0.49
- Winter wheat (9 cases, 5 practices): 0.26
- Wheat (47 cases, 3 practices): 0.21
- Oilseed rape (3 cases, 3 practices): 0.17

These effect sizes do not fall in the range of low and high increase rates mentioned in the text, except for OSR and wheat.

[50] Source: own derivation from database associated with the publication:

Rietra, R.; Heinen, M.; Oenema, O. A Review of Crop Husbandry and Soil Management Practices Using Meta-Analysis Studies: Towards Soil-Improving Cropping Systems. Land 2022, 11, 255. https://doi.org/10.3390/land11020255

Soft wheat

Figure 39 shows the relative difference in regions of the EU-27 and UK between the reported yield of soft wheat over the period 2015-2020 and the attainable yield according to GAEZ for the period 1981-2010. The attainable yield of a crop simulated by GAEZ represents the yield that could be achieved by farmers with good access to markets, inputs and extension services, reaching about 70-80% of the potential crop yield in non-irrigated conditions. Simulations use input for climate, soil and terrain conditions in the period 1981-2010.

Where differences are >0%, attainable yield is higher than reported, and regions may have a potential to increase the yield by improved management and/or irrigation. Regions with differences <0% already have yields higher than attainable according to the GAEZ simulations. These regions could be assumed to have reached their potential in the present conditions of environment and management.

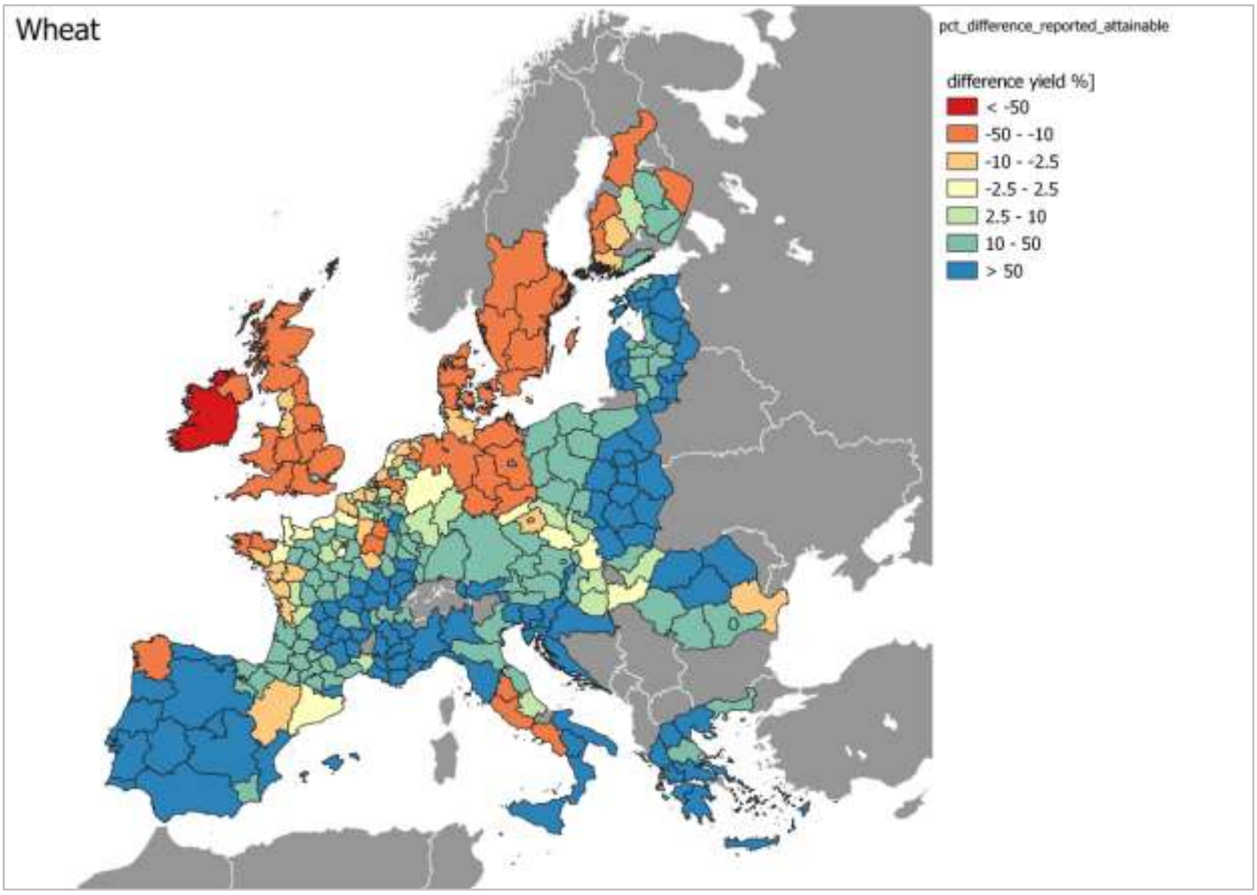

Figure 39: Relative difference between attainable and reported yield of soft wheat in regions in the EU-27 and UK according to resp. GAEZ (for the period 1981-2010) and national data sources and JRC (for the period 2015-2020).

Barley

For barley the map of relative differences in reported and attainable yield looks similar, except for regions in northern Germany, Netherlands and Denmark which have higher estimates of attainable yield according to GAEZ than reported in present conditions (differences up to 50%) (Figure 40). Clusters of regions with a potential for yield increase are observed in a.o. the southeastern part of France, Poland, Romania.

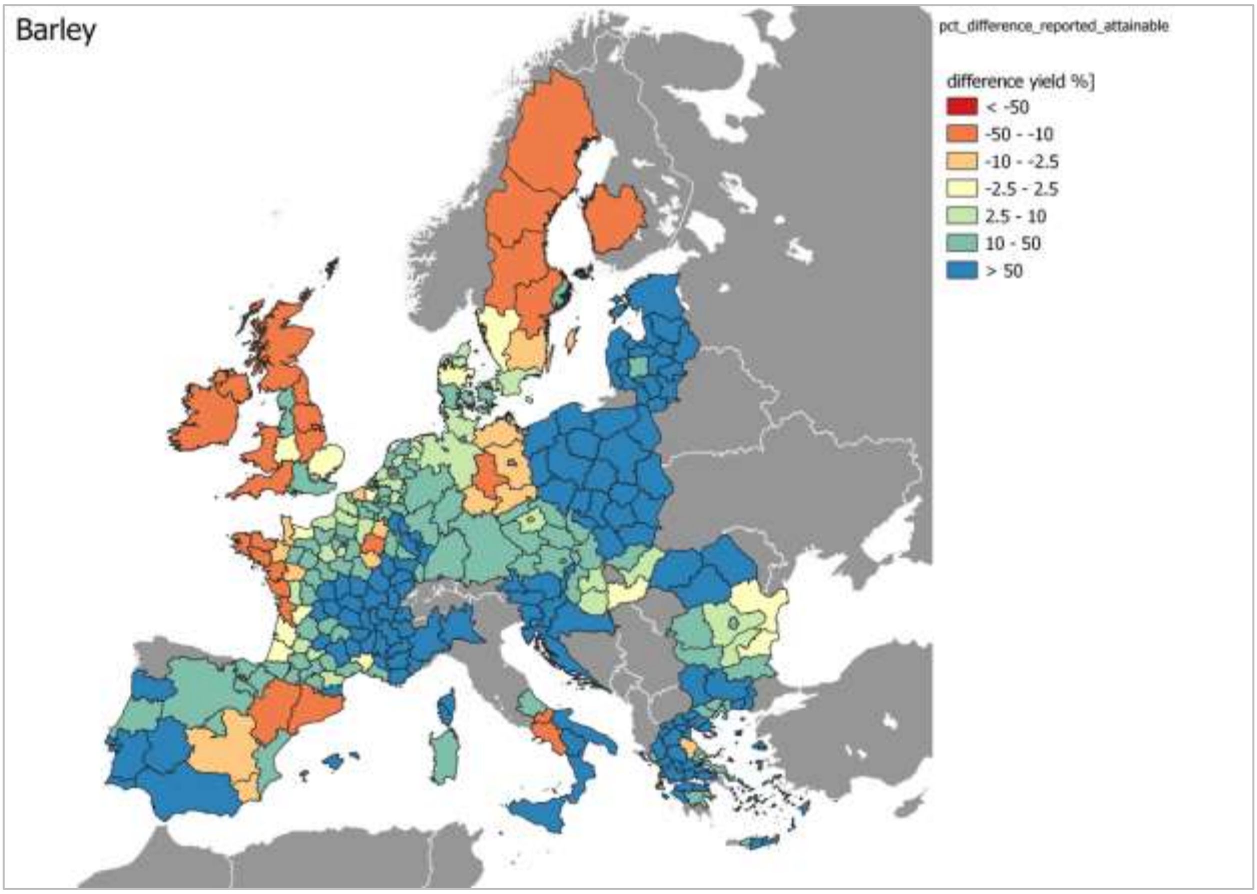

Figure 40: Relative difference between attainable and reported yield of barley in regions in the EU-27 and UK according to resp. GAEZ (for the period 1981-2010) and national data sources (for the period 2015-2020).

Grain maize

For grain maize, the picture is completely different, with the larger part of regions in the EU (for which data are available) characterized by higher reported yields than attainable according to GAEZ (Figure 41). It should be noted that the predictions of attainable yield by GAEZ apply to rainfed conditions. Potential for increase of yield under current conditions only seems present in the eastern part of Europe (Romania and Bulgaria, Poland, Croatia).

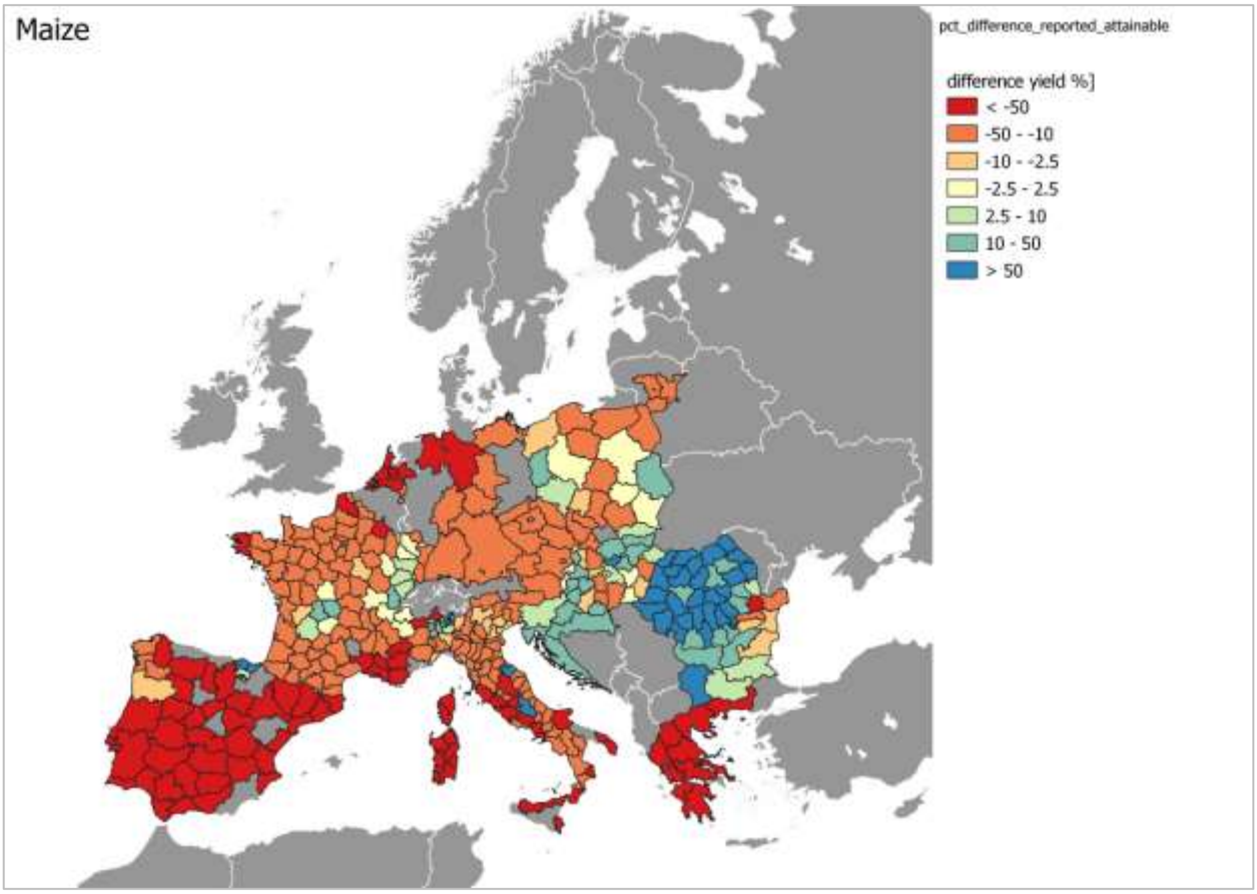

Figure 41: Relative difference between attainable and reported yield of grain maize in regions in the EU-27 and UK according to resp. GAEZ (for the period 1981-2010) and national data sources (for the period 2015-2020).

Oilseed rape

Reported (actual) yields for oilseed rape under present conditions are higher than attainable according to the GAEZ simulations for the period 1981-2011 by 10-50% in the UK and Ireland, Benelux and northwestern Germany, Denmark, southern Sweden and Romania and Bulgaria (Figure 42). In Spain also large regions with negative differences between attainable and reported yields are observed. The results suggest potential for increase to attainable yield of oilseed rape in eastern Europe (Slovakia, Poland) and large parts of France and Italy.

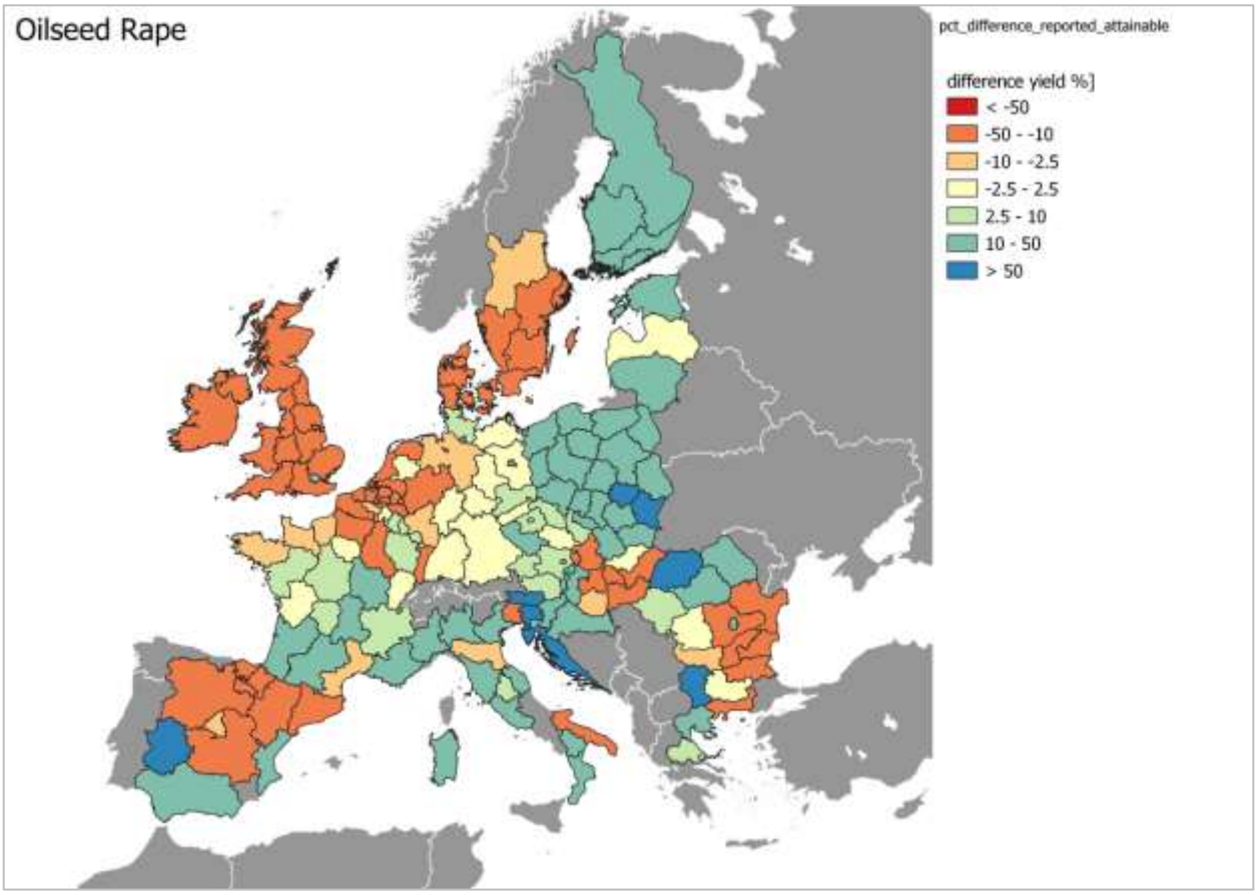

Figure 42: Relative difference between attainable and reported yield of oilseed rape in regions in the EU-27 and UK according to resp. GAEZ (for the period 1981-2010) and national data sources (for the period 2015-2020).

Sugarbeet

The map of relative differences between attainable and reported yield for sugarbeet shows fewer regions with reported data or with cultivation of the crop compared to the other crops (Figure 43). Most regions with data show differences <0% (orange and red colours), indicating that reported yields are already higher than attainable according to the GAEZ modelling. These regions would already have achieved their potential biomass production in the current situation. Potential for increase is available in Romania, Croatia, Hungary, Southern Poland according to the data.

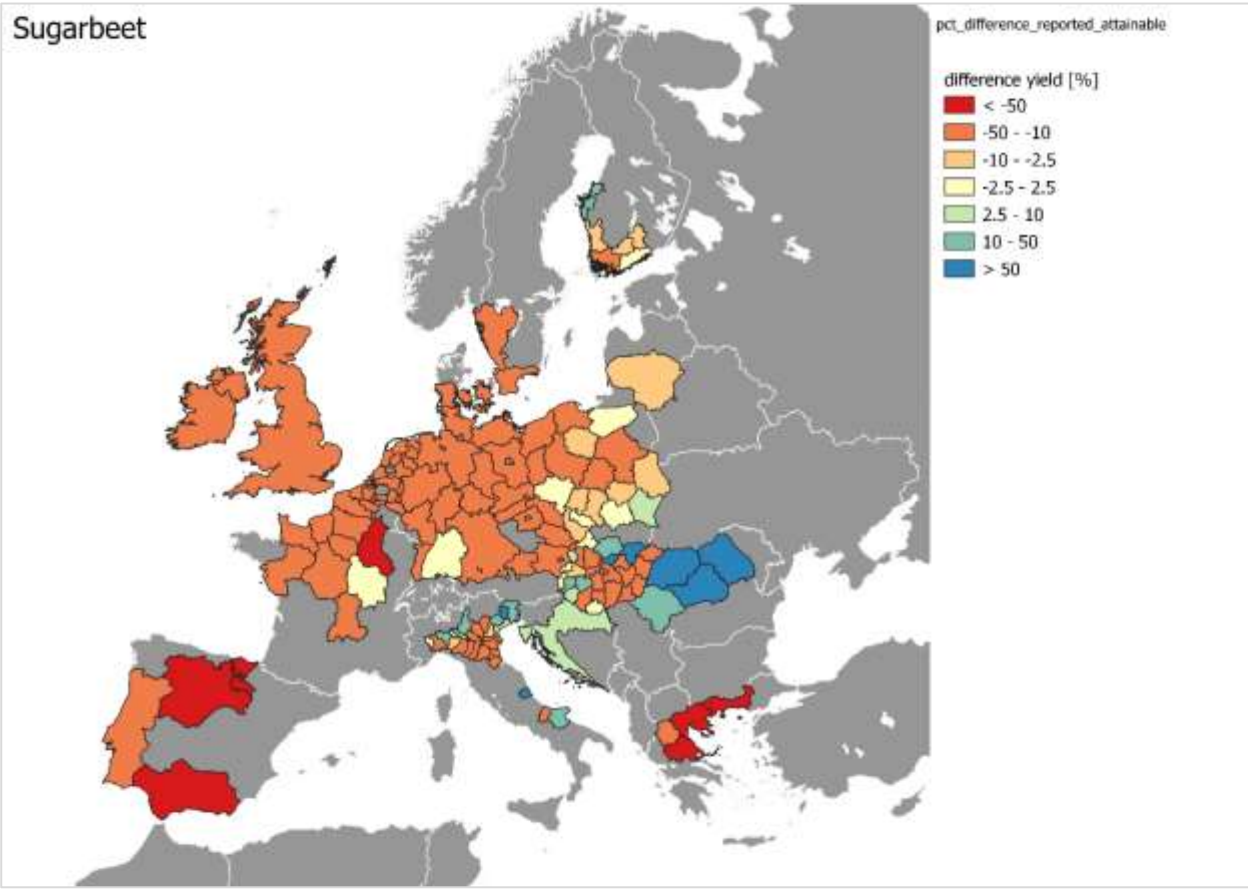

Figure 43: Relative difference between attainable and reported yield of sugarbeet in regions in the EU-27 and UK according to resp. GAEZ (for the period 1981-2010) and national data sources (for the period 2015-2020).

5.1. Reported versus attainable yield under climate change in future conditions

Figure 44 to Figure 48 show the relative difference between the reported yield of the five crops for the period 2015-2020 and the average attainable yield according to 4 climate change scenarios for four representative concentration pathways (see section 3.4) until 2040.

In regions with negative differences (in red-orange shades), the attainable yield under scenarios of climate change is below the reported yields for the current conditions. This would indicate a negative effect of climate change on crop yield. This applies to many regions for grain maize.

Regions with positive differences (in green-blue shades) have higher attainable yields under climate change scenarios than reported for current conditions. This would suggest that climate change would have positive effects on crop yield in these regions. For soft wheat and barley this applies to large parts of Europe; for the other crops this is seen in central and eastern Europe.

It should be noted that reported yields for current conditions may not correspond to attainable yields according to the GAEZ simulations for the (historic and) current period (1981-2011), and that therefore the difference between the reported and attainable yield under climate change has other causes than climate change alone. These may include model uncertainties of GAEZ and errors in reported values.

To illustrate the effect of climate change alone, we compare attainable crop yield simulated by GAEZ for current conditions (taken as 1981-2011) with attainable yield under climate change scenarios (average of 4 scenarios). The results are shown for the 4 crops in the next paragraph.

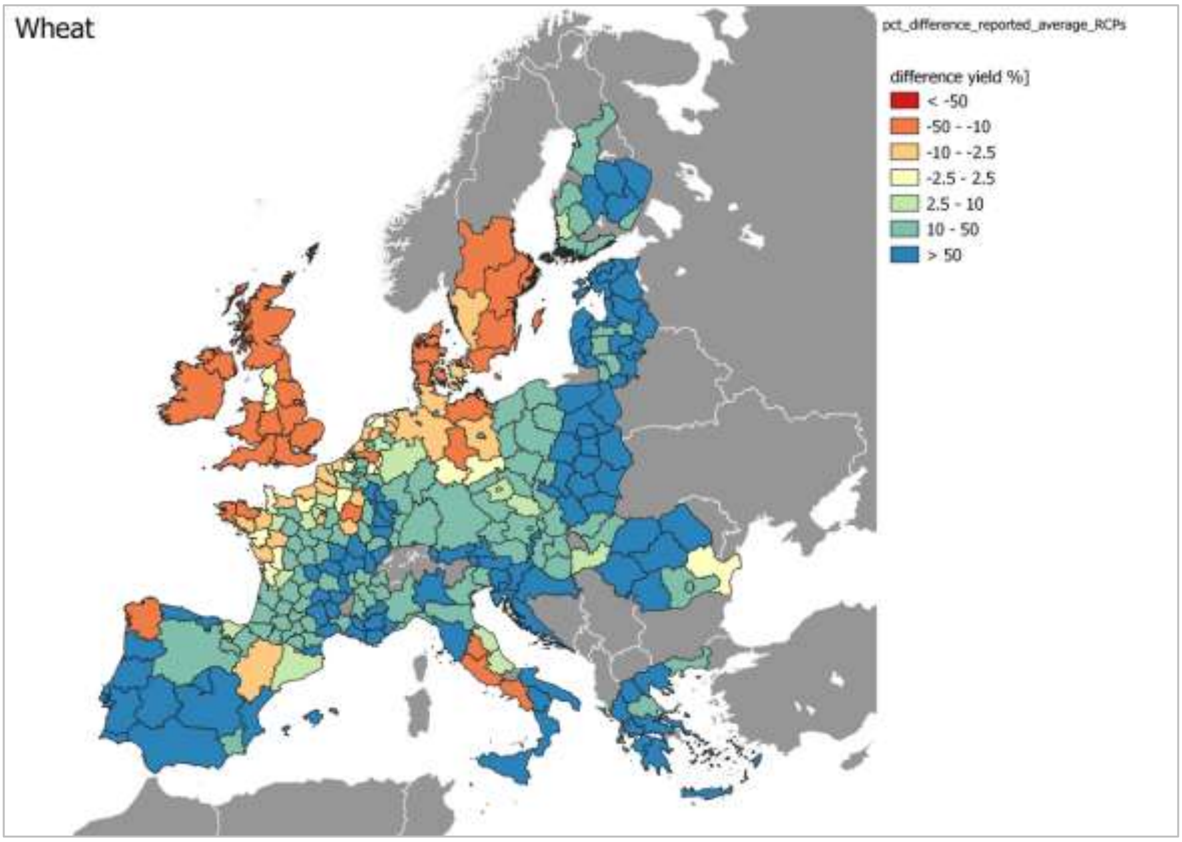

Figure 44: Relative difference (in %) between attainable yield of soft wheat in regions in the EU-27 and UK according to averaged GAEZ projections for climate change scenarios and reported yield in national data sources and JRC (for the period 2015-2020).

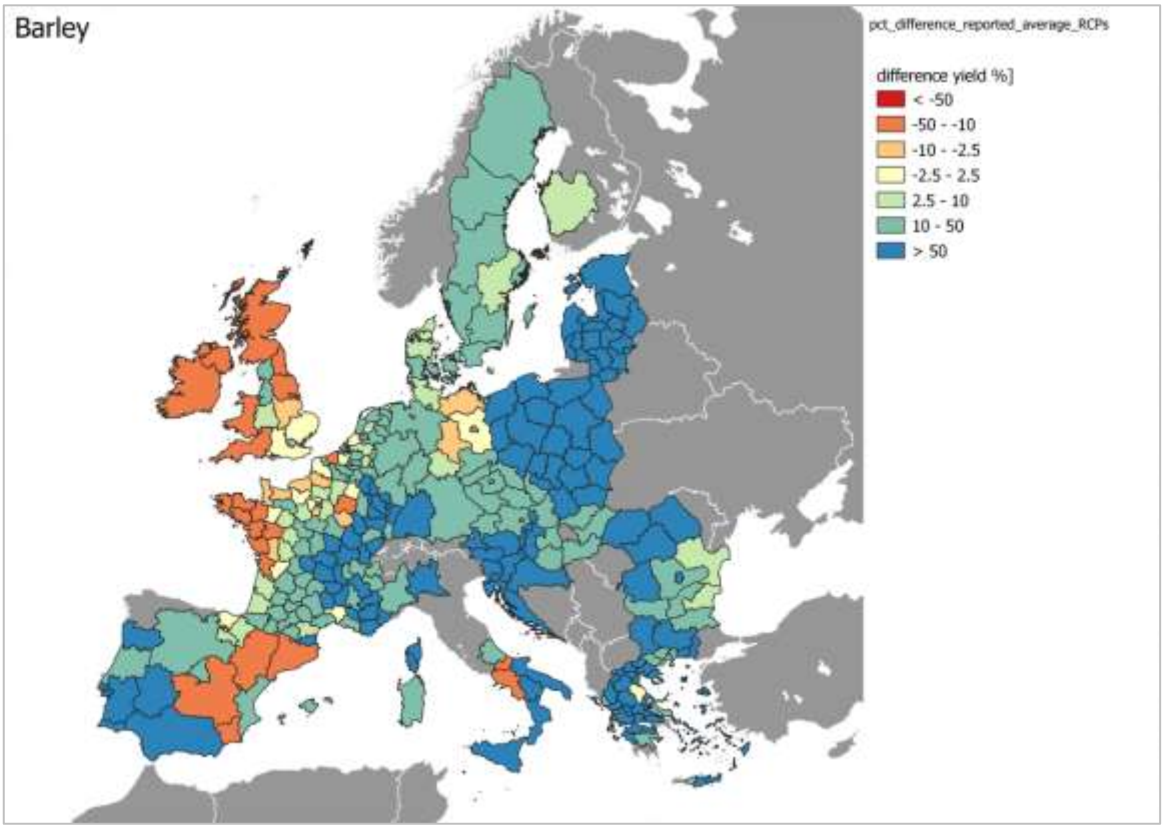

Figure 45: Relative difference (in %) between attainable yield of barley in regions in the EU-27 and UK according to averaged GAEZ projections for climate change scenarios and reported yield in national data sources (for the period 2015-2020).

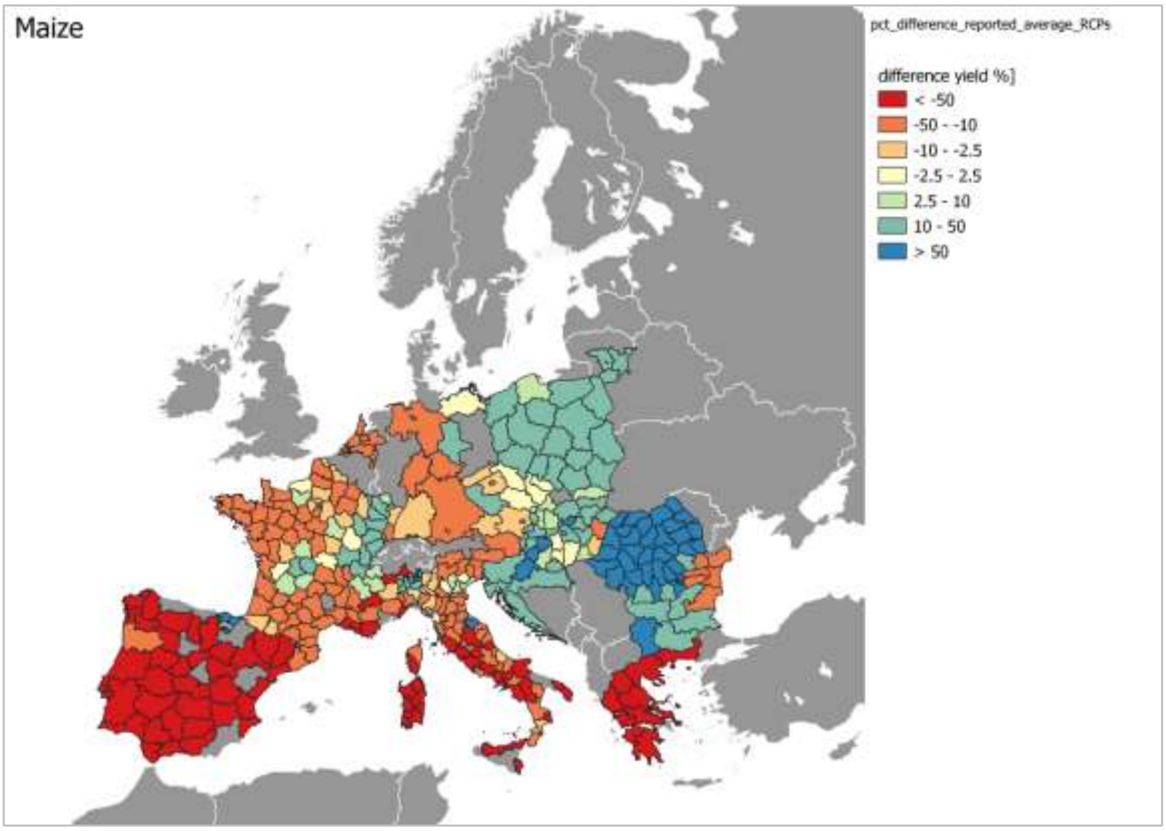

Figure 46: Relative difference (in %) between attainable yield of grain maize in regions in the EU-27 and UK according to averaged GAEZ projections for climate change scenarios and reported yield in national data sources (for the period 2015-2020).

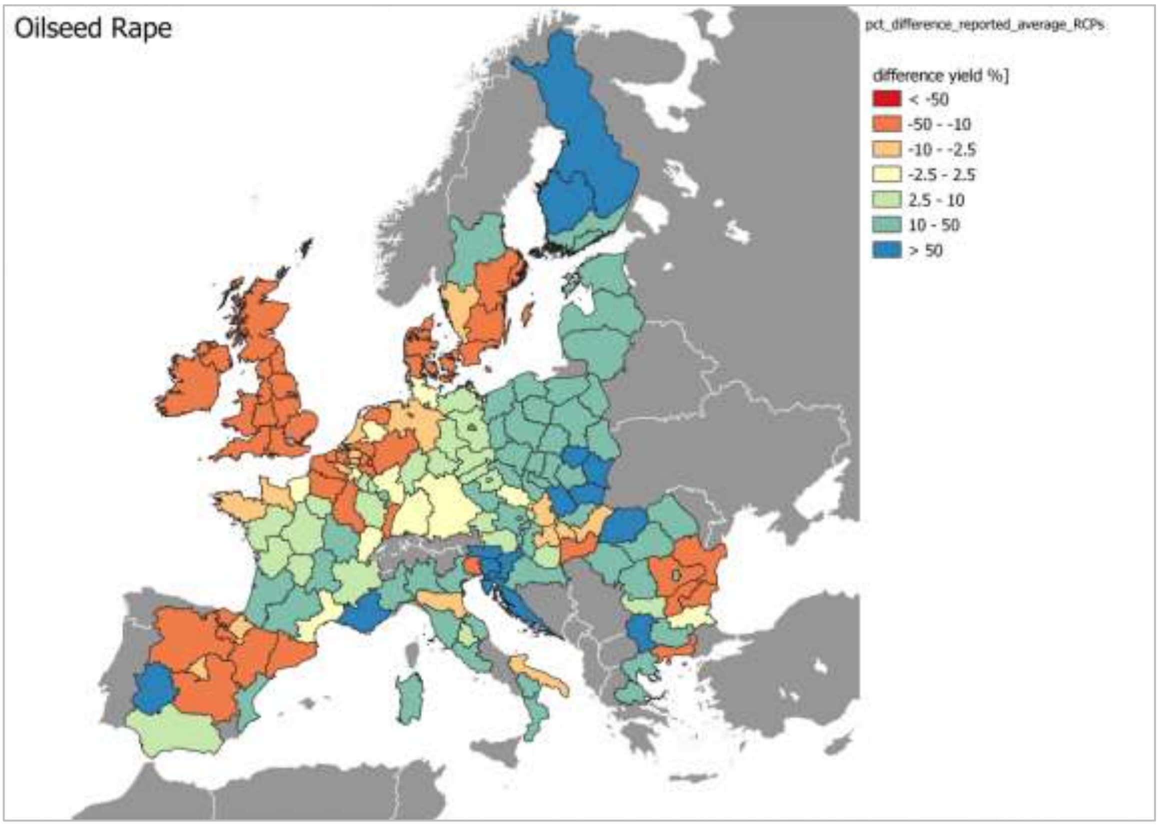

Figure 47: Relative difference (in %) between attainable yield of oilseed rape in regions in the EU-27 and UK according to averaged GAEZ projections for climate change scenarios and reported yield in national data sources (for the period 2015-2020).

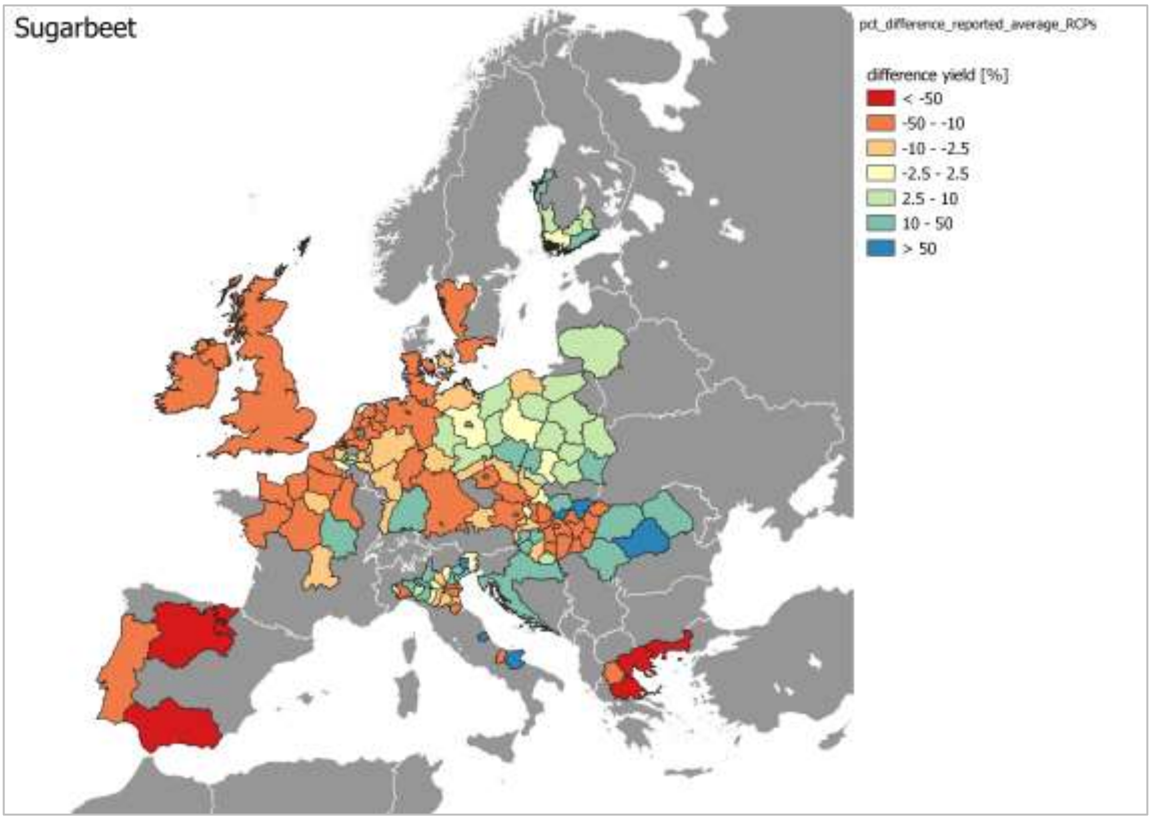

Figure 48: Relative difference (in %) between attainable yield of sugarbeet in regions in the EU-27 and UK according to averaged GAEZ projections for climate change scenarios and reported yield in national data sources (for the period 2015-2020).

5.2. Effects of climate change on attainable yield

Figure 49 to Figure 53 show the relative difference (in %) of attainable crop yield between current conditions (taken as 1981-2011) and future conditions of climate change (averaged over 4 scenarios) as simulated by GAEZ. Differences >0% (in green-blue shades) indicate places where projected yield under climate change is larger than the simulated attainable yield for the current climate conditions. Note that in both simulations, attainable yield is modelled under rainfed, non-irrigated conditions.

This would suggest a positive effect of climate change. These situations are observed for soft wheat, and barley and sugar beet in regions in northern and eastern Europe, for maize in large tractsparts of central Europe, and for oilseed rape also in northern Europe.

In regions with negative values for the difference (<0%) (red-orange shades), the average attainable yield under conditions of future climate is projected to be lower than the attainable yields for current climate conditions. This would indicate negative effects of climate change on attainable crop yield. For soft wheat and barley this concerns regions in Spain, France and Italy, southern UK with relative decreases in attainable crop yield between 2.5% and 50%; for grain maize regions in Italy, Spain and Greece would be affected. For oilseed rape, simulations show less effect of climate change on attainable crop yield, with differences up to -10% in yield for a few regions in the UK, Denmark, Poland and Spain. Regions with negative effects of climate change on the attainable yield of sugar beet are in Portugal, southern Spain, Greece, central Europe and the UK.

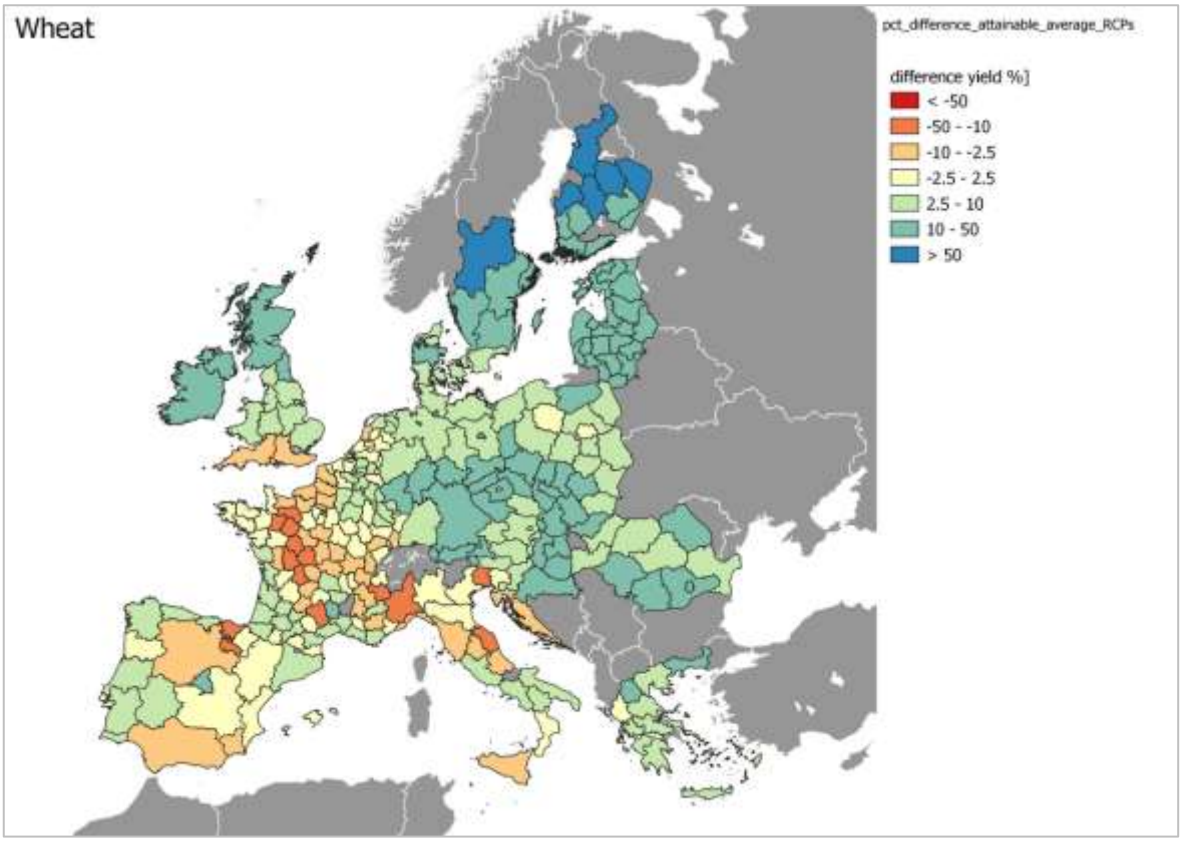

Figure 49: Relative difference (in %) between attainable yield of soft wheat according to GAEZ simulations for historic to current conditions (1981-2011) and averaged GAEZ projections for climate change scenarios until 2040, in regions in the EU-27 and UK.

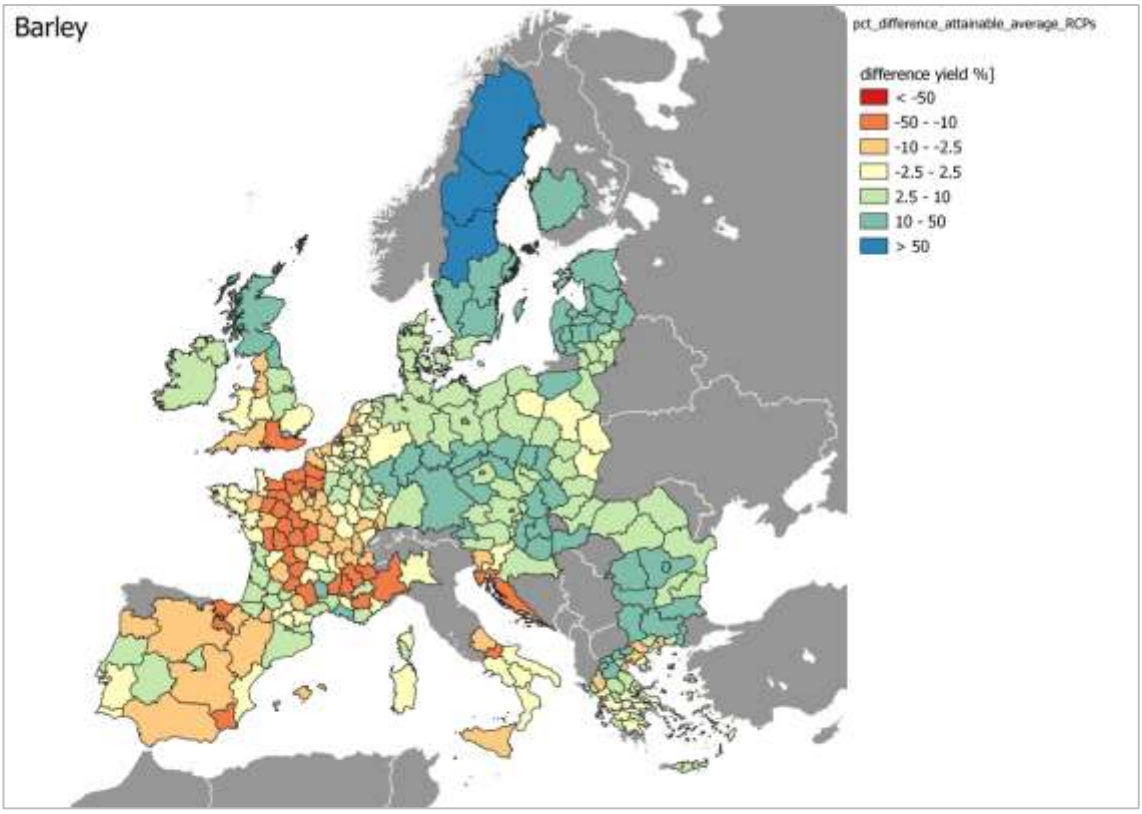

Figure 50: Relative difference (in %) between attainable yield of barley according to GAEZ simulations for historic to current conditions (1981-2011) and averaged GAEZ projections for climate change scenarios until 2040, in regions in the EU-27 and UK.

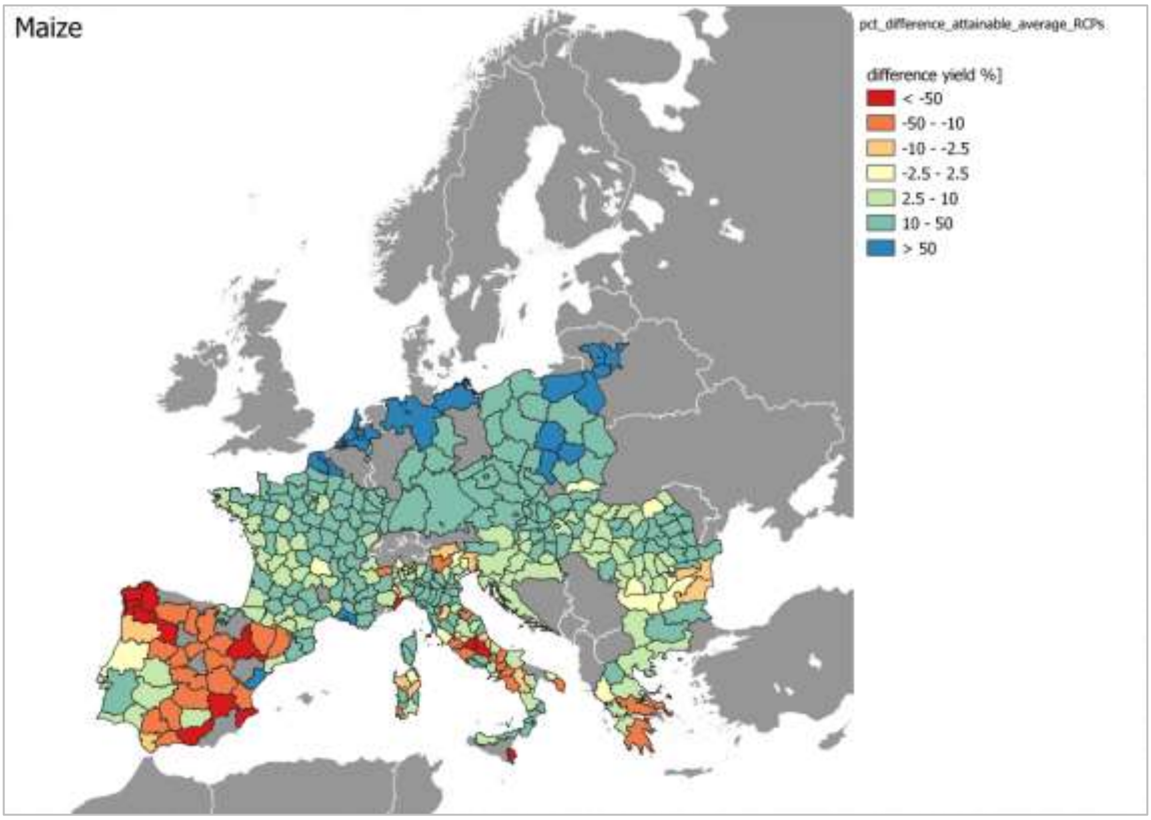

Figure 51: Relative difference (in %) between attainable yield of grain maize according to GAEZ simulations for historic to current conditions (1981-2011) and averaged GAEZ projections for climate change scenarios until 2040, in regions in the EU-27 and UK.

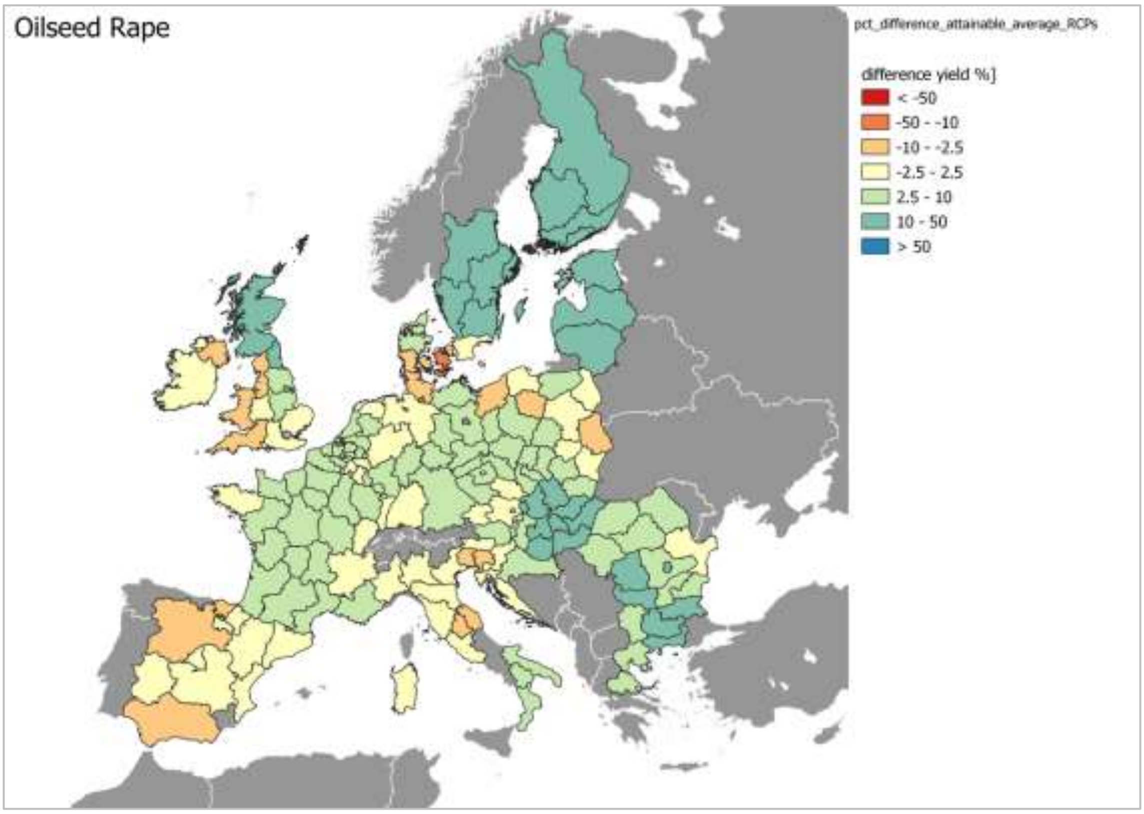

Figure 52: Relative difference (in %) between attainable yield of oilseed rape according to GAEZ simulations for historic to current conditions (1981-2011) and averaged GAEZ projections for climate change scenarios until 2040, in regions in the EU-27 and UK.

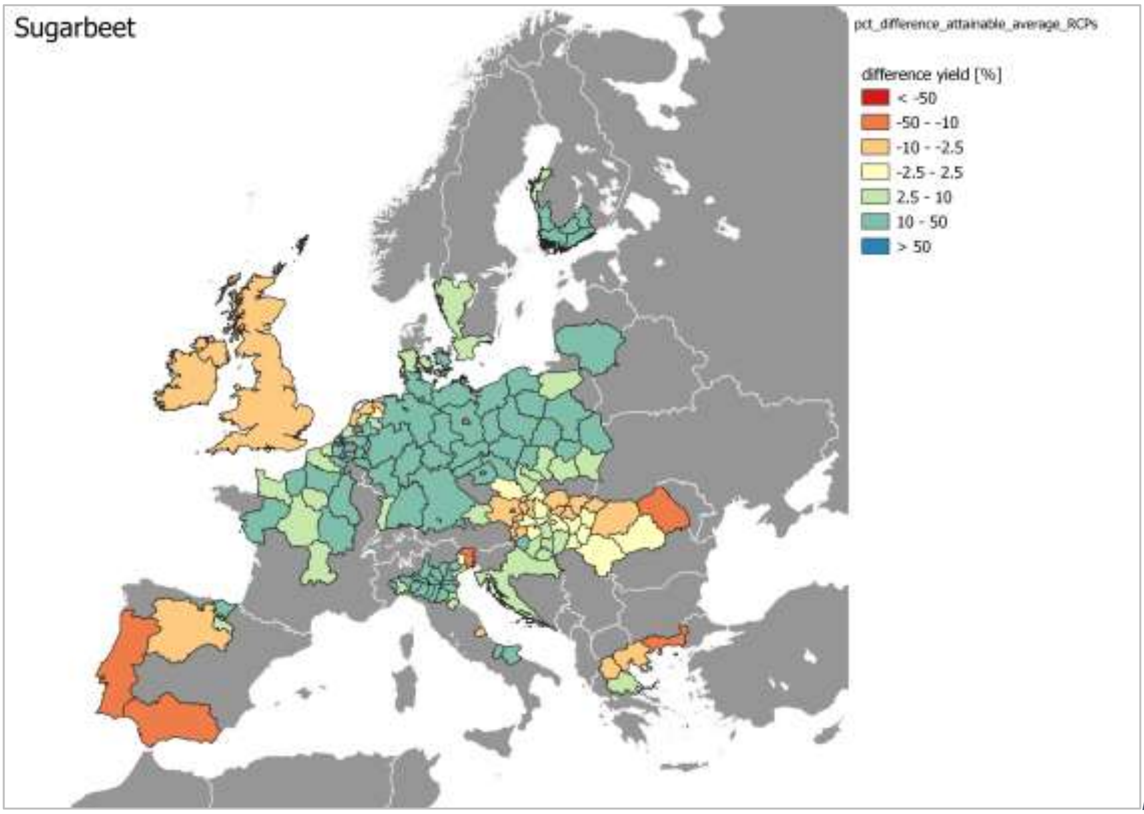

Figure 53: Relative difference (in %) between attainable yield of sugarbeet according to GAEZ simulations for historic to current conditions (1981-2011) and averaged GAEZ projections for climate change scenarios until 2040, in regions in the EU-27 and UK.

6. Estimated above-baseline biomass from conventional crops in EU27 & UK

Another approach for exploring the potential for additional biomass production is simply to extrapolate past yield trends into the future – either at the national, district, or the EU level. While this "statistics-based" method is fairly crude next to the more detailed analysis presented in Section 6, and should not be thought of as a prediction of future yields, it is nevertheless a useful first-order guide to which geographical areas might be candidates for further investigation. Moreover, it provides an order-of-magnitude upper estimate for the amount of additional biomass that might be available to biorefineries in future.

More specifically, we seek the annual yields (in units of t/ha/yr) and production (in units of kt/yr) of selected crops in all regions for the period 2020-30. Yields for a particular region are simply forecast into the future by fitting a line to the recorded yields in the period 2000-2020 (using a least-squares error minimisation), and then extrapolating this line to 2030. The *above baseline yield* is calculated as the difference between this extrapolated yield and the yield baseline, which was discussed in Sections 3.2 and 3.3. The *above baseline production* in each year is then calculated by multiplying the above baseline yield for a given region and crop by its harvested area. This above baseline production could potentially be certified as low ILUC-risk, if achieved on farms that also adopt additionality measures. For simplicity, we assume that the harvested area is static from 2020 onwards, though this may be revised in future analyses.

The calculation of the above baseline production is based on the rules laid out in RED II and associated regulations. Therein, additional production is to be assessed and certified at the *farm* (or farm-group) level. There is no legal avenue to identify above baseline production at the regional level and certify it as additional and therefore as low ILUC-risk; yet in the absence of extensive farm-level data, it is instructive to undertake an illustrative analysis at the national and district level. The results can then be interpreted as applicable to a hypothetical average farm in that area.

6.1. Additional biomass at the EU level

Figure 54, Figure 55, and Figure 56 present the potential above baseline production for cereal grains, oilseeds, and sugar beets respectively. Large gains above the baseline – in terms of the mass of material produced – are seen for wheat, barley, and sugar beet. Wheat and barley both experience high yield growth (averaging 0.33 t/ha/yr and 0.32 t/ha/yr respectively), and a large harvested area across the considered region (20.6 Mha and 5.0 Mha respectively[51]). Sugar beet has a lower harvested area (1.6 Mha), but much higher yields and yield growth, so there is a significant mass of above baseline material available by 2030.

Numerical data are presented in Table 15 of Annex V.

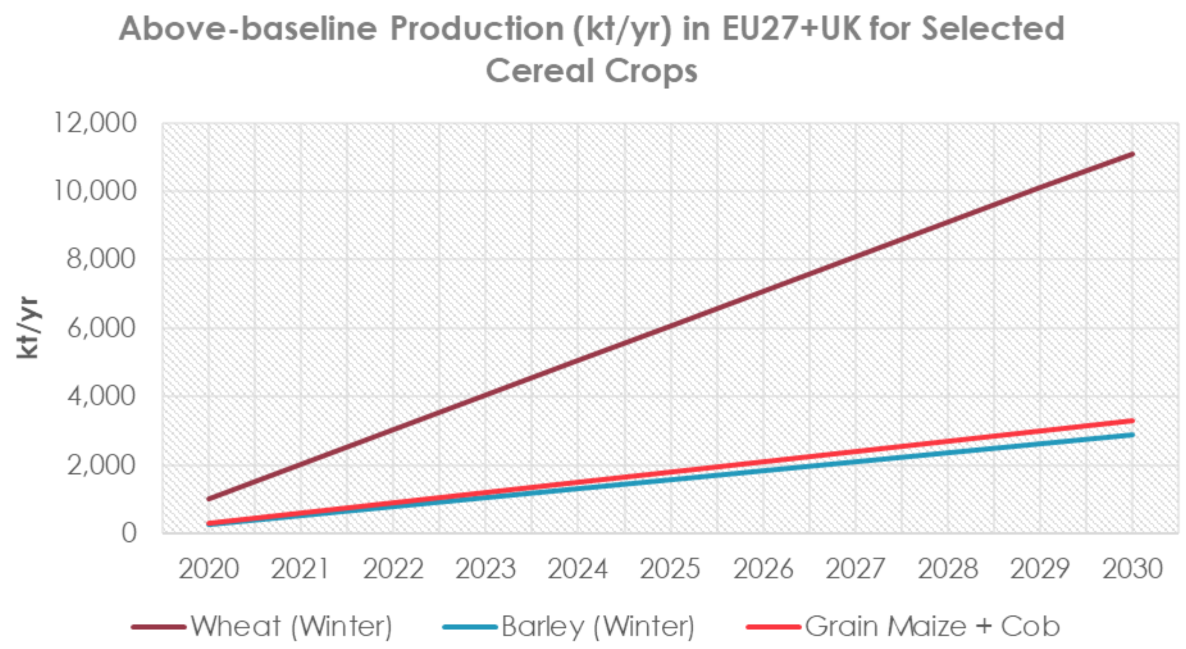

Figure 54: Estimate of the total annual above-baseline biomass production of cereal crops in the period 2020-30, for the EU27+UK.

[51] These are the land areas used for calculation based on the sum of declared national-level data; they differ slightly from the harvested area quoted for the EU as a whole.

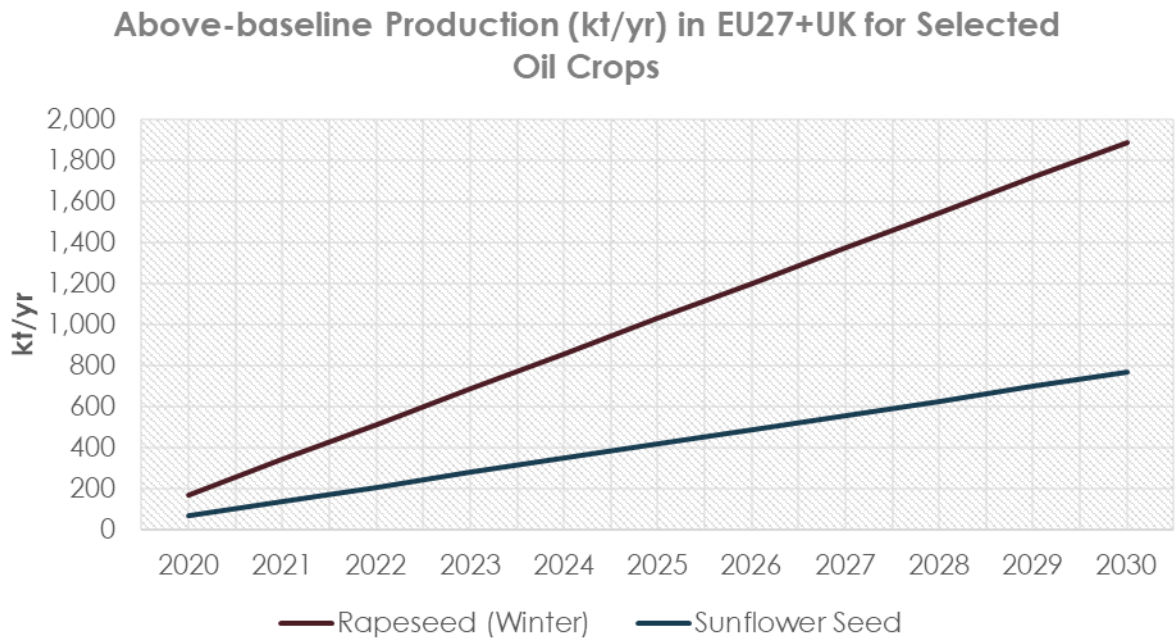

Figure 55: Estimate of the total annual above-baseline biomass production of oil crops in the period 2020-30, for the EU27+UK.

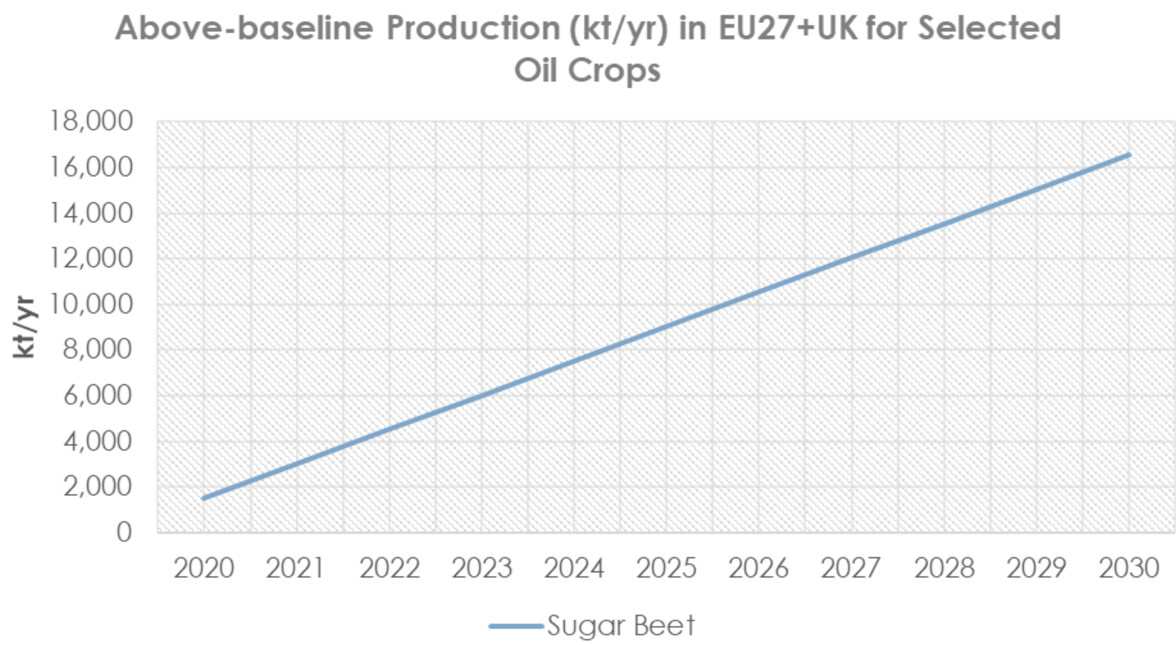

Figure 56: Estimate of the total annual above-baseline biomass production of sugar beet in the period 2020-30, for the EU27+UK.

6.2. Above baseline biomass at the national level

The results presented in the previous section point to potential above baseline feedstock production at the EU level. This section and the next localise more specifically where this production may take place – first locating it at the national level, and then (Section 7.3) at the NUTS2 district level.

The charts in Figure 57 to Figure 62 identify the countries in the EU27+UK with the highest potential for above baseline production, with one chart per crop. The quantity plotted as columns is the mean of the above baseline production over the years 2020-30[52] – in other words, how much above baseline material (in kt/yr) would be recovered in an average year from that country. The circles which are plotted against the right-hand vertical axis show the average above baseline yield (t/ha/yr) for each country; this quantity does not depend on the harvested area, and so provides a comparison between countries of where the greatest gains in productivity are being made. Tabulated data are presented in Annex VI.

Consequently, a country with a relatively high above baseline production but relatively low above baseline yield must be devoting a larger area to growing the crop in question. Conversely, a low above baseline production coupled with high above baseline yield suggests that the country has advanced performance for that crop and may have the option of producing much more above baseline material by re-allocating land to that crop.

Poland and Romania are examples of countries that demonstrate high potential above baseline production for a range of crops, in part due to large agricultural area dedicated to the crops in question and in part due to above-average historical yield gains. It would be reasonable, therefore, to look to these countries to lead in the production of additional bioenergy feedstock, provided adequate incentives are put in place and sustainability requirements can be satisfied.

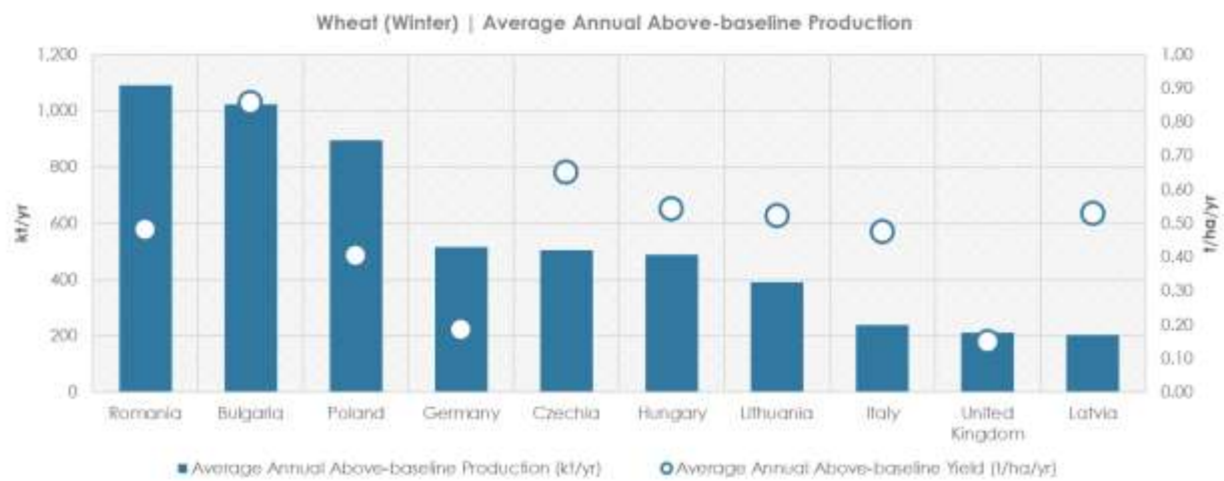

Figure 57: Top countries for production of additional wheat in the period 2020-30, as measured by the average annual production above the yield baseline.

[52] Since the additional production is described here by a straight line, this quantity is equal to the production in 2025.

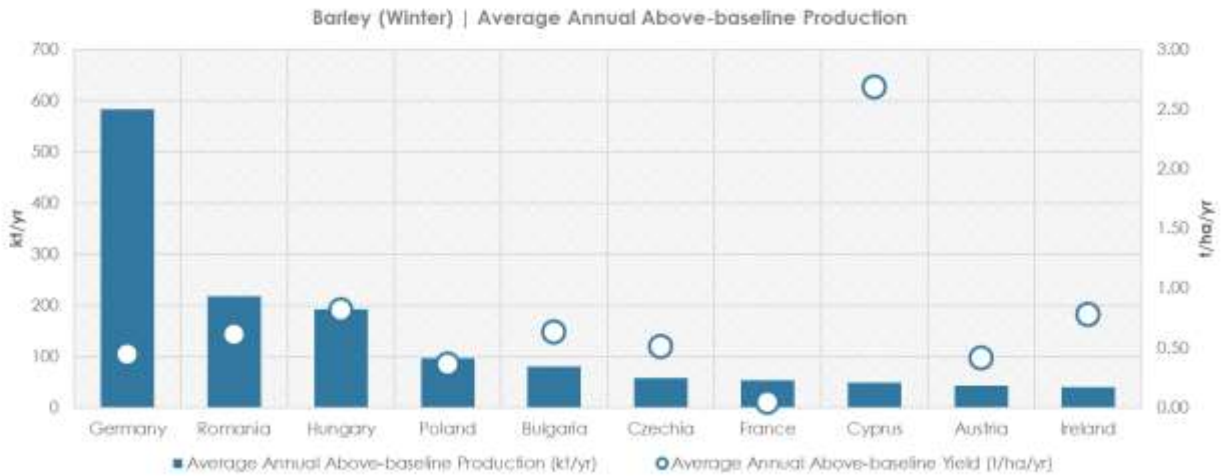

Figure 58: Top countries for production of additional barley in the period 2020-30, as measured by average annual production above the yield baseline.

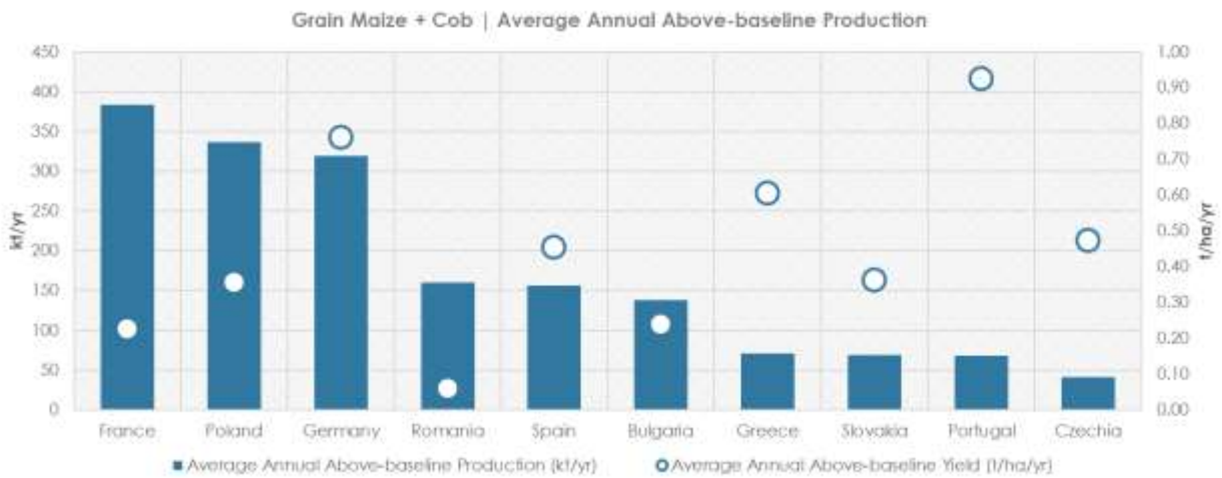

Figure 59: Top countries for production of additional grain maize in the period 2020-30, as measured by the average annual production above the yield baseline.

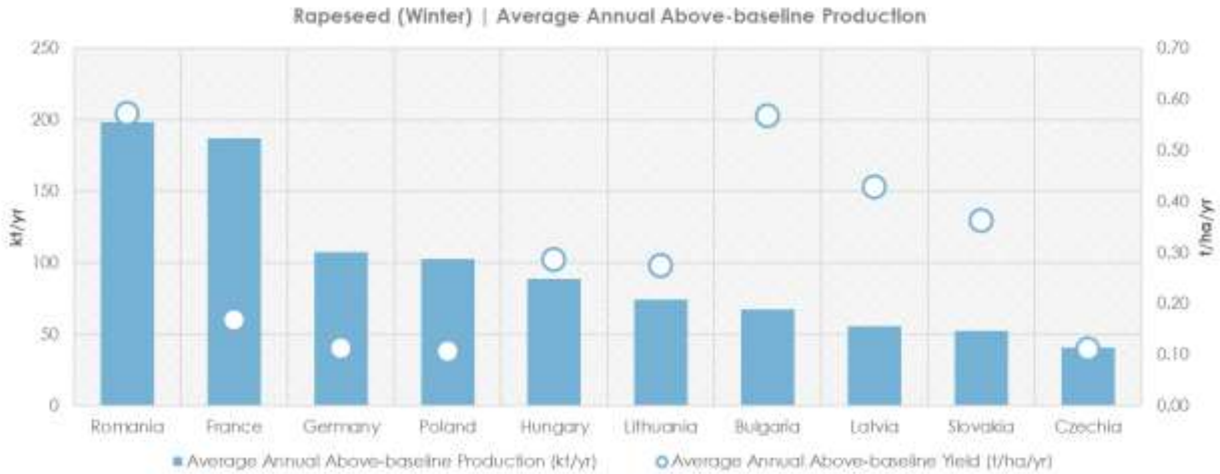

Figure 60: Top countries for production of additional rapeseed in the period 2020-30, as measured by the average annual production above the yield baseline.

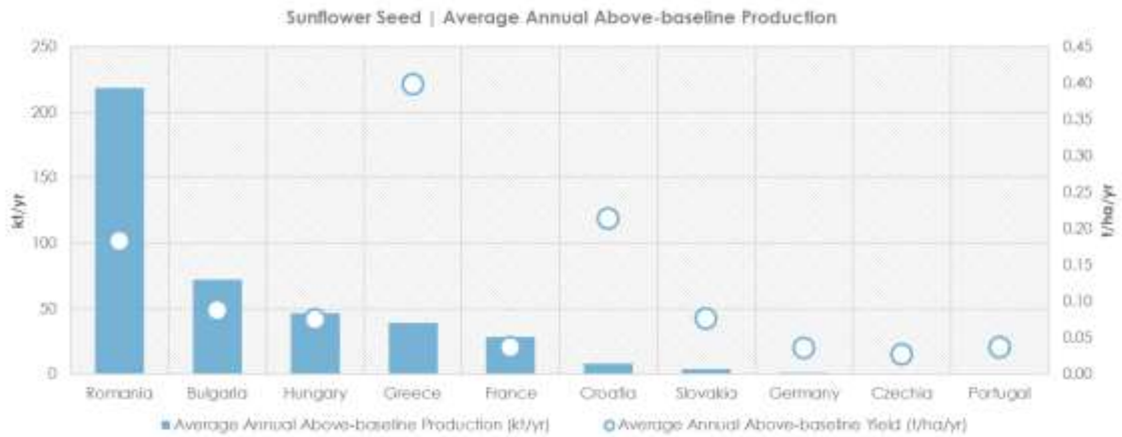

Figure 61: Top countries for production of additional sunflower seed in the period 2020-30, as measured by the average annual production above the yield baseline.

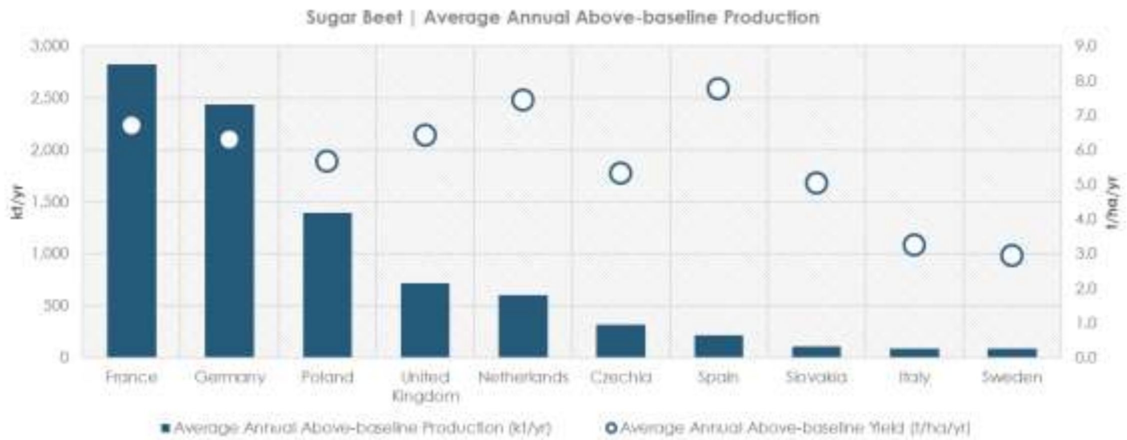

Figure 62: Top countries for production of additional sugar beet in the period 2020-30, as measured by the average annual production above the yield baseline.

6.3. Additional biomass at the NUTS2 level

The charts in Figure 63 to Figure 69 show the top NUTS2 regions[53] for potential above baseline biomass production; as in the previous section, there is one chart per crop; the 2020-30 average annual above baseline production (kt/yr) is plotted as columns, while the average annual above baseline yield for the region (t/ha/yr) is plotted as circles which reference a secondary axis. Tabulated data are presented in Annex VII.

Since data at the district level is sparser and of more variable quality than national data, these results may miss some high-performing regions. Nevertheless, the charts illustrate how the above analysis can be repeated at the district level in order to identify areas which, under the right economic conditions and respecting sustainability considerations, would be able to produce the most biofuel feedstock.

The top regions shown here may differ from the top countries of the previous section for two reasons. First, the size of the regions does not scale with the size of the host country, and the cultivated area for a given crop may differ markedly between regions in the same country, and hence from the national average. Second, within countries there can be wide variation in both yields (see, for instance,

Figure 9) and in yield growth, such that a large country with low overall above baseline production (for example) may still contain a region with high above baseline production.

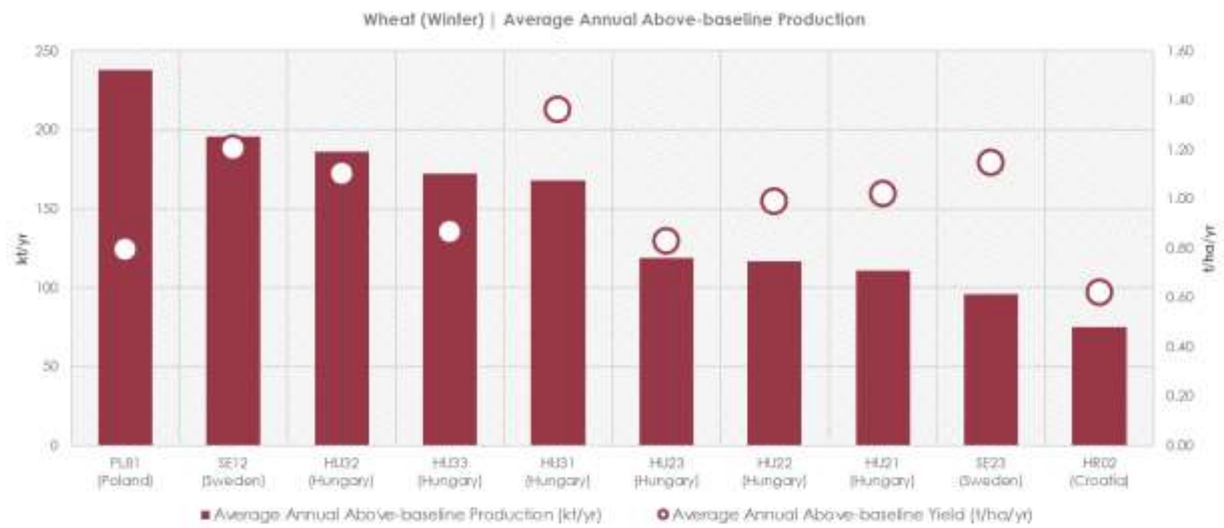

Figure 63: Top NUTS2 districts for production of additional wheat in the period 2020-30. The NUTS2 code is given, followed by the parent country in parentheses.

[53] The geographical locations of the NUTS2 regions can be found here: https://ec.europa.eu/eurostat/web/nuts/nuts-maps. From this page one can also access an interactive GIS tool.

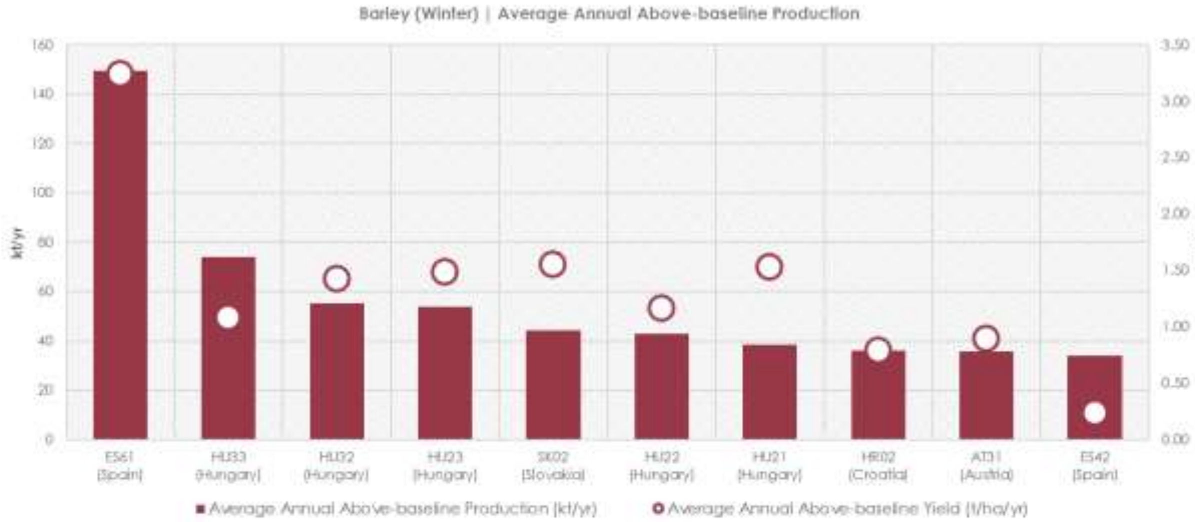

Figure 64: Top NUTS2 districts for production of additional barley in the period 2020-30. The NUTS2 code is given, followed by the parent country in parentheses.

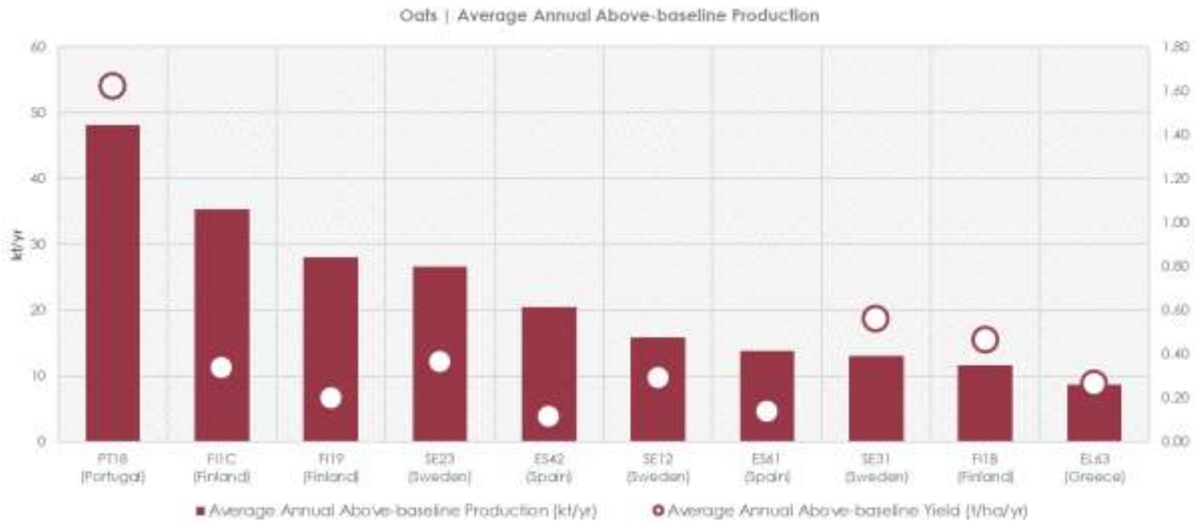

Figure 65: Top NUTS2 districts for production of additional oats in the period 2020-30. The NUTS2 code is given, followed by the parent country in parentheses.

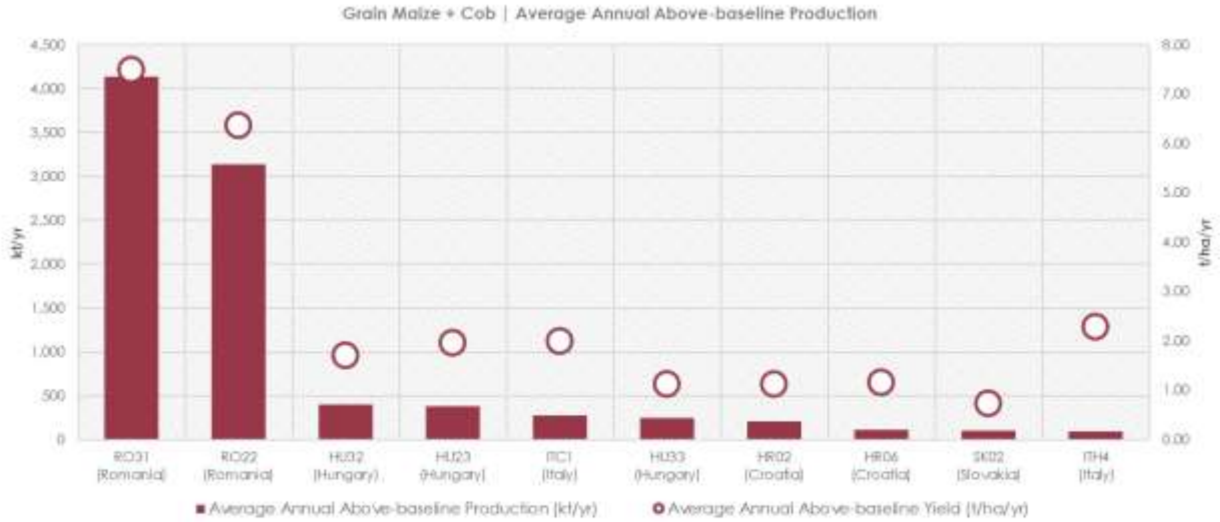

Figure 66: Top NUTS2 districts for production of additional grain maize in the period 2020-30. The NUTS2 code is given, followed by the parent country in parentheses.

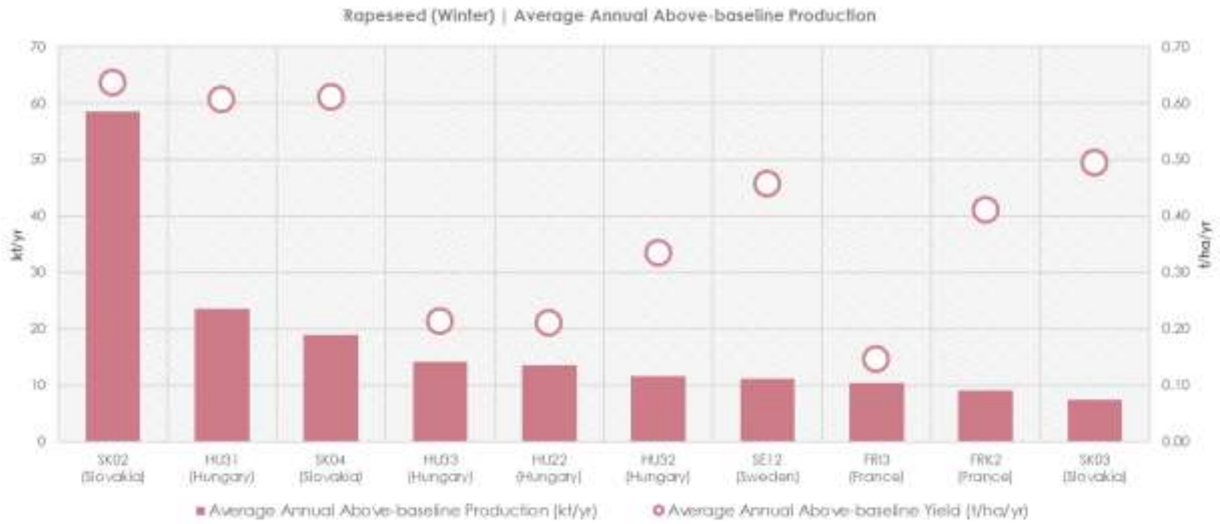

Figure 67: Top NUTS2 districts for production of additional rapeseed in the period 2020-30. The NUTS2 code is given, followed by the parent country in parentheses.

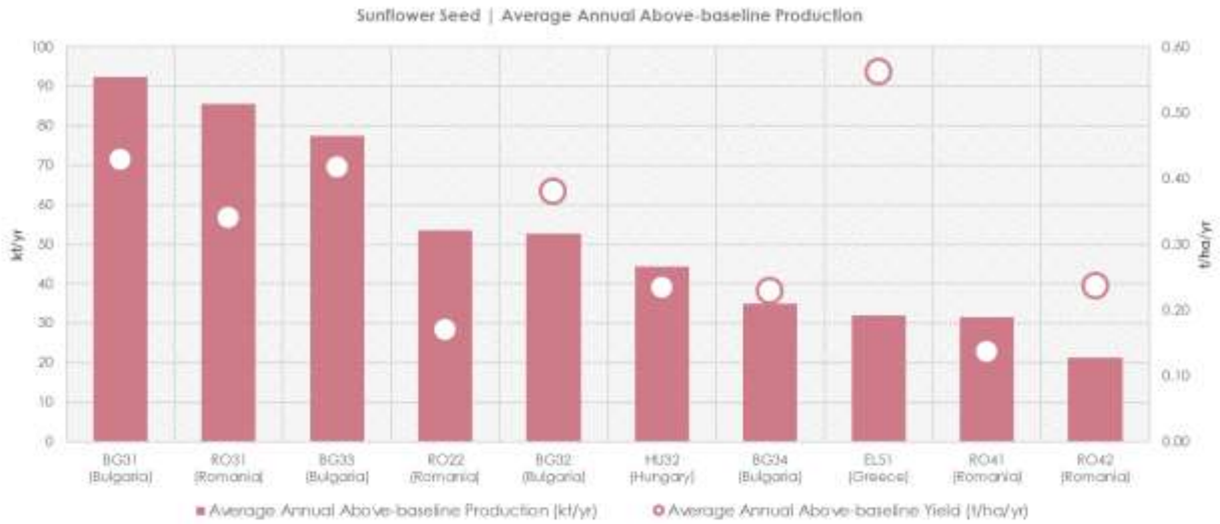

Figure 68: Top NUTS2 districts for production of additional sunflower seed in the period 2020-30. The NUTS2 code is given, followed by the parent country in parentheses.

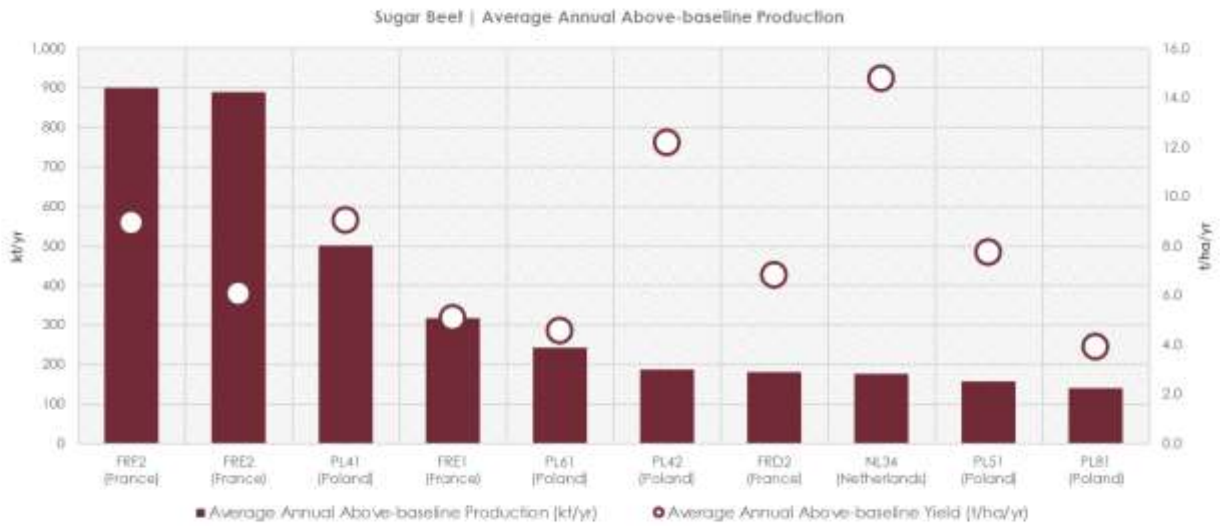

Figure 69: Top NUTS2 districts for production of additional sugar beet in the period 2020-30. The NUTS2 code is given, followed by the parent country in parentheses.

7. Conclusions

The continuing demand for bioenergy based on agricultural feedstocks creates a context for further development of the productive capacity of EU land; but this must be done in a way that minimises conflicts with food production, resource conservation, and ecological health. Support to grow energy crops while meeting these goals can incentivise – both directly and indirectly – production efficiencies, good management practices, and sound land stewardship, for instance through the rehabilitation of degraded land, or through crop rotations that regenerate soil health. The result of this will be an increased stock of land in good agricultural condition that – with the right safeguards and oversight – can add to the resiliency and flexibility of the agricultural sector and help to meet future demands for food, feed and biofuel in a sustainable manner. A core requirement here is ensuring that feedstock used is truly "additional", meaning that it is not being displaced from other uses and creating an increased demand for land elsewhere.

The concept of additional feedstock for biofuels receives legal status in the European Union's Renewable Energy Directive, and the regulatory basis to identify production as additional and certify it as low ILUC-risk is laid out in the related Commission Delegated Regulation on ILUC risk[54] and Implementing Regulation on certification[55]. These rules allow the certification of food and feed crop biomass, which is produced above a dynamic yield baseline following the application of measures to improve yields at the farm level. This report has explored some real-world implications of the legislative requirements, and has examined the scale of future feedstock production with three major objectives, viz.:

(i) Constructing the dynamic yield baselines for selected crops, using the RED II methodology and based on historical yields within the EU.
(ii) Assessing the potential for crop yield increases in Europe to provide additional biomass in the future.
(iii) Connecting this to the various land management practices which are known to positively impact yields.

The crops considered in this report are annuals and are conventional in the sense that they are already widely grown as food and feed crops in the EU and the UK. One benefit of this focus is that the crops are already well studied, and data and modelling tools are available for investigating their yield trends in time and across geography, as well as in response to changing management practices.

Using data collected by EUROSTAT, we were able to construct the dynamic yield baselines which form a central component of the additionality assessment. At the national level, these show high variability in time, as they are sensitive to the year in which the baseline is initialised. In some cases, this sensitivity is systematic, i.e., there is a strong background trend in national yields that diverges from the global trend used to extrapolate the baseline; however, there are countries and indeed years for which a high degree of *statistical* (that is, quasi-random) fluctuation is

[54] European Commission Delegated Regulation (EU) 2019/807.

[55] European Commission Implementing Regulation (EU) 2022/996

observed, presumably dominated by weather events. Naturally, these fluctuations are larger at the sub-national level, and will be further amplified at the farm level. The lesson to take from this is that the three-year average specified by RED II for initialising the baseline for annual crops sometimes fails to accurately set the baseline for a given region (and hence for a given farmer); therefore, there will be an element of randomness in the benefits that farmers can reap from low ILUC-risk certification.

Average yields also show great variability in space – both when considered across agro-ecological zones, and when considered from the perspective of administrative districts. It is possible to identify countries whose NUTS2 districts collectively possess a high spread in yields, and indeed neighbouring districts whose average yields diverge considerably. While these divergences may well be explained by inherent geographical and environmental conditions, they may also point to “yield gaps” arising from socio-economic or local bio-physical constraints. Such constraints may be surmountable, albeit with differing degrees of difficulty in different places; identifying the nature of the constraints and the steps necessary to overcome them will be an important step in unlocking Europe’s potential for additional feedstock production.

In a similar vein, we observe significant disparities between countries in terms of their average yield growth – that is, how their yields are changing over time. These disparities are amplified at smaller geographical scales, meaning that some NUTS2 districts experience yield growth much lower than their European neighbours (and possibly negative). In terms of the calculation of additional production that could be certified as low ILUC-risk, the relevant benchmark for comparison is the global average yield growth calculated from FAOSTAT data, because this is what sets the slope for the yield baseline (as dictated by the European Commission implementing regulation on certification[56]). A typical farm project in a region whose background yield slope exceeds the global average may be able to over-report additional feedstock production, while another one in a region whose yield slopes are smaller will struggle to produce certifiably additional feedstock under the current rules.

That being said, there is ample scope to improve agricultural performance – both ecological and productive – through a variety of farming and land management techniques. A non-exhaustive list of such techniques was included in the Commission’s aforementioned implementing regulation[57], and included items on advanced machinery and mechanisation, soil management, crop fertilisation and protections, adoption of different crop varieties, and multi-cropping practices. This report focusses on options for multi-cropping, rotations, and soil enrichment, providing descriptions of the practices, and evaluating their suitability on a crop-by-crop basis for European climate, soil, and ecological conditions.

Forecasting the impact on agricultural yields of taking these kinds of measures is critical to understanding the amounts of biomass that might be available in the future. This report has taken two approaches to projecting yield increases for selected crops: firstly, through detailed modelling, which requires characterisation of crop performance, local environmental factors and weather variability, as well as an overview of the constraints that determine policy priorities in

[56] Commission Implementing Regulation (EU) 2022/996.

[57] Annex VIII, Part A.2, Table 1.

the agricultural sector; and secondly, through an examination of past statistical trends in administrative districts in the EU27+UK.

Having identified areas which are already progressing on average at a greater rate than global benchmark, this report estimated the amount of above-baseline material available per year, assuming past trends continue into the near future (up to 2030); however, these calculations made no special consideration of additionality measures being taken at the farm level, and the resulting “above baseline material” is more a product of methodological technicalities than any genuine reward for agricultural efficiency or additionality measures. As has already been noted, for any given crop there is significant variance in the yield growth in different EU regions. While this is not unexpected, the implications with respect to the RED II’s low ILUC-risk methodology are clear: that the amount of above-baseline production has a strong dependence on geography independent of any additionality measures taken to improve harvests. Were there to be widespread uptake of the low ILUC-risk concept, this ‘tailwind’ yield effect would have a distorting effect on bioenergy incentives, encouraging the cultivation of crop bioenergy feedstocks in areas where background yield growth is high, while the opposite ‘headwind’ yield effect could undermining efforts to improve agricultural productivity in areas where yield growth is low. It is critical, therefore, to ensure sufficient safeguards are in place to ensure that low ILUC-risk certification does not (perversely) promote the diversion of business-as-usual crop gains into the bioenergy sector, and to ensure that farmers irrespective of geography are able to access incentives to adopt improved practices.

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Annex I. Inventory of available yield statistics for wheat, barley, maize and oilseed rape

Table 6: Inventory available yield statistics – total wheat (Joint Research Centre European Commission https://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx)

EU member states	Source
Austria	Joint Research Centre European Commission
Belgium	Joint Research Centre European Commission
Bulgaria	Joint Research Centre European Commission
Croatia	Joint Research Centre European Commission
Cyprus	Joint Research Centre European Commission
Czechia	Joint Research Centre European Commission
Denmark	Joint Research Centre European Commission
Estonia	Joint Research Centre European Commission
Finland	Joint Research Centre European Commission
France	Joint Research Centre European Commission
Germany	Joint Research Centre European Commission
Greece	Joint Research Centre European Commission
Hungary	Joint Research Centre European Commission
Ireland	Joint Research Centre European Commission
Italy	Joint Research Centre European Commission
Latvia	Joint Research Centre European Commission
Lithuania	Joint Research Centre European Commission
Luxembourg	Joint Research Centre European Commission
Malta	Joint Research Centre European Commission
Netherlands	Joint Research Centre European Commission
Poland	Joint Research Centre European Commission
Portugal	Joint Research Centre European Commission
Romania	Joint Research Centre European Commission
Slovakia	Joint Research Centre European Commission
Slovenia	Joint Research Centre European Commission
Spain	Joint Research Centre European Commission
Sweden	Joint Research Centre European Commission
United Kingdom	Joint Research Centre European Commission

Table 7: Inventory available yield statistics – (spring/winter) barley (URL EUROSTAT: https://ec.europa.eu/eurostat/data/database; sources accessed September 2021).

EU member states	Source
Austria	EUROSTAT (APRO_CPSH1)
Belgium	EUROSTAT (APRO_CPSH1)
Bulgaria	1991-2014: Agricultural Statistic Handbook of the Ministry of Agriculture, Agrosta cs (http://www.mzh.government.bg/MZH/Libraries/Списък_на_одобр_развъдни_орг/AgrostatisticalReferenceBookMAF-2000-2014.sflb.ashx) 2015-2019: EUROSTAT (APRO_CPSH1)
Croatia	2008-2012: Croatian Bureau of Statistics (https://www.dzs.hr/default_e.htm) 2013-2019: EUROSTAT (APRO_CPSH1)
Cyprus	No data

EU member states	Source
Czechia	EUROSTAT (APRO_CPSH1)
Denmark	EUROSTAT (APRO_CPSH1)
Estonia	EUROSTAT (APRO_CPSH1)
Finland	EUROSTAT (APRO_CPSH1)
France	Agreste (http://agreste.agriculture.gouv.fr/conjoncture/grandes-cultures-et-fourrages/)
Germany	EUROSTAT (APRO_CPSH1)
Greece	Hellenic Statistical Authority (http://www.statistics.gr/en/statistics/-/publication/SPG06/)
Hungary	EUROSTAT (APRO_CPSH1)
Ireland	EUROSTAT (APRO_CPSH1)
Italy	EUROSTAT (APRO_CPSH1)
Latvia	Statistical office Latvia (https://data.stat.gov.lv/pxweb/en/OSP_PUB/)
Lithuania	Statistical office Lithuania (https://osp.stat.gov.lt/)
Luxembourg	EUROSTAT (APRO_CPSH1)
Malta	No data
Netherlands	EUROSTAT (APRO_CPSH1)
Poland	EUROSTAT (APRO_CPSH1)
Portugal	Statistics Portugal (https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0000020&contexto=bd&selTab=tab2)
Romania	EUROSTAT (APRO_CPSH1)
Slovakia	EUROSTAT (APRO_CPSH1)
Slovenia	EUROSTAT (APRO_CPSH1)
Spain	EUROSTAT (APRO_CPSH1)
Sweden	EUROSTAT (APRO_CPSH1)
United Kingdom	EUROSTAT (APRO_CPSH1)

Table 8: Inventory available yield statistics – grain maize (URL EUROSTAT: https://ec.europa.eu/eurostat/data/database; sources accessed September 2021).

EU member states	Source
Austria	1990 – 2010: Statistics Austria (https://www.statistik.at/en/statistics/agriculture-and-forestry/crop-production-and-farming/arable-land-permanent-grassland) 2011-2019: EUROSTAT (APRO_CPSH1)
Belgium	No data
Bulgaria	Agricultural Statistic Handbook of the Ministry of Agriculture, Agrosta cs (http://www.mzh.government.bg/MZH/Libraries/Списък_на_одобр_развъдни_орг/AgrostatisticalReferenceBookMAF-2000-2014.sflb.ashx)
Croatia	Croatian Bureau of Statistics (https://www.dzs.hr/default_e.htm)
Cyprus	No data
Czechia	EUROSTAT (APRO_CPSH1)
Denmark	No data
Estonia	No data
Finland	No data
France	Agreste (http://agreste.agriculture.gouv.fr/conjoncture/grandes-cultures-et-fourrages/)

Germany	2000 – 2009: several statistical offices (https://de.wikipedia.org/wiki/Statistisches_Landesamt) 2010 – 2019: EUROSTAT (APRO_CPSH1)
Greece	EUROSTAT (APRO_CPSH1)
Hungary	Hungarian Central Statistical Office (https://statinfo.ksh.hu/Statinfo/themeSelector.jsp?&lang=en)
Ireland	No data
Italy	Istituto nazionale di statistica (http://dati.istat.it/Index.aspx?lang=en)
Latvia	No data
Lithuania	Statistical office Lithuania (https://osp.stat.gov.lt/)
Luxembourg	No data
Malta	No data
Netherlands	CBS (https://opendata.cbs.nl/statline/#/CBS/nl/)
Poland	Statistics Poland (https://stat.gov.pl/en/)
Portugal	Statistics Portugal (https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0000020&contexto=bd&selTab=tab2)
Romania	National institute of statistics (https://insse.ro/cms/en; http://datacube.statistics.sk/#!/view/en/VBD_SK_WIN/pl3001rr/Hectare%20yields%20of%20selected%20agricultural%20crops%20%5Bpl3001rr%5D)
Slovakia	Statistical Office of the Slovak Republic (http://datacube.statistics.sk/#!/lang/en)
Slovenia	No data
Spain	Ministerio de Agricultura, Pesca y Alimentación (https://www.mapa.gob.es/en/estadistica/temas/estadisticas-agrarias/agricultura/superficies-producciones-anuales-cultivos/)
Sweden	No data
United Kingdom	No data

Table 9: Inventory available yield statistics – oil seed rape (URL EUROSTAT: https://ec.europa.eu/eurostat/data/database; sources accessed July 2022).

EU member states	Source
Austria	EUROSTAT (APRO_CPSH1)
Belgium	EUROSTAT (APRO_CPSH1)
Bulgaria	EUROSTAT (APRO_CPSH1)
Croatia	EUROSTAT (APRO_CPSH1)
Cyprus	No data
Czechia	EUROSTAT (APRO_CPSH1)
Denmark	EUROSTAT (APRO_CPSH1)
Estonia	EUROSTAT (APRO_CPSH1)
Finland	EUROSTAT (APRO_CPSH1)
France	EUROSTAT (APRO_CPSH1)
Germany	EUROSTAT (APRO_CPSH1)
Greece	EUROSTAT (APRO_CPSH1)
Hungary	EUROSTAT (APRO_CPSH1)
Ireland	EUROSTAT (APRO_CPSH1)
Italy	EUROSTAT (APRO_CPSH1)
Latvia	EUROSTAT (APRO_CPSH1)
Lithuania	EUROSTAT (APRO_CPSH1)
Luxembourg	EUROSTAT (APRO_CPSH1)
Malta	No data
Netherlands	EUROSTAT (APRO_CPSH1)
Poland	EUROSTAT (APRO_CPSH1)
Portugal	No data
Romania	EUROSTAT (APRO_CPSH1)
Slovakia	EUROSTAT (APRO_CPSH1)
Slovenia	EUROSTAT (APRO_CPSH1)
Spain	EUROSTAT (APRO_CPSH1)
Sweden	EUROSTAT (APRO_CPSH1)
United Kingdom	EUROSTAT (APRO_CPSH1)

Table 10: Inventory available yield statistics – sugar beets (URL EUROSTAT: https://ec.europa.eu/eurostat/data/database; sources accessed September 2022).

EU member states	Source
Austria	EUROSTAT (APRO_CPSH1)
Belgium	EUROSTAT (APRO_CPSH1)
Bulgaria	No data
Croatia	EUROSTAT (APRO_CPSH1)
Cyprus	No data
Czechia	EUROSTAT (APRO_CPSH1)
Denmark	EUROSTAT (APRO_CPSH1)
Estonia	No data
Finland	Natural resources institute Finland - LUKE (http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__02%20Maatalous__04%20Tuotanto__14%20Satotilasto/01_Viljelykasvien_sato.px/?rxid=62120023-8519-4094-8eff-d18ae7bc66e1)
France	EUROSTAT (APRO_CPSH1)
Germany	EUROSTAT (APRO_CPSH1)
Greece	EUROSTAT (APRO_CPSH1)
Hungary	Hungarian Central Statistical Office (https://statinfo.ksh.hu/Statinfo/themeSelector.jsp?&lang=en)
Ireland	FAO (https://www.fao.org/faostat/en/#data/QCL)
Italy	Istituto nazionale di statistica (http://dati.istat.it/Index.aspx?lang=en)
Latvia	No data
Lithuania	EUROSTAT (APRO_CPSH1)
Luxembourg	No data
Malta	No data
Netherlands	EUROSTAT (APRO_CPSH1)
Poland	EUROSTAT (APRO_CPSH1)
Portugal	FAO (https://www.fao.org/faostat/en/#data/QCL)
Romania	EUROSTAT (APRO_CPSH1)
Slovakia	Statistical Office of the Slovak Republic (http://datacube.statistics.sk/#!/lang/en)
Slovenia	No data
Spain	EUROSTAT (APRO_CPSH1)
Sweden	EUROSTAT (APRO_CPSH1)
United Kingdom	EUROSTAT (APRO_CPSH1)

Annex II. FAOSTAT crop yield slopes

The global trend in yield growth for selected crops is provided in Table 11 for reference. This is used for calculating dynamic yield baselines for certifying low ILUC-risk production.

Table 11: Yield slopes for selected crops.

Crop	Yield Slope ($t/ha/yr^2$)	Source
Barley	0.035	Implementing Regulation
Maize	0.074	Implementing Regulation
Palm	0.200	Implementing Regulation
Rapeseed	0.036	Implementing Regulation
Soybean	0.028	Implementing Regulation
Sugarbeet	1.276	Implementing Regulation
Sugarcane	0.379	Implementing Regulation
Sunflower Seed	0.035	Implementing Regulation
Wheat	0.040	Implementing Regulation
Durum Wheat	0.040	Matches wheat
Rye	0.050	Calculated FAOSTAT 1998-2017
Oats	0.026	Calculated FAOSTAT 1998-2017

Annex III. Country codes

For reference, the country code abbreviations for EU countries and the UK are provided in Table 12.

Table 12: Country codes

Country ID	*Country Name*
AT	Austria
BE	Belgium
BG	Bulgaria
HR	Croatia
CY	Cyprus
CZ	Czech Republic
DK	Denmark
EE	Estonia
FI	Finland
FR	France
DE	Germany
GR	Greece
HU	Hungary
IE	Ireland
IT	Italy
LV	Latvia
LT	Lithuania
LU	Luxembourg
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SK	Slovakia
SI	Slovenia
ES	Spain
SE	Sweden
UK	United Kingdom

Annex IV. National yield statistics

Table 13 and Table 14 summarise two key statistics from the national-level Eurostat data: namely, the yield average and the yield slope, both calculated in the period 2000-20 for EU27+UK countries. A table entry of "—" indicates that no data / insufficient data are reported for that country-crop combination. Some small countries are omitted from the list.

Table 13: National yield averages for the period 2000-20, based on Eurostat data.

National Yield Average (t/ha/yr)	Wheat (Winter) C1111	Durum Wheat C1120	Rye C1210	Barley (Winter) C1310	Oats C1410	Rapeseed (Winter) I1111	Sunflower Seed I1120	Sugar Beet R2000
Austria	5.32	4.33	4.14	5.76	3.88	2.99	2.66	69.33
Belgium	8.59	--	--	8.12	5.32	--	--	83.95
Bulgaria	4.02	3.59	1.83	3.76	2.00	2.24	2.16	--
Czechia	5.47	--	4.53	4.83	3.22	3.02	2.34	57.56
Germany	7.55	5.32	5.13	6.68	4.58	3.60	2.17	67.07
Estonia	3.61	--	2.82	3.44	2.26	2.15	--	--
Spain	3.45	2.66	2.11	2.77	2.03	2.08	1.12	80.57
Finland	4.02	--	2.94	--	3.30	--	--	37.67
France	7.06	4.97	4.55	6.41	4.44	3.27	2.34	82.82
Croatia	5.39	4.85	3.10	4.47	2.88	2.54	2.65	52.42
Hungary	4.56	4.13	2.58	4.44	2.58	2.73	2.40	53.63
Ireland	8.93	--	--	8.12	7.19	4.09	--	--
Italy	5.28	3.04	2.94	3.89	2.34	2.52	2.19	55.82
Lithuania	4.28	--	2.35	3.50	2.07	2.55	--	48.69
Latvia	4.05	--	3.06	3.56	2.15	2.55	--	--
Netherlands	8.66	--	4.07	7.30	5.20	3.69	--	73.97
Poland	4.32	--	2.55	3.95	2.57	2.68	1.67	52.57
Portugal	2.42	2.26	0.98	2.63	--	--	0.85	58.59
Romania	3.52	2.97	2.32	3.32	1.87	2.07	1.78	32.71
Sweden	6.43	--	5.68	5.54	3.96	3.27	--	58.07
Slovenia	--	--	3.48	--	2.96	2.61	1.95	50.40
Slovakia	4.50	4.36	3.01	4.14	2.14	2.52	2.30	53.38
United Kingdom	7.84	--	4.30	6.48	5.59	3.44	--	63.60

Table 14: National yield slopes for the period 2000-20, based on Eurostat data.

National Yield Slope (t/ha/yr^2)	Wheat (Winter) C1111	Durum Wheat C1120	Rye C1210	Barley (Winter) C1310	Oats C1410	Rapeseed (Winter) I1111	Sunflower Seed I1120	Sugar Beet R2000
Austria	0.033	0.047	0.052	0.088	-0.001	0.032	0.007	0.685
Belgium	0.015	--	--	0.026	-0.094	--	--	0.194
Bulgaria	0.125	0.087	0.022	0.113	0.039	0.078	0.040	--
Czechia	0.083	--	0.074	0.106	0.036	0.039	0.022	0.996
Germany	0.014	0.004	-0.028	0.042	-0.013	0.001	-0.004	1.081
Estonia	0.127	--	0.079	0.155	0.024	0.066	--	--
Spain	0.052	0.030	0.046	0.014	0.019	0.026	0.013	1.411
Finland	0.049	--	0.089	--	0.015	--	--	0.237
France	0.001	0.048	-0.007	0.000	0.000	0.010	-0.003	0.468
Croatia	0.092	-0.002	0.057	0.110	0.034	0.035	0.052	1.711
Hungary	0.113	0.081	0.068	0.151	0.044	0.064	0.053	1.048
Ireland	0.028	--	--	0.088	0.044	0.040	--	--
Italy	0.049	0.054	0.029	0.049	0.009	0.062	0.019	0.986
Lithuania	0.087	--	0.015	0.082	0.021	0.058	--	1.620
Latvia	0.118	--	0.116	0.153	0.049	0.059	--	--
Netherlands	0.028	--	-0.067	0.114	-0.009	0.014	--	1.424
Poland	0.068	--	0.043	0.063	0.034	0.023	0.025	1.301
Portugal	0.029	0.067	0.008	0.069	--	--	0.062	-1.405
Romania	0.099	0.069	0.055	0.107	0.049	0.075	0.079	1.029
Sweden	0.051	--	0.049	0.049	0.014	0.014	--	1.197
Slovenia	--	--	0.058	--	0.045	0.052	0.074	1.188
Slovakia	0.097	0.091	0.054	0.128	0.044	0.073	0.047	1.196
United Kingdom	0.033	--	-0.193	0.037	-0.027	-0.010	--	0.960

Annex V. EU above-baseline production

Table 15 below presents the annual projected EU production for crops considered in this report, along with the average annual production and average yield in the period 2020-30. The projection is a linear extrapolation as described and graphed in Section 6 of the main text; the values presented in the table represent the total production above national baselines for all countries in the EU27+UK. These national baselines are calculated following the methodology stipulated in RED II and related regulations (see Section 2.2), and crucially rely on the global average yield trends from FAOSTAT which are quoted in Annex II.

Table 15: Projected EU production above the dynamic yield baseline for selected crops in the period 2020-30.

Crop Name	Crop ID	Harvested Area 2020 (kha)	EU Above-baseline Production (kt/yr)											Average Above-baseline Production 2020-30 (kt/yr)	Average Above-baseline Yield 2020-30 (t/ha/yr)
			2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030		
Wheat (Winter)	C1111	20,602	1,010	2,019	3,029	4,038	5,048	6,057	7,067	8,076	9,086	10,095	11,105	6,057	0.29
Durum Wheat	C1120	2,112	80	161	241	322	402	482	563	643	723	804	884	482	0.23
Rye	C1210	1,352	22	44	66	88	111	133	155	177	199	221	243	133	0.10
Barley (Winter)	C1310	5,042	263	527	790	1,054	1,317	1,581	1,844	2,108	2,371	2,635	2,898	1,581	0.31
Oats	C1410	2,698	47	95	142	189	236	284	331	378	425	473	520	284	0.11
Rapeseed (Winter)	I1111	5,428	172	343	515	686	858	1,029	1,201	1,373	1,544	1,716	1,887	1,029	0.19
Sunflower Seed	I1120	4,448	70	139	209	279	349	418	488	558	628	697	767	418	0.09
Sugar Beet	R2000	1,568	1,506	3,012	4,518	6,023	7,529	9,035	10,541	12,047	13,553	15,058	16,564	9,035	5.76

Annex VI. National above-baseline production

Table 16 below presents the average projected production and yield for selected crops at the national level. The time-period considered for the average is 2020-30, and the projection is a linear extrapolation as described and graphed in Section 6 of the main text. The values presented here are the total production above the respective national baseline, and in the interest of space, we show only the top 15 countries (ranked by additional production, t/yr).

National baselines are calculated following the methodology stipulated in RED II and related regulations (see Section 2.2), which relies on global average yield trends from FAOSTAT, given in Annex II.

Table 16: Projected above-baseline production and yield at the national level for selected crops in the period 2020-30. Only the top-producing countries are shown. Crop is shown at the top of each sub-table.

Wheat (Winter) | C1111															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Country	Romania	Bulgaria	Poland	Germany	Czechia	Hungary	Lithuania	Italy	United Kingdom	Latvia	Slovakia	Sweden	Croatia	Estonia	Austria
Average Above-baseline Production 2020-30 (kt/yr)	1,091	1,022	896	514	504	489	392	238	213	202	201	126	74	46	20
Average Above-baseline Yield 2020-30 (kt/yr)	0.48	0.86	0.40	0.19	0.65	0.54	0.52	0.48	0.15	0.53	0.59	0.31	0.51	0.39	0.08

Barley (Winter) | C1310															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Country	Germany	Romania	Hungary	Poland	Bulgaria	Czechia	France	Cyprus	Austria	Ireland	Slovakia	Italy	Croatia	Estonia	Lithuania

Average Above-baseline Production 2020-30 (kt/yr)	582	218	193	97	81	58	54	50	43	40	34	32	31	16	13
Average Above-baseline Yield 2020-30 (kt/yr)	0.45	0.61	0.82	0.36	0.63	0.51	0.05	2.69	0.42	0.78	0.67	0.12	0.53	0.71	0.53

Oats | C1410															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Country	Poland	Portugal	Romania	Sweden	Ireland	Lithuania	Germany	Latvia	United Kingdom	Czechia	Hungary	Croatia	Italy	Slovakia	France
Average Above-baseline Production 2020-30 (kt/yr)	133	55	27	14	11	9	8	7	7	3	2	2	1	1	1
Average Above-baseline Yield 2020-30 (kt/yr)	0.27	1.46	0.27	0.08	0.42	0.09	0.05	0.08	0.03	0.07	0.09	0.10	0.01	0.11	0.01

Rapeseed (Winter) | I1111															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Country	Romania	France	Germany	Poland	Hungary	Lithuania	Bulgaria	Latvia	Slovakia	Czechia	United Kingdom	Estonia	Sweden	Austria	Croatia
Average Above-baseline Production 2020-30 (kt/yr)	198	187	108	103	89	75	68	56	53	41	14	13	9	7	5

Average Above-baseline Yield 2020-30 (kt/yr)	0.57	0.17	0.11	0.11	0.29	0.27	0.57	0.43	0.36	0.11	0.04	0.23	0.09	0.23	0.12

Sugar Beet | R2000															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Country	France	Germany	Poland	United Kingdom	Netherlands	Czechia	Spain	Slovakia	Italy	Sweden	Romania	Croatia	Hungary	Austria	Lithuania
Average Above-baseline Production 2020-30 (kt/yr)	2,825	2,437	1,397	721	606	318	215	106	89	88	85	77	33	21	10
Average Above-baseline Yield 2020-30 (kt/yr)	6.71	6.31	5.68	6.43	7.43	5.34	7.77	5.04	3.25	2.96	3.72	7.37	2.54	0.78	0.75

Annex VII. District above-baseline production

Table 17 below presents the average projected production and yield for selected crops at the NUTS2 level. Refer to Annex VI for further description, as tables in this section follow the same format, except that here the top 15 districts are shown, indicated by their NUTS2 code[58] and their parent country.

Table 17: Projected above-baseline production and yield at the district level for selected crops in the period 2020-30. Only top-producing districts are shown. Crop is shown at the top of each sub-table.

Wheat (Winter) | C1111															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NUTS2 ID	PL81	SK02	SE12	HU32	HU33	HU31	HU23	HU22	HU21	SK04	SE23	HR02	SK03	ES22	ITH5
Parent Country	Poland	Slovakia	Sweden	Hungary	Hungary	Hungary	Hungary	Hungary	Hungary	Slovakia	Sweden	Croatia	Slovakia	Spain	Italy
Average Above-baseline Production 2020-30 (kt/yr)	238	207	196	186	172	168	119	116	111	110	96	75	49	37	35
Average Above-baseline Yield 2020-30 (kt/yr)	0.79	1.05	1.21	1.10	0.87	1.36	0.83	0.99	1.02	1.30	1.15	0.62	1.10	0.47	0.25

Barley (Winter) | C1310															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NUTS2 ID	ES61	HU33	HU32	HU23	SK02	HU22	HU21	HR02	AT31	ES42	HU31	ES41	ES43	ES52	ITH5
Parent Country	Spain	Hungary	Hungary	Hungary	Slovakia	Hungary	Hungary	Croatia	Austria	Spain	Hungary	Spain	Spain	Spain	Italy
Average Above-baseline Production 2020-30 (kt/yr)	149	74	55	54	44	43	39	36	36	34	32	31	27	26	21

[58] See Footnote 53 for a reference.

Average Above-baseline Yield 2020-30 (kt/yr)	3.24	1.08	1.42	1.48	1.55	1.17	1.53	0.79	0.89	0.24	1.67	0.48	2.92	3.15	0.93

Oats | C1410															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NUTS2 ID	PT18	FI1C	FI19	SE23	ES42	SE12	ES61	SE31	FI1B	EL63	FI1D	EL53	IE06	ES62	PL71
Parent Country	Portugal	Finland	Finland	Sweden	Spain	Sweden	Spain	Sweden	Finland	Greece	Finland	Greece	Ireland	Spain	Poland
Average Above-baseline Production 2020-30 (kt/yr)	48	35	28	27	20	16	14	13	12	9	8	5	5	4	4
Average Above-baseline Yield 2020-30 (kt/yr)	1.62	0.34	0.20	0.37	0.11	0.29	0.14	0.56	0.46	0.26	0.16	3.35	0.43	0.29	0.08

Rapeseed (Winter) | I1111															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NUTS2 ID	SK02	HU31	SK04	HU33	HU22	HU32	SE12	FRI3	FRK2	SK03	HU21	FRF2	SE23	HR02	FRE2
Parent Country	Slovakia	Hungary	Slovakia	Hungary	Hungary	Hungary	Sweden	France	France	Slovakia	Hungary	France	Sweden	Croatia	France
Average Above-baseline Production 2020-30 (kt/yr)	59	24	19	14	13	12	11	10	9	7	7	7	6	6	5
Average Above-baseline Yield 2020-30 (kt/yr)	0.64	0.61	0.61	0.21	0.21	0.33	0.46	0.15	0.41	0.49	0.20	0.05	0.41	0.17	0.04

Sunflower Seed | I1120															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NUTS2 ID	BG31	RO31	BG33	RO22	BG32	HU32	BG34	EL51	RO41	RO42	BG42	HU31	EL52	RO21	HU33
Parent Country	Bulgaria	Romania	Bulgaria	Romania	Bulgaria	Hungary	Bulgaria	Greece	Romania	Romania	Bulgaria	Hungary	Greece	Romania	Hungary
Average Above-baseline Production 2020-30 (kt/yr)	92	86	78	54	53	44	35	32	32	21	20	16	16	11	10
Average Above-baseline Yield 2020-30 (kt/yr)	0.43	0.34	0.42	0.17	0.38	0.23	0.23	0.56	0.14	0.24	0.22	0.22	0.53	0.05	0.07

Sugar Beet | R2000															
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NUTS2 ID	FRF2	FRE2	PL41	FRE1	PL61	PL42	FRD2	NL34	PL51	PL81	CZ02	NL23	PL52	SK02	NL11
Parent Country	France	France	Poland	France	Poland	Poland	France	Netherlands	Poland	Poland	Czechia	Netherlands	Poland	Slovakia	Netherlands
Average Above-baseline Production 2020-30 (kt/yr)	901	890	502	318	242	187	181	176	157	140	115	110	110	108	99
Average Above-baseline Yield 2020-30 (kt/yr)	8.93	6.06	9.05	5.08	4.56	12.20	6.81	14.77	7.74	3.93	7.15	12.62	7.20	5.69	7.30