Ref. Ares(2026)5032234 - 18/05/2026

MYMATCH

Deliverable 7.1

Agro-climate database + API documentation + agro-climate zones and suitability analysis and maps

Nature of the deliverable		
R	Document, report	X
DEM	Demonstrator, pilot, prototype	
DMP	Data Management Plan	
OTHER	Software, technical diagram, etc	

Dissemination level		
PU	Public (*fully open*)	X
SEN	Sensitive (*limited under the conditions of the Grant Agreement*)	
EU CI	EU Classified (*eu-restricted, eu-confidential, eu-secret under Decision 2015/444*)	

Deliverable No.	D7.1
Dissemination level	PU
Work Package	WP7
Task	Task 7.1
Lead beneficiary	CNR
Contributing beneficiaries	UNIPR, UNICATT, CNR
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Due date of deliverable	31.05.2026 (M18)
Actual submission date	30.04.2026 (M17)

Quality procedure			
Date	Version	Reviewers	Comments
02/05/2026	V1	Paola Battilani (UNICATT)	Answer to questions on the deliverables review process and Review dates
08/05/2026	V2	All partners	Review and update
12/05/2026	VF	Paola Battilani	Final check before submission.

Acknowledgements

This report is part of the deliverables from the project MYMATCH, which has received funding from the European Union's Horizon Europe research and innovation program under grant agreement N° 101181208. More information on the project can be found at www.mymatch-project.eu.

Document's objective and executive summary

Deliverable D7.1 documents the agro-climate data infrastructure and modelling outputs developed within MYMATCH to support climate-driven crop suitability analysis and subsequent fungi and mycotoxin simulations. The report integrates the agro-climate database and project cloud organisation, datasets generated or curated by WP4, WP5 and WP6, the technical Application Programming Interface (API), and the crop modelling and suitability analysis carried out in WP7.

The database component consolidates heterogeneous data streams, including literature-derived mycotoxin and exposure information, field sampling and fungal occurrence datasets, *in vitro* fungal response data, local and gridded weather information, climate projections, phenological simulations and derived agro-climatic indicators. Field and weather datasets provided in heterogeneous formats are harmonised within WP7 workflows; missing or incomplete local meteorological data are complemented through gridded reanalysis products and proximal open weather-station records where appropriate.

The suitability analysis is based on ensemble crop-climate simulations. For each crop, phenological variables and agro-climatic indicators were analysed under historical and future SSP scenarios. A domain-aware statistical framework was implemented to distinguish historically active areas, persistent future-active areas, newly flowering areas, and areas where simulated development is lost. This distinction is essential: newly flowering areas are not automatically interpreted as newly suitable areas, because a crop may reach flowering without completing maturity.

Results show that warming generally accelerates phenological development and increases the frequency of thermal stress indicators. However, the interpretation of geographical expansion changes substantially when flowering feasibility is evaluated together with maturity success. Across several crops, future climates may enable new areas to reach flowering or maturity, but these areas often differ strongly in terms of maturity probability, phenological timing and agro-climatic stress conditions. This demonstrates that climate-enabled phenological activation alone can overestimate agronomic suitability if it is not interpreted together with maturity success and crop-window stress indicators.

Contents

List of abbreviations

Abbreviation	Full Term
API	Application Programming Interface
AW	Area-weighted
CDD	Consecutive Dry Days
CHEFS	CompreHensive European Food Safety database
CMIP6	Coupled Model Intercomparison Project Phase 6
CSV	Comma-Separated Values
DOY	Day of Year
DSS	Decision Support System
EFSA	European Food Safety Authority
ERA5	ECMWF Reanalysis v5
FAIR	Findable, Accessible, Interoperable, Reusable
F-M	Flowering–Maturity
Flow DOY	Flowering Day of Year
Mat DOY	Maturity Day of Year
Dur F-M	Duration between flowering and maturity
pMat	Probability/frequency of reaching maturity
TropN	Tropical Nights
WetD	Wet Days
DryD	Dry Days

Abbreviation	**Full Term**
Precip	Precipitation sum
WSDI	Warm Spell Duration Index
Δ	Delta; future scenario mean minus historical mean, computed only over persistent pixels
ΔFlow DOY	Change in flowering Day of Year relative to historical conditions, computed only over persistent pixels
ΔMat DOY	Change in maturity Day of Year relative to historical conditions, computed only over persistent pixels
ΔDur F-M	Change in duration between flowering and maturity, computed only over persistent pixels
ΔTropN	Change in number of tropical nights, computed only over
ΔWSDI	Change in Warm Spell Duration Index days, computed only over persistent pixels
ΔWetD	Change in number of wet days, computed only over persistent
ΔDryD	Change in number of dry days, computed only over persistent
ΔPrecip	Change in precipitation sum, computed only over persistent
GCM	Global Climate Model
GDD	Growing Degree Days
GIS	Geographic Information System
INSPIRE	Infrastructure for Spatial Information in Europe
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
JSON	JavaScript Object Notation
MY	Mycotoxin

Abbreviation	Full Term
NetCDF	Network Common Data Form
REST	Representational State Transfer
SSP	Shared Socioeconomic Pathway
WKT	Well-Known Text
WP	Work Package

1. Introduction

MYMATCH aims to anticipate and manage climate-driven risks associated with mycotoxigenic fungi and mycotoxin contamination in European food systems. WP7 contributes to this objective by providing the climate, crop and agro-climatic modelling backbone needed to transform heterogeneous datasets into scenario-ready information layers.

D7.1 brings together data resources and modelling outputs generated across the project. It describes the database and cloud infrastructure, the technical API, the crop modelling framework and the suitability analysis. The suitability component represents climate-driven potential feasibility and stress-aware suitability, not actual cultivation patterns or operational yield forecasts.

2. Agro-climate database and data integration framework

The MYMATCH agro-climate database is part of the broader MYMATCH AI Platform architecture. The platform is being structured to integrate heterogeneous datasets, predictive models, climate projections, fungal ecology information and mycotoxin monitoring workflows into a unified digital ecosystem supporting scenario simulation, risk assessment and decision-making. The architecture explicitly includes the co-design methodology, logical and functional architecture, data architecture and end-to-end data flows, AI components, security model, DSS workflows, AgroSat integration and interoperability standards.

The database is organised through the project cloud infrastructure and provides the operational data layer for WP7 modelling activities. It links datasets from WP4, WP5, WP6 and WP7, together with selected external sources. These include literature-based mycotoxin and exposure datasets, field mycotoxin measurements, fungal ecology and *in vitro* experimental datasets, climate and weather data, land-use information, crop model outputs and external geospatial or monitoring resources such as AgroSat, Copernicus and national monitoring bodies.

Project cloud repository: https://cloud.mymatch-project.eu/

Within the MYMATCH technical architecture, two complementary components are distinguished. The Data Storage Server is based on PostgreSQL/PostGIS and supports structured data and spatial metadata handling. The Data Repository Server is based on NextCloud and is used for raw and harmonised dataset storage, file-level versioning and metadata management. Processed data are prepared for access by modelling workflows and downstream services through WP7 APIs.

The database workflow follows a structured data pipeline. Raw data are ingested through secure upload or API access, then validated, harmonised and transformed into model-ready formats. Harmonisation includes checks on units, temporal structure, spatial reference, variable naming, metadata completeness and consistency across work packages. Once validated, datasets are enriched with metadata following FAIR and INSPIRE principles, indexed spatially and temporally, and stored in versioned repositories. The resulting harmonised datasets can then be retrieved by the Scenario Builder, modelling engine, risk assessment layer and DSS components.

The agro-climate database therefore does not act as a passive file archive. It is a structured modelling backbone connecting climate forcing, local weather observations, crop phenology, agro-climatic indicators, fungal response data and mycotoxin occurrence/exposure information. This structure allows WP7 outputs to be used directly in downstream modelling chains, including crop–fungi–toxin–exposure simulations and spatial risk mapping. It also ensures traceability between original datasets, processed inputs, model outputs and final risk indicators.

For D7.1, the database supports three main functions. First, it provides a harmonised repository for essential agronomic, bioclimatic, climate, fungal and mycotoxin data. Second, it supplies model-ready inputs for crop suitability and future scenario simulations. Third, it enables the connection between WP7 agro-climate outputs and the broader MYMATCH platform, where results are structured to support subsequent integration into the Scenario Builder, Risk Assessment Layer, DSS and AgroSat visualisation workflows.

From a governance perspective, the database is aligned with the MYMATCH FAIR data strategy. Data are versioned, documented through metadata, spatially and temporally indexed, and organised to support reproducibility. This is particularly important because the platform combines heterogeneous sources with different spatial resolutions, temporal frequencies, formats and levels of completeness. The harmonised repository therefore provides the technical basis for transparent model execution, scenario comparison and future integration of AI-assisted data quality enhancement, anomaly detection and gap-filling procedures.

3. WP4 data resources: mycotoxin occurrence, exposure and literature-derived evidence

WP4 provides the mycotoxin-related evidence base for MYMATCH, mainly through literature-derived occurrence information, exposure-assessment resources and curated datasets describing the current availability and limitations of European mycotoxin data. The WP4 material reviews regulated and relevant mycotoxins, including aflatoxins, ochratoxin A, deoxynivalenol, zearalenone, fumonisins and T-2/HT-2 toxins, together with emerging and modified mycotoxins where information is available.

A key output of WP4 is the critical assessment of existing occurrence and exposure datasets. This includes information derived from the scientific literature, regulatory monitoring frameworks, EFSA-related exposure methodologies and the CHEFS database, which provides a curated occurrence-data backbone useful for harmonisation and cross-project interoperability. These resources help define the current baseline of available evidence and identify which toxin–commodity combinations are sufficiently documented and which remain poorly represented.

The main conclusion for WP7 is that WP4 data provide valuable contextual information for framing the mycotoxin issue and may support exposure assessment and model validation.. Available occurrence data are heterogeneous across countries, commodities, toxins, sampling strategies and analytical methods. They are also affected by left-censored observations, variable limits of detection and quantification, incomplete metadata and uneven temporal and spatial coverage. These limitations are especially relevant for emerging and modified mycotoxins, for which data availability is much weaker than for classical regulated toxins.

Therefore, WP4 outputs are used in MYMATCH primarily to support toxin prioritisation, scenario framing and the identification of data gaps. For occurrence data, the information extracted from literature and monitoring sources will be enriched, where possible, with CHEFS-derived datasets and harmonised across toxins, commodities, time periods and spatial units. This harmonised evidence base will be delivered to determine whether statistically meaningful baseline series can be generated. Where appropriate, AI-based methods will be evaluated in the next project phases to support data integration, pattern/anomaly detection, missing-data handling and uncertainty characterisation. The resulting enriched baselines will provide the reference context for connecting WP7 climate and crop suitability outputs with subsequent mycotoxin risk modelling activities.

4. WP5 field datasets and agro-climatic metadata

WP5 is collecting and organising a wide range of datasets related to field sampling, mycotoxigenic fungi occurrence, mycotoxin contamination, and associated agro climatic metadata. These datasets represent a fundamental input for WP7, supporting model calibration, agro climate zone characterization, and suitability simulations.

During the first project year, WP5 partners conducted extensive in field sampling across multiple European sites (maize, wheat, and tomato), leading to the collection of 144 samples, *versus* 143 initially planned. For each sampling point, partners are compiling agronomic metadata (cropping system information) and collecting meteorological data from local stations. Data collection process is still ongoing and several partners are still in the process of providing missing information.

Mycotoxin analyses are in progress for the first year of sampling (2025). 3 partners are in charge for chemical quantification, P2 (UNIPR) for maize, P3 (CNR) for wheat and P7 UMINHO for tomato. Parallel to chemical analyses, WP5 is conducting morphological and DNA based identifications of fungal contaminants from crop samples. Morphological identification has been completed for maize, wheat, and tomato samples collected in 2025 across most partners, while DNA based species-level identification is ongoing. These data will provide the first high resolution overview of fungal community composition and mycotoxigenic species distribution in European cropping systems.

The results obtained so far include detailed infection rate datasets for *Fusarium, Aspergillus, Alternaria, Penicillium*, and some information on other genera, both in cereals and tomato (the latter shared in symptomatic and asymptomatic fruits). These datasets will directly support WP7 by enabling the derivation of fungal pressure indicators, ecological response functions, and input layers for spatial risk mapping.

The final datasets to be delivered to WP7 will be consolidated once the metadata and the species level fungal identifications are fully available. The data currently uploaded to the cloud platform are summarised in several files: Excel files (crop field metadata; fungal isolation and genus level identification; infection rates) and Word documents (agronomic data related to crop fields).

In contrast, the meteorological data are not yet available in a harmonised format.

Overall, WP5 will provide WP7 with high resolution harmonised datasets including georeferenced fungal occurrence, infection rates, mycotoxin concentrations, and environmental and agronomic metadata, enabling enhanced agro climatic suitability analyses, and climate driven simulations for mycotoxin contamination in wheat, maize, and tomato.

5. WP6 fungal response datasets

Within WP6, *in vitro* experiments have generated data describing the response of key mycotoxigenic fungi (*Aspergillus flavus, Fusarium verticillioides, F. graminearum,* and *Alternaria* spp.) to environmental conditions relevant under climate change. Activities have included strain selection across partners, exchange of isolates, and growth and mycotoxin screening under a range of temperatures, including extreme conditions. These data are already available to be transferred to WP7. Further data have been obtained on fungal growth and, where available, mycotoxin production under controlled combinations of temperature, water activity and CO_2, as well as under single and co-inoculation conditions, allowing the assessment of species-specific responses and interactions.

Overall, WP6 outputs consist of structured datasets (microdata), including time-resolved measurements of fungal growth and mycotoxin production under different environmental conditions and species combinations. These data allow the quantification of the effects of environmental drivers and co-occurrence on fungal behaviour. All datasets are made available through Zenodo (DOI: 10.5281/zenodo.19592022).

For WP7, these data provide the basis for model improvement. They support the parameterisation and calibration of response functions to environmental variables, and improve the representation of fungal co-occurrence in predictive models. Their integration within the agro-climate database enables linking environmental conditions with fungal behaviour, contributing to more robust simulations across different agro-climatic contexts.

6. WP7 climate, crop and agro-climatic outputs

WP7 provides the climate forcing, crop modelling and agro-climatic indicator layers required to connect the data resources collected in WP4, WP5 and WP6 with climate-driven crop suitability and, subsequently, fungi and mycotoxin risk modelling. The WP7 workflow transforms harmonised climate projections into crop-specific phenological simulations and agro-climatic indicators computed over biologically relevant crop windows.

The climate forcing component is based on the ISIMIP3b archive, which provides bias-adjusted CMIP6 global climate model outputs suitable for impact modelling. For MYMATCH, the modelling chain uses a historical reference period covering 1981–2014 and future projections covering 2015–2100 under five Shared Socioeconomic Pathway scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. These scenarios allow the analysis to represent a gradient from low- to high-emission futures.

Climate-model uncertainty is addressed through ensemble processing. For each scenario, crop and indicator, the available GCM simulations are combined by averaging across GCMs while preserving the annual time dimension. This is important because the analysis does not rely only on long-term climatological means: probabilities, maturity frequencies and exceedance metrics are derived from yearly values over the full simulation period.

The crop modelling framework simulates crop-specific phenological development using thermal requirements, crop calendars and feasibility constraints. For each crop, essential parameters were retrieved from the literature, including base temperature, upper temperature threshold, sowing or starting date, thermal requirements for flowering and maturity, chilling requirements where applicable, maximum crop-cycle duration, and sensitivity ranges. Since climate scenario data are available at daily resolution, chilling hours for hazelnut were reconstructed from daily minimum, maximum and mean air temperature using a sinusoidal temperature approach. Sensitivity ranges of ±10% and ±20% were considered around the main crop parameters.

The modelling framework covers 13 crops: maize, rice, winter oat (W_oat), rye, winter wheat (W_wheat), winter barley (W_barley), tomato, pistachio, hazelnut, peanut, spring wheat, spring oat and spring barley. These include spring/summer annual crops, autumn/winter cereals, spring cereals and perennial/nut crops. The crop-model parameters used in the current modelling chain are summarised in Table 1.

Crop	Tbase (°C)	Tupper (°C)	Sowing (day)	Flowering (GDD)	Maturity (GDD)	Chillout N°hours	Kill DAS	Sensitivity
Maize	10	32	01/04	750	1500		180	10/20%
Rice	12	35	14/05	800	1230		180	10/20%
W_oat	0	30	01/11	700	1750		315	10/20%
Rye	4	35	01/10	800	1550		330	10/20%
W_wheat	0	35	01/01	800	1770		300	10/20%
W_barley	0	30	01/10	750	1650		315	10/20%
Tomato	5	32	01/05	525	2000		180	10/20%
Pistachio	7	35	01/01	730	3000		300	10/20%
Hazelnut	7	35	01/11	85	1621	535	315	10/20%
Peanut	10	35	15/05	686	1925		180	10/20%
S_wheat	0	35	01/04	650	1100		190	10/20%
S_oat	0	35	15/03	500	1000		190	10/20%
S_barley	0	35	01/04	560	920		190	10/20%

Table 1 Crop model parameters used in the WP7 modelling framework. GDD (Growing Degree Days) indicates the accumulated thermal requirement used to simulate crop development stages. Kill DAS (kill threshold in Days After Sowing) represents the maximum temporal window within which the crop must reach maturity, expressed as the number of days after sowing; beyond this threshold, the crop cycle is considered not feasible.

For maize, rice and winter wheat (W_wheat) parameters were retrieved from Battilani et al. 2012; for winter oat (W_Oat), rye and winter barley (W_barley) from Paredes et al. 2025 and FAO AquaCrop; for tomato from Saadi et al. 2015, Pathak & Stoddard 2018, Paredes et al. 2025, FAO AquaCrop and Di Gennaro et al. 2024. Spring wheat (S_wheat) from Saiyed et al. 2009 and FAO AquaCrop; for spring oat (S_oat) from Peltonen-Sainio&Rajala 2007; for spring barley from Pullens et al. 2021; for hazelnut from Bregaglio et al. 2016 and Bregaglio et al. 2020; for pistachio from Kaminiaris et al. 2020; for peanut from Crosta et al. 2024.

The WP7 outputs include both phenological indicators and agro-climatic stress indicators (Table 2-3). Phenological outputs describe the timing and feasibility of crop development, while agro-climatic indicators quantify thermal and hydrological conditions during relevant periods. For the suitability analysis, the most important agro-climatic variables are computed within the crop-specific flowering–maturity window, so that stress conditions are evaluated during the period most directly relevant for crop development and subsequent fungi/mycotoxin modelling.

Indicator	Domain	Definition / calculation
flowering_doy	Phenology	Day of year when flowering is reached.
maturity_doy	Phenology	Day of year when maturity is reached.
duration_flowering_maturity	Phenology	Number of days between flowering and maturity.
p_maturity	Phenology / suitability	Frequency or probability of reaching maturity over the analysed years.
chill_doy	Phenology / chilling	Chilling-related day-of-year indicator for hazelnut.
new_flowering	Domain metric	Land pixels where flowering is absent historically but occurs in a future scenario.
new_maturity	Domain metric	Land pixels where maturity is absent historically but occurs in a future scenario.
persistent	Domain metric	Land pixels active both historically and in the future scenario.
lost	Domain metric	Land pixels active historically but inactive in the future scenario.

Table 2 Phenological and suitability indicators produced in WP7

Indicator	Domain / window	Definition / calculation
prec_sum	General / crop window	Total precipitation over the selected period or flowering–maturity window.
wet_days	General / crop window	Number of days with precipitation above the wet-day threshold. In the crop-window analysis, this corresponds to days with RR > 1 mm.
dry_days	Crop window	Number of dry days in the flowering–maturity window. Reconstructed as flowering–maturity window length minus wet days; conceptually equivalent to RR < 1 mm days.
max_dry_days / dry_spell_cdd_max	General / crop window	Maximum length of consecutive dry days. This is a dry-spell intensity indicator and is distinct from the total number of dry days.
max_wet_days	General	Maximum length of consecutive wet days.
tropical_nights	General / crop window	Number of days with daily minimum temperature above the tropical-night threshold.
summer_days	General	Number of days with daily maximum temperature above the summer-day threshold.
max_summer_days	General	Maximum consecutive summer-day spell length.
frost_days	General	Number of days with minimum temperature below 0 °C.
max_frost_days	General	Maximum consecutive frost-day spell length.
ice_days	General	Number of days with maximum temperature below 0 °C.
cold_spell_duration	General	Duration of cold-spell events.
warm_spell_duration / wsdi_days	General / crop window	Warm Spell Duration Index; number of days belonging to warm-spell events. In the suitability analysis, wsdi_days is computed within the flowering–maturity window.
heavy_prec_days	General	Number of days with heavy precipitation.
very_heavy_prec_days	General	Number of days with very heavy precipitation.
bio_degree_days	General	Biologically relevant accumulated degree days.
growing_season_len	General	Length of the growing season.

Table 3 Agro-climatic indicators generated in WP7

A key methodological point is that dry_days and dry_spell_cdd_max are not interchangeable. dry_days describes the total number of dry days within the flowering–maturity window, while dry_spell_cdd_max describes the maximum length of a consecutive dry period. The first indicator captures cumulative dry-day exposure, whereas the second captures dry-spell persistence and intensity.

The crop-window indicators used directly in the suitability analysis are therefore:

- tropical nights;
- wet days;
- dry days;
- precipitation sum;
- WSDI days;
- maximum consecutive dry spell length.

These indicators are combined with phenological outputs to characterise both crop feasibility and stress exposure. In particular, the analysis distinguishes whether a crop reaches flowering, whether it reaches maturity, how long the flowering–maturity period lasts, and what thermal or hydrological conditions occur during that period.

Together, these WP7 outputs provide the spatial and temporal crop–climate backbone for the suitability analysis presented in the following section. They also provide the environmental context required for subsequent fungi and mycotoxin modelling, where crop phenology, maturity success, heat stress, wet/dry conditions and precipitation during sensitive crop stages are expected to influence fungal development and toxin risk.

7. API documentation

The MYMATCH API provides programmatic access to climate scenario data, seasonal forecasts, weather station data, gridded weather data and crop model outputs. The current base URL is: https://mmws.ibe.cnr.it

- Climate Change Scenario

Method: POST

Body: JSON

Response format: netCDF

URL: https://mmws.ibe.cnr.it/cc_scenario

Body

JSON payload to be included in the request body:

```
{
   "scenario": "type_of_scenario",
   "model": "type_of_model",
   "all_the_years": bool,
   "period": { "start": number,
          "end": number
```

```
        },
    "ensemble": string
}
```

Scenario	Options: - SSP1–1.9 - SSP1–2.6 - SSP2–4.5 - SSP3–7.0 - SSP5–8.5	Required
Model	Options: - GFDL-ESM4 - IPSL-CM6A-LR - MPI-ESM1-2-HR - MRI-ESM2-0 - REG-ENEA - ensemble	Required
All_the_years	True/False	Required
Period	Only if **All_the_years** is set to false • start: YYYY • end: YYYY	Optional
Ensemble	- all	Required

ensemble = multi-model mean across the available GCMs

Response

NetCDF files containing the following variables:timestamp,

- rainfall,
- air_temperature_min,
- air_temperature_max,
- air_temperature_average,
- relative_humidity_average,
- global_radiation_average,
- wind_speed_average,
- max_dry_days (Drought spell)
- max_frost_days (Cold spell)
- cold_spell_duration
- warm_spell_duration
- max_summer_days (Hot spell)
- max_wet_days (Wet spell)
- bio_degree_days
- growing_season_len
- frost_days
- ice_days
- heavy_prec_days

- very_heavy_prec_days
- prec_sum
- wet_days
- summer_days
- tropical_nights

- **Seasonal forecast**

Method: POST

Body: Polygon or Point in WKT format

Content-type: plain/text

Output format: netCDF

URL: https://mmws.ibe.cnr.it/seasonal_forecast/{date_from}/{date_to}/{srid}

Parameters

Date_from	format: YYYY-MM-DD	Required
Date_to	format: YYYY-MM-DD	Required
Srid	String containing the EPSG code for the geometric object provided in the body. Example: 4326 for the WGS84 coordinate reference system (Lat/Long).	Required

Body

A polygon or a geometric point in Well-Known Text (WKT) format:

POINT(22.3 55.4)

POLYGON((15.3408796956482 41.3898739487845,15.345171230072 41.3963128878931,15.3467590978088 41.3934154442214,15.3500206639709 41.3959909560854,15.3523810079041 41.389004643142,15.3408796956482 41.3898739487845))

Response

NetCDF file containing the extracted time series for the input point or polygon, with the following variables::

- timestamp,
- rainfall,
- air_temperature_min,
- air_temperature_max,
- air_temperature_average,
- relative_humidity_average,

- global_radiation_average,
- wind_speed_average,
- max_dry_days (Drought spell)
- max_frost_days (Cold spell)
- cold_spell_duration
- warm_spell_duration
- max_summer_days (Hot spell)
- max_wet_days (Wet spell)
- bio_degree_days
- growing_season_len
- frost_days
- ice_days
- heavy_prec_days
- very_heavy_prec_days
- prec_sum
- wet_days
- summer_days
- tropical_nights

- **Weather stations**

Method: GET

Output format: JSON Array

URL: https://mmws.ibe.cnr.it/weather_stations/{station_code}/{date_from}/{date_to}

Parameters

Date_from	Format: YYYY-MM-DD	Required
Date_to	Format: YYYY-MM-DD	Required
Station_code	Station code from the list provided by the partners	Required

Response

JSON array with the following structure:

```
[
  {
    "rainfall": float",
    "air_temperature_min": float,
    "air_temperature_max": float,
    "air_temperature_avg": float",
```

```
        "relative_humidity_avg": float,
        "relative_humidity_max": float,
        "global_radiation_average": float,
        "wind_speed_average": float,
            "timestamp": YYYY-MM-DD HH:mm:ss
    }
]
```

- **Weather gridded**

Method: POST

Body: Polygon or Point in WKT format

Content-Type: plain/text

Output format: netCDF

URL: https://mmws.ibe.cnr.it/weather_gridded/{date_from}/{date_to}/{srid}

Parameters

Date_from	Format: YYYY-MM-DD	Required
Date_to	Format: YYYY-MM-DD	Required
Srid	String containing the EPSG code for the geometric object provided in the body. Example: 4326 for the WGS84 coordinate reference system (Lat/Long).	Required

Body

A polygon or a geometric point in Well-Known Text (WKT) format:

POINT(22.3 55.4)

POLYGON((15.3408796956482 41.3898739487845,15.345171230072 41.3963128878931,15.3467590978088 41.3934154442214,15.3500206639709 41.3959909560854,15.3523810079041 41.389004643142,15.3408796956482 41.3898739487845))

Response

NetCDF file containing the extracted time series for the input point or polygon, with the following variables::

- timestamp,
- rainfall,

- air_temperature_min,
- air_temperature_max,
- air_temperature_average,
- relative_humidity_average,
- global_radiation_average,
- wind_speed_average,
- max_dry_days (Drought spell)
- max_frost_days (Cold spell)
- cold_spell_duration
- warm_spell_duration
- max_summer_days (Hot spell)
- max_wet_days (Wet spell)
- bio_degree_days
- growing_season_len
- frost_days
- ice_days
- heavy_prec_days
- very_heavy_prec_days
- prec_sum
- wet_days
- summer_days
- tropical_nights

- **Model**

Method: POST

Body: JSON

Output format: JSON

URL: https://mmws.ibe.cnr.it/cc_model

Body

JSON object with the following structure::

```
{
   "scenario": "type_of_scenario",
   "model": "type_of_crop",
   "all_the_years": bool,
   "period": { "start": number,
             "end": number
           },
    "ensemble": string
}
```

Scenario	Options: - SSP1–1.9 - SSP1–2.6 - SSP2–4.5 - SSP3–7.0 - SSP5–8.5	Required
Crop	Options: - Maize, - Rice, - Winter Oat, - Rye, - Winter Wheat, - Winter Barley, - Tomato, - Pistachio, - Hazelnut, - Peanut, - Spring Wheat, - Spring Oat, - Spring barley	Required
All_the_years	True/False	Required
Period	Only if **All_the_years** is set to false	Not mandatory

	- start: YYYY - end: YYYY	
Ensemble	Options: - number of the ensemble member - all	Required

Ensemble= specific ensemble member identifier

Response

JSON array with the following structure:

```
[
  {
    "flowering_doy": integer,
    "maturity_doy": integer,
    "t_stress_in_pheno_stages": float,
    "phenological_feasibility": float",
    "maturity_success": boolean,
    "dorman_related_stress": float
  }
]
```

Service	Method	Endpoint	Input	Output	Purpose
Climate Change Scenario	POST	/cc_scenario	JSON	NetCDF	Climate scenario layers by SSP, model, period and ensemble.
Seasonal forecast	POST	/seasonal_forecast/{date_from}/{date_to}/{srid}	WKT	NetCDF	Seasonal forecast variables for a point or polygon.
Weather stations	GET	/weather_stations/{station_code}/{date_from}/{date_to}	URL parameters	JSON array	Station-based weather time series.

Weather gridded	POST	/weather_gridded/{date_from}/{date_to}/{srid}	WKT	NetCDF	Gridded weather variables for a point or polygon.
Crop model	POST	/cc_model	JSON	JSON array	Model outputs such as flowering DOY, maturity DOY and maturity success.

Table 4 MYMATCH API services summary

8. Suitability analysis: methodological approach

The suitability analysis is based on pixel-wise yearly simulations. Historical simulations cover 1981–2014, while future simulations cover 2015–2100 for each SSP. For each crop, scenario and variable, ensemble time series are obtained by averaging across GCMs while preserving the annual dimension. This preserves interannual variability and allows probabilities and frequencies to be computed across years rather than from climatological means only. The modelling framework covers 13 crops, five future SSP scenarios and 11 indicators. Ten indicators are analysed for all crops, while chill_doy is included only for hazelnut. This results in 131 crop–indicator combinations per scenario and 655 crop–indicator–scenario statistical records for the future period. Considering the available GCM–scenario files, the analysis is based on 22,568 crop–year–GCM simulation units: 1,326 for the historical period and 21,242 for the future SSP period. These simulations are evaluated over a 138 × 90 spatial grid, with statistics restricted to the land mask of 6,232 land pixels. A domain-aware statistical framework is applied because not all pixels are valid in both historical and future periods. For each crop and scenario, the analysis distinguishes historically active pixels, persistent pixels that are active in both historical and future simulations, newly active pixels that were inactive historically but become active in the future, and lost-active pixels that were historically active but become inactive in a future scenario. Area statistics are computed both as land-pixel fractions and, where used for reporting, as area-weighted percentages using latitude-based weights. Within this domain-aware framework, a further distinction is made between newly flowering areas and newly maturing areas. Newly flowering areas identify land pixels where flowering is absent historically but occurs in a future scenario. Newly maturing areas identify land pixels where maturity is absent historically but occurs in a future scenario. This distinction is essential because reaching flowering does not necessarily imply completion of the crop cycle. Therefore, maturity-based metrics are used as the main indicator of effective climatic feasibility, while flowering-based metrics are retained as an early-stage phenological activation indicator. Changes relative to historical conditions are computed only for persistent pixels, where historical and future scenario values are both defined. Newly active pixels are not assigned a delta relative to historical values, because no valid historical baseline exists for those pixels. Instead, newly maturing areas are characterised through their future scenario mean conditions. This approach is applied to both phenological variables and agro-climatic indicators. For each crop and scenario, p_maturity is evaluated within the relevant new domains. In newly flowering areas, it indicates whether pixels that newly reach flowering also proceed to maturity. In newly maturing areas, it indicates the stability or frequency with which maturity is reached under the scenario conditions. Low p_maturity values therefore indicate marginal feasibility even where maturity becomes possible in at least part of the future period. Agro-climatic conditions in newly maturing areas are summarised using future scenario means. These include tropical nights, WSDI days, wet days, dry days, precipitation sum and maximum consecutive dry-spell length within the flowering–maturity window. This allows newly maturing areas to be characterised not only by their spatial extent, but also by the stress conditions under which maturity is achieved. Because DOY variables can be misleading when flowering occurs very late and maturity is only occasionally reached, flowering DOY, maturity DOY and flowering–maturity duration are always interpreted together with p_maturity. This avoids overinterpreting areas where warming enables partial phenological development but does not support stable completion of the crop cycle. Unless otherwise specified, all future scenario statistics reported in the following tables and figures are computed over the full 2015–2100 simulation period for each SSP scenario.

9. Domain-aware suitability results

The domain-aware analysis highlights that climate-driven crop suitability cannot be interpreted solely from the apparent expansion of phenological activity. A key outcome of the analysis is the distinction between areas where crops newly reach flowering and areas where crops newly reach maturity. This distinction is essential because, for several crops, warming enables flowering in new areas without necessarily allowing completion of the crop cycle. Therefore, newly flowering areas represent potential phenological activation, whereas newly maturing areas provide a more robust indication of effective climate-driven expansion of crop feasibility. Across the analysed crops, future scenarios generally show an increase in the spatial extent of maturity feasibility, particularly under higher-emission pathways. However, the magnitude and quality of this expansion differ strongly among crops. Some crops show large increases in new maturity areas but only moderate probabilities of reaching maturity within those areas, indicating marginal or unstable suitability. Other crops show limited spatial expansion but relatively high maturity probability where expansion occurs, suggesting more stable but geographically constrained suitability gains. A common signal across most crops is the acceleration of phenological development in historically suitable areas. In persistent areas, flowering and maturity generally occur earlier under future scenarios, and the duration between flowering and maturity tends to shorten. This pattern is consistent with warming-driven acceleration of crop development. However, shorter flowering–maturity periods should not be automatically interpreted as positive. A shortened reproductive or grain-filling phase may reduce the time available for biomass accumulation, yield formation or quality development, depending on the crop and management context. Thus, phenological acceleration may maintain or expand climatic feasibility while simultaneously increasing the risk of reduced agronomic performance.

Thermal stress indicators increase consistently across crops, especially warm spell duration index days and tropical nights. This increase is particularly strong for summer crops and perennial/nut crops. In persistent areas, the rise in WSDI is one of the clearest indicators of increasing heat stress. For maize, WSDI increases by about 17 days under SSP585; for tomato by about 27 days; for pistachio by about 44 days; and for peanut by about 31 days. These changes indicate that future suitability is not simply a question of whether crops can complete their phenological cycle, but whether they can do so under increasingly stressful thermal conditions. Water-related indicators show more complex behaviour. In several crops, dry days decrease in the flowering–maturity window, while precipitation also decreases. This apparent contradiction reflects the fact that the flowering–maturity window itself shifts in time and duration under future climates. A reduction in dry days does not necessarily imply improved water availability, especially when total precipitation decreases and thermal stress increases. In addition, shorter crop windows can mechanically reduce the number of dry days counted in that window. Therefore, precipitation, dry days, wet days and crop-window duration must be interpreted jointly rather than independently. The analysis of new maturity areas provides a more realistic interpretation of geographical expansion. In newly maturing areas, the scenario mean conditions show whether the new areas are climatically favourable or only marginally feasible. For example, maize and rice show relatively large new maturity areas under SSP585, but their maturity probabilities in these new areas remain low to moderate, around 0.23. This means that, although maturity becomes possible over a substantial additional area, it is not yet a highly stable outcome. In contrast, winter and spring cereals often show smaller new flowering areas but relatively high maturity probability in newly maturing areas. This suggests that, when expansion occurs, it is more consistently associated with completion of the crop cycle. The results also demonstrate that apparent expansion based on flowering alone can strongly overestimate actual suitability. For maize, under SSP585 the newly flowering area is about 10% of the land domain, but the newly maturing area is much larger, about 34% area-weighted, with a mean p_maturity of about 0.23. This indicates that much of the future maturity expansion does not necessarily correspond to areas where flowering was absent historically; rather, it includes areas where flowering may already have been possible but maturity was not reliably achieved. Therefore, maturity-based metrics are more appropriate for assessing effective crop feasibility. The distinction between historical persistent areas and new maturity areas also helps clarify the meaning of “suitability”. In historically suitable areas, the relevant question is how future climate changes the conditions under which crops already complete their cycle. In these areas, the analysis relies on deltas relative to historical conditions. In newly maturing areas, the relevant question is not the delta from historical conditions, because no valid historical maturity baseline exists. Instead, these areas are characterised by their future absolute conditions, including phenological timing, p_maturity and agro-climatic stress indicators. This approach avoids assigning artificial deltas to areas where historical crop development was not defined.

Overall, the results support a cautious but robust interpretation: future warming may increase the geographical feasibility of crop development for several crops, but this expansion is often accompanied by stronger heat stress, shorter crop cycles, and in some cases low stability of maturity in newly feasible areas. Consequently, the suitability maps and statistics should be interpreted as climate-driven feasibility and stress layers, not as direct predictions of future crop distribution or productivity. They provide the necessary crop–climate context for subsequent fungi and mycotoxin risk modelling, where timing of crop stages, maturity success, heat stress, wet/dry conditions and precipitation during sensitive windows are all relevant drivers.

10. Crop-specific synthesis

- ***Maize (table 5-6)***

In persistent areas, maize shows a clear and progressive acceleration of phenological development across the SSP gradient. Flowering advances from approximately −7 days under SSP119 to more than −15 days under SSP585, while maturity advances from about −8 to −17 days. The flowering–maturity period shortens consistently, from around −3 days in the low-emission scenarios to about −6.5 days under SSP585. This indicates that warming accelerates crop development and compresses the reproductive window. Agro-climatic stress increases substantially in the same persistent areas. Tropical nights increase progressively, reaching almost +6 days under SSP585, while WSDI increases strongly, from about +6 days under SSP119 to more than +17 days under SSP585. Precipitation during the flowering–maturity window decreases across all scenarios, with the strongest reduction under SSP585. Dry days also decrease, but this should be interpreted together with the shorter crop window and reduced precipitation; it does not necessarily indicate improved water conditions. In newly maturing areas, maize becomes feasible under relatively late phenological timing and increasing thermal stress. Flowering occurs around DOY 213–216, while maturity shifts from about DOY 260 under low scenarios to around DOY 249 under SSP585. The duration of the flowering–maturity period declines from about 67 to 56 days across the SSP gradient. Thermal stress in these new maturity areas increases markedly, with tropical nights rising from about 5 to more than 15 days and WSDI from about 19 to more than 34 days. Mean p_maturity remains low to moderate, increasing from about 0.05 to 0.23, indicating that newly maturing maize areas remain relatively unstable. Overall, maize shows an expansion of maturity feasibility under warming, but this expansion occurs under compressed phenological windows and increasing thermal stress. The results support a cautious interpretation: future climates may allow maize to complete maturity in new areas, but these areas are not necessarily agronomically optimal.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-7.37	-7.59	-3.29	2.70	5.94	-2.70	-3.44
SSP126	-7.92	-8.47	-3.68	3.14	7.51	-2.91	-4.64
SSP245	-10.86	-11.51	-4.81	4.37	11.14	-3.93	-5.26
SSP370	-13.31	-14.20	-5.73	5.15	14.24	-4.68	-6.33
SSP585	-15.46	-16.62	-6.56	5.69	17.38	-5.36	-7.57

Table5 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	212.90	260.17	67.34	0.046	4.65	18.72	17.67	49.67	113.20
SSP126	214.25	259.59	64.85	0.054	5.49	18.69	16.01	48.84	98.48
SSP245	213.97	257.24	62.92	0.118	7.47	21.95	18.18	44.74	115.29
SSP370	216.62	252.27	59.07	0.176	12.00	29.82	18.36	40.71	121.91
SSP585	216.02	248.59	56.51	0.226	15.35	34.34	18.44	38.07	121.90

Table 6 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Rice (table 7-8)***

In persistent areas, rice also shows strong phenological acceleration. Flowering advances from about −8 days under SSP119 to about −16 days under SSP585, while maturity advances from about −9 to −18 days. The flowering–maturity duration shortens consistently, reaching approximately −7.5 days under SSP585. This pattern indicates a clear warming-driven shortening of the rice reproductive phase. Thermal stress increases across scenarios, although less sharply than for maize in terms of tropical nights. Tropical nights increase by about +1.7 to +3 days, while WSDI rises from about +4 to nearly +12 days. Precipitation decreases strongly in the flowering–maturity window, from about −8 mm under SSP119 to nearly −15 mm under SSP585. Dry days also decrease, again requiring careful interpretation because both crop timing and window length change. In newly maturing areas, rice shows a consistent shift toward earlier maturity and shorter crop-window duration. Flowering occurs around DOY 243 under low scenarios and around DOY 241 under SSP585, while maturity advances from about DOY 273 to DOY 262. Duration decreases from about 55 to 45 days. Thermal stress increases clearly, with tropical nights rising from about 3 to more than 10 days and WSDI from about 16 to 31 days. p_maturity rises from about 0.06 to 0.23, suggesting increasing but still moderate stability of maturity in newly feasible areas. Overall, rice shows substantial new maturity feasibility, but this occurs under shorter developmental windows, declining precipitation and increasing heat stress. As for maize, maturity expansion should be interpreted as climate feasibility rather than robust agronomic suitability.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-7.81	-8.78	-3.97	1.69	4.27	-2.78	-8.25
SSP126	-8.77	-9.84	-4.45	1.98	5.53	-3.09	-9.29
SSP245	-11.68	-13.10	-5.78	2.58	8.24	-4.10	-11.49
SSP370	-14.14	-15.75	-6.77	2.91	10.19	-4.83	-13.35
SSP585	-16.39	-18.11	-7.55	3.05	11.78	-5.41	-14.67

Table7 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	243.03	273.27	54.88	0.059	3.43	16.40	13.23	41.65	95.02
SSP126	243.63	271.89	52.96	0.065	3.97	18.26	12.77	40.19	84.24
SSP245	242.76	267.76	49.94	0.128	5.42	22.04	12.48	37.46	80.20
SSP370	242.36	264.80	47.16	0.182	7.96	27.05	12.08	35.08	72.73
SSP585	241.33	261.62	44.96	0.228	10.65	31.14	11.93	33.03	68.49

Table8 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity

window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Winter oat (table9-10)***

In persistent areas, winter oat shows a different pattern from summer crops. Flowering changes little across scenarios, ranging from a slight advance to a small delay under SSP585. Maturity, however, advances strongly, from about −7 days under SSP119 to nearly −19 days under SSP585. The flowering–maturity duration shortens only moderately, by about −1 to −2.3 days. This suggests that warming primarily affects the timing of maturity rather than flowering. Thermal stress increases in persistent winter oat areas, mainly through WSDI. Tropical nights remain low, increasing by about +0.3 to +1.1 days, while WSDI rises from about +4 to nearly +16 days. Precipitation changes are modest and not monotonic, with small positive or negative variations depending on scenario. Dry days decrease slightly. Overall, the persistent-domain response is dominated by earlier maturity and increased warm-spell exposure, rather than by strong changes in tropical nights. In newly maturing areas, winter oat shows comparatively robust maturity feasibility. Flowering occurs around DOY 192 under SSP119 and around DOY 184 under SSP585, while maturity advances from about DOY 257 to DOY 229. The duration shortens substantially in absolute terms across scenarios, from about 65 to 45 days. p_maturity remains relatively high, increasing from about 0.67 to 0.74. Thermal stress increases, but remains moderate compared with summer crops. Overall, winter oat appears to gain new maturity feasibility with relatively stable p_maturity. The main concern is not failure to mature, but the combination of earlier maturity and increasing warm-spell exposure.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-0.30	-6.72	-0.69	0.28	4.41	-0.35	1.40
SSP126	-1.01	-8.78	-0.83	0.35	5.75	-0.48	3.28
SSP245	-0.22	-12.52	-1.53	0.58	9.28	-0.54	-0.73
SSP370	-0.01	-17.04	-2.03	0.82	13.10	-1.11	0.87
SSP585	1.33	-19.45	-2.34	1.11	15.88	-1.15	1.10

Table9 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	191.75	257.14	65.39	0.668	1.46	2.97	20.43	44.96	162.31
SSP126	190.44	252.49	62.05	0.687	1.67	3.69	19.90	42.16	151.57
SSP245	187.78	243.30	55.52	0.704	2.32	5.68	19.02	36.51	132.40
SSP370	184.20	233.51	49.31	0.722	3.60	9.55	17.40	31.91	103.91
SSP585	183.81	228.69	44.88	0.742	4.57	12.27	16.70	28.19	91.06

Table 10 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Rye (table11-12)***

In persistent areas, rye shows a non-linear phenological response across the SSP gradient. Flowering changes only moderately, with small advances under low and intermediate scenarios and almost no change under SSP585. Maturity advances under SSP119, SSP126 and SSP245, but the area-weighted mean maturity DOY increases under SSP370 and SSP585. This pattern suggests that the persistent-domain average is affected by shifts in the spatial distribution and timing of valid maturity events, rather than reflecting a simple uniform delay of rye development. For this reason, maturity DOY for rye should be interpreted together with the other phenological indicators rather than in isolation. This sign reversal reflects a shift in the subset of persistent valid pixels and should not be interpreted as a generalized delay in rye maturation. The flowering–maturity duration provides a more consistent signal, shortening progressively from about −1 day under SSP119 to about −4 days under SSP585. Agro-climatic stress increases progressively in persistent rye areas. Tropical nights rise from about +0.6 to +2.5 days across the SSP gradient, while WSDI increases from about +3.5 to +14.5 days. Precipitation changes are modest compared with summer crops, while dry days decrease by about −1 to −3 days. Overall, the persistent-domain response for rye indicates increasing warm-spell exposure and a shorter flowering–maturity window, while maturity timing itself shows a more spatially complex response. In newly maturing areas, rye shows moderate-to-good maturity stability. Flowering shifts from around DOY 161 under SSP119 to about DOY 152 under SSP585, while maturity occurs around DOY 245 under SSP119 and around DOY 220 under SSP585. The flowering–maturity duration decreases from about 85 to 68 days. p_maturity increases from about 0.62 to 0.68, indicating that newly maturing rye areas are more stable than those of several summer crops. Thermal stress increases in these new maturity areas, but remains below the levels observed for maize, tomato, pistachio or peanut. Overall, rye shows meaningful expansion of maturity feasibility under future climates, with moderate p_maturity and increasing thermal stress. The main robust signals are the shortening of the flowering–maturity duration and the increase in WSDI. The maturity DOY response in persistent areas should be treated cautiously because it likely reflects changes in the spatial composition of valid maturity pixels.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-1.97	-8.67	-0.91	0.56	3.49	-1.04	6.30
SSP126	-2.86	-11.40	-1.10	0.71	4.60	-1.21	9.05
SSP245	-2.48	-18.43	-1.99	1.23	7.56	-1.67	4.72
SSP370	-2.26	27.97	-2.97	1.81	11.21	-2.48	4.12
SSP585	-0.20	29.98	-4.06	2.49	14.48	-2.91	2.38

Table11 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	160.54	245.25	84.71	0.618	1.15	1.96	27.31	57.40	227.75
SSP126	158.72	241.20	82.48	0.624	1.37	2.38	26.65	55.83	218.20
SSP245	155.32	232.07	76.75	0.642	2.06	3.72	25.03	51.72	193.02
SSP370	151.98	222.22	70.24	0.662	3.05	6.43	22.51	47.73	154.82
SSP585	152.14	220.23	68.09	0.678	4.01	9.20	21.72	46.37	143.73

Table 12 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Winter wheat (table 13-14)***

In persistent areas, winter wheat shows a consistent advancement of both flowering and maturity. Flowering advances from about −4 days under SSP119 to about −14 days under SSP585, while maturity advances from about −6 to −16 days. The flowering–maturity duration shortens progressively, reaching about −3.8 days under SSP585. This indicates a clear acceleration of crop development in historically active areas. Thermal stress increases mainly through WSDI rather than tropical nights. Tropical nights remain relatively low, increasing by less than +1 day under SSP585, while WSDI increases by about +12 days. Precipitation declines under the highest scenario, reaching about −13 mm under SSP585. Dry days decrease slightly, again partly linked to the shorter and shifted flowering–maturity window. In newly maturing areas, winter wheat shows relatively stable maturity feasibility. Flowering occurs around DOY 205 under SSP119 and around DOY 192 under SSP585, while maturity advances from about DOY 250 to DOY 232. Duration declines from about 46 to 40 days. p_maturity remains relatively high, around 0.62–0.64 across scenarios. Thermal stress increases, but remains moderate compared with summer crops.

Overall, winter wheat shows a coherent warming response: earlier phenology, shorter crop windows, moderate heat-stress increase, and relatively stable maturity in newly feasible areas. This suggests more robust expansion of maturity feasibility than for maize, rice, tomato, pistachio or peanut.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-3.87	-5.53	-0.80	0.16	2.60	-0.38	2.49
SSP126	-4.78	-7.29	-0.87	0.19	3.50	-0.33	3.98
SSP245	-7.17	-10.18	-1.62	0.32	5.77	-0.53	-0.59
SSP370	-8.85	-12.85	-2.32	0.50	8.79	-0.94	-0.90
SSP585	-14.09	-15.59	-3.78	0.79	11.91	-0.97	-13.02

Table13 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	204.55	250.43	45.88	0.623	0.48	1.64	15.40	30.48	117.97

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP126	202.54	247.13	44.59	0.620	0.55	2.04	15.39	29.20	116.35
SSP245	198.56	241.18	42.63	0.616	0.81	3.03	14.97	27.66	108.93
SSP370	195.10	235.30	40.20	0.623	1.27	5.00	13.76	26.44	88.55
SSP585	192.24	232.05	39.81	0.642	2.07	7.62	13.40	26.41	80.97

Table14 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Winter barley (table 15-16)***

In persistent areas, winter barley shows a mixed phenological signal. Flowering is slightly delayed, especially under higher scenarios, reaching about +6 days under SSP585. In contrast, maturity advances strongly, by about −6.5 days under SSP119 and about −15.8 days under SSP585. The flowering–maturity duration shortens moderately, by about −0.7 to −1.6 days. This indicates a redistribution and compression of phenological timing rather than a uniform advancement of all stages. Thermal stress increases progressively. Tropical nights rise modestly, reaching about +1.1 days under SSP585, while WSDI increases by about +11 days. Precipitation changes are small and mostly positive, unlike many summer crops, while dry days decline slightly to moderately. In newly maturing areas, winter barley shows relatively robust maturity feasibility. Flowering occurs around DOY 171 under SSP119 and around DOY 161 under SSP585, while maturity advances from about DOY 250 to DOY 218. Duration shortens from about 78 to 58 days. p_maturity increases from about 0.59 to 0.66 across scenarios. Thermal stress increases, but remains moderate compared with summer crops.

Overall, winter barley shows expansion of maturity feasibility under warming, with moderate p_maturity and increasing WSDI. The delayed flowering signal in persistent areas should be noted, as it indicates that phenological responses are not simply linear advancements across all stages.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	0.32	-6.50	-0.72	0.19	3.26	-0.23	4.20
SSP126	0.36	-8.02	-0.82	0.23	4.20	-0.34	5.62

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP245	2.24	-11.47	-1.28	0.37	6.73	-0.51	1.11
SSP370	3.60	-14.32	-1.52	0.62	9.75	-0.72	2.17
SSP585	6.02	-15.75	-1.64	1.09	10.70	-0.89	1.80

Table15 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	171.48	249.57	78.08	0.594	0.87	1.97	22.92	55.16	188.90
SSP126	169.79	245.11	75.32	0.602	1.03	2.31	21.85	53.47	178.03
SSP245	167.88	235.99	68.11	0.628	1.49	3.65	19.30	48.81	147.12
SSP370	164.11	225.67	61.56	0.645	2.16	5.62	17.16	44.40	116.98
SSP585	160.57	218.35	57.78	0.661	2.99	8.03	15.86	41.92	99.59

Table16 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Tomato (table 17-18)***

In persistent areas, tomato shows strong acceleration of phenology and severe increases in heat stress. Flowering advances by about −4 to −8 days across scenarios, while maturity advances more strongly, reaching about −15 days under SSP585. The flowering–maturity duration shortens markedly, from about −6 days under SSP119 to nearly −11 days under SSP585. Thermal stress increases strongly. Tropical nights rise from about +5.5 days under SSP119 to more than +11 days under SSP585, while WSDI increases from about +9 to more than +27 days. Precipitation decreases sharply, reaching about −20 mm under SSP585. Dry days also decrease, but this occurs together with a much shorter crop window and lower precipitation, so it should not be read as an improvement in water availability. In newly maturing areas, tomato maturity feasibility remains weak. p_maturity is very low, increasing only from about 0.03 to 0.12 across scenarios. Newly maturing areas are characterised by short flowering–maturity duration, high tropical nights and very high WSDI. Under high scenarios, precipitation in these areas is very low. This indicates that new maturity areas for tomato are highly marginal.

Overall, tomato shows limited and unstable expansion of maturity feasibility. Persistent areas experience strong heat-stress increases and shorter crop windows, while newly maturing areas remain characterised by low p_maturity and severe thermal stress.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-4.30	-5.72	-6.02	5.49	9.29	-3.96	-11.47
SSP126	-4.59	-6.21	-6.66	6.02	10.83	-4.41	-13.18
SSP245	-5.99	-8.17	-8.02	7.64	15.43	-5.54	-16.47
SSP370	-7.17	-11.10	-9.33	9.52	20.57	-6.38	-17.94
SSP585	-8.15	-15.11	-10.79	11.40	27.03	-7.45	-20.51

Table 17 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	207.45	244.98	37.52	0.030	8.59	24.19	9.09	28.43	59.82
SSP126	207.95	245.24	37.29	0.028	10.49	27.63	9.28	28.01	62.08
SSP245	207.55	242.91	35.37	0.055	12.92	34.94	8.87	26.50	54.58
SSP370	209.05	239.26	30.21	0.082	18.89	47.25	7.56	22.65	41.23
SSP585	211.95	238.39	26.44	0.118	25.27	58.31	6.99	19.45	33.72

Table 18 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Pistachio (table 19-20)***

In persistent areas, pistachio shows strong phenological acceleration. Flowering advances from about −9 days under SSP119 to about −17 days under SSP585, while maturity advances from about −9 to −24 days. The flowering–maturity duration shortens progressively, reaching nearly −9 days under SSP585. This indicates a strong warming-driven acceleration of the crop cycle. Thermal stress increases severely. Tropical nights increase by about +4 to +8 days, while WSDI increases from about +14 to more than +44 days. This is one of the strongest WSDI increases among all analysed crops. Precipitation declines under all scenarios, especially under SSP585, while dry days decrease moderately. The combined signal is one of accelerated phenology under substantially increased heat stress. In newly maturing areas, pistachio shows low maturity stability. p_maturity increases from near zero to about 0.14 under SSP585, but remains low overall. These new maturity areas are extremely heat-stressed, with very high tropical nights and WSDI. Precipitation decreases strongly along the scenario gradient.

Overall, pistachio shows some expansion of maturity feasibility, but the new maturity domain remains highly marginal. Persistent areas also experience strong increases in heat stress, indicating that future suitability may be constrained more by stress intensity than by phenological feasibility alone.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-8.84	-8.59	-3.49	4.18	14.31	-4.19	-3.17
SSP126	-9.67	-9.61	-3.87	4.79	17.32	-4.93	-5.43
SSP245	-11.96	-12.74	-5.08	5.95	23.82	-5.92	-6.79
SSP370	-14.98	-17.01	-6.83	6.85	34.07	-6.36	-7.47
SSP585	-17.42	-23.54	-8.86	8.19	43.97	-7.00	-10.22

Table19 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	166.51	237.32	70.80	0.003	44.35	37.94	26.46	44.35	146.62
SSP126	165.97	236.95	70.98	0.008	45.58	41.19	25.40	45.58	138.12

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP245	165.70	232.27	66.57	0.021	48.91	54.01	22.47	48.91	105.66
SSP370	169.34	225.64	56.30	0.060	49.88	73.12	16.43	49.88	66.37
SSP585	172.33	223.03	50.70	0.141	50.50	83.30	14.77	50.50	58.13

Table 20 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Hazelnut (table 21-22)***

In persistent areas, hazelnut shows marked phenological acceleration and increasing thermal stress. Flowering advances from about −4 days under SSP119 to about −11 days under SSP585, while maturity advances from about −7 to −15 days. The flowering–maturity duration shortens substantially, reaching about −9.6 days under SSP585. Tropical nights increase by about +3 to +7 days, while WSDI rises from about +6 to +18 days. Precipitation decreases under the higher scenarios. Hazelnut also shows an important chilling-related signal. Chill DOY advances by about −8 to −11 days across scenarios, indicating a shift in chilling-related timing. This is relevant because hazelnut suitability depends not only on summer maturity feasibility but also on winter chilling conditions and dormancy-related processes. In newly maturing areas, hazelnut p_maturity remains low to moderate, increasing from about 0.06 to about 0.21 across scenarios. These areas show long flowering–maturity durations, increasing tropical nights and increasing WSDI under high scenarios. Chill DOY in newly maturing areas shifts earlier, reaching about DOY 73 under SSP585.

Overall, hazelnut suitability should be interpreted as a balance between maturity feasibility, summer stress and chilling constraints. The crop shows some new maturity feasibility, but also non-negligible lost areas and a strong shift in chill-related timing. This makes hazelnut one of the crops requiring the most cautious interpretation.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip	ΔChill DOY
SSP119	-3.86	-6.73	-5.28	3.14	6.37	-5.23	3.39	-7.95
SSP126	-5.08	-7.82	-5.72	3.74	7.91	-5.17	0.42	-7.80
SSP245	-7.52	-10.39	-7.11	4.73	9.95	-6.05	-3.31	-7.66

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip	ΔChill DOY
SSP370	-10.62	-13.07	-8.13	5.96	13.89	-6.75	-4.87	-10.06
SSP585	-10.93	-14.62	-9.63	7.19	17.54	-7.41	-10.48	-11.44

Table21 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip	Chill DOY
SSP119	154.67	257.53	102.86	0.064	10.75	3.46	42.84	60.02	273.64	82.09
SSP126	151.57	256.19	104.62	0.061	10.74	3.49	42.70	61.92	258.89	81.49
SSP245	150.59	248.53	97.94	0.077	10.84	4.41	39.15	58.80	228.27	78.71
SSP370	148.73	240.96	92.23	0.137	13.92	7.67	35.86	56.38	192.45	76.09
SSP585	146.99	238.64	91.65	0.205	20.74	13.35	33.83	57.82	179.17	72.96

Table22 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Peanut (table 23-24)***

In persistent areas, peanut shows strong phenological acceleration and severe stress increases. Flowering advances from about −7 days under SSP119 to about −13 days under SSP585, while maturity advances from about −6 to −19 days. The flowering–maturity duration shortens substantially, reaching almost −13 days under SSP585. Thermal stress increases strongly, particularly WSDI, which rises from about +11 to more than +31 days. Tropical nights increase by about +2.4 to +4 days. Precipitation decreases sharply, reaching about −23 mm under SSP585. Dry days also decrease, but again this occurs within a shortened and shifted crop window and should not be interpreted as improved water conditions. In newly maturing areas, peanut remains highly marginal. p_maturity increases from about 0.02 to about 0.17, but remains low. These areas are characterised by very high tropical nights, very high WSDI and strongly declining precipitation across the SSP gradient. Under SSP585, newly maturing areas have very high heat stress and very low precipitation. Overall, peanut shows some maturity expansion, but this expansion is weak and highly stressed. Persistent areas also undergo strong cycle shortening and stress intensification. Peanut should therefore be interpreted as one of the crops for which apparent warming-driven feasibility is strongly constrained by agro-climatic stress.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-6.89	-5.95	-5.55	2.43	11.20	-3.57	-10.85
SSP126	-7.83	-6.86	-6.16	2.85	13.65	-4.13	-12.33
SSP245	-9.62	-9.74	-8.17	3.50	18.20	-5.01	-13.89
SSP370	-11.57	-14.11	-10.67	3.71	25.01	-6.40	-19.20
SSP585	-13.38	-19.18	-12.86	4.05	31.09	-9.69	-22.65

Table23 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	170.04	241.29	71.26	0.016	35.18	39.16	23.48	47.77	118.02
SSP126	170.25	240.29	70.04	0.017	37.33	45.11	21.97	48.07	99.44
SSP245	171.21	233.66	62.45	0.051	41.11	58.66	18.27	44.18	68.56
SSP370	174.55	227.52	52.97	0.100	44.31	77.05	14.49	38.49	39.47
SSP585	176.20	225.93	49.73	0.172	48.40	88.38	12.70	37.03	29.50

Table24 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Spring wheat (table 25-26)***

In persistent areas, spring wheat shows a moderate but consistent acceleration of phenology. Flowering advances from about −3 days under SSP119 to about −7 days under SSP585, while maturity advances from about −3 to −9 days. The flowering–maturity duration shortens by about −1 to −2.4 days. This indicates warming-driven acceleration, but less severe than for maize, rice, tomato or peanut. Thermal stress increases moderately. Tropical nights rise from about +0.3 to +1.6 days, while WSDI increases from about +2.4 to +5.4 days. Precipitation decreases under all scenarios, especially SSP585, while dry days decline slightly. The stress increase is present but remains moderate compared with summer crops. In newly maturing areas, spring wheat shows high maturity stability. p_maturity is around 0.80–0.84 across scenarios. Flowering and maturity occur progressively earlier along the SSP gradient, while the flowering–maturity duration remains relatively stable around 32–33 days. Thermal stress increases but remains comparatively low.

Overall, spring wheat shows a relatively robust expansion of maturity feasibility, with high p_maturity in newly maturing areas and moderate stress increases. It is one of the crops for which warming-driven expansion appears more coherent and less marginal.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-3.21	-3.28	-1.05	0.33	2.39	-0.37	-1.01
SSP126	-3.46	-3.67	-1.11	0.38	2.85	-0.45	-2.13
SSP245	-4.48	-4.93	-1.37	0.59	3.92	-0.73	-2.43
SSP370	-5.75	-6.55	-1.71	0.93	5.28	-0.80	-2.64
SSP585	-7.33	-9.01	-2.40	1.57	5.42	-0.88	-7.08

Table25 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	198.86	232.20	33.34	0.796	0.31	1.02	11.52	21.82	94.29
SSP126	198.38	231.30	32.92	0.797	0.38	1.23	11.50	21.42	90.76
SSP245	196.54	228.64	32.10	0.806	0.60	1.78	10.83	21.27	82.82
SSP370	194.02	225.93	31.91	0.821	1.06	3.14	10.38	21.53	73.92
SSP585	191.64	223.99	32.36	0.843	2.11	4.85	9.74	22.61	60.50

Table 26 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights;

WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Spring oat (table 27-28)***

In persistent areas, spring oat shows a consistent advancement of flowering and maturity. Flowering advances from about −4 days under SSP119 to about −8 days under SSP585, while maturity advances from about −4 to −9 days. Duration shortens moderately, by about −1 to −2.2 days. Thermal stress increases moderately. Tropical nights remain low, increasing by less than +1 day under SSP585, while WSDI increases by about +6 days. Precipitation decreases under high scenarios, while dry days decrease slightly. Overall, the stress signal is present but much weaker than for summer crops. In newly maturing areas, spring oat shows relatively high maturity stability. p_maturity remains around 0.75–0.79. Flowering shifts earlier from about DOY 190 to DOY 183, and maturity from about DOY 226 to DOY 218. Duration remains around 35 days. These results indicate that spring oat gains maturity feasibility in new areas with relatively stable completion of the cycle.

Overall, spring oat appears comparatively resilient in terms of maturity feasibility, although persistent and newly maturing areas both experience some increase in warm-spell exposure and reduced precipitation under high scenarios.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-4.13	-3.78	-1.00	0.12	2.47	-0.24	-0.95
SSP126	-4.45	-4.25	-1.05	0.14	2.94	-0.30	-2.12
SSP245	-5.89	-5.67	-1.28	0.23	4.09	-0.45	-1.74
SSP370	-6.81	-7.26	-1.51	0.39	5.59	-0.59	-2.01
SSP585	-7.80	-9.28	-2.23	0.69	5.83	-0.65	-6.86

Table 27 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	190.38	226.31	35.93	0.753	0.11	0.87	12.33	23.60	105.23
SSP126	189.79	225.16	35.37	0.751	0.14	1.04	12.34	23.04	102.18
SSP245	187.62	222.07	34.45	0.757	0.23	1.51	11.88	22.57	93.87
SSP370	184.84	219.29	34.45	0.771	0.40	2.77	11.45	23.00	84.25
SSP585	182.72	217.63	34.91	0.789	0.77	4.53	10.80	24.12	70.23

Table 28 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

- ***Spring barley (table 29-30)***

In persistent areas, spring barley shows consistent phenological advancement. Flowering advances from about −3 days under SSP119 to about −7 days under SSP585, while maturity advances from about −3 to −8 days. The flowering–maturity duration shortens modestly, by about −1 to −2 days. Thermal stress increases moderately. Tropical nights increase by about +0.2 to +1 day, and WSDI by about +2 to +4 days. Precipitation decreases progressively, reaching about −5.5 mm under SSP585, while dry days decrease slightly. Compared with summer crops, stress increases remain limited. In newly maturing areas, spring barley shows high maturity stability. p_maturity increases from about 0.78 to about 0.82 across scenarios. Flowering and maturity occur earlier under higher SSPs, while the flowering–maturity duration remains close to 30 days. Thermal stress increases but remains moderate.

Overall, spring barley shows a relatively robust and coherent expansion of maturity feasibility. The main signal is earlier development with moderate stress increase, rather than severe marginality.

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP119	-3.28	-3.23	-0.87	0.20	1.81	-0.33	-1.21
SSP126	-3.58	-3.54	-0.90	0.22	2.18	-0.41	-2.22
SSP245	-4.74	-4.58	-1.07	0.34	3.04	-0.60	-2.60
SSP370	-5.85	-5.74	-1.35	0.57	4.12	-0.65	-2.94

SSP	ΔFlow DOY	ΔMat DOY	ΔDur F-M	ΔTropN	ΔWSDI	ΔDryD	ΔPrecip
SSP585	-6.97	-8.38	-1.90	0.98	4.26	-0.68	-5.52

Table 29 Persistent areas: deltas vs historical. ΔFlow DOY = flowering day-of-year change; ΔMat DOY = maturity day-of-year change; ΔDur F-M = change in flowering–maturity duration; ΔTropN = tropical nights change; ΔWSDI = Warm Spell Duration Index change; ΔDryD = dry days change within the flowering–maturity window; ΔPrecip = precipitation-sum change within the flowering–maturity window.

SSP	Flow DOY	Mat DOY	Dur F-M	pMat	TropN	WSDI	WetD	DryD	Precip
SSP119	194.46	224.60	30.14	0.776	0.21	0.73	11.42	18.72	91.80
SSP126	193.72	223.80	30.08	0.780	0.28	0.88	11.22	18.86	87.23
SSP245	191.80	221.21	29.42	0.790	0.41	1.25	10.75	18.67	78.50
SSP370	189.03	218.47	29.44	0.805	0.71	2.38	10.28	19.16	70.49
SSP585	187.07	216.97	29.90	0.821	1.33	4.07	9.76	20.13	59.37

Table 30 New maturity areas: scenario mean conditions. Flow DOY = flowering day of year; Mat DOY = maturity day of year; Dur F-M = flowering–maturity duration; pMat = probability/frequency of reaching maturity over the simulated years; TropN = tropical nights; WSDI = Warm Spell Duration Index days; WetD = wet days within the flowering–maturity window; DryD = dry days within the flowering–maturity window; Precip = precipitation sum within the flowering–maturity window.

11. Conclusions and next steps

D7.1 establishes the agro-climate database, API documentation, crop modelling framework and suitability-analysis outputs required to support the next stages of MYMATCH modelling and platform implementation. The deliverable consolidates the data backbone linking literature-derived mycotoxin information, field datasets, fungal experimental data, weather observations, climate projections, crop phenology and agro-climatic indicators.

All spatial outputs generated by the suitability analysis, including maps and raster layers for the analysed crops, indicators and SSP scenarios, are stored in the MYMATCH project cloud. These outputs represent the operational spatial basis for subsequent analyses and can be used for visual inspection, figure production, scenario comparison and further model integration.

As an example, this deliverable reports the spatial evolution of p_maturity for pistachio (Figure 1) across the historical period and the future SSP scenarios. In this context, p_maturity represents the probability or frequency of reaching maturity over the analysed simulation years. No additional maps are included in the main text because the full suitability workflow generated more than 2800 figures across crops, indicators and scenarios. These outputs have been synthesised into the statistical tables presented in the suitability analysis, which provide a more compact and comparable summary of phenological feasibility, maturity success, agro-climatic stress and domain-aware changes across crops and SSP scenarios.

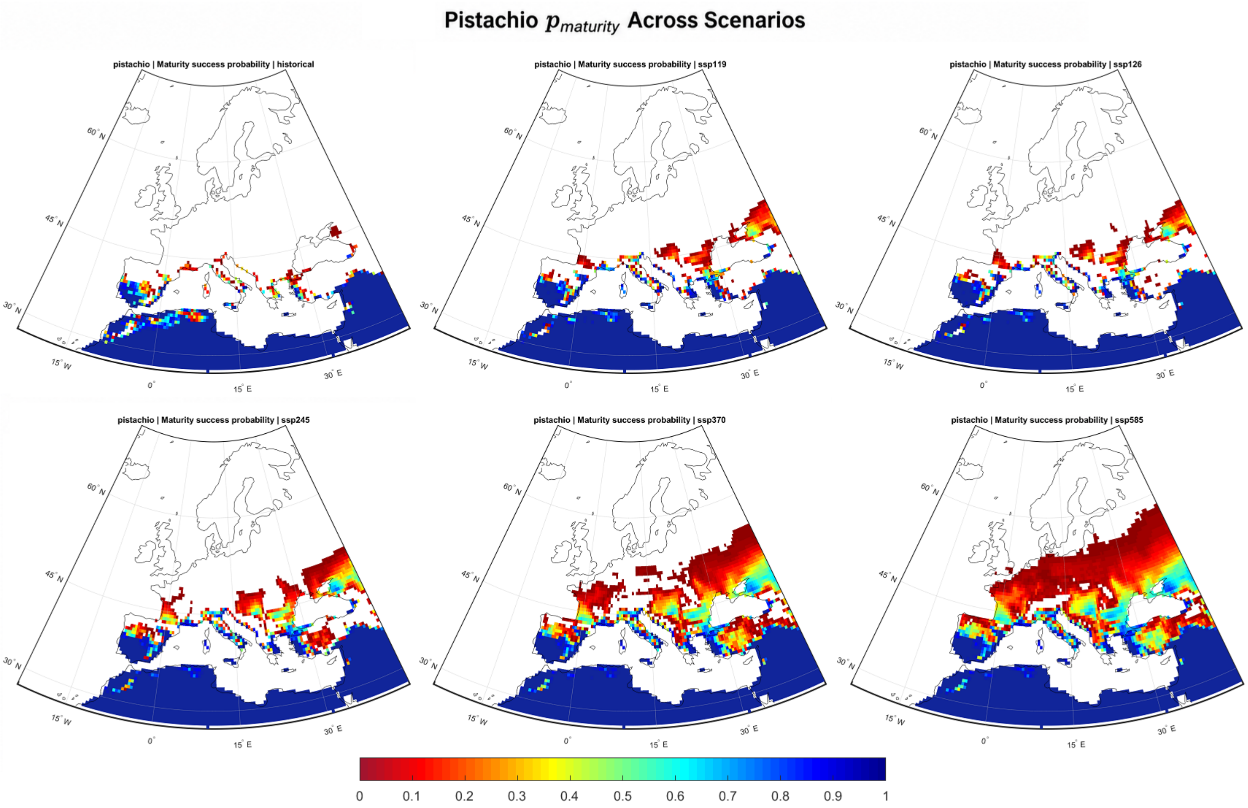

Figure 1 Example of spatial p_maturity patterns for pistachio across the historical period and future SSP scenarios. p_maturity represents the probability/frequency of reaching maturity over the analysed simulation years.

The work presented in D7.1 provides the basis for subsequent implementation within the MYMATCH DSS platform through the API services already developed and documented. The API services documented in D7.1 provide the technical basis for programmatic access and for progressive integration into the DSS workflow. This is essential to make the outputs usable not only for internal modelling activities, but also for stakeholders, including researchers, farmers, food-chain operators, risk assessors and policy-oriented users.

The suitability analysis demonstrates that climate-driven phenological feasibility and agronomic suitability must be interpreted separately. Future warming may enable flowering or maturity in new areas, but these areas must be assessed together with maturity probability, phenological timing and agro-climatic stress conditions.

Similarly, historically active areas may remain phenologically feasible while experiencing shorter crop cycles, stronger thermal stress and altered water availability. The outputs should therefore be interpreted as climate-driven feasibility and stress layers, not as final predictions of actual crop distribution or operational yield potential.

The next step will be to connect these WP7 outputs with mycotoxin risk modelling. WP4 data will be further exploited to extract, harmonise and reconstruct occurrence information wherever possible, including through integration with CHEFS-derived datasets and AI-supported approaches for data enrichment, gap filling, anomaly detection and uncertainty characterisation. This step will help define more consistent mycotoxin occurrence baselines and identify toxin–commodity combinations suitable for statistical or predictive modelling.

In parallel, WP5 field datasets and WP6 fungal-response datasets will be integrated into the modelling workflow for mycotoxin assessment. WP5 will provide field-based information on crop, fungal occurrence, mycotoxin contamination, agronomic metadata and local weather conditions. WP6 will provide controlled experimental data describing fungal growth and mycotoxin production responses to environmental drivers. Together, these datasets will support the calibration and validation of fungi and mycotoxin models under current and future climate conditions.

Future work will also include further refinement of local weather harmonisation, integration of land-use and land-cover constraints, and linkage of crop suitability outputs with fungal ecology and toxin-production models. This will allow MYMATCH to move from climate-driven crop feasibility layers toward operational risk indicators that can support scenario-based assessment, DSS visualisation and stakeholder-oriented decision support.

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