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RESEARCH ARTICLE

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A geospatial decision support system to support policy implementation on climate change in EU

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Abstract

Climate change (CC) is a global problem bringing multiple different changes in different regions that exacerbate the conflict between landscape demands. Policy in EU and elsewhere are facing the huge challenge of CC by developing specific regulations and strategies (e.g., European climate law, RDP 2014–2020) generally shaped in the United Nations Frameworks Convention on Climate Change (UNFCCC). The "new EU strategy on adaptation to climate change" sets out how the EU can adapt to the unavoidable impacts of CC and become climate resilient by 2050. Unfortunately, the factual implementation of these policies remains critical. Most often there is a lack of science-based decision support tools empowering regional and local levels to act toward climate resilience. Here we have produced a strong interdisciplinary research effort to support the implementation of the EU strategy on adaptation to CC by providing free web-based Decision Support Systems having a strong focus on factual territories. Our Geospatial Decision Support System aims to support local authorities/communities, scientists, and other stakeholders in EU and more in detail in Italy in better understanding and implementing local adaptation to climate change by means of a "Climate Change Resilience" toolbox oriented to evaluate the climatic anomalies and thermal crop adaptation. Specifically, in this research, two implemented tools have been discussed: (i) tool on General climatic variation and (ii) tool on Crop thermal adaptation. These tools are demonstrated in two different case studies at both EU and national level. Such a toolbox has been produced in the framework of the LANDSUPPORT Horizon 2020 project (www.landsupport.eu).

KEYWORDS
climate change, crop adaptation, Land support, National Adaptation Strategies (NASs), UNFCCC, web-based decision support systems

1 | INTRODUCTION

Climate change (CC) is a global problem and according to the latest Intergovernmental Panel on Climate Change report (IPCC's Sixth Assessment Report, AR6; Portner et al., 2022), the chances of crossing the global warming level of 1.5°C or even 2°C in the next decades are concrete if a rapid reduction in greenhouse gas emissions at large scale will be not realized. In addition to and as a consequence of the temperature rise, CC is bringing multiple different changes in different regions—which will all increase with further warming. These include changes in the water cycle (heavy rainfall and associated flooding, longer and more severe drought) with different intensity region by region.

In this global context, the United Nations and the Food and Agriculture Organization of the United Nations (FAO), have underlined the need for an increase in crop productivity and quality, based on scientific and sustainable practices to improve resource use efficiency (water and nutrients), thereby also contributing to meeting the broader aims of food security, rural development, and livelihood enhancement.

It is well established that CC has both direct and indirect effects on agricultural productivity (Bonfante, Impagliazzo, et al., 2017; Jabal et al., 2022; Lobell et al., 2011; Wang et al., 2018) and—in many instances—it is connected to drought, flooding, and the geographical redistribution of pests and diseases. More specifically, CC has a direct influence on agricultural sectors in ways that depend both on the magnitude and type of climatic change, in terms of patterns of weather variables (e.g., precipitation and temperature), and on local capacity to absorb these (Li et al., 2011).

For instance, temperature changes can directly influence the duration of the growing season or the establishment of the different phenological stages, determining suitability of the territory for specific crop cultivation. The reduction in rainfall can affect the crop water availability and thereby its yield. In addition, it must be also considered the effect on crop production due to the occurrence of extreme events (heat waves, heavy rainfalls). In the cropping systems' management, the expected conditions imply a change in the current type and timing of agronomic practices (e.g., sowing and harvesting date, fertilization, irrigation) and offer the opportunity to define novel strategies of adaptation and mitigation to future climate.

The scientific communities are so-called to support the resilience of the agricultural system through the evaluation of CC's effect in the short, medium, and long term to provide clear prospects for the future to the different stakeholders involved.

Evaluation of the future effects of CC has to be made in different ways for different crops, for example, food crops (e.g., maize) have to be evaluated according to their responses in terms of adaptability (changing in land suitability) and/or yield (Monaco et al., 2014; Sommer et al., 2013), while expected fruit quality must be taken into account for other agricultural systems (e.g., grapevine, Bonfante, Alfieri, et al., 2017).

Policy in EU and elsewhere are facing the huge challenge of CC by developing specific regulations and strategies (e.g., European climate law, RDP 2014–2020[1]) generally shaped in the United Nations Frameworks Convention on Climate Change (UNFCCC). In this respect, a key item has been the adoption on 24 February 2021 of the “*new EU strategy on adaptation to climate change*”. This strategy sets out how the EU can adapt to the unavoidable impacts of CC and become climate resilient by 2050. The strategy acknowledges that:

- EU Member States need to act by preparing “*National Adaptation Strategies (NASs), as cross-sectoral planning instruments to inform and prioritize actions and investments towards climate change adaptation*”.
- Information is the basis for decision-making. Thus, the Strategy has to bridge current knowledge gaps especially referring to damage and adaptation costs and benefits including regional and local risk assessments, and tools to support decision-making.

Unfortunately, the factual implementation of decision-making at regional and local levels remains a critical item and this is unfortunate because real changes require local implementation. We believe that there is a need to further support the implementation of the *EU strategy on adaptation to* CC by providing free web-based Decision Support Systems having a strong focus on factual territory thus having a strong geospatial focus. These systems must have (i) a multidisciplinary nature since CC requires the involvement of different scientific communities and (ii) must be rooted into quantitative scientific approaches and models devoted to specific goals.

Thus the objective of this contribution is the development of a Geospatial Decision Support System based on scientific knowledge to support local authorities/communities in the EU and more in detail in Italy in better implementing local adaptation to CC by obtaining local CC data and their impact on the agricultural system. To this respect, the toolbox has a special potential toward the full implementation of the EU Climate Adaptation Strategy.

Here, we shall demonstrate the “Climate Change Resilience” toolbox that can be used by both (i) EU national, regional, and local authorities having the task to implement the National Plan for Climate Adaptation and (ii) by farm associations/consortia (or single farmers) that plan agricultural weather-impacted activities. The toolbox is also of interest to stakeholders (e.g., environmental protection authorities, water district authorities, landscape planners) who are involved in regional and local planning of the use of land and other environmental resources.

The toolbox will be demonstrated in two separate case studies: (i) at the EU level analyzing climatic anomalies obtained from NUTS (Nomenclature of Territorial Units for Statistics; 1) country, 2) region, 3) province, 4) municipalities administrative levels) at 2, 3, and 4 levels, and (ii) at the Italian level in the agricultural sector by demonstrating the use of the tool on “Crops- thermal sums anomalies”.

This toolbox has been developed within the EU LANDSUPPORT Horizon 2020 project. A detailed description of the LANDSUPPORT infrastructure is available at www.landsupport.eu while here we only report the main findings and implementations related to the CC resilience toolbox.

2 | THE GEOSPATIAL CYBER-INFRASTRUCTURE

The CC toolbox can be found through the LANDSUPPORT dashboard. The toolbox is available with different functionalities according to the scale of the application that the user selects. The system is built on a Geospatial Cyberinfrastructure (GCI) platform (e.g., Yang et al., 2010), which allows both static and dynamic data acquisition (e.g., on-the-fly data processing and visualization.

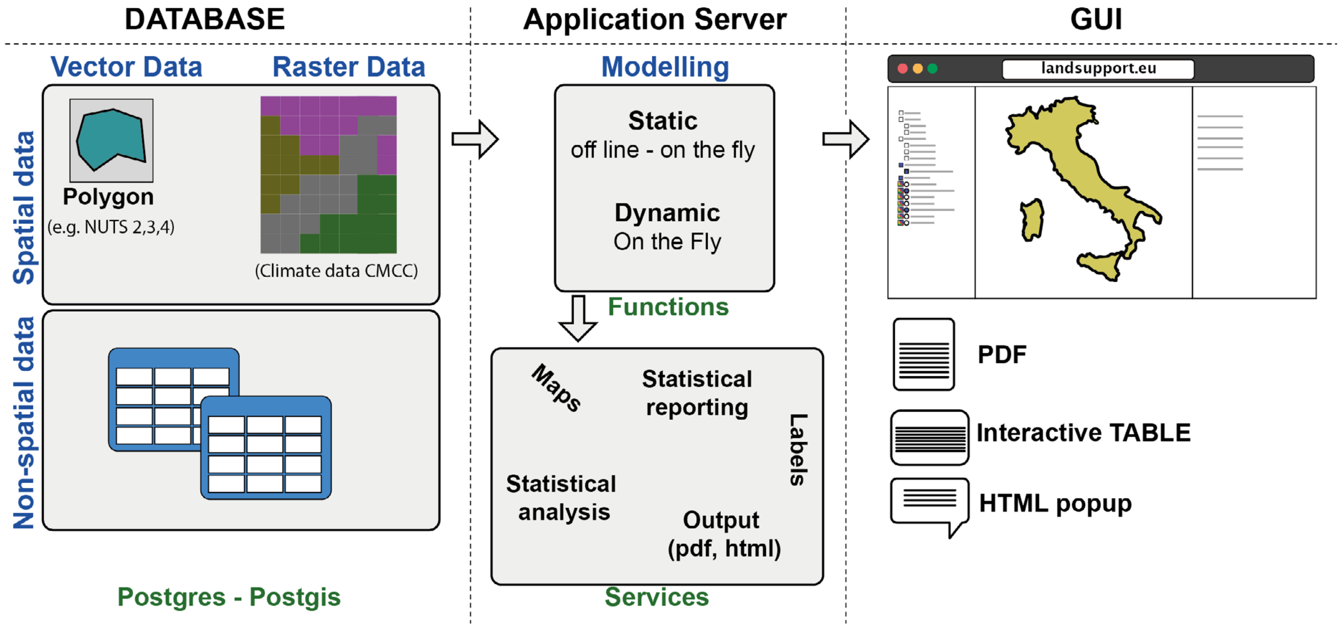


FIGURE 1 Geospatial Cyber-Infrastructure operating mode. The flow of data feeds different server functions, which in turn produce a set of services that can be accessed by the dashboard. GUI, graphical user interface. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 1 illustrates the LANDSUPPORT architecture which is at 3 levels: (i) database, (ii) application server, (iii) Graphical User Interface (GUI) This architecture, as already mentioned, allows to support many other tools (Mileti et al., 2022).

The database is composed of two main types of data: spatial data and non-spatial data. The first type includes vector data and raster data. Vector data is represented by polygons and multipolygons, raster data typically, composed of pixel arrays, of continuous or discrete values. In the case of CC tools, all data is collected and managed in PostgreSQL, a well-known open source database. Postgres through the PostGIS extension enables the management of spatial data. Although not the case covered in this paper, for many LANDSUPPORT tools the raster data is managed separately, through an optimized database called rasdaman (Baumann et al., 2021) which allows the storage, management and retrieval of very large multidimensional arrays. The data contained in the database is processed through both static and dynamic models and produces various types of output for the end user: pdf reports, interactive tables, and informative Html popups. The GUI is the level where the interaction between the user and the tools takes place.

2.1 | The graphical user interface (GUI)

The layout of the Landsupport dashboard GUI is schematically represented in Figure 2. It includes graphical tools, territorial data aggregation processes (visualization and analysis), the creation of maps and tables, intuitive navigation tools, and the operating scale (European, National, Regional, and Local). The dashboard can be schematically divided into three sections: (i) "data viewer", (ii) "map", and (iii)"Analysis tools"'box. The first section (Figure 2a–c), allows the activation and deactivation of the various thematic layers in an easy and intuitive way, showing the legend, and customizing the transparency of each layer. The second section (Figure 2d) is dedicated to the view of maps selected from the "layers" tab or obtained as results of tools application. Finally, the third section consists of two main tabs, "Toolbox" (Figure 2e), which allows the user to explore all the operating tools of the LANDSUPORT S-DSS family, and the "Results" tab (Figure 2f), designed to display the results of each processing launched by the user. For each result (run_id) it is possible to obtain a series of summary information including the type of model applied, the spatial scale selected, and the processing status.

At the top of the dashboard are available several GIS tools such as "measure distances and surfaces", "point locator", "find a place" and "draw polygon or point". The latter allows the user to draw a custom Region Of Interest (ROI), composed of a set of area of interest (AOI), save it within a public (or personal) domain, and use it as an area within which to run a selected tool. Each ROI can be edited or deleted.

2.2 | The "Climate Change Resilience" toolbox

The S-DSS toolbox dedicated to supporting the implementation of the EU Climate Adaptation Strategy, able to furnish local information on the expected CC data, impacts, and agricultural systems adaptation is called "Climate Change Resilience" toolbox and is located in the folder called "Support Public Authorities" (Figure 2). According to the operative spatial scale selected by the user (European, National or regional), different specific tools are activated to reply to user requests in terms of "Climate change indicators".

ID	Model	Scale	Status
1523	Crops – thermal sums anomalies	Italy	Ended
1522	Land – general climatic anomalies	Italy	Started

FIGURE 2 A general outline of the S-DSS dashboard. ROI, region of interest. [Colour figure can be viewed at wileyonlinelibrary.com]

In particular, the "Land-General climatic anomalies" indicators are available from the European to regional scale, and the "Crops-thermal sums anomalies" indicators are available at country and regional scale. Once the application scale has been selected, which sets the system on suitable data and models, the user can choose whether to use the toolbox within specific pre-selectable administrative units throughout the European territory (from municipality moving upward), or within the ROI that he has drawn and saved.

3 | METHODOLOGY APPLIED

3.1 | Climate information

Expected climate variation of selected climate indicators has been evaluated by using COSMO-CLM (Rockel et al., 2008) developed within the international consortium CLM Assembly. More specifically the climate data are obtained with a specific COSMO CLM configuration employing a spatial resolution of 0.0715°(about 8 km) developed over Italy by Fondazione CMCC.[2] This dataset is largely used in Italy to assess the impact of CC over Italy. Specifically, the climate data obtained by these simulations were validated, showing good agreement with various high-resolution observational datasets, in terms of average temperature and precipitation (Bucchignani et al., 2015) and in terms of extreme patterns (Zollo et al., 2015).

Three different climate simulations were performed:

- Historical simulation: the COSMO CLM simulation covers a period using available model climate observations. The boundary conditions are provided by the general circulation model (GCM) CMCC-CM (Scoccimarro et al., 2011), with an atmospheric component (ECHAM5) having a horizontal resolution of approximately 85 km. In this simulation the climate forcing of the GCM is determined by observed greenhouse gases, covering the reference period 1981–2005.
- Scenarios: two simulations using COSMO-CLM were performed over the period 2006–2100. The same GCM used in the historical period was used as driver of the RCM but adopting radiative

forcing given by two standard IPCC (Intergovernmental Panel on Climate Change) CMIP5 greenhouse gas (GHG) concentrations (Meinshausen et al., 2011) pathways, respectively named RCP4.5 and RCP8.5. The RCP 4.5 scenario exhibits a stabilisation in GHG emissions, while the RCP 8.5 has a rapidly increasing GHG concentration.

Moreover, in order to make available climate assessments on a European scale through the "Climate Change Resilience" toolbox, an ensemble of high-resolution regional climate models (RCMs) performed in the framework of the EURO-CORDEX program (Hennemuth et al., 2017; Jacob et al., 2020) with spatial resolution 0.11° (about 12 km) have been evaluated under the RCP4.5 and 8.5 scenarios. This dataset is largely used in literature and in several studies to assess impacts of CC or to support climate adaptation paths at different scales (Ellena et al., 2020, Ricciardi et al., 2023).

3.2 | Climate change indicators toolbox

3.2.1 | Land-General climatic variation tool

In order to assess the evolution of the climate hazard, variation of different specific climate indicators has been calculated and then reported by comparing the values assumed by the climate indicators on the two future periods (2041–2070 and 2071–2100), considering the two different scenarios RCP4.5 and RCP8.5, and the reference period (1981–2010[3]).

The selected climate indicators represent specific characteristics (both average and extreme) of the climate that are relevant to the agricultural system. Analyzing the variation of these specific indicators permits quantifying specific climate trends for these sectors. This approach is largely adopted in the literature to provide preliminary indications of the impacts of CC in different environmental and economic sectors (Jacob et al., 2014; Reder et al., 2022).

Specifically, in this research, it was considered the variation of climate indicators based on the following variables: 2 m maximum, mean and minimum daily temperature, and daily precipitation.

3.2.2 | Crop-Thermal sums anomalies tool

In order to assess the evolution of the crop adaptation to CC specific crop indicators were identified and the crop requirements were selected from the literature (Table 1; Stöckle et al., 2003 modified). The impacts of CC were defined in terms of thermal indicators anomalies realized during the most important phenological stages of crop growth offering a means to assess whether the projected changes in temperature could have significant consequences for sowing, emergence, flowering, and harvesting of different crops.

Crop thermal indicators anomalies (mean value) have been calculated (and thus reported) as the difference between the future period (2021–2050) and the reference period (1981–2010). The climate anomalies have been carried out by taking into account the IPCC scenarios RCP4.5 and RCP8.5.

The applied and reported Crop indicators are.

- sowing period Length (number of days).
- emergence period Length (number of days).
- harvesting period Length (number of days).
- extreme events of minimum temperature (during the emergence period).
- extreme events of minimum temperature (during the first 15 days of the emergence period).
- number of times in which harvesting is not reached.

The evaluation of thermal indicators followed a four-step procedure:

1. Identification of the sowing date: This step involved observing a steady mean temperature (e.g., equal to or above a specific threshold, such as 15°C for maize) for seven consecutive days.

2. Calculation of thermal sum using different base temperature thresholds (Tbase) corresponding to the crop's phenological stage (e.g., emergence, flowering, harvest). See the table above for details. The formula used was:

$$\mathrm{GDDcrop} = \sum_{s}^{h} (Tmean - Tbase)$$

- Tmean: Mean daily temperature.
- s: Sowing.
- h: Harvest.

3. Verification of whether the thermal crop requirement is met and determination of the number of days required. If the mean daily temperature remains lower than the Tbase for more than 7 days, the calculation is stopped as the crop does not complete its cycle, indicating any adaptation in that specific year. The condition checked is "seven consecutive days with Tmean < Tbase". Once this condition is met, the GDD calculation is halted.

4. After identifying the crop's phenological phases and achieving the crop cycle (points 1, 2, and 3), the occurrence of extreme thermal events during flowering (heatwaves) or emergence stage (frosts) is calculated:

Extreme event: (Emergence) Tmin < −2°C, (Flowering) Tmax >32°C.

The following indicators are calculated as variations from January 1st (for spring–summer crops) or September 1st (for winter crops):

- Variation in the length of the sowing period (n° of days): This indicates the estimated change in the number of days for the sowing period between the reference climate and the future climate scenario analyzed. Negative numbers indicate an earlier sowing date, while positive values indicate a later one.
- Variation in the length of the emergence crop stage (n° of days): This represents the estimated change in the duration of the emergence stage between the reference climate and the future climate

TABLE 1 Crop and thermal requirements (Stöckle et al., 2003 modified).

Group	Crop	Phenological stage	T. Sowing (°C)	DAY start count	GDDsum (°D)	Tbase	Tcutoff	Group	Crop	Phenological stage	T. Sowing (°C)	DAY start count	GDDsum (°D)	Tbase	Tcutoff
Herbaceous/ cereals	Barley	Sowing	12°C	01-Sep	0	0	0	Herbaceous/ cereals	Maize FAO 500	Sowing	15°C	01-Jan	0	0	0
		Emergence			60	0	40			Emergence			70	9	40
		Flowering			1290	0	40			Flowering			990	6	40
		Harvest			1940	0	40			Harvest			2190	6	40
	Sugar beet	Sowing	12–15°	01-Sep	0	0	0		Maize FAO 600	Sowing	15°C	01-Jan	0	0	0
		Emergence			300	2	35			Emergence			70	9	40
		Harvest			2900	2	28			Flowering			990	6	40
										Harvest			2690	6	40
	Rye	Sowing	8°	01-Sep	0	0	0		Maize FAO 700	Sowing	15°C	01-Jan	0	0	0
		Emergence			130	0	40			Emergence			30	9	40
		Flowering			980	0	40			Flowering			1300	6	40
		Harvest			2380	0	40			Harvest			3100	6	40
	Wheat	Sowing	10°C	01-Sep	0	0	0	Horticoltural crops	Tomato	Sowing	15–18°	01-Jan	0	0	0
		Emergence			50	0	40			Emergence			50	9	40
		Flowering			1150	0	40			Flowering			700	9	40
		Harvest			2250	0	40			Harvest			1900	7	35
	Rapeseed	Sowing	10°C	01-Sep	0	0	0		Potato	Sowing	8–10°	01-Jan	0	3	0
		Emergence			40	2.6	40			Emergence			360	3	30
		Flowering			850	4	30			Harvest			750	3	30
		Harvest			1520	4	30		Phennel	Sowing	8–10°	01-Sep	0	5	0
	Alfa alfa	Sowing	8°C	01-Sep	0	0	0			Emergence			50	5	30
		Emergence			200	5	40			Harvest			1350	5	30
		Flowering			1800	7	40		Artichoke	Sowing	8–10°	01-Sep	0	5	0
		Harvest			2000	0	40			Emergence			50	5	30
	Soyabean	Sowing	10°C	01-Jan	0	0	0			Harvest			2012	5	30
		Emergence			80	9	35		Zucchini	Sowing	18°	01-Jan	0	0	0
		Flowering			1180	10	35			Emergence			50	9	40
		Harvest			2180	10	35			Harvest			1900	7	35
	Millet (foxtail)	Sowing	15°C	01-Jan	0	0	0		Eggplant	Sowing	18°	01-Jan	0	0	0
		Emergence			50	9	40			Emergence			50	9	40
		Flowering			800	6	40			Harvest			1900	7	35
		Harvest			1700	6	40								

scenario analyzed. Negative numbers indicate a shorter duration, while positive values indicate a longer duration.

- Variation in the length of the harvesting crop stage (n° of days): This indicates the estimated change in the duration of the harvesting stage between the reference climate and the future climate scenario analyzed. Negative numbers indicate a shorter duration, while positive values indicate a longer duration.
- Extreme events of minimum temperature (during the emergence period): This represents the estimated change in the number of thermal extreme events (Tmin < -2°C) during the emergence stage between the reference climate and the future climate scenario analyzed. Negative numbers indicate a reduction in extreme events, while positive values indicate an increase. Low temperatures during crop emergence can significantly reduce crop production.
- Extreme events of minimum temperature (during the first 15 days of the emergence period): This indicates the estimated change in the number of thermal extreme events (Tmin < -2°C) during the first 15 days after crop emergence between the reference climate and the future climate scenario analyzed. Negative numbers indicate a reduction in extreme events, while positive values indicate an increase. Low temperatures after crop emergence can significantly reduce crop production.
- Extreme events of maximum temperature (during the flowering period): This represents the estimated change in the number of thermal extreme events (Tmax >32°C) during the flowering stage between the reference climate and the future climate scenario analyzed. Negative numbers indicate a reduction in extreme events, while positive values indicate an increase. High temperatures during crop flowering can negatively affect pollination and crop production.
- Difference in crop adaptation (harvesting reached): This indicates the estimated change in the number of years in which the crop is considered adapted (i.e., when specific thermal requirements for the crop have been met) between the reference climate and the future climate scenario analyzed. Negative numbers indicate an improvement in crop adaptation, while positive values indicate a worsening (Table 1).

Finally, at each phenological stage, a set of complementary climatic indicators, aimed at providing information about extreme weather dynamics potentially impacting the crops are reported and computed as mean values of:

- Maximum yearly length of consecutive dry days (daily rainfall <1 mm) [proxy for droughts]
- Number of days with precipitation exceeding 20 mm [proxy for heavy precipitations]
- Seasonal temperature values (DJF December January February, MAM March April May, JJA June July August, SON September October November)
- Cumulative precipitation value over the period April–September.

The complementary climatic indicators have been computed as the difference between future and reference periods (RCP4.5 and RCP8.5) as done for the crop thermal indicators.

4 | CASE STUDIES

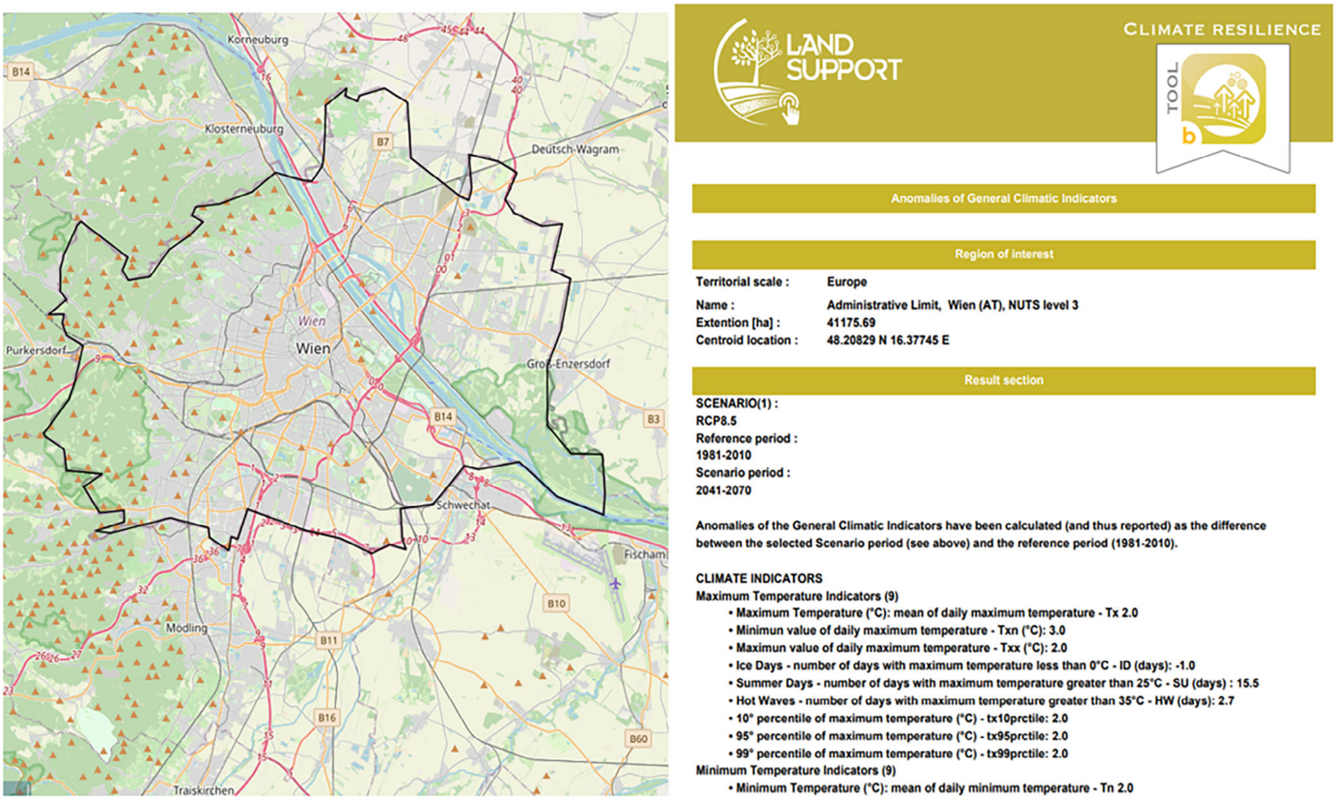
The EU Climate Adaptation Strategy requests European Public Authorities (ministries, regions, and municipalities according to the different EU countries) to define adaptation plans to challenge CC and to integrate adaptation actions into the various ordinary and sectoral planning tools (the impacts of CC affect all sectors: forests, agriculture, urban settlements, water resources, hydrogeological instability, coastal areas, transport, …). In this framework, the free availability, at any administrative unit level (from municipality moving upward), of the most common climate indicators can be beneficial to face the impacts of CC in the various sectors. As previously described, the “Climate Change Resilience” toolbox allows displaying an evaluation of the variation of the most important climate-related indicators among reference periods (1981–2010) and future climate scenarios (RCP 4.5 and 8.5). In particular, the general climatic variation indicators tool refers to the predicted future time intervals 2041–2070 and 2071–2100 and the crops' thermal sums anomalies indicators tool to 2021–2050 of climate scenarios RCP 4.5 and 8.5.

Following a toolbox practical use demonstration in two separate case studies exploiting the datasets integrated into the system: (i) at EU level analyzing general climatic anomalies data at NUTS 3 level with a spatial resolution of about 12 km and (ii) at national level by analyzing crops thermal sums anomalies for a specific agricultural system at spatial resolution of about 8 km.

4.1 | Case 1-Adaptation plan in EU territorial authorities (NUTS 2,3,4)

The first case study demonstrates the use of the “Land General climatic anomalies” tool in three regions of interest of EU corresponding to NUTS level 3, namely: Province of Napoli, south of Italy (Città Metropolitana di Napoli) including 92 municipalities with a total extension of 1172 km^2, Wien federal city (Land) extended for 415 km^2 and the Province of Brussel-hoofdstad including 19 municipalities with a total extension of 162 km^2. The same procedure can be performed at any NUTS level (country, region, province, municipalities administrative levels) in all EU. In this example, the user selects the tool at EU level choosing the study areas above with the aim to analyze potential anomalies expected in three regions at different latitudes. The user applies the tool for both RCP 4.5 and RCP 8.5 scenarios simulating the time interval 2041–2070. Below in Figures 3 and 4 are reported respectively one of the study areas alongside an example of a report generated on-the-fly by the tool, and a graph summarizing a selection of some of the available indicators.

For the three regions as expected the scenario RCP8.5 predicts higher differentials. Generally, the maximum temperature indicators



Anomalies of General Climatic Indicators

Region of interest

Territorial scale : Europe
Name : Administrative Limit, Wien (AT), NUTS level 3
Extention [ha] : 41175.69
Centroid location : 48.20829 N 16.37745 E

Result section

SCENARIO(1) :
RCP8.5
Reference period :
1981-2010
Scenario period :
2041-2070

Anomalies of the General Climatic Indicators have been calculated (and thus reported) as the difference between the selected Scenario period (see above) and the reference period (1981-2010).

CLIMATE INDICATORS
Maximum Temperature Indicators (9)
- Maximum Temperature (°C): mean of daily maximum temperature - Tx 2.0
- Minimun value of daily maximum temperature - Txn (°C): 3.0
- Maximun value of daily maximum temperature - Txx (°C): 2.0
- Ice Days - number of days with maximum temperature less than 0°C - ID (days): -1.0
- Summer Days - number of days with maximum temperature greater than 25°C - SU (days) : 15.5
- Hot Waves - number of days with maximum temperature greater than 35°C - HW (days): 2.7
- 10° percentile of maximum temperature (°C) - tx10prctile: 2.0
- 95° percentile of maximum temperature (°C) - tx95prctile: 2.0
- 99° percentile of maximum temperature (°C) - tx99prctile: 2.0

Minimum Temperature Indicators (9)
- Minimum Temperature (°C): mean of daily minimum temperature - Tn 2.0

FIGURE 3 Case study 1: administrative area of Wien (AT), NUTS level 3. On the right is the map of AOI visualized on the S-DSS dashboard, and on the left is the report generated on-the-fly by the "Land General climatic anomalies" tool. [Colour figure can be viewed at wileyonlinelibrary.com]

show increasing temperatures with differentials from the reference period increasing from north to south. Minimum temperature indicators show decreasing number of frost days with the area of Wien showing a major decrease. Mean temperature data are expected to be on average above the threshold of 17°C with the province of Napoli slightly warmer than Wien and Brussel provinces. Rainfall indicators show increasing total precipitations with major values expected for the area of Wien.

According to the data delivered by the tool, Napoli is expected to be the province with the greatest increase in maximum and minimum temperatures with a decrease in rainfall in the RCP.4.5 scenario and an increase in the RCP8.5. For the province of Wien are expected minor increases in maximum temperatures and greater increases in minimum temperatures with important increases in rainfall. Finally, for the Brussels area, less important variations are expected with minor increases in maximum and minimum temperatures and in rainfall. This selected set of indicators tends to classify the province of Brussels as the area which for the period and the scenarios considered will be the least affected by climatic variations among the three selected study areas.

4.2 | Case 2-Evaluating impact CC on agriculture

The second case study shows the application of the "Crop thermal sums anomalies" tool in two regions of interest in Italy chosen as areas suited to wheat production. The areas are located in the north and south of the country, respectively the Valtellina valley, a region of the Alps with an extension of 3200 km^2 and a region located in the east of Campania region (south of Italy) with an extension of 150 km^2. For this case study the user through the tool's interface has drawn the AOI because he is interested in specific areas vocated to cereal production rather than whole territorial units. The aim here is to obtain data about crop thermal indicators anomalies with reference to specific thresholds for sowing, emergence, flowering, and harvesting. The user needs to analyze the potential resilience of the two regions in reference to wheat cultivation in the future scenario.

He applies the tool suited for the national scale (Italy) simulating within the AOIs the time interval 2021–2050. Table 2 shows the data produced on-the-fly by the "Crop-Thermal sums anomalies" tool organized for a quick comparison.

As expected, the data show that the RCP8.5 scenario envisages higher differentials compared to the reference period. Some of the indicators reported show significantly different values between south and northern Italy. In particular considering both RCP scenarios: the sowing period length will get longer by a week/2 weeks for the Valtellina area while for the east Campania, the period length will be longer by 4/8 days; the emergence period length will be longer (3.7 to 5.6 days) for the Valtellina and shorter (−3.0 to −2.0) for east Campania; the extreme events of minimum temperatures during the

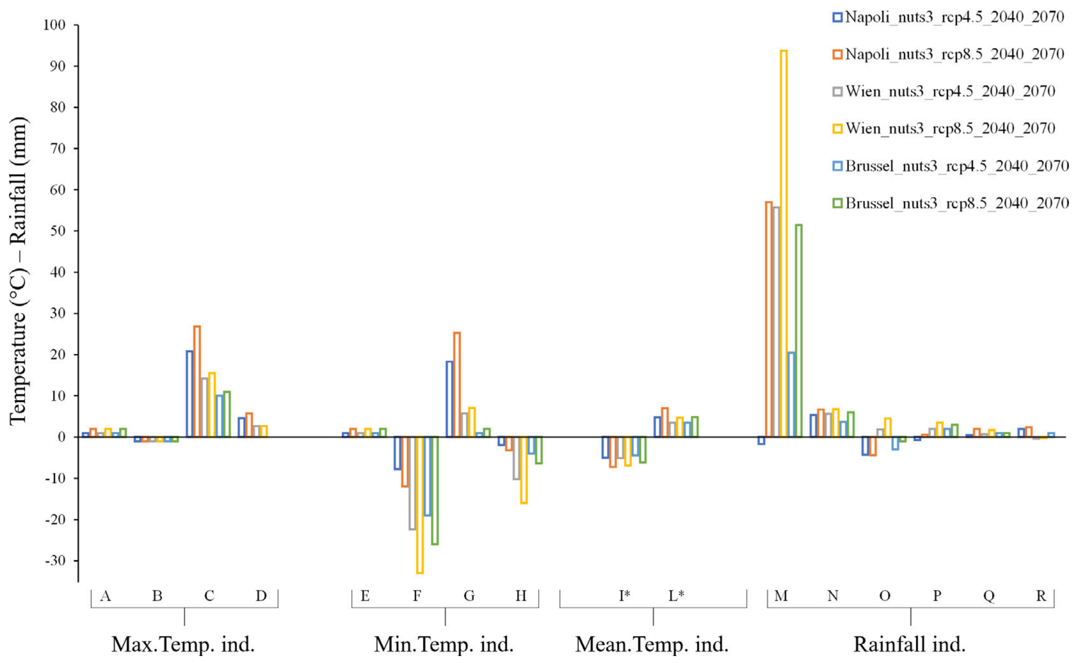


FIGURE 4 Graph summarizing for the output of case study 1 a selection of some of the available climatic indicators: A: Mean of daily maximum temperature (°C); B: Ice Days—number of days with maximum temperature less than 0°C (days); C: Summer Days—number of days with maximum temperature greater than 25°C (days); D: Hot Waves—number of days with maximum temperature greater than 35°C (days); E: Mean of daily minimum temperature (°C); F: Frost Days—number of days with minimum temperature less than 0°C (days); G: Tropical Nights—number of days with minimum temperature greater than 20°C (days); H: Consecutive Frost Days—maximum number of consecutive days with minimum temperature less than 0°C (days); I*: Heating Degree Days—sum of 17°C minus mean temperature (°C); L*; Growing Degree Days—sum of mean temperature greater than 4°C (°C); M: Precipitation sum (mm); N: Maximum 1-day precipitation amount (mm); O: Number of days with precipitation greater than or equal to 1 mm (days); P: Number of days with precipitation greater than or equal to 10 mm (days); Q: Number of days with precipitation greater than or equal to 20 mm (days); R: Consecutive Dry Days—largest number of consecutive days with precipitation less than 1 mm (days); * (°C ×100). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Indicators of crop thermal sums anomalies obtained with "Crop—Thermal sums anomalies" tool in Valtellina and east of Campania area of interests.

	Valtellina		East Campania	
Indicators	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Sowing period length (days)	6.8	14.7	4.0	8.0
Emergence period length (days)	3.7	5.6	−3.0	−2.0
Flowering period length (days)	−6.8	−17.6	−14.0	−17.0
Harvesting period length (days)	−8.8	−5.9	3.0	0.0
Extreme events of min. temp. (during the emergence period)	8.3	−0.5	−6.0	−10.0
Extreme events of min. temp. (during the first 15 days of the emergence period)	0.0	0.0	−2.0	−5.0
Extreme events of max. temp. (during the flowering period)	2.0	0.0	−1.0	1.0
Number of times in which harvesting is not reached	−0.4	−0.5	−7.0	−15.0

emergence period will increase (8.3 for RCP 4.5) or will slightly decrease (−0.5 for RCP 8.5) in number in the Valtellina region while in east Campania will decrease definitely (−6 or −10 events); finally, the number of times in which the harvesting is not reached is expected to be a quite unchanged for Valtellina (−0.4 or −0.5), while for east Campania it is expected to be equal to −7.0 or −15 according to the scenario selected, which means that the crop will better adapt to future thermal regimes, reducing the risk of not complete the growing cycle compared to the reference period. Analyzing this information, the user can conclude that the CC scenarios considered in the comparison between the two areas predict greater impacts on wheat crops for the area located in northern Italy than expected for that located in the south.

The results obtained in the AOI of the Campania region have been subjected to a kind of validation through a comparison with the

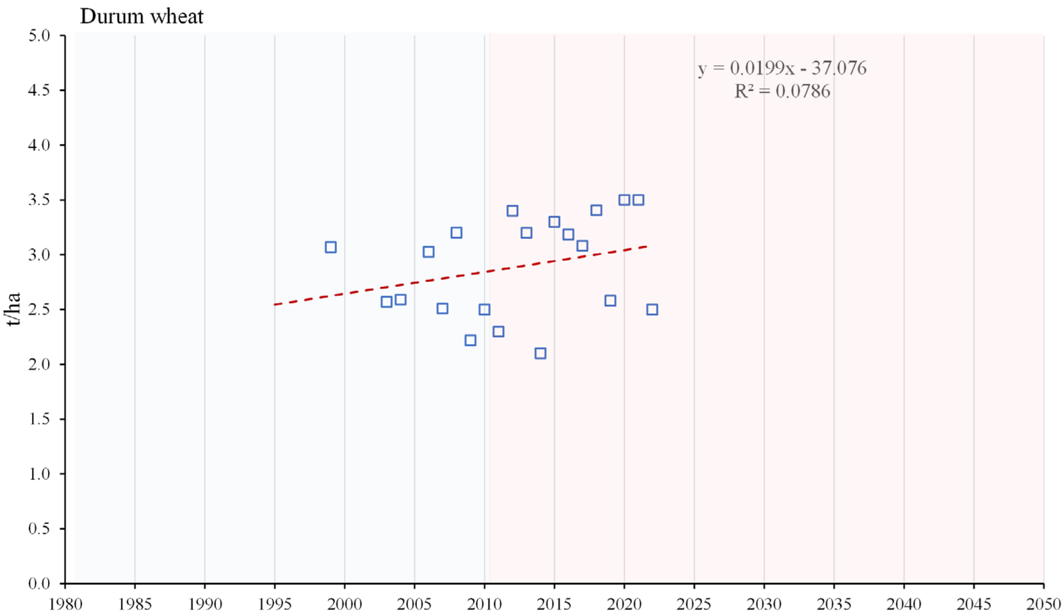


FIGURE 5 The trend of yield production of durum wheat in the AOI of the Campania region from 1990 to 2022. Data from the Italian National Institute of Statistics (ISTAT). [Colour figure can be viewed at wileyonlinelibrary.com]

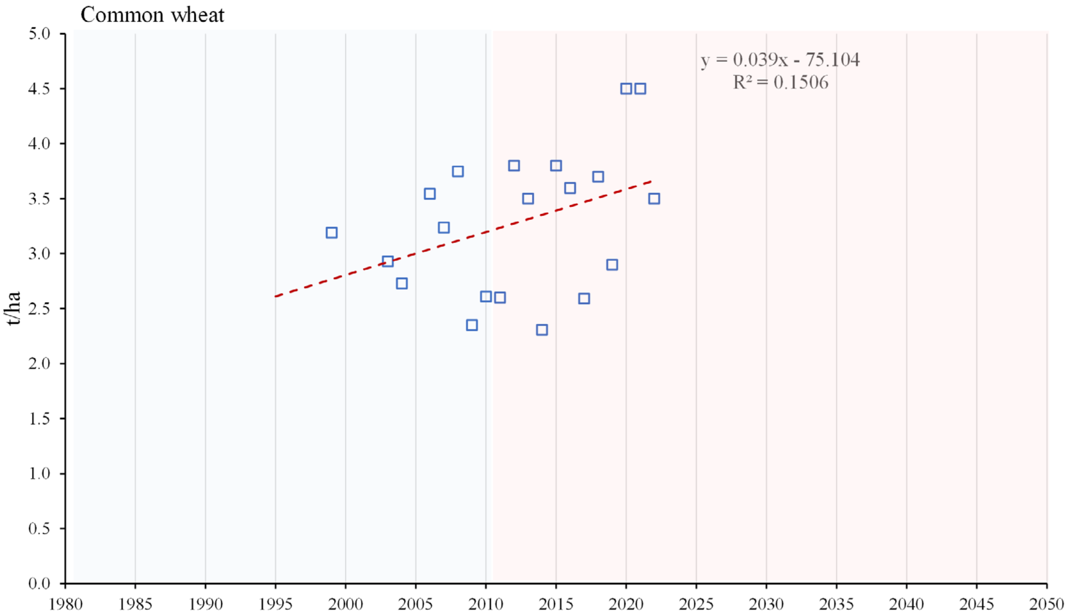


FIGURE 6 The trend of yield production of common wheat in the AOI of the Campania region from 1990 to 2022. Data from Italian National Institute of Statistics (ISTAT). [Colour figure can be viewed at wileyonlinelibrary.com]

real yield data measured by the Italian National Institute of Statistics (ISTAT) about durum and common wheat production during the period 1990–2022. Figures 5 and 6 showed a trend of increase in wheat production (durum and common) in the study area, which is in line with the "Crop-Thermal sums anomalies" tool results. The fact, improvement in wheat adaptation can be expected after an increase in the thermal regime in that area, with a reduction in extreme thermal events and a relative decrease in rainfall. This last information, which tendentially seems to be in contrast with an increase in crop production, confirms in this study area the goodness of correlation between these two independent datasets.

The study area of the Campania region is characterized by heavy clay soils that in winter are near water saturation, forcing the wheat roots to place in the first 20 cm of soil (Puig-Sirera et al., 2022). Thus a decrease in rainfall events during the wheat growing season in this environment can only improve crop adaptation and then production.

5 | CONCLUSION

CC is known to be a global problem having both direct and indirect effects on agricultural productivity. Policies on CC mitigation and adaptation are in place in many countries. In EU, the "new EU strategy on adaptation to climate change" (2021) set line of action to all EU Member States requiring to set-up and implement "National Adaptation Strategies (NASs), as cross-sectoral planning instruments to inform and prioritize actions and investments towards climate change adaptation", but the factual implementation of these CC policies at regional and local levels to support decision-making remains a critical item. The scientific community cannot only be taken into account to warn about CC danger and its impact on ecosystems but also to support the resilience of community by providing science-based operational tools to challenge CC.

Here—in agreement with this LDD special issue requiring submissions on "the implementation of S-DSS to address the various sustainable land uses in different sectors such as agriculture, … CC "we developed a Geospatial Decision Support System, based on scientific knowledge, to support local authorities/communities in EU and more in further detail (for agriculture) in Italy in better implementing adaptation to CC.

We demonstrated that the freely available web-based toolbox (www.landsupport.eu) named "Climate Change Resilience" works at any administrative level (any NUTS level) for the entire EU and can evaluate the impact of climatic anomalies (e.g., temperature and rainfall expected changes) in general or specifically on agriculture (e.g., selected crops).

The toolbox has been demonstrated through two separate case studies: (i) at the EU level analyzing climatic anomalies at country, region, province, and municipalities administrative levels and (ii) on the agricultural productivity by demonstrating the use of the tool on "Crops-thermal sums anomalies" in the case of Italy.

To the best of our knowledge, this is the 1st Geospatial DSS system enabling it to support any NUTS level for the entire EU providing CC data for different RCP and time scenarios. In addition, it is the 1st S-DSS system working for the entire Italy enabling to evaluate the impact of CC on crops.

Despite the evidence that the implemented tools reflect the best current solution in terms of scientific approaches, here we must also emphasize that one of the main limitations of the toolbox is the spatial resolution of ingested data by tools (e.g., RCP scenarios resolution). An improvement in spatial resolution (currently 8 and 12 km respectively for Italy and EU; see materials and methods) is indeed required to make the DSS results more reliable and thus more useful to different stakeholders.

In this sense, the system has been built to be flexible, replicable, and transferable everywhere. These features are extremely important because update and revision on dataset on CC impact varies almost every year and our system (based on Landsupport GCI) enables us to easily update the database without real changes in the IT infrastructure or change in writing new IT codes thus with a very good value for money.

Furthermore, we must highlight that the climatic crop adaptation tool requires further improvement. For example, it would be important to introduce the effect of soil spatial variability on crop water availability under CC. This means that more complex models must be applied to simulate the soil–plant and atmosphere system (SPA), the algorithms adapted to the Web DSS, and new information added in the database (e.g., soil map with soil hydraulic properties). Also in this case the limitation in the DSS performance is not strongly dependent on the scientific approach applied but on the quality and resolution of soil spatial information available, which in most cases are not able to support SPA model application and make an evaluation of dynamic soil ecosystem functions.

In a more general view, we hope that research efforts—like the current contribution—bringing science-based databases, models, and GUI into operational freely based tools can contribute to narrowing the large distance existing between the scientific community and stakeholders.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in Landsupport DSS at https://app.landsupport.eu/. These data were derived from the following resources available in the public domain:—Landsupport DSS, https://app.landsupport.eu/.

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ENDNOTES

[1] Europe: RDP 2014–2020. Priority N. 4, promoting resource efficiency and supporting the shift toward a low-carbon and climate-resilient economy in the agriculture, food, and forestry sectors. https://ec.europa.eu/sfc/en/2014/quickguides/PRGEAFRDP#-priority-1-5858. Italy: Azioni del programma Rete Rurale Nazionale. Azione 4.2.1 Servizi per la diffusione della innovazione. C:/Users/Admin/Downloads/Allegato_azioni_RRN_-Rev_Dic_2016..pdf; Law n. 4/2011 National Integrated Production Quality System; National guidelines for integrated crop production/phytosanitary defense and weed control (DM n.4890 of 08.05.2014).

[2] Recently, some data from this dataset has been distributed through the CMCC DDS system (https://dds.cmcc.it/#/dataset/climate-projections-8km-over-italy/historical).

[3] For the period 2006–2010 forcing are based on IPCC RCP4.5.

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