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RESEARCH ARTICLE

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High performance computing to support land, climate, and user-oriented services: The HIGHLANDER Data Portal

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Abstract

The Italian territory is located at the heart of one of the global hot spots of climate change, where the implementation of climate-smart land management practices is imperative to guarantee the present and future maintenance of ecosystem functions as well as the sustainability of human socioeconomic activities. The project HIGHLANDER (HIGH performance computing to support smart LAND sERvices) led by Cineca aims at building a comprehensive and multi-sector framework for land-management decision-making in Italy. The project relies on high quality information on different components of the landscape, with a focus on climate-driven processes, and state-of-the-art computing infrastructures. The HIGHLANDER Data Portal maximizes the impact of HIGHLANDER results by providing access to data products and services. In this article, we describe the architectural features of the platform, as well as the available HIGHLANDER datasets and downstream applications.

KEYWORDS

climate, forecasts, HPC, land, observations, projections

1 | INTRODUCTION

Climate change poses significant challenges worldwide (IPCC, 2022), requiring the development of climate resilience strategies to minimize its impacts (Filho, 2019). In this context, efforts are being made to achieve sustainable land management and integrate climate information into decision-making processes (Haregeweyn et al., 2023; Motavalli et al., 2013). However, the complexity of Earth's systems and human activities have historically hindered comprehensive approaches to these issues, often treating ecosystems and sectors separately. To optimize land management, an integrated, multi-actor approach at the landscape level is needed, particularly in Italy, a country characterized by diverse land covers, geomorphological contexts, and resource availability undergoing rapid transformations. The Mediterranean region, including the Italian territory, is a climate change hot spot (Giorgi, 2006), facing increased temperatures (Acero et al., 2014; del Río et al., 2011; El Kenawy et al., 2011; Elena Xoplaki et al., 2003) and decreased precipitation (Giorgi & Lionello, 2008; Sousa et al., 2011; Vicente-Serrano & Cuadrat-Prats, 2007), as well as an enhanced frequency of extreme weather events (IPCC, 2022). Italy also experiences fast land use changes and demographic dynamics (Santini & Valentini, 2010). Smart land management practices, encompassing agriculture, forestry, and water management, should address both the challenges and opportunities of climate change adaptation and mitigation. Only the access to abundant data and improved computing capabilities can support informed decision-making for various stakeholders involved in land planning, farming, policy-making, research, and governance.

In response to the challenges posed by climate change and its associated pressures, the HIGHLANDER project (HIGH performance computing to support smart LAND sERvices) was developed to facilitate sustainable land management from both environmental and socio-economic perspectives.

HIGHLANDER focuses on three main interconnected objectives. Firstly, it aims to design and implement a comprehensive framework that incorporates diverse data, indicators, and tools. This framework utilizes advanced approaches such as remote and in situ monitoring data, analytical tools, numerical models, and machine learning algorithms. By providing dedicated services, these resources will be accessible to a wide range of users. Additionally, the framework will generate user-tailored indicators and indices to condense information, including assessments of hazards and risks.

Secondly, the project seeks to leverage state-of-the-art High Performance Computing (HPC) infrastructures. This involves generating, post-processing, hosting, distributing, and making available existing and next-generation data, indicators, and tools. HPC-based services will facilitate the effective integration of information into decision-making processes, strategies, and plans at various spatial-temporal scales and sectoral levels.

The third objective of HIGHLANDER is to ensure the long-term functionality of the services. This is achieved through active involvement and engagement of real users. By testing and promoting the repeatability, transferability, and scalability of services, the project aims to develop sustainable solutions.

Cineca Interuniversity Consortium leads and coordinates the HIGHLANDER project. As a prominent national facility for supercomputing applications and research, Cineca provides cutting-edge HPC resources and support to academic and industry organizations. The project benefits also from collaborations with various partners, including regional environmental protection agencies (the Agenzia Regionale per la Prevenzione e l'Ambiente of Emilia-Romagna, ARPAE, and the Agenzia Regionale per la Prevenzione e l'Ambiente of Piedmont, ARPAP), the European Centre for Medium-Range Weather Forecasts (ECMWF), the University of Tuscia (UNITUS; in particular, the Department for Innovation in Biological, Agro-food and Forest systems, DIBAF), the Foundation Euro-Mediterranean Center on Climate Change (CMCC), the Foundation Edmund Mach (FEM), Deda Next (https://www.dedanext.it/, last access: September 29, 2023), and ART-ER Attractiveness Research Territory. Finally, HIGHLANDER takes advantage of the participation of territorial associations of potential users, such as the Confederazione Italiana di Agricoltori of Piedmont (CIA Piedmont), a renowned union of farmers with over 10,000 associates, and many others that were attracted during the project. The expertise and resources contributed by these partners ensure the integration of technical, scientific, social, and policy aspects. This collaborative effort aims to create multi-thematic services based on HPC/Cloud solutions, facilitating sustainable land management practices.

Overall, the HIGHLANDER project seeks to enhance the sharing and the interoperability of large datasets related to climate predictions, observational data, and other types of relevant information, paving the way for a comprehensive approach to disaster risk reduction, climate change adaptation, and land management. To articulate these objectives HIGHLANDER has deployed the HIGHLANDER Data Portal (https://dds.HIGHLANDERproject.eu/, last access: September 29, 2023). This web platform gives access to HIGHLANDER's Downstream Applications and pre-Operational Services (DApOS), which consist of both data products and applications where users can visualize and explore data, as well as extract valuable information for their activities and communities.

The platform was envisioned to fulfill the need for an open data platform at a national level to host high-resolution climate data particularly relevant for the Italian territory. In this way, the future prospect for HIGHLANDER Data Portal is to become the national access point to climate data supported by the recently founded National Agency for Meteorology and Climatology ItaliaMeteo, complementing the Mistral Meteo-hub platform for weather data (Bottazzi et al., 2021). To this aim, the partnership established in HIGHLANDER is determined to ensure the sustainability of the platform on a long term and as a result, an agreement has been signed for the management of intellectual property rights, and the updating and maintenance of the platform services, in view of continuity after the project ended in January 2023. The partners are also committed to promote the platform so that new initiatives and projects are designed in a way that new datasets and applications can be gradually integrated. ItaliaMeteo, which did not participate directly in the HIGHLANDER project, has a strategic interest in the maintenance and update of HIGHLANDER's climatological data. The agency, is considered a partner to the agreement and, therefore, will be one of the parties responsible for coordinating the activities in the field of Meteorology and Climatology at a national level. The role is of key importance because it implies supporting state and regional authorities in charge of civil protection functions, health and environmental protection, agricultural policy, in the areas of their respective competences, in particular within the framework of the national alert system for meteo-hydrogeological and hydraulic risk, as well as of the implementation of the plan on precision agriculture and climate change mitigation and adaptation measures.

In this paper, we present the HIGHLANDER Data Portal architecture, features, data products, and applications. The work is organized as follows. Section 2 presents a technical description of the HIGHLANDER Data Portal, including its high-level architecture and data harmonization. The role that HPC plays in HIGHLANDER project is reported in Section 3. In Section 4 and Section 5 we present the datasets and DApOS available through the HIGHLANDER Data Portal. Section 6 describes how users can access the data. Finally, Section 7 summarizes the main highlights of this article.

2 | HIGHLANDER DATA PORTAL: HIGH-LEVEL ARCHITECTURE AND DATA HARMONIZATION

The HIGHLANDER platform is based on the microservice architecture, which presents a modular structure in which the individual components are deployed independently. Figure 1 shows a graphical representation of the different components of the platform as well as the data

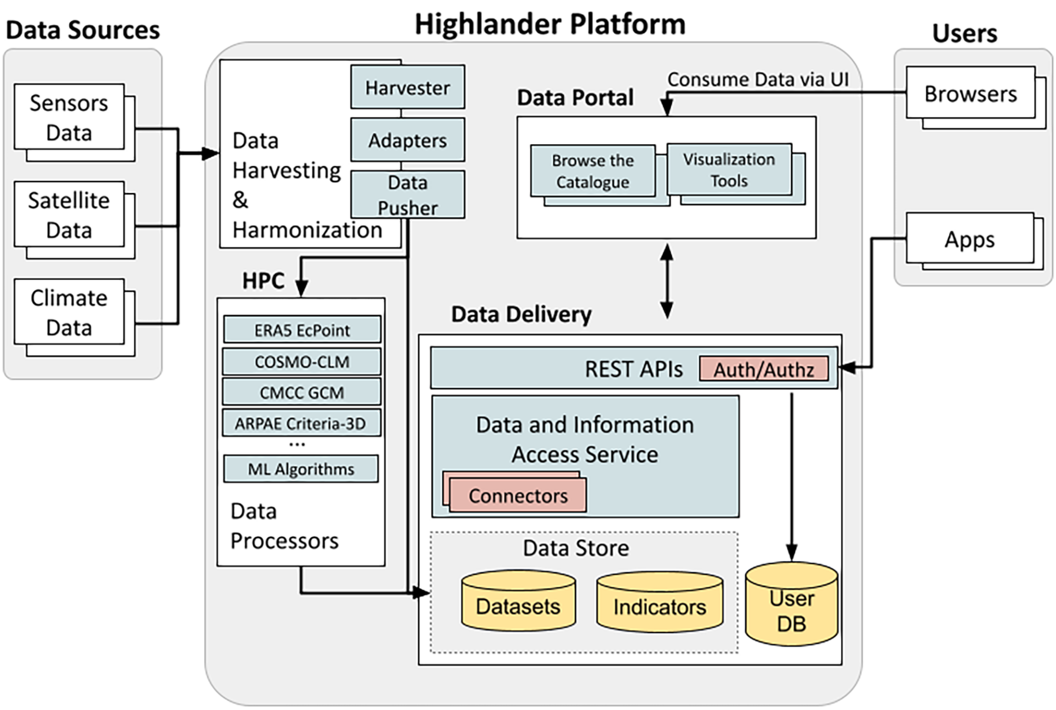

FIGURE 1 High-level architecture of HIGHLANDER platform.

flows and access points for end users. This simplified view of the architecture highlights the main tasks of the system: data processing and delivery. Data available from providers are harvested and harmonized as described below. Then, statistical and numerical physical models and machine learning algorithms exploit these data to fulfill the development of the DApOSes. Due to the large amount of data and time-consuming elaboration, these procedures greatly benefit from the employment of HPC resources. The results are then stored in a data repository and made accessible to the end user through the HIGHLANDER Data Delivery System (DDS).

A web data portal, as the main front-end component, provides access to the dataset repository and to different visualization tools expected by the various DApOS. On the back-end side, data is collected into a catalog and served through RESTful APIs. Among the back-end services, in addition to the APIs that implement the functionalities exposed to the end users it is worth mentioning a map service with the purpose of providing geo-referenced layers for data visualization on a map. A task manager takes care of executing asynchronous tasks and any user request with long processing times. To make these services more easily manageable and deployable a *container-based* solution has been adopted (Merkel, 2014). Containerization (using Docker) allows to package the application software with all of its dependencies into a *standardized unit* and creates an environment that is isolated from the rest of the applications and can be run anywhere. This allows to create the components as building blocks of a wider system and makes the services easier to manage and maintain. The deployment of such containers is represented in Figure 2.

HIGHLANDER makes use of three broad kinds of data, that is, extracted from: in situ sensors, satellite images, and climate data derived from observations and model simulations. The project strongly leans on common international standards that guarantee the accessibility and reusability of relevant data across borders and sectors. In particular, regarding the domain of spatial information, it follows the principles of the European INSPIRE Directive (https://inspire.ec.europa.eu/, last access: September 29, 2023; Cetl et al., 2019). Using standards helps data harmonization, saves time and resources, avoids mistakes, and enables the comprehension of the results in a wider context. The INSPIRE Directive requires that common implementing rules (IR) are adopted in several specific areas: metadata, data specifications, network services, data and service sharing and monitoring, and reporting. A user must be able to find spatial datasets and services, and to establish whether they may be suitable for their use case and for what purposes they are useful. The INSPIRE Metadata regulation defines the indispensable set of metadata necessary to fulfill this premise, that is, to allow the identification of the information resource for which the metadata is created, its classification, the identification of its geographic location and temporal reference, and the evaluation of its quality and validity. Furthermore, this regulation needs to set a consistent framework with regards the IRs

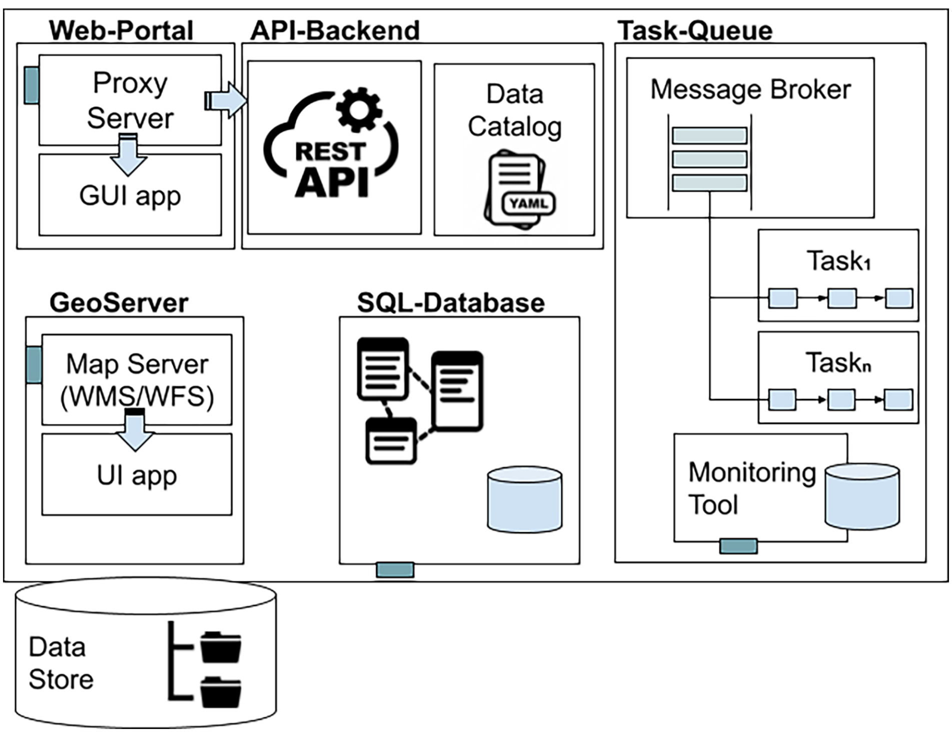

FIGURE 2 Graphical representation of the HIGHLANDER container based-solution.

established on the interoperability of spatial datasets and services, constraints related to access and use, and the organization responsible for the resource. In addition, the metadata record contains the information necessary to monitor that the metadata record itself is correctly kept updated.

The potential of Internet of Things (IoT) devices relies on their ability to capture and render available local information about the world around them. Also, data are frequently gathered in various structures, incompatible protocols, and unclear semantics. In order to tackle these challenges, it is necessary to build a well-defined interface, from where uniform data can be queried. The Open Geospatial Consortium (https://www.ogc.org/, last access: September 29, 2023) (OGC) has addressed this demand and developed the SensorThings API standard, an open, geospatial-enabled, and unified way to interconnect devices throughout the IoT. Hence, the SensorThings API is a standard for the collection, storage, and retrieval of time series data.

HIGHLANDER project also makes use of the datasets provided by the ESA Copernicus Sentinel 2. Sentinel-2 is a European wide-swath, high-resolution, multi-spectral imaging mission. Each of the satellites carries a single payload: the Multi-Spectral Instrument (MSI). MSI samples 13 optical spectral bands at different spatial resolutions (four bands at 10 m, six bands at 20 m, and three bands at 60 m). Sentinel-2 data offers a view on the reflectance properties of vegetation or target features. Additional remote sensing data are used for specific applications developed by HIGHLANDER. This is the case of airborne data, such as Light Detection and Ranging (LiDAR) or hyperspectral. To be able to safely join these non-satellite inputs, routines to ensure data comparability are set up. Climate data are harmonized as any variable is provided under the same format. One of the first aspects to consider in climate modeling outputs is the data format. Climate research considers three generic categories: GRIdded Binary (GRIB, https://www.unidata.ucar.edu/software/netcdf/, last access: September 29, 2023), Network Common Data Format (NetCDF, http://www.nco.ncep.noaa.gov/pmb/docs/grib2/, last access: September 29, 2023), and Hierarchical Data Format (HDF, http://hdfeos.org/, last access: September 29, 2023). All of these formats are portable (machine independent) and self-describing, that is, they can be examined and read by the appropriate software without the user expected to know the structural details of the file. Further, additional information about the data in the shape of metadata may be included in the file, for example, textual information about each variable's contents and units, or numerical information describing the grid type, the coordinates (e.g., time, level, latitude, longitude). The most recent and used data formats are as follows: netCDF4 (NetCDF Version 4.x), GRIB2 (GRIB Edition 2), HDF5 (HDF Version 5.x).

3 | THE ROLE OF HIGH PERFORMANCE COMPUTING IN HIGHLANDER

Most of the computational hours used in this project were invested in climate simulations. In fact, the climate simulations of reanalysis and projection were performed by CMCC on the Cineca's infrastructure. Cineca designed, set up, and made available all the necessary HPC and CLOUD infrastructure required.

Two different architectures were used for the simulations (Table 1): GALILEO for VHR-REA_IT and GALILEO100 for VHR-PRO_IT. In the former case, the HPC is equipped with 1022 36-core compute nodes. Each one contains two 18-core Intel Xeon E5-2697 v4 (Broadwell) at 2.30 GHz. All the compute nodes have 128 GB of memory. The long-term run was performed using 60 nodes, corresponding to 2160 cores, and employed about 61 h to perform a 1-year simulation. The long-term simulation produced a large amount of data, 8 TB of output data and greater than 70 TB of forcing data, including the 3D boundary data needed for the downscaling. For the VHR-PRO_IT simulations, the HPC is equipped with 554 computing nodes with 48 cores. Each node contains 2xCPU x86 Intel Xeon Platinum 8276-8276 L (24 cores at 2.4 GHz). All computing nodes have 384 GB of memory. The long-term simulation has been performed exploiting 54 nodes, corresponding to 2484 cores, taking approximately 43 h per simulation year. It produced a large amount of data (i.e., 16.5 TB of output data and greater than 53 TB of forcing data), including the 3D boundary data needed for the downscaling.

4 | DATASETS

Datasets distributed by HIGHLANDER or/and used as an input to the DApOS can be grouped into background

TABLE 1 HPC resources used for VHR-REA_IT and VHR-PRO_IT HIGHLANDER datasets.

Dataset	Cluster	Core hours	Nodes
VHR-REA_IT	GALILEO	$12\ 10^6$	60 nodes (2160 cores)
VHR-PRO_IT	GALILEO100	$18\ 10^6$	54 nodes (2592 cores)

and foreground datasets (see Appendix A). The background datasets are generated by a project partner prior to the project or under other funding. They can also be provided by third-party organizations. The background datasets Tree Talker Fire, Animal Talker, Tree Talker have an open data licence and they are produced by project partners. Other background datasets, such as Sentinel-2 images, high-resolution aerial data, and LiDAR aerial data are produced and hosted by third-party entities and are publicly available with an open data licence and with standard web access. In particular, the last two datasets belong to observational programs developed by the Trento Province (Italy). Finally, the background datasets on climatic requirements of native and invasive forage species in pastures and mycotoxin values on common wheat and corn are provided by the University of Turin and CIA, respectively, and are only available for the project partners.

The foreground datasets are generated by the partners of HIGHLANDER project under HIGHLANDER funding. Among them we find the dynamical downscaling of ERA5 (VHR-REA_IT) and of climate projections (VHR-PRO_IT), and statistical downscaling of ERA5 and of sub-seasonal predictions. Moreover, the data products of each DApOS are considered a foreground dataset as well.

The following sections briefly describe the downloadable datasets that users can access through the HIGHLANDER Data Portal. Table 2 presents a complete list of them. Each item contains at least a data product. The parameters and units of these data products are also provided. Furthermore, the table reports the licence under which the data are published.

4.1 | Downscaling of ERA5 at 2.2 km over Italy

The dynamical downscaling of ERA5 over Italy (*Very High Resolution Dynamical Downscaling of ERA5 Reanalysis over Italy*, VHR-REA_IT; Raffa et al., 2021) is a dataset produced by CMCC in the framework of the HIGHLANDER project. VHR-REA_IT provides outputs from climatic model simulations driven by the ECMWF ERA5 reanalysis (Hersbach et al., 2020), originally available at 31 km spatial resolution, downscaled on a grid spacing of 2.2 km (i.e., convection permitting scale) in HIGHLANDER. ERA5 is the latest climate reanalysis produced by the ECMWF, and provides hourly data on many atmospheric, land-surface, and sea-state parameters together with estimates of uncertainty. ERA5 data are available on the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) on a regular latitude-longitude grid at 0.25° × 0.25° resolution, with atmospheric parameters on 37 pressure levels. Currently, ERA5 covers the period from 1940 to the present. It continues to be extended forward in time, with daily updates being available 5 days behind real time. The dynamical downscaling was applied through the Regional Climate Model (RCM) COSMO5.0_CLM9 (Rockel et al., 2008) using the GALILEO supercomputer hosted at Cineca. All the details regarding the creation of this dataset can be found in Raffa et al. (2021), in particular, a configuration for more accurate representation of urban scale dynamics was used. The temporal resolution of the output is hourly as it is for ERA5. The spatial domain covers the whole Italian territory to provide a very detailed (in terms of space–time resolution) and comprehensive (in terms of meteorological variables, see Table 2) set of climatological data for at least the last 40 years, from January 1981 to December 2020. These data are available under CC BY 4.0 licence.

4.2 | Dynamical downscaling with COSMO-CLM of historical (1981/2005) and future climate (2006/2070) projections

The Very High Resolution climate projection (VHR-PRO_IT; Raffa et al., 2023) dataset is produced within the HIGHLANDER project, with an horizontal resolution of ≈2.2 km, using as boundary conditions for the RCM COSMO-CLM mentioned above the simulations from the CMCC-Climate Model (CMCC-CM, Scoccimarro et al., 2011) over the period 1981–2070, adopting the IPCC historical (1981–2005) plus Representative Concentration Pathways (RCPs) 4.5 and 8.5 (2006–2070) scenarios (Riahi et al., 2011). To go from the ≈80 km horizontal resolution of the CMCC-CM to the ≈2.2 km of the planned runs in HIGHLANDER, an intermediate (nested) dynamical downscaling has been previously conducted at CMCC through the configuration of the same RCM COSMO-CLM (Rockel & Geyer, 2008) at ≈8 km over Italy, still under the RCPs 4.5 and 8.5. According to the 5th Assessment Report of IPCC, RCP 8.5 assumes a trajectory for atmospheric greenhouse gases (GHG) concentration which leads to a radiative forcing of $+8.5\ \mathrm{W\ m^{-2}}$ (approximately 1370 ppmv CO_2-equivalent) by the end of the century. RCP 8.5 is thus often defined as “the worst-case scenario” because such an increase in the radiative flux is only possible if no (or very mild, or ineffective) mitigation strategies are adopted. RCP 4.5 is instead a stabilization scenario where total radiative forcing is stabilized, shortly after 2100, to $4.5\ \mathrm{W\ m^{-2}}$ (approximately 650 ppm CO_2-equivalent) by employing technologies and strategies to reduce GHG emissions.

TABLE 2 Description of the HIGHLANDER datasets. In particular, we report the following information: (1) full name; (2) name of the data products included in each dataset; (3) licence; (4) physical variables and indexes included in each data product and their units.

Dataset	Product	Licence	Variable [units]
Downscaling of ERA5 @2.2 km over Italy	VHR-REA_IT	CC BY 4.0	Surface evaporation [kg m^2]; averaged surface net downward short-λ radiation [W m^{-2}]; averaged surface net downward long-λ radiation [W m-2]; total cloud cover; mean sea level pressure [Pa]; 2 m specific humidity [kg kg^{-1}]; 2 m dew point temperature [°K]; 2 m maximum temperature [°K]; 2 m minimum temperature [°K]; total precipitation amount [kg m^{-2}]; 2 m temperature [°K]; U-component of 10 m wind [m s^{-1}]; V-component of 10 m wind [m s^{-1}]; surface snow amount [m]; soil water content [m]
Dynamical Downscaling with COSMO-CLM of historical (1981/2005) and future climate (2006/2070) projections	VHR-PRO_IT-HIST; VHR-PRO_IT RPC8.5; VHR-PRO_IT RPC4.5	CC BY 4.0	(as for VHR-REA_IT)
Downscaling of ERA5 using ECMWF's ecPoint post-processing	Percentiles; Bias-corrected ensemble members	CC BY 4.0	Minimum temperature at 2 m in 24 h [°K]; Maximum temperature at 2 m in 24 h [°K]; Total precipitation in 24 h [kg m^{-2}]; Total precipitation in 12 h [kg m^{-2}]
Downscaling of sub-seasonal forecasts (using ECMWF's ecPoint post-processing)	Percentiles; Bias-corrected ensemble members	Free for research	Minimum temperature at 2 m in 24 h [°K]; Maximum temperature at 2 m in 24 h °[K]; Mean temperature at 2 m in 24 h [°K]; Total precipitation in 24 h [kg m^{-2}]
Soil Erosion Indicators (1991–2050) @2.2 km over Italy		CC BY 4.0	Rainfall erosivity, R-factor [MJ mm ha^{-1} h^{-1} $year^{-1}$]; Soil Loss, SL [t ha^{-1} $year^{-1}$]
Sub-seasonal irrigation forecasts	(1) Irrigation forecast; (2) Precipitation forecast	(1) CC BY 4.0; (2) Free for Research	Irrigation forecast [mm]; Precipitation forecast [mm]
Irrigation Projections	Annual Irrigation	(1) CC BY 4.0; (2) Free for Research	Irrigation forecast [mm]; Precipitation forecast [mm]
Well-being Indicators at 2.2 km over Italy	Daily (1989–2020); Daily Projection (1989–2050)	CC BY 4.0	Apparent Temperature [°C]; Discomfort Index [°C]; Humidex [°C]; Wind Chill [°C]
	Bio-climatic Indicators Historic (1991–2020) and Future (2021–2050)	CC BY 4.0	Annual Mean Temperature [°C]; Mean Temperature of Warmest Quarter [°C]; Mean Temperature of Coldest Quarter [°C]; Annual Precipitation [mm]; Precipitation of Wettest Month [mm]; Precipitation of Driest Month [mm]; Precipitation Seasonality (Coefficient of Variation) [unitless]; Precipitation of Wettest Quarter [mm]; Precipitation of Driest Quarter [mm]; Precipitation of Warmest Quarter [mm]; Precipitation of Coldest Quarter [mm]; Mean Diurnal Range (Mean of monthly [max. temp. – min. temp.]) [°C]; Isothermality (×100) [%]; Temperature Seasonality (standard deviation ×100)

(Continues)

TABLE 2 (Continued)

Dataset	Product	Licence	Variable [units]
			[unitless]; Max Temperature of Warmest Month [°C]; Min Temperature of Coldest Month [°C]; Temperature Annual Range [°C]; Mean Temperature of Wettest Quarter [°C]; Mean Temperature of Driest Quarter [°C]
Indicators of bio-climatic conditions and forest suitability	Forest species suitability Historic (1991–2020) and Future (2021–2050)	CC BY 4.0	Abies alba [suitability 0–1]; Acer campestre [suitability 0–1]; Carpinus betulus [suitability 0–1]; Castanea sativa [suitability 0–1]; Corylus sp [suitability 0–1]; Fagus sylvatica [suitability 0–1]; Fraxinus ornus [suitability 0–1]; Larix decidua [suitability 0–1]; Ostrya carpinifolia [suitability 0–1]; Picea abies [suitability 0–1]; Pinus cembra [suitability 0–1]; Pinus halepensis [suitability 0–1]; Pinus pinaster [suitability 0–1]; Pinus sylvestris [suitability 0–1]; Quercus cerris [suitability 0–1]; Quercus ilex [suitability 0–1]; Quercus petraea [suitability 0–1]; Quercus pubescens [suitability 0–1]; Quercus robur [suitability 0–1]; Quercus suber [suitability 0–1]
Changes in the land suitability for vegetation over Piedmont region	CompI (1991–2020); Aflatoxin Index (1991–2020); RCP8.5-CompI (2021–2050); RCP8.5-Aflatoxin Index (2021–2050); RCP8.5-Habitat suitability (1991–2020, 2041–2050); RCP8.5-Suitability change (1991–2050); RCP8.5-Rangesize change (1991–2050); RCP8.5-Range map (1991–2020, 2041–2050)	CC BY 4.0	CompI Index [%]; Aflatoxin Index [%]; Sweet chestnut [suitability 0–1]; European beech [suitability 0–1]; European larch [suitability 0–1]; Mesophilic oaks [suitability 0–1]; Other broadleaves [suitability 0–1]; Norway spruce and Silver fir [suitability 0–1]; Scots pine [suitability 0–1]; Black locust [suitability 0–1]; Thermic oaks [suitability 0–1]
Variation in milk production in Friuli-Venezia Giulia	Variation in milk production, April–May and July–August (1989–2050)	CC BY 4.0	Prediction of milk from residual [hg]
Climate indicators for forest fire hazard	Fire Weather Index (FWI); Drought Code (DC): Fine Fuel Moisture Code (FFMC)	CC BY 4.0	Probability of exceeding the 50th, 90th, and 95th percentiles
IOT animal sensor data	Sensors on animals	CC BY 4.0	Animal position [AnimalCollar + GPS]: altitude, latitude, longitude; Animal movement neck [AnimalCollar]: x,y, and z-axis (average value and standard deviation); Environmental Relative Humidity [AnimalCollar]; Environmental Temperature [AnimalCollar]; Animal movement leg [AnimalButton]: x,y, and z-axis (average value and standard deviation); Environmental Relative Humidity [AnimalButton]; Environmental Temperature [AnimalButton]; Animal skin Temperature [AnimalButton]

The temporal resolution of outputs is hourly and runs to cover the whole Italian territory and neighboring areas according to the necessary computation boundary, so to provide a very detailed (in terms of space–time resolution) and comprehensive (in terms of meteorological fields, see Table 2) dataset of projected climatological data for 90 years (1981–2070).

4.3 | Downscaling of ERA5 using ECMWF's ecPoint post-processing

ERA5-ecPoint products are the first ever probabilistic global reanalysis products for point scales. They are based on the ECMWF ERA5 reanalysis (Hersbach et al., 2020), run at 0.3° horizontal resolution (≈31 km), but downscaled to point scale using ecPoint post-processing (see Hewson & Pillosu, 2021). The products comprise 24-h rainfall and 24-h minimum, maximum, and mean 2 m temperature, and are probabilistic in nature, being stored as percentiles (1-to-99) for each grid box. Downscaling means that values stored are expected to better represent in situ measurements (i.e., from rain gauges and thermometers), while the raw ERA5 output refers instead to average values for the modeled grid scale (i.e., over regions measuring about 31 km by 31 km). ecPoint is a new and innovative decision-tree-based statistical post-processing technique specifically developed by ECMWF to downscale relatively low-resolution numerical model output (e.g., from global models). One applies ecPoint to individual model realizations, although post-processed ensemble member outputs can subsequently be aggregated together (as in Section 4.4). ecPoint products include the predicted sub-grid variability, together with bias corrections for grid-box means (which both vary according to diagnosed grid-box weather type).

Figure 3 shows minimum temperatures for December 19, 2021, when anticyclonic conditions with a strong low inversion made model replication are particularly challenging. Raw ERA5 values (panel a) over northernmost Italy and nearby Alpine areas are, in some net sense, much too low. The ecPoint bias-corrected gridscale values (panel b) show higher minima here, correcting some but not all of the error. Meanwhile, in some other areas ecPoint is reducing minima. For example the slightly lower values over the northern Appenines in Emilia Romagna look better, while coastal zones and small islands have better, lower values generally, because of a focussed correction for where the model systematically under-represents the land fraction. Meanwhile the 10th percentile (panel c) shows a form of "worst-case scenario" for minimum temperature. On average observations should be less than this about 10% of the time, due mainly to sub-grid variability. In Switzerland, for example, some very localized low minima, probably situated in valleys, seem to fall into this class.

While ecPoint-ERA5 products are available for Italy from the HIGHLANDER portal, worldwide data will be made available in the ECMWF Climate Data Store later in 2024. The years currently covered are 1950 to 2021.

4.4 | Downscaling of sub-seasonal forecasts (using ECMWF's ecPoint post-processing)

The ecPoint post-processing tools cited in Section 4.3 are also utilized here (albeit with different decision trees) by applying them to ECMWF sub-seasonal (Sub-SEA) ensemble forecasts, from day 16 to 30. Outputs are then delivered for daily minimum, maximum, and mean 2 m temperatures, and 24 h precipitation, each in percentile format. Figure 4 shows an example forecast from May 2022, for 24 h rainfall >10 mm, for 18 days into the future. This is to illustrate what the post-processing does, rather than what a forecast product should necessarily look like (ordinarily at such leads users will focus on outputs for multi-day periods, not just single days). The ecPoint output shown is clearly smoother, and so seemingly more "sensible," with probabilities reduced slightly in many areas, but increased in some. For example, the zero probability patch in Umbria (central Italy) is eradicated, and changed to 3–4%, which is reasonable given that such local detail cannot be relied upon so far ahead. Observations (c) are also shown for comparison. While one should not of course infer too much from one case for 1 day, especially at such long leads, the verification graph (d) nonetheless shows ecPoint forecasts for >10 mm/24 h to be much more reliable overall than the raw ensemble between days 16 and 30. Other global verification plots (not shown) indicate reliability improvements across many thresholds (consistent with medium range data in Hewson & Pillosu, 2021). To measure another component of forecast skill, the discrimination ability, we used the ROC area score. This showed minor improvements from ecPoint post-processing for most thresholds, but bigger improvements for large totals such as 50 mm/24 h. This is not unexpected; discrimination ability for extended range rainfall forecasts is innately low, and hard to improve upon, although for more extreme totals we seem to benefit from being able to represent with ecPoint localized extremes that very rarely appear in raw model output because of the large (36 km) grid size.

The use of the sub-seasonal ecPoint products is free of charge for all research applications and educational use

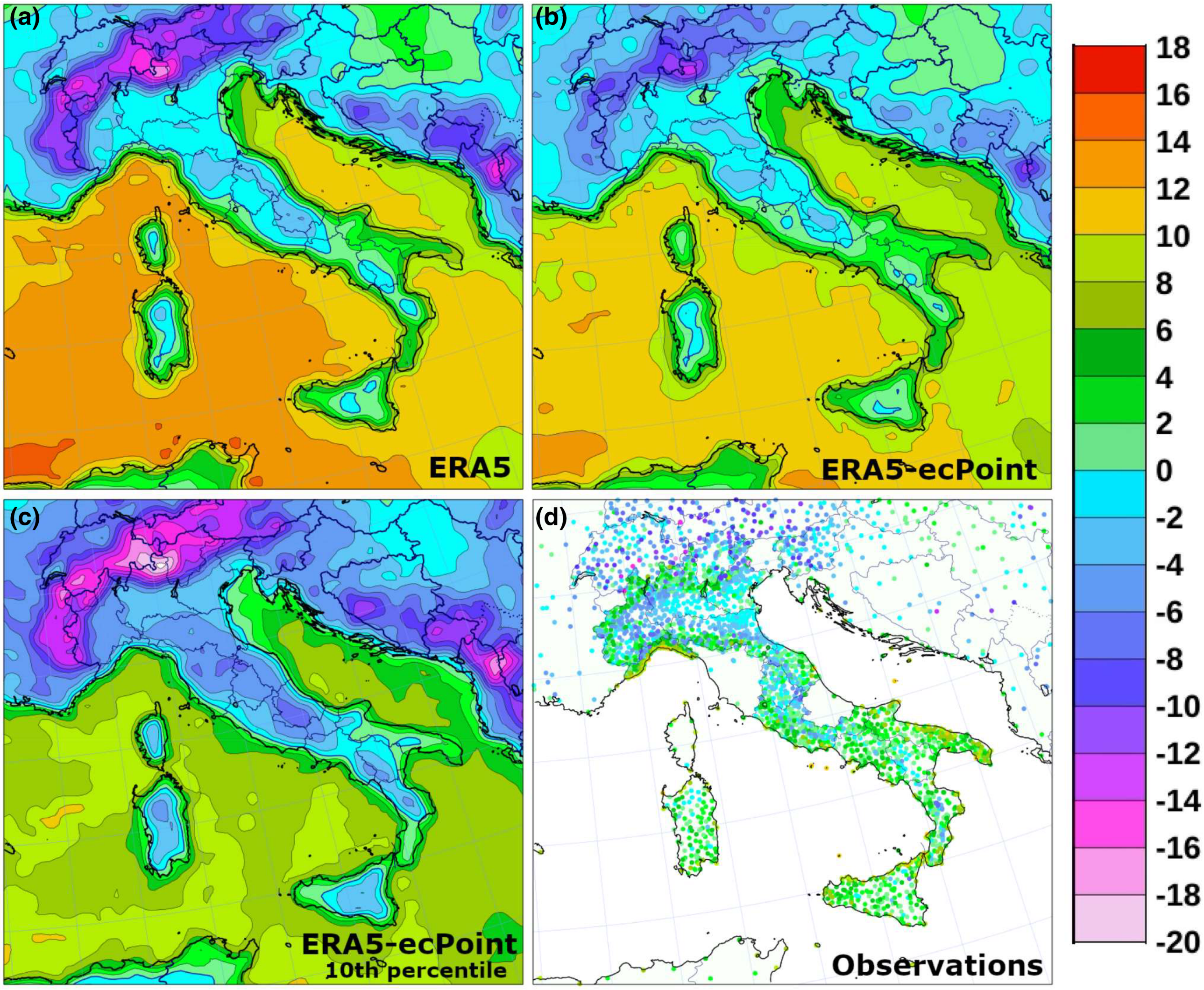

FIGURE 3 Minimum 2 m temperatures for 00-24UTC December 19, 2021, as depicted in (a) ERA5, (b) the ERA5-ecPoint gridscale bias-corrected equivalent, (c) the 10th percentile of ERA5-ecPoint, (d) observations. Note that ecPoint post-processing targets 2 m temperatures over land, so values shown over the sea should be representative of small islands where they exist.

and to support national governmental obligations related to the protection of life and property (operational meteorology at national or subnational level). The use of real-time ECMWF sub-seasonal forecast within HIGHLANDER is free and for use by the project partners for the purposes of the project only and cannot be used for commercial purposes. The irrigation application described in Section 4.6 uses these post-processed forecasts.

4.5 | Soil erosion indicators (1991–2050) @2.2 km over Italy

Extreme climate conditions affect the maintenance of soil functions, especially in areas particularly subject to rainfall-induced erosion. The DApOS on Soil Erosion in HIGHLANDER is based on a consolidated empirical model, the Revised Universal Soil Loss Equation (RUSLE; Renard, 1997, Panagos, Borrelli, et al., 2015, Renard et al., 2017) to generate assessment (1991–2020) and projections (2021–2050) about the rainfall erosivity and potential loss of soil on both forests and agricultural areas at very high spatial resolution (2.2 km for rainfall erosivity and 250 m for soil loss). Such a dataset at very high resolution at national scale can support in identifying regions particularly at risk under changes in climate variability and extreme events, so to formulate strategies to reduce soil erosion through appropriate management of forests and agricultural fields, also in terms of working practices and soil protection measures.

The dataset has been created using the VHR-REA_IT (Raffa et al., 2021) and VHR-PRO_IT under RCP8.5 (Raffa et al., 2023) datasets described above, and

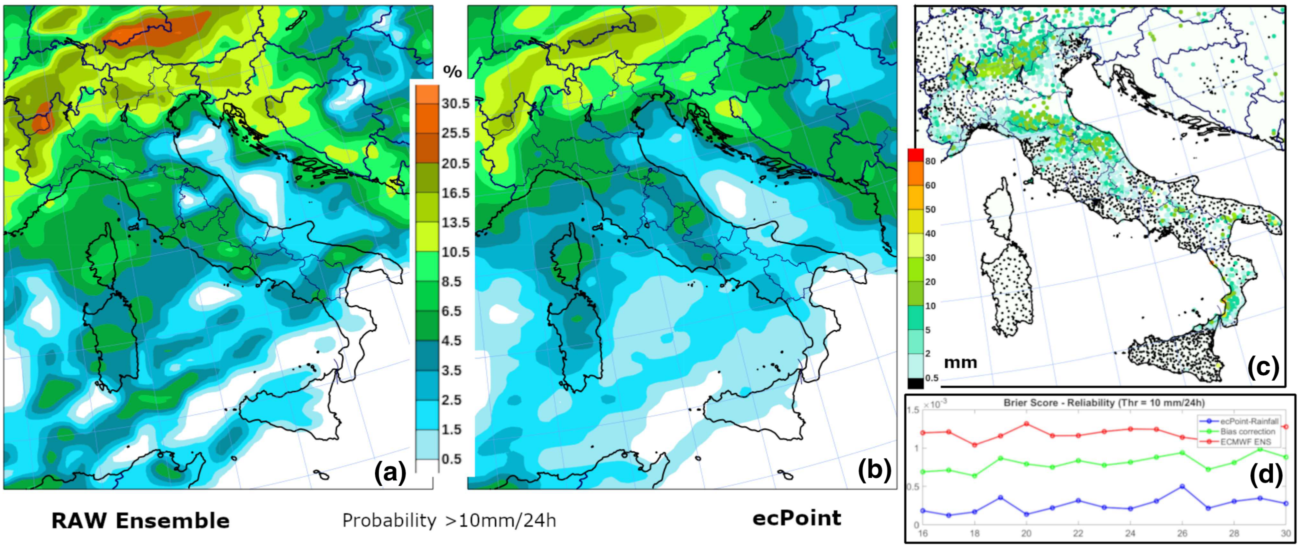

FIGURE 4 Example extended range forecast outputs for 1 day, with observations and long period verification for comparison. (a,b) Forecasts for probability of 24 h rainfall >24 mm, data time 00UTC May 12, 2022, valid 00-24UTC May 29, 2022 (day 18) from (a) raw ensemble and (b) ecPoint post-processed equivalent. (c) 24 h raingauge observations for May 29, 2023 for comparison. (d) long period verification, based on global raingauge reports for 2020, showing the reliability component of the Brier Score (y-axis) for forecast rainfall >10 mm/24 h, at different lead times (x-axis = day number): smaller is better; 0 is perfectly reliability. Red, green, and blue are respectively for raw ensemble, ecPoint bias-corrected (gridscale) output, full ecPoint output.

exploiting the soil susceptibility datasets (considered almost static in time) provided by the RUSLE2015 (https://esdac.jrc.ec.europa.eu/content/soil-erosion-water-rusle2015), produced by Panagos, Borrelli, et al. (2015). In particular rainfall time series have been operated to calculate rainfall erosivity under 12 algorithms evaluated having good performances over Italy from recent literature (Padulano et al., 2021). Users can access the data through the DSS and download NetCDF data clipped over the selected territorial unit.

4.6 | Sub-seasonal irrigation forecasts

HIGHLANDER project has also approached the creation of crop water requirement forecasts (see Section 5.4). These data products are the outcomes of a climate service developed by ARPAE to address the irrigation water management in agriculture by producing seasonal probabilistic forecasts and deterministic weekly forecasts of irrigation, as described by Villani et al. (2021)). The sub-seasonal forecasts of irrigation needs for crops cover a 4-week period and are the result of the combination of different data sources such as information on agricultural land use derived from satellite data, Emilia-Romagna Region soil map, observed weather data, and HIGHLANDER sub-seasonal forecast, by means of an agro-hydrological model (CRITERIA-1D, Bittelli et al., 2010, 2011).The Netcdf data available through HIGHLANDER Data Portal contains irrigation and precipitation forecasts expressed as a statistical distribution in the shape of a set of five percentiles: 5th, 25th, 50th, 75th, and 95th. The sub-seasonal irrigation forecasts cover three Land Reclamation and Irrigation Boards (*consorzi di bonifica* in Italian) of Emilia-Romagna region: Consorzio di Bonifica della Burana, Consorzio di Bonifica della Renana, and Consorzio di Bonifica della Romagna. The delivery of the forecast is weekly (usually on Tuesday) according to the emission of sub-seasonal forecasts produced by ECMWF. The HIGHLANDER Data Portal allows the users to filter their data request by variable, Land Reclamation and Irrigation Board, temporal coverage, and distribution percentile.

4.7 | Irrigation projections

This dataset is similar to the one described in Section 4.6 but in this case the irrigation projections are calculated using the HIGHLANDER VHR-PRO_IT climate projection dataset for three study areas: Ofanto (Apulia), Faenza (Emilia-Romagna), and Piana Rotaliana (Trento Province). In more detail, the projections are computed for daily temperature (minimum and maximum) and daily total precipitation in the time period between 2021 and 2050. The reference period expands 1991–2020, and the IPCC RCP8.5 scenario was adopted. The crop water needs are computed by the agro-hydrological model CRITERIA-1D (https://github.com/ARPA-SIMC/CRITERIA1D, last access: September 29, 2023), which is a one dimensional restriction of CRITERIA-3D (https://github.com/ARPA-SIMC/CRITERIA3D, last access: September 29, 2023) model (Bittelli et al., 2010, 2011). The crop map used for Faenza area is derived from iColt service developed by ARPAE (Villani et al., 2021), whereas for Ofanto Irrigation District it is extracted from Corine Land Cover (Bossard et al., 2000) and for Piana Rotaliana data are taken from cadastral maps (https://geoportale.cartografia.agenziaentrate.gov.it, last access: September 29, 2023). Soil data needed by the simulation model derive from the pedological map of Emilia-Romagna Region (https://ambiente.regione.emilia-romagna.it, last access: September 29, 2023) for Faenza study area, whereas for the other study cases they are taken from SoilGrids portal (https://soilgrids.org/, last access: September 29, 2023) by the International Soil Reference and Information Centre (ISRIC, https://www.isric.org/, last access: September 29, 2023). The provided output are the estimated annual irrigation water needs for the climate (1991–2020) and projection (2021–2050) periods expressed as a statistical distribution (5th, 25th, 50th, 75th, and 95th percentiles) for each study area.

4.8 | Well-being indicators at 2.2 km over Italy

The downscaling at very high resolution of ERA5 reanalysis (Section 4.1) allows to reproduce the interactions between atmosphere and surface considering spatially detailed land use distribution. Time series of climate variables were used to calculate four indicator proxies of human well-being: wind chill, humidex, discomfort index, and apparent temperature. The wind chill (WC) expresses the cooling sensation caused by the combined effect of temperature and wind, and it is calculated using the formulation by Osczevski and Bluestein (2005). The discomfort index (DI) is considered one of the best indices to quantify the overall effect of temperature and humidity on the sensation of heat or cold perceived by the human body. It is derived following the work by Thom (1959). The humidex (H) is based on a simple empirical relationship that considers the air temperature and vapor pressure, the latter in turn function of temperature and relative humidity, and calculated according to Masterton and Richardson (1979)). Finally, the apparent temperature (AT) considers all the environmental and body conditions that influence human thermoregulation. AT is derived through the empirical formula by Steadman (1984), that assumes outside shaded environment, and combines air temperature, vapor pressure, and wind speed. The temporal coverage of the hourly well-being indicators dataset is from 01/01/1981 to 31/12/2020 under VHR-REA_IT. Daily minimum, mean, and maximum values are provided. The same indicators have been calculated over the VHR-PRO_IT dataset from 1981 until 2050 under RCP8.5.

4.9 | Indicators of bio-climatic conditions and forest suitability

This dataset provides information on the current and future land suitability for 20 Mediterranean forest species (see Table 2). The dataset covers the entire Italian territory. It was produced by applying a Species Distribution Modeling (SDM; Guisan & Zimmermann, 2000; Guisan & Thuiller, 2005) approach. Correlative SDMs are models that use species–environment relationships to explain and predict distributions of species. SDMs are currently the primary tool for predicting suitable habitats for species (Noce et al., 2017, 2019). In particular, the Maximum Entropy (MAXENT; Phillips et al., 2006) machine learning algorithm was applied. Starting from the current distribution of forest species based on spatial data from the Italian National Inventory (INFC; Gasparini et al., 2022), the MAXENT model was calibrated using the 19 bio-climatic Indicators defined by Worldclim (https://www.worldclim.org/, last access: September 29, 2023). Bio-climatic variables are derived from the monthly temperature and rainfall values in order to generate more biologically meaningful variables. The bio-climatic variables (see Table 2) quantify annual (e.g., mean temperature, cumulated precipitation) and intra-annual trends (e.g., annual range in temperature and precipitation, temperature of the coldest and warmest month, or precipitation of the wet and dry quarters, where a quarter is a period of 3 months). In practice, the variables are derived from the VHR-REA_IT dataset in the period 1991–2020. Then, maps of future land suitability projections for the 20 forest species were produced using the same 19 bio-climatic indicators recalculated for the period 2021–2050 using the VHR-PRO_IT dataset under RCP8.5 bias-corrected under a simple delta method (Beyer et al., 2020).

4.10 | Changes in the land suitability for vegetation over Piedmont region

This dataset encompasses the results of the analysis regarding the impacts of climate change on the land suitability over Piedmont region on two main topics: viticulture vocationality (Fraga et al., 2013; Santos et al., 2012) and development of pathogenic fungi on crops (Battilani

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et al., 2016). The results are given for two climate periods: 1991–2020 and 2021–2050, which describe present climate conditions and future climate assuming the RCP8.5 emission scenario, respectively.

The regional suitability to the cultivation of vineyard for the production of wine is assessed through the composite index (CompI) developed by Malheiro et al. (2010), computed by ARPAP. The CompI summarizes the information given by several indices presented in the same study. It is computed for each year separately and ranges between 0 and 1 depending on whether the conditions on the values of three indexes (Dryness Index, Hydrothermic Index, and Heliothermal Index) and the daily minimum temperatures are simultaneously qualified. The variables used for the calculation of synthetic indices are daily minimum, maximum, and mean temperatures, daily mean relative humidity as well as daily cumulative precipitation. We refer to the work by Malheiro et al. (2010) for a complete description of each index and their weight in the computation of the final CompI index.

ARPAP, in collaboration with CIA, addresses the evaluation of the risk related to the presence of mycotoxins in corn by calculating and analyzing values of Aflatoxin Index (AFI). AFI is associated to a probability of overcoming the threshold of 5 μg of mycotoxin per kilogram of maize at harvest. It is obtained by applying a logistic equation between AFI and 6 years of field data of Aflatoxin content in maize collected in Italy (Battilani et al., 2016).

4.11 | Variation in milk production in Friuli-Venezia Giulia (1989–2050)

The presented findings showcase the variation in milk production (in hg) achieved through the utilization of a machine learning model developed in HIGHLANDER. The dataset specifically pertains to the “Pezzata Rossa Italiana” breed of cattle. The results encompass the Friuli-Venezia Giulia region and nearby provinces exclusively. The recorded data includes the periods of April–May (temperate season) and July–August (warm season), spanning from 1989 to 2050. The responsibility for this dataset lies with our partner, UNITUS, who obtained the data by leveraging IoT animal sensor data (Section 4.13) and the VHR-PRO_IT dataset (Section 4.2).

4.12 | Climate indicators for forest fire hazard

This study presents a collection of appropriate indicators for evaluating the potential impacts of changing mean climate conditions and increased variability on forest fire potential (hazards) in the Alpine region, from the past to the future. These indicators are based on the Fire Weather Index System (FWI), which takes into account the influence of fuel moisture and wind on forest fire behavior and spread, utilizing daily meteorological conditions (van Wagner, 1987). The data provided in this research compare the forest fire potential between the reference period (1991–2020) and the near future period (2021–2050), focusing on the key components of the FWI. These assessments are conducted using the Very High-Resolution Climate datasets available within the project.

4.13 | IOT animal sensor data

The AnimalTalker is a device that can continuously monitor the physiological functions of animals in real time. It does so by measuring indexes of physiological stress and discomfort, as well as behavioral attitudes. The sensors, known as AnimalButtons, can be placed on the animals in the most suitable positions for gathering information. The number of sensors used can vary depending on the specific application, such as reproductive monitoring, feeding, or general wellness. These AnimalButtons are connected to a gateway called AnimalCollar via Bluetooth (BLE 5.0). The AnimalCollar collects the measurements from all the sensors and makes them accessible through the Internet. The data can be transmitted using either NB-IoT or LoRa technologies. Once the data are stored on the server, it can be queried at an individual or group level. The dataset available, provided by our partner UNITUS, contains IoT data from dairy farming during the summer season of 2022.

5 | APPLICATIONS

HIGHLANDER web platform gives not only access to the aforementioned datasets but also to several applications for multi-level and -sector users. Most of the applications are grouped into nine DApOS. The DApOS address the needs of a set of use cases expanding a wide range of land management areas. Like other recent data portals (Bottazzi et al., 2021), HIGHLANDER Data Portal provides tools for visualizing datasets using a Web Map Service (WMS). Specifically, each variable is represented on a tiled webmap over which it is possible to navigate and to zoom, as shown in Figure 5. The graphical user interface provides users with a list of filters that can be used to browse the datasets in terms of data product, physical variable, time period, and geographical region. For most DApOS, custom maps can be created and

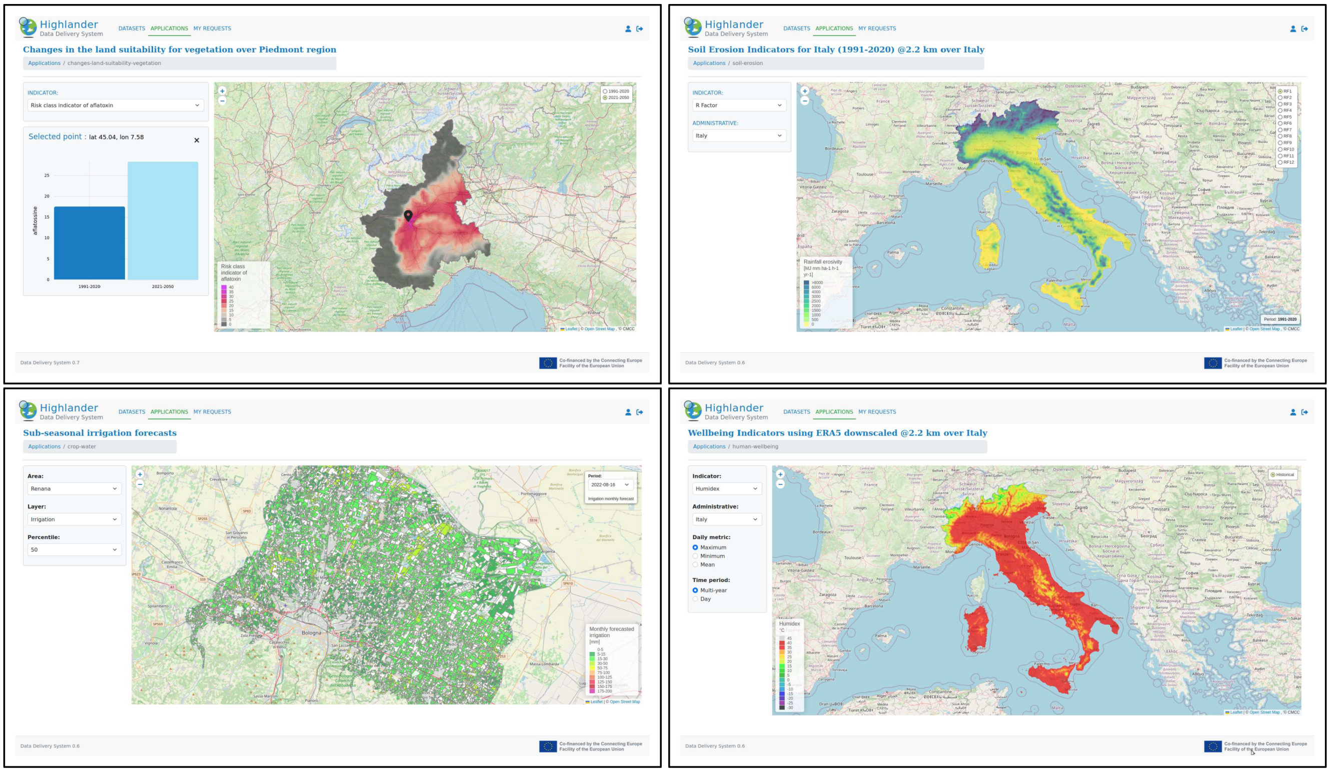

FIGURE 5 Examples of the visualization provided by the following DApOS'es (from left to right, top to bottom): Changes in the land suitability for vegetation (ARPAP, CIA), Soil Erosion (CMCC), Crop water requirement forecast (ARPAE), Human well-being (CMCC).

downloaded on the fly. In Sections 5.1–5.10, we describe the DApOS in the context of the use cases developed by the HIGHLANDER project, and the different applications available for each of them in the HIGHLANDER Data Portal. Table 3 displays the institution responsible for each DApOS, and their background and foreground datasets (Section 4). Section 5.11 describes the only HIGHLANDER Data Portal Application that does not belong to one of the originally envisioned DApOS of the HIGHLANDER project.

5.1 | Land suitability for vegetation: Indicators of bio-climatic conditions and forest suitability

Analyses of the impact of climate change on the European forest vegetation, carried out by the CMCC Foundation for Southern Europe and Russia (Noce et al., 2019; Noce & Santini, 2018), among others (Peñuelas et al., 2017), reveal evidence for a northward migration of the main Mediterranean forest species. In this scenario, the Alpine region will likely become a refuge for forest vegetation lacking optimal habitat conditions at lower latitudes. The aforementioned studies rely on data covering an extended geographical domain, which is crucial to overcome the limitations of their coarse spatial resolution. However, data with finer spatial resolution are needed in order to retrieve results for smaller geographical areas with heterogeneous topography. The very high resolution of HIGHLANDER datasets VHR-REA_IT and VHR-PRO_IT under RCP8.5 (Section 4.1 and 4.2, respectively) overcomes this issue and enables predictions on the evolution (i.e., shift, reduction, expansion) of the habitats of several forest species within the Italian territory at a high geographical resolution. The results focus on the most valuable forest species in terms of provided ecosystem services, such as wood production, recreational purposes (Noce & Santini, 2018).

In practice this DApOS, led by CMCC, relies on the calculation of present and future indicators of bio-climatic conditions and forest suitability by exploiting HIGHLANDER data and the MAXENT algorithm for the Species Distribution Modeling (Section 4.9). The level of spatial detail achieved enables the optimization of the activities of the forestry sector, farmers, and territorial managers.

The Application first shows, for illustrative purposes, the current distribution of broadleaf versus coniferous forests, according to the forest types' classification of the High Resolution Layers dataset available from the

TABLE 3 The table reports for each DApOS the input (I) and output (O) datasets. Furthermore, the table reports whether the data are downloadable (D) or/and graphically displayed (G) through the HIGHLANDER Data Portal applications.

		DApOS									
		Land suitability for forest (CMCC)	Changes in the land suitability for vegetation (ARPAP, CIA)	Human well-being (CMCC)	Water cycle and sustainability of competing uses (CMCC)	Soil Erosion (CMCC)	Forest fire predictions and control (CMCC, UNITUS)	Forest fire potential (ARPAP)	Natural parks environmental management (FEM, UNITUS, Deda Next)	Crop water requirement forecast (ARPAE)	IoT for animal well-being (UNITUS)
Background Data	Tree Talker Fire						IG				
	Animal Talker										IG
	Tree Talker								IG		
	Sentinel-2						I		I	I	
	HR aerial data								I		
	LiDAR						I		I		
	Climatic requirements of forage species in pastures										
	DON/AFLATOXIN on common wheat and corn		I								
Foreground Data	VHR-REAJT	I	I	I	I	I	I	I	I		I
	VHR-PROJT	I	I	I	I	I	I	I	I		I
	Downscaling of subseasonal forecasts using ECMWF's ecPoint post-processing									I	
	SUB-SEA						I		I	I	I
	Soil Erosion Indicators for Italy					ODG					
	Sub-seasonal irrigation forecast									ODG	
	Irrigation projections				ODG						
	Well-being indicators using ERA5 downscaled at 2.2 km over Italy			ODG							
	Changes in the land suitability for vegetation over Piedmont region		ODG								
	Variation in milk production in Friuli-Venezia Giulia (1989–2050)										OD
	Indicators of bio-climatic conditions and forest suitability	ODG									
	Climate indicators for forest fire hazard							OD			

Copernicus Land Monitoring Service (https://land.copernicus.eu/pan-european/high-resolution-layers/forests/forest-type-1/status-maps/forest-type-2018?tab=metadata, last access: September 29, 2023). Then drop-down menus allow users to select: i) the indicator type to visualize, among temperature- or precipitation-based bio-climatic indicators or forest suitability; ii) based on the choice above, the bio-climatic indicator or forest species; (iii) the period of analysis, between the recent 1991–2020 and the future 2021–2050; and (iv) the territorial unit of interest, among administrative units (whole country, regions, provinces, and municipalities) or hydrographic basins. After the user's choices and area selection on the map, a child Application is launched with a static map of the indicator selected and histogram of classified values. A report can be also downloaded.

5.2 | Changes in the land suitability for vegetation

HIGHLANDER establishes the framework to formulate and calculate the bio-climatic indicators and climate extremes indices needed to characterize the Italian territory in terms of the current vegetation habitats. Statistical and complex approaches (e.g., machine learning, and particularly, deep-learning) can then be used to combine climate-based indicators and indices with other territorial characteristics (i.e., elevation, slope, continentality) to investigate the likely geographical evolution of ecosystems, from forests species to cultivations (e.g., grapevine, cereal crops, and vegetables). As for the previous DApOS (Section 5.1), this application uses VHR-REA_IT and VHR-PRO_IT datasets and the BIOMOD2.0 package (Thuiller et al., 2009, https://CRAN.R-project.org/package=biomod2, last access: September 29, 2023), frequently used for forest ecosystems and easily transferable to crop vegetation data. This DApOS addresses different impacts of climate variability in two types of cultivations: the development of fungal pathogens on cereals and the change in the grapevine vocationality.

The agricultural sector is particularly sensitive to climate variability. Thus, climate change entails great threats to worldwide agriculture activities. Among these potential hazards, the introduction or enhanced development of crop pathogens or pest species can be particularly harmful. In Piedmont, as in other regions of cereal production in Italy, climate change could lead to the development of fungal pathogens (e.g., *Fusarium* and *Aspergillus*) responsible for the production of dangerous mycotoxins (e.g., deoxynivalenol, commonly known as DON, and aflatoxin). These substances represent a health issue for humans and animals (Haque et al., 2020). HIGHLANDER, with the leadership of ARPAP, aims at evaluating and predicting the potential risk of development of fungal diseases of cereals in Piedmont. This phenomenon is expected to represent a greater risk when particular stages of the plant growth occur in specific conditions of temperature and humidity. In particular, HIGHLANDER enables the creation of high-resolution maps of the expected development of the pathogenic fungus (Section 4.10). These data products are of great importance to both the actors of the cereal-zoo-technical supply chain responsible for the quality and healthiness of the processed food products, and the local public administrations.

On a global scale, the impacts of climate change on viticultural suitability are expected to be significant. Assuming a RCP 8.5 scenario, the area suitable for viticulture will decrease 25%–73% in major wine producing regions by 2050 in the Mediterranean region (Hannah et al., 2013). This DApOS aims at evaluating the impact of future climate variability on the viticulture sector for a sample of representative grape varieties in Piedmont (Section 4.10). An example of implications considered under climate-related hazards we highlight the changes in grapevine phenology and berry's biochemical composition, that not only influence yields but also the crop exposure and vulnerability to phytopathogenic risks. The results of this DApOS, led by ARPAP, are of key importance to update the Protected Designations of Origin (PDO) disciplinaries.

Global change is actively pervading and shaping socio-ecological patterns worldwide (Ellis, 2015). Progressive (i.e., species loss and migration, phenological shifts) and abrupt (i.e., extreme climatic events) shifts are already challenging human society and will likely increase during the 21st century. Human has been altering landscapes and ecosystems for millennia (Butchart et al., 2010). As a consequence of land-use and climate changes, the distributions of many terrestrial organisms are currently shifting in most parts of the world (Acácio et al., 2017; Alexander et al., 2018). For example, poleward and upslope to cooler latitudes and elevations have been observed worldwide (Lenoir et al., 2020; Vitasse et al., 2021). Indeed, mountain areas are particularly sensitive to these shifts. Even if in these areas the distance required by an organism to cross isotherms and keep track of climate change is smaller than flatter regions, because of the sharp temperature gradient (Rolland, 2003), species living at the upper elevation have less land surface available, and higher habitat fragmentation (Carlson et al., 2014; Giezendanner et al., 2019; Vitasse et al., 2021). In the light of climate change, policymakers and environmental managers need analytical tools to develop reliable and solid predictions in order to address management activities such as forest production and biodiversity conservation. To do that, species distribution models (SDMs) emerge as the most common models across ecology, evolution, and conservation (Zurell et al., 2020). SDMs are correlative models that relate occurrences of species (both as presence/absence or abundance) as response variables to environmental drivers (e.g., climate, land use, vegetation, soil, anthropic activities) as explanatory variables (Guisan & Zimmermann, 2000). As in present days, there is still ongoing discussion on theoretical and technical issues, including modeling techniques, selection and evaluation of models, handling of spatial autocorrelation, and, most importantly, variable selection (Araújo et al., 2019; Maria & Udo, 2017; Mod et al., 2016). Indeed, many studies develop SDMs using climate data derived from CHELSA (Climatologies at high resolution for the earth's land surface areas; Karger et al., 2017) or Worldclim (Hijmans et al., 2005), but few studies include a thorough validation and comparison of different climate datasets. For instance, Bobrowski et al. (2021) compared SDMs trained with CHELSA and Worldclim in the Himalaya mountains, showing that the former dataset performs better than the latter one. Araújo et al. (2019)), instead, suggested that a golden standard for SDMs in terms of predictors is always missing because of the lack of accurate biological knowledge regarding the species involved, or the lack of data on the relevant environmental variables for the species at the appropriate spatial extent and resolution. With the help of historical data from the past, high-resolution models on the past and future climate, the future dynamic trends of Mediterranean forests (mainly the Alpine ones) will be analyzed at the level of specific composition and alteration of the regimes of natural disturbances.

The application lets the user to visualize the climate indicators for grapevine vocationality, the risk class indicator of aflatoxin, or the probability maps of changes in forest species suitability. In the case of the probability maps of changes in forest species suitability, additional drop-down menus are present to let the user choose the forest species of interest and the type of map among habitat suitability, binary map showing expected absence or expected presence, the difference between future and current suitability, or the expected change in binary projections of the species. A radio button on the map allows to choose the periods and input datasets between VHR-REA_IT and VHR-PRO_IT. Clicking any point on the map it is possible to see a bar chart comparing the selected indicator's value across periods for the selected point of interest.

5.3 | Human well-being in rural and urban areas: Well-being indicators using ERA5 downscaled over Italy

Several studies carried out in the last decades have described the multiple ways in which climate change is challenging human well-being in terms of both physical and mental health (Berry et al., 2010; D'amato & Cecchi, 2008; Epstein & Moran, 2006; Padhy et al., 2015; Patz et al., 2005). This applies particularly in large urban settlements, where the urban micro-climate is highly influenced by physical processes caused by the occupation of soils by artificial areas.

The high spatio-temporal resolution datasets from last generation climate simulations adopted in HIGHLANDER allow to reproduce the interaction between atmospheric conditions and their perception in great detail and with a special configuration for urban areas (Sections 4.1 and 4.2). Indeed, satellite-based products like CORINE Land Cover enable to distinguish with better spatial detail the land use distribution for civil and industrial purposes from rural vegetated areas.

This DApOS, led by CMCC, includes the computation of suitable indicators (Section 4.8) at hourly level and then provided as daily statistics. Many of these indicators are based on a combination of temperature, air humidity, and/or wind to assess perceived air conditions that influence human health and performance in conducting social life and economic activities (Scoccimarro et al., 2017). Combining all this pieces of information the population comfort level can be evaluated at the present and projected in the future differentiating urban versus rural contexts. This study allows the optimization of the actions planned by the local administrations and urban planners to minimize the pernicious impacts of climate change on the health of citizens.

The Application's drop-down menus allow users to select: i) the well-being indicator to visualize, among WC, H, DI, AT (Section 4.8); ii) the administrative unit of interest, among the whole country, regions, provinces, and municipalities; and (iii) the period of interest, if the historical one, based on VHR-REA_IT, or the future anomalies, based on VHR-PRO_IT under RCP8.5. If the historical period is selected, both multi-year average (1991–2020) or single day indicator's metrics as mean, minimum, and maximum values can be chosen through radio-button choices; if the future period is selected, submenus allow choosing again daily statistics—of future vs. historical anomalies in this case—averaged on the long term at annual or seasonal level. After the user's choices and area selection on the map, a child Application is launched with a static map of the indicator selected and histogram of classified values. A report can be also downloaded.

5.4 | Crop water requirements forecast

Climate change has critical impacts on the availability of water resources and, as a consequence, in agriculture. For instance, both the crop irrigation requirements and the optimal irrigation methods are expected to change significantly along the course of climate variability. Therefore, the optimal management of water resources needs to be driven by climate-informed decisions (Ceglar & Toreti, 2021). In this context, this DApOS, which is developed by ARPAE, is conceived as a climate service that provides both sub-seasonal forecasts of irrigation needs for crops and the expected variations under climate change projections.

The synthesis between agro-meteorological modeling and remote sensing, together with innovative climatic products, is the key to the development of a climate service aimed at forecasting irrigation needs of crops. The identification of crops in the field by satellite images analysis allows to create an early crop map and subsequently, using a water balance model, the assessment of irrigation volumes on the study area. Hence, this climate service is developed for the management of water resources which, fed with sub-seasonal forecasts, produce information of strategic value in order to plan water distribution for irrigation purposes.

5.4.1 | Sub-seasonal irrigation forecasts

The sub-seasonal irrigation forecasts are the outcomes of a climate service addressed to irrigation water management in agriculture developed by ARPAE, including seasonal probabilistic forecasts (Villani et al., 2021) and deterministic weekly forecasts of irrigation. The sub-seasonal (+4 weeks) forecasts of irrigation water needs for crops are the result of the combination of different data sources such as information on agricultural land use from satellite data, Emilia-Romagna Region soil map, observed weather data, and HIGHLANDER downscaled sub-seasonal forecasts, by means of the agro-hydrological model CRITERIA-1D (https://github.com/ARPA-SIMC/CRITERIA1D), that is a one-dimensional restriction of CRITERIA- 3D model (Bittelli et al., 2010. The provided data are irrigation and precipitation forecasts expressed as a statistical distribution, of which 5th, 25th, 50th, 75th, and 95th percentiles are available. The delivery of the forecast is weekly according to the emission of downscaled sub-seasonal forecasts produced by ECMWF.

The applications allow the user to select the area of interest choosing among Renana, Burana, or Romagna. For each area it is possible to choose to visualize the layer of the different kind of crops, the layer related to the monthly irrigation forecast, or the one related to the monthly precipitation forecast. An additional drop-down menu allows the selection of the different percentiles. The forecast period can be selected using a drop-down menu on the map. Clicking on an area on the map it is possible to visualize the details related to the crop of the selected area and a bar chart comparing the different percentiles of the forecasted irrigation and precipitation on that area.

5.4.2 | Irrigation projections

The irrigation projections are computed using HIGHLANDER high resolution climate dataset VHR-PRO produced by CMCC, in four study areas: Ofanto irrigation district (Puglia), Faenza (Emilia-Romagna), Piana Rotaliana (Trento Province), and three pointwise locations nearby Alessandria, Carmagnola, and Saluzzo (Piedmont). The first three are geographical impact studies, while the fourth is a study on points of interest. In more detail, the projections are computed using daily temperature (minimum and maximum) and daily precipitation for 2021–2050 period with respect to 1991–2020 reference period, adopting the IPCC RCP8.5 scenario. As in the case of sub-seasonal irrigation forecast, the crop water needs are computed using the agro-hydrological model CRITERIA -1D. The provided output are the estimated annual irrigation water needs for the reference (1991–2020) and projection (2021–2050) periods expressed as statistical distribution (5th, 25th, 50th, 75th, and 95th percentiles) for each study area.

The applications allow the user to select the area of interest choosing among Ofanto, Faenza, or Trento. For each area it is possible to choose to visualize the layer of the different kind of crops, the layer related to the annual irrigation needs based on VHR-REA_IT input data, or the layer related to the annual irrigation needs based on VHR-PRO_IT input data. An additional drop-down menu allows the selection of the different percentiles. Clicking on an area on the map it is possible to visualize the details related to the crop of the selected area and a bar chart comparing the different percentiles of the annual irrigation needs on that area for the selected scenario.

5.5 | Water cycle and sustainability of competing uses: Drought assessment

Climate change influences the availability of water resources and makes indispensable an accurate distribution planning between civil, industrial, energy, and agricultural use. Besides, water management must take into account the minimum vital flow needed to preserve the functions of the ecosystems from which these resources are taken.

Climate variables and climate-based indicators and indices can drive hydrological evaluations in terms of both average trends and variability of water scarcity/excess conditions, often manifesting as slow- to fast-onset events (spanning from droughts to floods) with consequences on lands.

The DApOS is developed by CMCC and it is also connected with the one on “Crop water requirements forecasts in Apulia pilot,” conducted by ARPAE in the area of Capitanata irrigation consortium. The aim is to provide a future assessment of the hydrological drought regime of the Ofanto River Basin only basing on climate information (e.g., precipitation and temperature) expected in the future. This allows overcoming the limitation of climate modeling, whose projections do not usually include river discharges. The DApOS leverages on one hand on historical records of river discharges for cascading sub-catchments in the river basin to assess the spatial variability of hydrological drought. On the other hand, it leverages on the VHR-REA_IT and VHR-PRO_IT datasets, the latter under RCP8.5, in order to provide spatial patterns of climate-related droughts. Then, from these outputs, further evaluations can be conducted to assess the sustainability of water withdrawals in the long-term future, considering competing water demands for hydro-power, domestic, agricultural, and ecological uses.

The Application allows user to select, directly by radio-buttons on the map, the periods and input datasets between VHR-REA_IT and VHR-PRO_IT (Sections 4.1 and 4.2). Other drop-down menus allow to select: (i) the meteorological or hydrological drought indicator, respectively the Standardized Precipitation Index (SPI; McKee et al., 1993) and the Standardized Streamflow Index (SSI; Shamshirband et al., 2020); (ii) the drought metric of interest, like number of events, average duration, average magnitude, average intensity, or total duration; and (iii) the accumulation periods, from 1 to 12 months. After the user's choices and sub-basin selection on the map, a child Application is launched with a static map of the indicator/metric value of the sub-basin, and with a bar chart comparing the selected indicator's metric across periods and scenarios.

5.6 | Soil erosion: Soil erosion indicators (1991–2050) @2.2 km over Italy

Extreme climate conditions affect the maintenance of soil functions, especially in areas particularly subject to rainfall-induced erosion, such as the Mediterranean basin (Ballabio et al., 2017; Panagos, Ballabio, et al., 2015; Panagos, Borrelli, et al., 2015). Identifying areas prone to suffering from such phenomenon is crucial, particularly at a great level of geographical detail, in order to formulate the best strategies to mitigate its impact.

To achieve this goal, this DApOS, led by the CMCC, relies on a selection of rainfall erosivity empirical models (Padulano et al., 2021) and on the RUSLE model (Panagos, Borrelli, et al., 2015; Renard, 1997) to generate projections of the potential loss of soil due to intense rainy events and land management in rural areas, including forests and agricultural fields. The application of the approach at national scale allows to map the Italian locations more at risk. The Application allows user to select, directly by radio-buttons on the map, one among the 12 rainfall erosivity algorithms (Section 4.5). Others drop-down menus allow to select: (i) the indicator to explore, between the rainfall erosivity (R factor) and the soil loss; (ii) the period of interest, if the historical one, based on VHR-REA_IT, or the future anomalies, based on VHR-PRO_IT under RCP8.5; and (iii) the territorial unit of interest, among the whole country, regions, provinces, and municipalities, or hydrographic basins. After the user's choices and unit selection on the map, a child Application is launched with a static map of the indicator value of the units, and with a histogram of the indicator's values. A report can be also downloaded.

5.7 | Forest fire predictions and controls

Conservation of forest resources and prevention of forest fires are fundamental activities to mitigate and reduce the present and future harmful climate change impacts (Abatzoglou & Williams, 2016; Resco et al., 2021). There are several services and projects to monitor, through remote and proximal sensing data, the progression of forest fires and the conditions that can trigger and foster them (e.g., European Forest Fire Information System (EFFIS, https://effis.jrc.ec.europa.eu/, last access: September 29, 2023).

In the framework of HIGHLANDER, the Department for Innovation in Biological, Agricultural, and Forestry Systems (DIBAF) of the UNITUS, in collaboration with CMCC, have developed a DApOS that provides a forest fire risk analysis service in several forested natural parks of the Apulia regions. The application focuses on the medium-term timescales throughout the late spring-early fall period. To this end, they have set up and applied a model based on remote and proximal data (e.g., Sentinel-2 products and IoT, respectively; see Section 2) and meteorological predictions properly integrated thanks to machine learning and Big Data analysis tools. It provides fundamental information for the optimal management of green areas and natural parks, and thus, for preserving the forest ecosystem while guaranteeing the safety of human settlements nearby.

5.7.1 | Tree-Talker fire

The application consists of a dashboard comprising a map where the locations of the sensors are shown. Clicking on the different sensors' location, an info window shows the most recent information available for each sensor and provides a link to the visual representation of the historical data.

5.7.2 | Fire risk prediction

The application consists of a live map where the user can choose a fire risk index among total risk, conifer risk, ilex risk, or trojana risk and see its evolution over time. The user can choose to overlap also the layers related to the location of the different species of interest which are conifer, ilex, or trojana. Clicking on the map it is possible to see the value of the selected index for the selected point.

5.8 | Forest fire potential

The conditions potentially favorable to the triggering of forest fires are closely linked to weather, in particular to temperatures and rainfall. Current climate projections foresee scenarios characterized by a rise in temperatures and a variation in the rainfall regime. In turn, this will translate into a variation in the pattern of the risk of forest fires, and consequently, into an adjustment of management policies and actions aimed at limiting the impacts of this hazard.

This DApOS, coordinated by ARPAP, aims to assess the risk of forest fires and its evolution. With the help of historical data, high-resolution models using past and future climatic data can predict the forthcoming dynamic trends of Mediterranean forests. The purpose is to develop a climate service from which either local administrations, entities in charge of the management of Natural Parks, and tourism-related services suppliers, among others, can benefit. In practice, suitable bio-climatic indicators and climate extremes indices are computed to assess the past-to-future impacts of changing mean climate conditions and accelerated variability on forest fire potential. Then, the hazards information can be complemented by territorial characteristics (e.g., accessibility, transport network, settlements) to plan tailored forest fire prevention and management according to natural resources and human assets at risks.

5.9 | Natural parks environmental management

Climate change heavily impacts the management of natural reserves and parks (Baron et al., 2009). The rise of temperature and the change in the temporal patterns of seasons will inevitably challenge the faunistic and floristic balance of these protected areas, and the bodies in charge of their management will have to undertake actions to mitigate the negative impact of future climate scenarios. This DApOS, led by FEM, in collaboration with DIBAF, consists of a natural park environmental management service aiming at the creation of a model that captures the interaction between the inhabitants of the natural ecosystems and the changing landscape conditions. In practice, the DApOS monitors the condition of vegetation and the movements and habits of animals over time. The forecasts thus obtained can support the entities in the management of parks and reserves. This service is divided into several workflows. Each of them is designed to address a different issue under the same overarching scope. The visualization services of this DApOS is managed by the HIGHLANDER partner Deda Next.

5.9.1 | Forest monitoring

This workflow combines the information from airborne remote sensing data (hyperspectral and LiDAR) and field data to create tree species and aboveground biomass maps (AGB; Naik et al., 2021, 2022), estimated for each individual tree crown. Species were classified using a Supervised Vector Machines classifier on monthly composites of Sentinel-2 satellite image. Individual tree crowns were delineated using a state-of-the-art method developed by FEM and implemented in the R library: itcSegment (Dalponte et al., 2015). The equations for the estimation of diameters and biomass are described by Jucker et al. (2017), and link the height and crown area with the biomass.

The application allows the user to visualize both the layer related to the tree species and the one related to the aboveground biomass on a queriable live map.

5.9.2 | Mountain pasture monitoring

Remote sensing data are frequently used to characterize grassland areas (Fava et al., 2009 and references therein).

Building on previous studies, the goal of this workflow is using satellite remote sensing data to calculate Spectral Vegetation Indices (SVI) changes across different years or during the same foraging season, providing useful information for a more sustainable pasture management. The SVIs considered are: Normalized Difference Vegetation Index (NDVI, Rouse Jr et al., 1974), Green Normalized Difference Vegetation Index (NDVIg, Gitelson et al., 1996), MERIS Terrestrial Chlorophyll Index (MTCI, Dash & Curran, 2004), Normalized Difference Water Index (NDWI, Gao, 1996), and Red-Edge Normalized Difference Vegetation Index ($RENDVI^{865.740}$, Sakowska et al., 2019). The area of interest is the Natural Park of Paneveggio (Province of Trento), a protected area of almost 20,000 hectares of which 30% is covered with pastures during the summer season.

The application allows the user to visualize on live maps all the SVIs and their evolution over time. Additional layers showing the pasture areas and the park boundaries can be enabled. Clicking on the map it is possible to see the value of the selected SVI for the selected point. The user also has the possibility to compare maps related to two different dates on a side-to-side view.

5.9.3 | Forest trees physiological conditions monitoring

This workflow aims at monitoring forest trees physiological conditions within Paneveggio Natural Park. To this end two networks of 25 Tree-Talker sensors (one in a beech forest and one in a spruce forest) have been installed inside the park for continuous monitoring of the following single-tree parameters: leaves spectrum reflectance, trunk growth, water usage, soil and stem humidity, air temperature, and plant stability. The data gathered are subsequently used to understand the response of trees to climate variability.

The Tree-Talker devices are connected by using LoRa protocol of radio communication to the gateway TT-Cloud, which in turn connects to the Internet via GPRS network and sends data to a computer server. Data collected by the Tree-Talkers have been harmonized by the OGC SensorThings API standard. In particular, FROST (https://github.com/FraunhoferIOSB/FROST-Server; last access: September 29, 2023) is the open-source implementation of the SensorThings API standard adopted in the project. FROST was developed by Fraunhofer IOSB, and its source code is publicly available under GNU Lesser General Public License v3.0.

The application consists of a dashboard comprising a map where the locations of the Tree-Talker sensors are shown. Clicking on the different sensors' location, an info window shows the most recent information available for each sensor and provides a link to the visual representation of the historical data.

5.9.4 | Vaia storm

Vaia storm hit northeastern Italy between October 29, and 30, 2018, with wind gusts reaching speeds as high as 200 km/h (Chirici et al., 2019; Motta et al., 2018). Its destructive impact on certain forests in the regions of Lombardy, Veneto, Trentino-Alto Adige/Südtirol, and Friuli-Venezia Giulia are noticeable at present time, 4 years later. The Vaia storm not only razed more than 40,000 hectares of forest to the ground, it also created the ideal conditions for the bark beetle to feed and reproduce. This workflow has created forest wind-throws maps using high spatial resolution multi-spectral satellite images and a technique by Dalponte et al. (2020) based on 2D Change Vector Analysis (CVA; Johnson & Kasischke, 1998). CVA is a method of change detection that evaluates both the magnitude and the direction of the change vector.

The application allows the user to visualize all the resulting forest wind-throws maps on a live map. An additional layer showing the park boundaries can be enabled. Clicking on the map it is possible to see the values of all the data related to the selected point.

5.9.5 | Bark beetle and forest stress monitoring

Bark beetle outbreaks are common hazards of coniferous forests and can cause landscape-level tree mortality and potentially lead to devastating environmental and economic consequences (Dalponte et al., 2022; Hlásny et al., 2021). The combined use of remote sensing data and machine learning algorithms has been proven a powerful tool to detect the events at an early stage (Mojtaba Marvasti-Zadeh et al., 2022). The workflow has developed an automatic dead tree detection system using Sentinel-2 remote sensing data and Google Earth Engine platform (https://earthengine.google.com/ last access: September 29, 2023; https://earthengine.google.com/; last access: September 29, 2023) to track the areas affected by the plague and its evolution (Dalponte et al., 2022).

The application allows the user to visualize on a live map the locations most impacted by bark beetle proliferation classified by year or by month and a layer showing the confidence level for such estimation. The user can also filter by year or by level of confidence the data to be displayed on the map. An additional layer showing the park boundaries can be enabled. Clicking on the map it is possible to see the values of the data related to the selected point.

5.9.6 | Grassland mowing detection

The optimal management of grassland use has significant impacts on the preservation of meadow ecosystem (Andreatta, Gianelle, Scotton, Vescovo, & Dalponte, 2022). This workflow has developed an algorithm that estimates the optimal annual number of meadow cuts at a high spatial resolution. The algorithm is based on the analysis of time series of vegetation indices derived from Sentinel-2 images, and was calibrated and tested on 240 ha of meadows in four sites (Lusia, Predazzo, Viote, Vigolana; Province of Trento). The details on the algorithm are published by Andreatta, Gianelle, Scotton, and Dalponte (2022), Andreatta, Gianelle, Scotton, Vescovo, and Dalponte (2022). The resulting information on grassland use is relevant on both company and territorial scales, and for administrative, agriculture, livestock, environmental, and naturalistic purposes.

The application allows the user to visualize on a live map the NDII (Normalize Difference Infrared Index) or the mowing frequency and their evolution over time. Additional layers showing the reference data and the park boundaries can be enabled. Clicking on the map it is possible to see the value of the data from the selected layer for the selected point.

5.10 | IoT for animal well-being: Rocca Respampani pasture monitoring

The integration of short- and long-term climate data, satellite observations, and in situ IoT data on which apply animal welfare models, can produce precious information for both breeders and policymakers (Boukhris et al., 2019; Freeman et al., 2013; Li et al., 2014). The former can, for instance, adjust the number of animals they are currently employing, switch to other breeds/species with a lower water requirement, or better resilience to heat stress. They can also invest in technologies able to save or recycle the water, or mitigate heat through spraying or ventilation systems. The latter can deliberate programs to assist breeders, industries, and zoo-technical research. Furthermore, climate change can challenge the strategies that farmers currently adopt to ensure well-being and health conditions of their livestock, while maximizing the quality of the final product. To support these activities, this application allows breeders to prevent the stress caused to animals by excessive temperature changes, especially in barn farms, and to monitor health conditions of animals in a non-invasive way, especially when grazing freely, through the use of modern IoT technologies. This DApOS is led by UNITUS and aims at using the collected data and medium-term forecasts, to build the monitoring and medium-term projection of the welfare of farms.

As for the case of the mountain pasture monitoring workflow of the Natural Parks environmenal management DApOS, the developed application shows the Spectral Vegetation Indices and its changes across different years or during the same mountain pasture season. These indexes are calculated using satellite remote sensing data and provide useful information for a more sustainable pasture management. The user can visualize on a live map all the SVIs and their evolution over time. Additional layers showing the pasture areas and the Rocca Respampani boundaries can be enabled. Clicking on the map it is possible to see the value of the selected SVI for the selected point. The user also has the possibility to compare maps related to two different dates on a side-to-side view.

5.11 | Downscaling of ERA5 @2.2 km over Italy

Warming stripes are a recent and very communicative way to present climate anomalies, showing clearly and vividly how global, regional up to country-level average temperatures have risen over nearly two centuries with respect to the 1971–2000 average. Exploiting the VHR-REA_IT dataset (Section 4.1), an Application has been released to visualize stripes over Italy over different administrative units (regions, provinces, and municipalities) plus hydrographic basins that can be selected by users over a live map. Besides the finer spatial discretization allowed by very high resolution data with respect to the original warming stripes based on ERA5, the HIGHLANDER warming stripes for Italy have three additional novelties that can be explored by users: (i) they are calculated against two Climate Normal (30-year) periods currently adopted by the World Meteorological Organization (WMO), that is, 1981–2010 and 1991–2020; (ii) they look at anomalies at annual and seasonal levels; and (iii) they provide anomalies for daily mean, maximum, and minimum temperatures. This is the only application available in the HIGHLANDER Data Portal which does not belong to a specific HIGHLANDER DApOS. The application has different drop-down menus to allow the user to select among all the options above. The related data are shown on a live map while the child application presents the spatially aggregated anomalies in the form of warming stripes.

6 | DATA ACCESS, POLICY, AND LICENCES

One of the goals of HIGHLANDER is to facilitate and promote the reuse of data by providing free access to observational and forecast data as well as visualization tools, by means of a web platform: the HIGHLANDER Data Portal (https://dds.highlanderproject.eu/, last access: September 29, 2023). The portal gives access to the datasets described in Section 4 and the applications described in Section 5. Registration is free-of-charge and can be easily requested by sending an e-mail to the address given in the portal's section *Contact*. Registered users can download data and run customized data queries. Furthermore, they have access to a personal space through which they can manage their query history (e.g., check the status of each request, download the query in the shape of a JSON file). These functionalities can also be achieved by directly interacting with the APIs that the platform exposes. The personal space of each user is granted a 5GB storage volume. Unregistered users can still explore the general information and content of each dataset, as well as navigate the deployed applications. A summary of the features associated to each type of user can be found in the portal's section *About*.

One of the strategies that the project leverages to enhance dataset discovery is deployment of the HIGHLANDER Open Data Catalogue. This catalog is a customized version of the Comprehensive Knowledge Archive Network (CKAN; https://ckan.org), the open-source data portal software developed and managed by the Open Knowledge Foundation (https://okfn.org). CKAN is one of the reference software for the publication of both government and enterprise open data. The HIGHLANDER Open Data Catalogue is compliant with the Italian Extension of the Data Catalog Vocabulary application profile (DCAT-AP IT), a convention for describing public sector catalogs, aimed at ensuring semantic interoperability between European open data portals. The HIGHLANDER Open Data Catalogue contains not only metadata but also relevant ancillary information (e.g., audio-visual material, publications) and links to the data and applications on the HIGHLANDER Data Portal. Then, the Italian National Catalog (https://dati.gov.it) is fed with the standardized data of the HIGHLANDER Open Data Catalogue. Subsequently, the European Open Data Portal (https://data.europa.eu) is fed with the data from the Italian National Catalogue.

Most data collections integrated into the platform are published under a Creative Commons Attribution 4.0 International (CC BY 4.0; https://creativecommons.org/licenses/by/4.0/, last access: September 29, 2023). The SUB-SEA dataset (Section 4.4) is published under a ECMWF standard licence for real-time forecast data. The sub-seasonal irrigation forecasts are available under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY NC 4.0; https://creativecommons.org/licenses/by-nc/4.0/, last access: September 29, 2023). See Table 2.

7 | SUMMARY AND DISCUSSION

The HIGHLANDER project has designed and implemented a multidisciplinary framework of highly detailed and harmonized data to support land services. Combining remote and in situ monitoring, analytical tools, numerical models to machine learning algorithms, the project aims to create valuable information that can be directly exploited by a wide range of users through dedicated applications. The project data are collected in a repository and made accessible and distributed through the HIGHLANDER Data Portal, presented in this article. Beyond the project partners, the end users of these data and applications include land planners, farmers, forest managers, water providers, entrepreneurs, service providers, policymakers, practitioners, educators, researchers, and public administrations and local governments. Leveraging the capabilities of Cineca's HPC infrastructure made it possible to generate, post-process, and host the large amount data generated inside the project. The implemented HPC-based services will enable a more effective and rapid integration of information into decisions, strategies, and planning of land management activities at different interacting spatial–temporal scales and sectoral levels.

The establishment of a data portal plays a pivotal role in managing and leveraging vast amounts of information effectively. Such portals serve as centralized repositories, enabling access to valuable data and facilitating informed decision-making processes. While data portals at an international level offer a wide range of data across different regions and domains, the significance of a national or regional data portal is that it provides a more focused and targeted approach to address specific challenges and requirements at a higher granularity. It allows stakeholders, including researchers, policymakers, and land managers, to access localized data that is crucial for understanding regional trends, making informed land management decisions, and promoting sustainable practices. By providing region-specific datasets, the portal provides deeper insights and allows for solutions tailored to the unique challenges faced by that particular area.

Highlander DApOS can be considered test cases for the project and the platform functionalities, where high resolution climate data are exploited through different applications. With its wealth of information on land management, climate change, and socioeconomic factors, the HIGHLANDER Data Portal is already a valuable resource for researchers, land managers, and policymakers. This motivates strategic interest in the long-term maintenance of the platform, as well as its further development. In the future, the portal is expected to expand its dataset offerings, encompassing more regions, land types, and relevant variables, eventually becoming the national entry-point for climate data for the Italian territory. This growth will enhance its effectiveness in supporting evidence-based decision-making, facilitating collaboration, and fostering innovation in land management practices.

In conclusion, the Highlander project and the establishment of the Highlander Data Portal have been important initiatives that will have positive impacts. By providing a comprehensive and accessible platform for land-related data, the project empowers stakeholders with the necessary tools to address pressing environmental challenges, enhance land management strategies, and foster sustainable development. The localized focus of the data portal reinforces the notion that effective land management requires tailored solutions that account for the specific characteristics and needs of different regions. Ultimately, the Highlander project sets the stage for improved understanding, collaboration, and action toward a more sustainable and resilient future.

AUTHOR CONTRIBUTIONS

Michele Bottazzi: Software (equal); visualization (equal); writing – original draft (equal). **Lucia Rodriguez Muñoz:** Software (equal); writing – original draft (lead). **Beatrice Chiavarini:** Software (equal); visualization (equal). **Cinzia Caroli:** Conceptualization (equal); project administration (equal); supervision (equal); writing – original draft (supporting). **Giuseppe Trotta:** Methodology (equal); software (equal); validation (equal); writing – original draft (supporting). **Chiara Dellacasa:** Project administration (equal); supervision (equal). **Gian Franco Marras:** Resources (equal); writing – original draft (supporting). **Margherita Montanari:** Project administration (equal); supervision (equal). **Monia Santini:** Conceptualization (equal); formal analysis (equal); investigation (equal); resources (equal); writing – original draft (supporting). **Marco Mancini:** Conceptualization (equal); data curation (equal); investigation (equal); resources (equal); software (equal). **Alessandro D'anca:** Conceptualization (supporting); data curation (equal); investigation (equal); resources (equal); software (equal). **Paola Mercogliano:** Investigation (equal); resources (equal). **Mario Raffa:** Data curation (equal); investigation (equal); resources (equal); software (equal). **Giulia Villani:** Data curation (equal); formal analysis (equal); investigation (equal); resources (equal). **Fausto Tomei:** Data curation (equal); formal analysis (equal); resources (equal); software (equal). **Nicola Loglisci:** Data curation (equal); formal analysis (equal); investigation (equal); resources (equal). **Estibaliz Gascòn:** Data curation (equal); investigation (equal); resources (equal). **Tim Hewson:** Conceptualization (equal); resources (equal); supervision (supporting); writing – review and editing (supporting). **Giovanni Chillemi:** Conceptualization (equal); resources (equal); supervision (supporting). **Riccardo Valentini:** Investigation (equal); supervision (supporting). **Damiano Gianelle:** Investigation (equal); resources (equal); supervision (supporting). **Elena Massarenti:** Investigation (equal); resources (equal). **Martina Forconi:** Software (equal); supervision (equal); visualization (equal). **Lucia Mazzoni:** Conceptualization (equal); supervision (supporting). **Gabriella Scipione:** Conceptualization (equal); funding acquisition (lead); project administration (lead); supervision (lead).

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CONFLICT OF INTEREST STATEMENT

We have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

Data and information about the results of the HIGHLANDER project can be found on the HIGHLANDER Data Portal: https://dds.highlanderproject.eu.

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REFERENCES

Abatzoglou, J.T. & Williams, A.P. (2016) Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, 113(42), 11770–11775.

Acácio, V., Dias, F.S., Catry, F.X., Rocha, M. & Moreira, F. (2017) Landscape dynamics in mediterranean oak forests under global change: understanding the role of anthropogenic and environmental drivers across forest types. *Global Change Biology*, 23(3), 1199–1217.

Acero, F.J., García, J.A., Gallego, M.C., Parey, S. & Dacunha-Castelle, D. (2014) Trends in summer extreme temperatures over the iberian peninsula using nonurban station data. *Journal of Geophysical Research: Atmospheres*, 119(1), 39–53.

Alexander, J.M., Chalmandrier, L., Lenoir, J., Burgess, T.I., Essl, F., Haider, S. et al. (2018) Lags in the response of mountain plant communities to climate change. *Global Change Biology*, 24(2), 563–579.

Andreatta, D., Gianelle, D., Scotton, M. & Dalponte, M. (2022) Estimating grassland vegetation cover with remote sensing: a comparison between landsat-8, sentinel-2 and planetscope imagery. *Ecological Indicators*, 141, 109102.

Andreatta, D., Gianelle, D., Scotton, M., Vescovo, L. & Dalponte, M. (2022) Detection of grassland mowing frequency using time series of vegetation indices from sentinel-2 imagery. *GIScience & Remote Sensing*, 59(1), 481–500. Available from: https://doi.org/10.1080/15481603.2022.2036055

Araújo, M.B., Anderson, R.P., Márcia Barbosa, A., Beale, C.M., Dormann, C.F., Early, R. et al. (2019) Standards for distribution models in biodiversity assessments. *Science Advances*, 5(1), eaat4858.

Bottazzi, M., Scipione, G., Marras, G.F., Trotta, G., D'Antonio, M., Chiavarini, B., et al. (2021) The italian open data meteorological portal: Mistral. *Meteorological Applications*, 28(4), e2004. Available from: https://doi.org/10.1002/met.2004

Ballabio, C., Borrelli, P., Spinoni, J., Meusburger, K., Michaelides, S., Beguería, S. et al. (2017) Mapping monthly rainfall erosivity in europe. *Science of the Total Environment*, 579, 1298–1315.

Baron, J.S., Gunderson, L., Allen, C.D., Fleishman, E., McKenzie, D., Meyerson, L.A. et al. (2009) Options for national parks and reserves for adapting to climate change. *Environmental Management*, 44(6), 1033. Available from: https://doi.org/10.1007/s00267-009-9296-6

Battilani, P., Toscano, P., Van der Fels-Klerx, H.J., Moretti, A., Camardo Leggieri, M., Brera, C. et al. (2016) Aflatoxin b1 contamination in maize in europe increases due to climate change. *Scientific Reports*, 6(1), 24328. Available from: https://doi.org/10.1038/srep24328

Berry, H.L., Bowen, K. & Kjellstrom, T. (2010) Climate change and mental health: a causal pathways framework. *International Journal of Public Health*, 55(2), 123–132.

Beyer, R., Krapp, M. & Manica, A. (2020) An empirical evaluation of bias correction methods for palaeoclimate simulations. *Climate of the Past*, 16(4), 1493–1508. Available from: https://doi.org/10.5194/cp-16-1493-2020

Bittelli, M., Pistocchi, A., Tomei, F., Roggero, P.P., Orsini, R., Toderi, M. et al. (2011) CRITERIA-3D: a mechanistic model for surface and subsurface hydrology for small catchments. In: Shukla, M.K. (Ed.) *Soil Hydrology, Land Use and Agriculture: Measurement and Modelling*, pp. 253–265. Available from: https://doi.org/10.1079/9781845937973.0253

Bittelli, M., Tomei, F., Pistocchi, A., Flury, M., Boll, J., Brooks, E. et al. (2010) Development and testing of a physically based, three-dimensional model of surface and subsurface hydrology. *Advances in Water Resources*, 33, 106–122. Available from: https://doi.org/10.1016/j.advwatres.2009.10.013

Bobrowski, M., Weidinger, J., Schwab, N. & Schickhoff, U. (2021) Searching for ecology in species distribution models in the himalayas. *Ecological Modelling*, 458, 109693.

Bossard, M., Feranec, J. & Otahel, J. (2000) *CORINE land cover technical guide: addendum 2000*, Vol. 40. Copenhagen: European Environment Agency.

Boukhris, I. et al. (2019) The impact of extreme weather conditions on dairy cow behavior, welfare, and productivity. *Frontiers in Veterinary Science*, 6, 337.

Butchart, S.H.M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J.P.W., Almond, R.E.A. et al. (2010) Global biodiversity: indicators of recent declines. *Science*, 328(5982), 1164–1168.

Carlson, S.M., Cunningham, C.J. & Westley, P.A.H. (2014) Evolutionary rescue in a changing world. *Trends in Ecology & Evolution*, 29(9), 521–530.

Ceglar, A. & Toreti, A. (2021) Seasonal climate forecast can inform the european agricultural sector well in advance of harvesting. *NPJ Climate and Atmospheric Science*, 4(1), 42. Available from: https://doi.org/10.1038/s41612-021-00198-3

Cetl, V., Tomas, R., Kotsev, A., Nunes, V., de Lima, R.S. & Jobst, M. (2019) *Establishing common ground through INSPIRE: the legally-driven European spatial data infrastructure*. Cham: Springer International Publishing, pp. 63–84. Available from: https://doi.org/10.1007/978-3-319-72434-8_3

Chirici, G., Giannetti, F., Travaglini, D., Susanna Nocentini, S., Francini, G.D'A., Calvo, E. et al. (2019) Forest damage inventory after the "vaia" storm in Italy. *Forest – Rivista di Selvicoltura Ed Ecologia Forestale*, 16, 3–9. Available from: https://doi.org/10.3832/efor3070-016

Dalponte, M., Marzini, S., Solano-Correa, Y.T., Tonon, G., Vescovo, L. & Gianelle, D. (2020) Mapping forest windthrows using high spatial resolution multispectral satellite images. *International Journal of Applied Earth Observation and Geoinformation*, 93, 102206. Available from: https://doi.org/10.1016/j.jag.2020.102206

Dalponte, M., Reyes, F., Kandare, K. & Gianelle, D. (2015) Delineation of individual tree crowns from als and hyperspectral data: a comparison among four methods. *European Journal of Remote Sensing*, 48(1), 365–382.

Dalponte, M., Solano-Correa, Y.T., Frizzera, L. & Gianelle, D. (2022) Mapping a european spruce bark beetle outbreak using sentinel-2 remote sensing data. *Remote Sensing*, 14(13), 3135.

D'amato, G. & Cecchi, L. (2008) Effects of climate change on environmental factors in respiratory allergic diseases. *Clinical & Experimental Allergy*, 38(8), 1264–1274.

Dash, J. & Curran, P.J. (2004) The MERIS terrestrial chlorophyll index.

del Río, S., Herrero, L., Pinto-Gomes, C. & Penas, A. (2011) Spatial analysis of mean temperature trends in Spain over the period 1961–2006. *Global and Planetary Change*, 78(1–2), 65–75.

El Kenawy, A., López-Moreno, J.I. & Vicente-Serrano, S.M. (2011) Recent trends in daily temperature extremes over northeastern Spain (1960–2006). *Natural Hazards and Earth System Sciences*, 11(9), 2583–2603.

Elena Xoplaki, J., González-Rouco, F., Luterbacher, J. & Wanner, H. (2003) Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and ssts. *Climate Dynamics*, 20(7), 723–739.

Ellis, E.C. (2015) Ecology in an anthropogenic biosphere. *Ecological Monographs*, 85(3), 287–331.

Epstein, Y. & Moran, D.S. (2006) Thermal comfort and the heat stress indices. *Industrial Health*, 44(3), 388–398.

Fava, F., Colombo, R., Bocchi, S., Meroni, M., Sitzia, M., Fois, N. et al. (2009) Identification of hyperspectral vegetation indices for mediterranean pasture characterization. *International Journal of Applied Earth Observation and Geoinformation*, 11(4), 233–243. Available from: https://doi.org/10.1016/j.jag.2009.02.003

Filho, W.L. (2019) *Handbook of climate change resilience*. Switzerland: Springer International Publishing. https://books.google.it/books?id=14nitgEACAAJ

Fraga, H., Malheiro, A., Pereira, J.M. & Santos, J. (2013) Future scenarios for viticultural zoning in europe: Ensemble projections and uncertainties. *International Journal of Biometeorology*, 57, 925. Available from: https://doi.org/10.1007/s00484-012-0617-8

Freeman, D.W. et al. (2013) Effects of weather conditions on milk yield and composition in Holstein cows. *Journal of Dairy Science*, 96(6), 3620–3628.

Gao, B.-C. (1996) Ndwi—a normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58(3), 257–266.

Gasparini, P., Di Cosmo, L., Floris, A. & De Laurentis, D. (2022) *Italian National Forest Inventory—Methods and results of the third survey*. Switzerland: Springer International Publishing. Available from: https://doi.org/10.1007/978-3-030-98678-0

Giezendanner, J., Bertuzzo, E., Pasetto, D., Guisan, A. & Rinaldo, A. (2019) A minimalist model of extinction and range dynamics of virtual mountain species driven by warming temperatures. *PLoS One*, 14(3), e0213775.

Giorgi, F. (2006) Climate change hot-spots. *Geophysical Research Letters*, 33(8), L08707.

Giorgi, F. & Lionello, P. (2008) Climate change projections for the mediterranean region. *Global and Planetary Change*, 63(2–3), 90–104.

Gitelson, A.A., Kaufman, Y.J. & Merzlyak, M.N. (1996) Use of a green channel in remote sensing of global vegetation from eos-modis. *Remote Sensing of Environment*, 58(3), 289–298.

Guisan, A. & Thuiller, W. (2005) Predicting species distribution: offering more than simple habitat models. *Ecology Letters*, 8(9), 993–1009. Available from: https://doi.org/10.1111/j.1461-0248.2005.00792.x

Guisan, A. & Zimmermann, N.E. (2000) Predictive habitat distribution models in ecology. *Ecological Modelling*, 135(2), 147–186. Available from: https://doi.org/10.1016/S0304-3800

Hannah, L., Roehrdanz, P.R., Ikegami, M., Shepard, A.V., Rebecca Shaw, M., Gary Tabor, L. et al. (2013) Climate change, wine, and conservation. *Proceedings of the National Academy of Sciences*, 110(17), 6907–6912. Available from: https://doi.org/10.1073/pnas.1210127110

Haque, M.A., Wang, Y., Shen, Z., Li, X., Saleemi, M.K. & He, C. (2020) Mycotoxin contamination and control strategy in human, domestic animal and poultry: a review. *Microbial Pathogenesis*, 142, 104095. Available from: https://doi.org/10.1016/j.micpath.2020.104095

Haregeweyn, N., Tsunekawa, A., Tsubo, M., Fenta, A.A., Ebabu, K., Vanmaercke, M. et al. (2023) Progress and challenges in sustainable land management initiatives: a global review. *Science of the Total Environment*, 858, 160027. Available from: https://doi.org/10.1016/j.scitotenv.2022.160027

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J. et al. (2020) The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. & Jarvis, A. (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 25(15), 1965–1978.

Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J. et al. (2021) Bark beetle outbreaks in europe: state of knowledge and ways forward for management. *Current Forestry Reports*, 7(3), 138–165. Available from: https://doi.org/10.1007/s40725-021-00142-x

IPCC. 2022. Climate change 2022: Impacts, adaptation and vulnerability. contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change. 3056. https://doi.org/10.1017/9781009325844

Johnson, R.D. & Kasischke, E.S. (1998) Change vector analysis: a technique for the multispectral monitoring of land cover and condition. *International Journal of Remote Sensing*, 19(3), 411–426. Available from: https://doi.org/10.1080/014311698216062

Jucker, T., Caspersen, J., Chave, J., Antin, C., Barbier, N., Bongers, F. et al. (2017) Allometric equations for integrating remote sensing imagery into forest monitoring programmes. *Global Change Biology*, 23(1), 177–190.

Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W. et al. (2017) Climatologies at high resolution for the earth's land surface areas. *Scientific Data*, 4(1), 1–20.

Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T., Murienne, J. et al. (2020) Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, 4(8), 1044–1059.

Li, Y. et al. (2014) Impact of heat stress on milk production in a temperate climate: a case study in Australia. *International Journal of Biometeorology*, 58(10), 2097–2107.

Malheiro, A.C., Santos, J.A., Fraga, H. & Pinto, J.G. (2010) Climate change scenarios applied to viticultural zoning in europe. *Climate Research*, 43(3), 163–177.

Maria, B. & Udo, S. (2017) Why input matters: selection of climate data sets for modelling the potential distribution of a treeline species in the himalayan region. *Ecological Modelling*, 359, 92–102. Available from: https://doi.org/10.1016/j.ecolmodel.2017.05.021

Marvasti-Zadeh, S.M., Goodsman, D., Ray, N. & Erbilgin, N. (2022) Early detection of bark beetle attack using remote sensing and machine learning: a review. arXiv e-Prints, Art. arXiv:2210.03829.

Masterton, J.M. & Richardson, F.A. (1979) Humidex: a method of quantifying human discomfort due to excessive heat and humidity.

McKee, T., Doesken, N.J. & Kleist, J. (1993) The relationship of drought frequency and duration of time scales. *8th Conference on Applied Climatology, Anaheim, 17–22 January 1993*, pp. 179–184.

Merkel, D. (2014) Docker: lightweight linux containers for consistent development and deployment. *Linux Journal*, 2014(239), 2.

Mod, H.K., Scherrer, D., Luoto, M. & Guisan, A. (2016) What we use is not what we know: environmental predictors in plant distribution models. *Journal of Vegetation Science*, 27(6), 1308–1322.

Motavalli, P., Nelson, K., Udawatta, R., Jose, S. & Bardhan, S. (2013) Global achievements in sustainable land management. *International Soil and Water Conservation Research*, 1(1), 1–10. Available from: https://doi.org/10.1016/S2095-6339(15)30044-7

Motta, R., Ascoli, D., Corona, P., Marchetti, M. & Vacchiano, G. (2018) Selvicoltura e schianti da vento. Il caso della "tempesta Vaia". *Forest@ – Rivista di Selvicoltura Ed Ecologia Forestale*, 15, 94–98. Available from: https://doi.org/10.3832/efor2990-015

Naik, P., Dalponte, M. & Bruzzone, L. (2021) Prediction of forest aboveground biomass using multitemporal multispectral remote sensing data. *Remote Sensing*, 13(7), 1282. Available from: https://doi.org/10.3390/rs13071282

Naik, P., Dalponte, M. & Bruzzone, L. (2022) Generative feature extraction from sentinel 1 and 2 data for prediction of forest aboveground biomass in the italian alps. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 15, 4755–4771.

Noce, S., Caporaso, L. & Santini, M. (2019) Climate change and geographic ranges: the implications for russian forests. *Frontiers in Ecology and Evolution*, 7, 57.

Noce, S., Collalti, A. & Santini, M. (2017) Likelihood of changes in forest species suitability, distribution, and diversity under future climate: the case of southern europe. *Ecology and Evolution*, 7(22), 9358–9375.

Noce, S. & Santini, M. (2018) Mediterranean forest ecosystem services and their vulnerability, 10.

Osczevski, R. & Bluestein, M. (2005) The new wind chill equivalent temperature chart. *Bulletin of the American Meteorological Society*, 86(10), 1453–1458. Available from: https://doi.org/10.1175/BAMS-86-10-1453

Padhy, S., Sarkar, S., Panigrahi, M. & Paul, S. (2015) Mental health effects of climate change. *Indian Journal of Occupational and Environmental Medicine*, 19(1), 3–7. Available from: https://doi.org/10.4103/0019-5278.156997

Padulano, R., Rianna, G. & Santini, M. (2021) Datasets and approaches for the estimation of rainfall erosivity over Italy: a comprehensive comparison study and a new method. *Journal of Hydrology: Regional Studies*, 34, 100788.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S. et al. (2015) Rainfall erosivity in europe. *Science of the Total Environment*, 511, 801–814.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K. et al. (2015) The new assessment of soil loss by water erosion in europe. *Environmental Science & Policy*, 54, 438–447. Available from: https://doi.org/10.1016/j.envsci.2015.08.012

Patz, J.A., Campbell-Lendrum, D., Holloway, T. & Foley, J.A. (2005) Impact of regional climate change on human health. *Nature*, 438(7066), 310–317.

Peñuelas, J., Sardans, J., Filella, I., Estiarte, M., Llusià, J., Ogaya, R. et al. (2017) Impacts of global change on mediterranean forests and their services. *Forests*, 8(12), 463. Available from: https://doi.org/10.3390/f8120463

Phillips, S.J., Anderson, R.P. & Schapire, R.E. (2006) Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190(3), 231–259. Available from: https://doi.org/10.1016/j.ecolmodel.2005.03.026

Raffa, M., Adinolfi, M., Reder, A., Marras, G.F., Mancini, M., Scipione, G. et al. (2023) Very high resolution projections over Italy under different CMIP5 IPCC scenarios. *Scientific Data*, 10(1), 238.

Raffa, M., Reder, A., Marras, G.F., Mancini, M., Scipione, G., Santini, M. et al. (2021) Vhr-rea_it dataset: very high resolution dynamical downscaling of era5 reanalysis over Italy by cosmo-clm. *Data*, 6(8), 88. Available from: https://doi.org/10.3390/data6080088

Renard, K.G. (1997) *Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE)*. Washington, DC: United States Government Printing.

Renard, K.G., Laflen, J.M., Foster, G.R. & McCool, D.K. (2017) The revised universal soil loss equation. In: *Soil erosion research methods*. Routledge, pp. 105–126.

Resco, V., de Dios, J., Hedo, À.C., Camprubí, P.T., Del Castillo, E.M., Martínez, J. et al. (2021) Climate change induced declines in fuel moisture may turn currently fire-free pyrenean mountain forests into fire-prone ecosystems. *Science of the Total Environment*, 797, 149104.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G. et al. (2011) Rcp 8.5—a scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 109(1), 33. Available from: https://doi.org/10.1007/s10584-011-0149-y

Rockel, B., Will, A. & Hense, A. (2008) The regional climate model cosmo-clm (cclm). *Meteorologische Zeitschrift*, 17(4), 347–348. Available from: https://doi.org/10.1127/0941-2948/2008/0309

Rockel, B. & Geyer, B. (2008) The performance of the regional climate model clm in different climate regions, based on the example of precipitation. *Meteorologische Zeitschrift*, 17(4), 487–498.

Rolland, C. (2003) Spatial and seasonal variations of air temperature lapse rates in alpine regions. *Journal of Climate*, 16(7), 1032–1046.

Rouse, J.W., Jr., Haas, R.H., Deering, D.W., Schell, J.A. & Harlan, J.C. (1974) Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation. Technical Report.

Sakowska, K., MacArthur, A., Gianelle, D., Dalponte, M., Alberti, G., Gioli, B. et al. (2019) Assessing across-scale optical diversity and productivity relationships in grasslands of the italian alps. *Remote Sensing*, 11(6), 614.

Santini, M. & Valentini, R. (2010) Predicting hot-spots of land use changes in Italy by ensemble forecasting. *Regional Environmental Change*, 11(3), 483–502. Available from: https://doi.org/10.1007/s10113-010-0157-x

Santos, J., Malheiro, A., Pinto, J. & Jones, G. (2012) Macroclimate and viticultural zoning in europe: observed trends and atmospheric forcing. *Climate Research*, 51, 89–103. Available from: https://doi.org/10.3354/cr01056

Scoccimarro, E., Fogli, P.G. & Gualdi, S. (2017) The role of humidity in determining scenarios of perceived temperature extremes in europe. *Environmental Research Letters*, 12(11), 114029. Available from: https://doi.org/10.1088/1748-9326/aa8cdd

Scoccimarro, E., Gualdi, S., Bellucci, A., Sanna, A., Fogli, P.G., Manzini, E. et al. (2011) Effects of tropical cyclones on ocean heat transport in a high-resolution coupled general circulation model. *Journal of Climate*, 24(16), 4368–4384.

Shamshirband, S., Hashemi, S., Salimi, H., Samadianfard, S., Asadi, E., Shadkani, S. et al. (2020) Predicting standardized streamflow index for hydrological drought using machine learning models. *Engineering Applications of Computational Fluid Mechanics*, 14(1), 339–350.

Sousa, P.M., Trigo, R.M., Patrick Aizpurua, R., Nieto, L.G. & Garcia-Herrera, R. (2011) Trends and extremes of drought indices throughout the 20th century in the mediterranean. *Natural Hazards and Earth System Sciences*, 11(1), 33–51.

Steadman, R.G. (1984) A universal scale of apparent temperature. *Journal of Climate and Applied Meteorology*, 23(12), 1674–1687. http://www.jstor.org/stable/26181147

Thom, E.C. (1959) The discomfort index. *Weatherwise*, 12(2), 57–61. Available from: https://doi.org/10.1080/00431672.1959.9926960

Thuiller, W., Lafourcade, B., Engler, R. & Araújo, M.B. (2009) Biomod–a platform for ensemble forecasting of species distributions. *Ecography*, 32(3), 369–373.

Hewson, T.D. & Pillosu, F.M. (2021) A low-cost post-processing technique improves weather forecasts around the world. *Communications Earth & Environment*, 2(1), 132. Available from: https://doi.org/10.1038/s43247-021-00185-9

Vicente-Serrano, S.M. & Cuadrat-Prats, J.M. (2007) Trends in drought intensity and variability in the middle Ebro valley (ne of the iberian peninsula) during the second half of the twentieth century. *Theoretical and Applied Climatology*, 88(3), 247–258.

Villani, G., Tomei, F., Pavan, V., Pirola, A., Spisni, A. & Marletto, V. (2021) The icolt climate service: seasonal predictions of irrigation for Emilia-Romagna, Italy. *Meteorological Applications*, 28(4), e2007. Available from: https://doi.org/10.1002/met.2007

Vitasse, Y., Ursenbacher, S., Klein, G., Bohnenstengel, T., Chittaro, Y., Delestrade, A. et al. (2021) Phenological and elevational shifts of plants, animals and fungi under climate change in the e uropean a lps. *Biological Reviews*, 96(5), 1816–1835.

van Wagner, C.E. (1987) *Development and structure of the Canadian forest fire weather index system*. Forestry Technical Report: 35. Ottawa: Canadian Forestry Service.

Zurell, D., Franklin, J., König, C., Bouchet, P.J., Dormann, C.F., Elith, J. et al. (2020) A standard protocol for reporting species distribution models. *Ecography*, 43(9), 1261–1277.

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APPENDIX A

HIGHLANDER FOREGROUND AND BACKGROUND DATASETS

This Appendix presents a summary of HIGHLANDER background and foreground datasets and their roles in the different DApOS. In particular, Table 3 indicates which datasets are input and outputs of each DApOS. Furthermore, the table states whether the dataset is downloadable (D) or/and graphically displayed on the platform (G).