D1.2 - Leveraging bio-geo-physical data outputs to enhance social value for climate adaptation. Interim Report

WP1 - Task 1.2
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Executive Summary

D1.2 provides an interim report summarising the current progress in leveraging bio-geo-physical (BGP) data outputs to enhance social value for climate adaptation. This underpins a core component of CROSSEU given the increasing urgency to assess and manage BGP and socio-economic (SE) risks arising from climate change across sectors, regions, and governance levels. The final version due in M30.

Work Package 1 (WP1) focuses on developing a framework for assessing climate-related BGP and socio-economic SE risks. Deliverable D1.2 contributes to this effort through three primary objectives to:

1. **Provide a climate data/scenario protocol** to ensure consistency in inputs and outputs across CROSSEU.
2. **Identify, process as needed and harmonise BGP risk data** that are shared via an internal harmonised data repository (using observational, reanalysis, and climate model sources) to support integrated assessment.
3. **Support the integration of BGP data into wider modelling tasks and decision-support systems**, to better inform future policy pathways and adaptation strategies.

The methodology applied included a data needs assessment across the project's eight CSs, a review of available data, and the development of a project climate data/scenario protocol. Key challenges addressed include spatial and temporal inconsistencies, differing classification systems, data licensing constraints, and computational limitations.

The deliverable lays the groundwork for ongoing work in WP1 to provide global indicators of climate hazards for SE modelling (T1.3). It supports the development of the externally facing Integrated Assessment Framework (T1.4) and Harmonised Data Repository (HDR) (T1.5), both of which feed into the public-facing Decision Support System (DSS) in WP3. It also supports ongoing provision of data to the eight CSs covered in WP2.

Keywords

Harmonisation; BGP data; SE data; Climate Risk Assessment

Abbreviations and acronyms

Acronym	Description
BGP	Bio-geophysical
CC	Climate change
CCHs	Climate Change Hotspots
CMIP	Coupled Model Intercomparison Project
CSs	Case Studies
DMP	Data Management Plan
ECS	Equilibrium Climate Sensitivity
EGD	European Green Deal
GCM	Global Climate Model
HDR	Harmonised Data Repository
IAF	Integrated Assessment Framework
IPCC	Intergovernmental Panel on Climate Change
M&A	Mitigation and Adaptation
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
SE	Socio-economic
SSPs	Shared Socioeconomic Pathways
STL	Storyline
WP	Work Package

1. Introduction

The European Green Deal (EGD) lays down clear guard rails for social, economic, environmental and cultural transformation, such as the reduction of climate-damaging actions and adaptation to cope with the expected consequences of climate change (CC) and to enhance the resilience of socio-ecological systems. Achieving this requires a deep understanding of the socio-economic risks and opportunities arising from climate change and extreme weather events. The CROSSEU project, funded by Horizon Europe, seeks to address this need by developing a cross-sectoral framework for assessing and managing bio-geophysical (BGP) and socio-economic (SE) risks at local, national, and regional scales.

Aligned to this, Work Package 1 (WP1) of CROSSEU is focused on developing the framework for assessing climate-related BGP and socio-economic SE risks. In particular, the activities of WP1 (i) review research gaps and co-design the operationalization of the project implementation (T1.1), (ii) collect impact data on BGP risks of climate change (T1.2); (iii) collect data and model SE risks of climate change(T1.3); (iv) build a flexible Integrated Assessment Framework (IAF) (T1.4), and (v) create a harmonized impact data repository (T1.5) to be further used by other WPs, and made available for public use through the CROSSEU science-based DSS (WP3).

1.1. Purpose of this deliverable

The interim deliverable (with a final report due in M30) describes the BGP data and modelling outputs and added social value for climate change adaptation. In doing so it outlines the climate/BGP data/scenario protocol developed to ensure that data from different sources is harmonised to facilitate a consistent evaluation of multiple impacts and risks across sectors and regions. This is key given the climate and BGP data feeds into the case studies evaluating sectoral climate change hotspots (CCHs) and event-based storylines (STL) in WP2, with a summary of the methods to ensure consistent data inputs and outputs of case studies presented here. Outputs from additional BGP modelling processes to support SE modelling (T1.3) are also presented.

1.2. Structure of the deliverable

The interim deliverable is structured as follows:

- Chapter 2: Review of existing climate and BGP data
- Chapter 3: Framework for supporting harmonised modelling
- Chapter 4: Data Sources and Types

- Chapter 5: Global indicators of climate hazards for SE modelling
- Chapter 6: Addressing data challenges and limitations
- Chapter 7: Conclusions

2. Review of existing climate and BGP risk data

BGP risk refers to the physical manifestation of environmental events and processes and associated hazards driven by climate change (e.g., flooding, heatwaves and drought). These risks have been exacerbated by a changing climate. The subsequent risks pose adverse consequences for human and ecological systems, reflecting dynamic interactions between hazards, the exposure and vulnerability of affected systems and responses (Ara Begum et al., 2022). In this case, BGP elements are combined with information on vulnerability and exposure to explore the wider consequences on climate sensitive sectors such as health, agriculture, fisheries and threats to biodiversity.

Consideration of human dimensions are therefore crucial to integrate socio-economic vulnerability aspects into the risk framework and assess how risks will evolve under global warming, socio-economic development and adaptation pathways.

Decision-makers across government, industry, finance, and civil society often rely on scientific evidence underpinned by BGP risk data. Risk-based assessments can inform the development of adaptation plans, for example:

- **Infrastructure Planning:** Understanding flood zones or heat exposure can guide resilient construction.
- **Policy and Regulation:** Governments need harmonised data to set equitable adaptation targets, allocate resources, and comply with international agreements such as the Paris Agreement.
- **Disaster Preparedness:** Timely, standardised data improves early warning systems and emergency responses.

However, whilst modelling approaches and our understanding of climate-related risks is growing, shortcomings remain in the availability of data and information, particularly at more regional and local scale and for specific sectors (IPCC, 2022). Furthermore, risks can vary widely when considered at more local levels, and across different communities, with a need for evidence to inform place-based climate adaptation that addresses local vulnerabilities (Smith et al., 2025).

One area of concern is that the current landscape of BGP risk data is often fragmented, inconsistent, and difficult to integrate across disciplines, geographies, and timeframes. This can limit the accessibility and useability of data and related information, and poses a challenge for users, including researchers and policymakers, aiming to understand the landscape of climate-related risks driven by different hazards, and across different sectors and regions (United Nations Environment Programme, 2024)

Inconsistencies in BGP risk data arise as datasets are generated by a diverse array of actors using different models, modelling approaches and frameworks. For example, researchers often require specific climate variables which can originate from different sources (e.g. observations, reanalysis and/or climate projections).

Observational data comprises information from weather stations or via other systems such as satellite or aircraft. These datasets can provide accurate and localised representation of actual conditions, essential for monitoring current climate and to validate and model future climate (Kotlarski et al., 2019). However, historical time periods can differ, as can the recording equipment and approaches used, impeding comparison across regions and time. Furthermore, constraints can arise due to differences in the density of meteorological stations, which are often more pronounced in low and middle-income countries, or regions with complex topography (Mistry et al., 2022).

Reanalysis datasets combine past observational data with weather forecasting models to provide consistent historical records of meteorological variables covering different spatial and temporal resolutions (Mistry et al., 2022). They aim to generate the best possible estimate of meteorological variables, often focused on average conditions and sometimes estimates of uncertainties due to the modelling process, as opposed to directly reproducing observational records (Keller & Wahl, 2021).

Climate projections provide estimates of how the climate system could change, based on different scenarios about GHGs emissions and socio-economic change over short and longer time periods. Climate models provide projected outputs for a wide range of climate variables at different spatial and temporal resolutions (IPCC, 2023).

Furthermore, hazard-specific datasets also exist which can be generated from observational, reanalysis or climate model datasets. This normally includes some form of additional data processing to represent and/or quantify indicators related to a specific hazard e.g. river flooding or heatwave events.

Whilst good practice should ensure reanalysis datasets, observations and projections use consistent formats, naming conventions and units, for example, inconsistencies can exist. Different end-users may wish to interpret or compare BGP data from different repositories or try to integrate data to support further risk analysis. If different input data are used, with different characteristics, then outputs from climate risk models will also differ. This can also impede the potential to assess or model multi-hazard risk (Poljanšek et al., 2019). Traditional risk assessment approaches tend to focus on the impacts of single hazards in isolation and sector specific models are constructed independently and do not interact (Frieler et al., 2017), which can result in an underestimation of climate risks to a given region (Stalhandske et al., 2024). Consistency in the use of climate and BGP risk data is required to help support a more system-wide evaluation of multi-hazard risks.

Consequently, a lack of harmonisation can undermine coordinated and effective climate risk assessment, capture only a partial picture of climate-related risks for a region, and hinder progress on climate change adaptation planning and decision making.

Previous and ongoing EU HORIZON projects such as The H2020 ESPREssO project (Enhancing Synergies for Disaster Prevention in the European Union) highlighted that advances are still needed to better support risk assessments, including to inform effective climate change adaptation. This included a need to harmonise spatial and temporal scales when reporting hazards across the EU (Zuccaro et al., 2020). The CLIMAAX (CLIMAte risk and vulnerability Assessment framework and toolboX) project aims to develop a robust and coordinated framework that can help standardise approaches to climate risk assessment across regions of the EU.

As CROSSEU integrates complex information from climate risk data sets and non-climatic sectoral data this messaging is important for the project. In CROSSEU BGP and SE data is collected from existing datasets and derived through the project via risk modelling covering a variety of climate and socio-economic contexts of the EU; key natural hazard categories (storms, floods, heatwaves, droughts, and snow avalanches); multi-hazard risk and indirect climate change impacts and spillover effects to Europe. The CROSSEU case studies cover the United Kingdom and Czech Republic, Central and South-Eastern Europe, South Western Denmark and Northern Germany, Northeastern Italy, the European Alps and Carpathians, the Lower Danube, and Europe as a whole.

Given the coverage of case studies, a range of different climate risk models are drawn upon. To support the modelling, CROSSEU identifies, reviews and collects BGP data from existing resources, including observational data, reanalysis data and modelled results. This includes data on climate variables, climate-related hazards, and derived data on climate-related risks where appropriate (table 1).

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Table 1. Overview of key dataset characteristics, variables and indicators used in the analysis of climate-related hazards and risks

Dataset	Description	Type	Time coverage	Spatial coverage	Metrics /Indicators	Link
ERA5	Reanalysis dataset providing hourly estimates of atmospheric, land, and oceanic climate variables	Reanalysis	1940-present (hourly)	Global 0.25° x 0.25° (atmosphere)0.5° x 0.5° (ocean waves)	temperature, precipitation, wind, soil moisture, etc.	https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview
ERA5-DROUGHT	Recon-struction of drought indices	Recon-struction based on ERA5	1940-present (monthly)	Global (0.25 x 0.25)	SPEI, SPI	https://xds-preprod.ecmwf.int/datasets/derived-drought-historical-monthly?tab=overview
Fire danger indices historical data from the Copernicus Emergency Management Service	Recon-struction of fire-favourable meteoro-logical conditions.	Recon-struction based on ERA5 reanalysis	1940-present	Global (0.25 x 0.25)	Build up index, Drought code, Duff moisture code, Fine fuel moisture code, Fire daily severity rating, Fire weather index, Initial fire spread index	https://ewds.climate.copernicus.eu/datasets/cems-fire-historical-v1?tab=overview
Climate extreme indices and heat stress indicators derived from CMIP6 global climate projections			1850-2300 (shorter for most models and products) (yearly, monthly, daily)	0.5 x 0.5 to 2.8125 x 2.8125 depending on the model	Cold days, old nights, Cold spell duration, Consecutive dry days, Consecutive wet days, Heat index, Humidex, Indoor universal thermal climate index, Wet-bulb temperature, Indoor wet-bulb globe temperature, etc.	https://cds.climate.copernicus.eu/datasets/sis-extreme-indices-cmip6?tab=overview
E-OBS – ECA&D	ECA&D is a database of daily meteoro-	Obser-vational	1950-present	Europe (0.1 x 0.1 and 0.25 x 0.25)	temperature, precipitation,	https://surfobs.climate.copernicus.eu/dataaccess/

	logical station data contri-buted by over 80 countries, mainly in Europe and surroun-ding regions.				wind, soil moisture, etc.	access_eobs.php
ISIMIP	The Inter-Sectoral Impact Model Inter-compari-son Project (ISIMIP) provides data from a structured approach, uniformly assessing the impacts of climate change across various sectors and geo-graphic regions	Modelled	1850-2100	Global (0.5 x 0.5)	atmospheric variables (temperature, precipitation, etc.) and sector specific data, e.g. crop yield, discharge (if modelled)	https://www.isimip.org/
IPCC Interactive Atlas (AR6)	Web-tool for flexible analysis of climate change infor-mation under-pinning WPI of IPCC AR6	Modelled	Warming level	Global	Atmospheric and ocean variables	https://interactive-atlas.ipcc.ch/
Climate Analytics Impact Explorer	Web-tool visualising climate change impacts at different levels of global warming and under	Modelled	Warming level	National, Regional	Various	https://climate-impact-explorer.climateanalytics.org/

	different policy scenarios					
Tyndall Searchable global inventory	Searchable data base displaying climate impacts predicted to occur for global warming of 1.5°C to 4°C above pre-industrial levels	Modelled	End of 21st century	National	Various (e.g. temperature, wind, heat stress, flooding)	https://www.gov.uk/government/publications/climate-impacts-at-the-global-regional-and-country-scale-literature-review
COACCH	Climate change impact scenario explorer at NUTS2 level for the European Union and UK	Modelled	2015-2070 (in 5-year steps)	NUTS 2 (EU + UK)	Various (e.g., GDP, Fish catches, crop yields, electricity demand)	https://www.scenarioxplorer.coacch.eu
IMPACT2C	Web-Atlas summarising climate change impact at 2°C of global warming	Modelled	Warming levels	Pan-European	Various	https://www.atlas.impact2c.eu/en/
PESETA (TRACE)	Territorial Risk Assessment of Climate in Regions in Europe (TRACE)	Modelled	Warming levels	Europe (NUTS3)	Various (e.g. death rates, labour productivity, tourism)	https://joint-research-centre.ec.europa.eu/projects-and-activities/peseta-climate-change-projects-0/jrc-peseta-v_en https://drmkc.jrc.ec.europa.eu/risk-data-hub#/atlas

EURO-CORDEX regional climate model data		Modelled	1951-2100, depending on experiment	Europe (0.11 x 0.11)	Atmospheric variables	https://www.euro-cordex.net/
BioVars		Reanalysis	1971-2098		35 bioclimatic indicators	https://doi.pangaea.de/10.1594/PANGAEA.904278 https://www.nature.com/articles/s41597-020-00726-5#Sec5
CRU		Reconstruction based on CRU TS			scPDSI	https://crudata.uea.ac.uk/cru/data/drought/

3. Framework for supporting harmonised modelling

3.1. CROSSEU requirements

CROSSEU will facilitate an improved understanding of the nature and extent of physical risks and the SE impacts at different levels of warming (and implicitly, less or more ambitious mitigation measures), with and without adaptation, accounting for uncertainty in regional climate projection, using different scenarios of projected climate, land use and SE change.

The eight CSs under WP2 all have different data needs and requirements. In addition, in WP1 modelling of socio-economic impacts of climate change will be undertaken (T1.3) underpinned by climate data as well as modelling of income inequality that requires the provision of historical and future country-aggregated climate hazard indicators.

The BGP data will be derived from different sources, including EU databases. An initial needs assessment and consultation with modellers from WP1 and WP2 provided an outline of the models, required BGP and SE data inputs, scales, resolutions, consideration of different climate and SE scenarios, data formats and anticipated outputs.

The data needs assessment was used to firstly provide an assessment of the level of consistency based on proposed methods across the CSs, and where this could be enhanced. Overall, it was highlighted that there was relatively good overlap in the proposed data sources, mostly using CMIP5 and CMIP6 where possible. There was consistency in that CSs could all represent the RCP8.5/SSP585 scenario and had capacity to run an ensemble size of at least 5 climate models. The development of a climate data/scenario protocol aimed to ensure consistency across these aspects. Further areas where harmonization of data and consistency across the CSs were also identified, particularly in relation to the specific time-slices that would be modelled and selection of the ensemble members.

Secondly, the data needs assessment was used to identify relevant datasets that could be recommended and used based on the initial review of BGP data highlighted above and CS needs. Thirdly, the needs assessment was used to identify where additional data processing and provision of climate variables would be required to support climate risk modelling in a harmonised manner.

Provision of harmonised data is essential given the need to ensure consistent climate risk assessments across the case studies and to boost the potential for regional analyses to be upscaled and/or applied to other regions in the EU and UK. Figure 1 highlights some of the main ways in which the BGP data will feed into various WPs and tasks, and the importance of ensuring a harmonised approach across these. Ultimately it will support consistent risk and impact assessment across the CSs and help boost the potential upscaling for other regions.

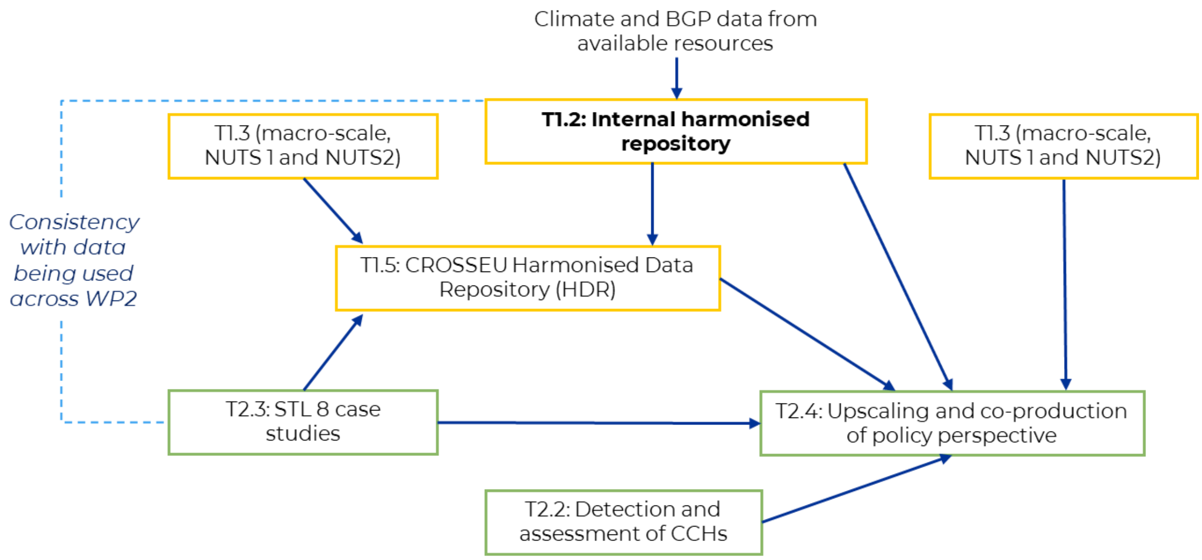

Figure 1: Linking data across the CROSSEU Work packages

3.2. Climate data/scenario protocol

The protocol developed here facilitates a harmonised and consistent approach, as far as technically feasible, to the risk assessment, across the range of case studies and modelling tasks. It underpins the development of the internal harmonised data repository and supports the provision and sharing of data across the modelling teams.

Whilst adhering to the requirements of the CROSSEU project it also recognises that there can be both data limitations and computational constraints in terms of computing power and time that can limit the number of scenarios that can be simulated. Therefore, it is important that the sets of scenarios covered are carefully selected and are representative of a range of potential futures and key political targets (Frieler et al., 2017).

Table 2 highlights the primary source of climate data, version and resolution used to address the needs of the case studies.

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Table 2: Overview of main BGP input data to support case studies

Case study name (sectors of interest)	Geographical context	Climate data	Version	Resolution
1. Heat (health)	Czech Republic and UK (Prague and London)	Euro-CORDEX	CMIP5	0.11°
2. Drought (Agriculture, food security, water, energy, forestry, biodiversity, tourism)	Central and South-Eastern Europe	Euro-CORDEX	CMIP5	0.11°
3. Storms (Agriculture, transport, health, tourism, biodiversity, water, energy)	South-Western Denmark and Northern Germany	DMI's Klimaatlas (Euro-CORDEX)	CMIP5	1 km & 0.11°
4. Storms - floods/flash floods (Agriculture, transport, health, tourism, biodiversity, water, energy)	North-Eastern Italy	CORDEX-FPSCONV	CMIP5	2.5-3 km
5. Snow (Tourism, forestry, transport)	European Alps and Carpathians	Euro-CORDEX	CMIP5	0.11°
6. Indirect due to shifting seasonality and water availability (Agriculture, water, biodiversity, health, energy)	Lower Danube	Euro-CORDEX	CMIP5	0.11°
7. Indirect due to multi-hazard risks (Energy)	Europe	CMIP6	CMIP6	0.25° (aggregate to NUTS3)
8. Spillover effects due to climate	Europe	ISIMIP (bias corrected)	CMIP6	0.5°

impacts globally (Agriculture)				

In addressing the SoA CROSSEU includes CSs that utilise higher resolution climate model data that can be combined with SE data to produce relevant risk indicators for certain sectors and regions. CS3 and CS4 both use high resolution climate data (1km and 3km respectively) given the focus on storms. In other CSs there are limitations in the availability of downscaled data and limitations in doing this in a consistent manner. For example, the existing and dynamically downscaled Euro-CORDEX data is based on CMIP5 models and available at 0.11° resolution, providing time-series (daily and monthly) covering the period 1950-2100. The CORDEX derived high resolution set ECLIPS only provides averages over periods and no daily data, hence is not suitable for the needs of the CSs in CROSSEU.

Similarly, the recently created, convection permitting, EUCP data uses mainly CMIP5 models, providing data at 2.2-3 km resolution but only for the time periods 1996-2005, 2041-2050, and 2090-2099. Also, only for standard variables whereas others (e.g. snow related) are unlikely to be available from these sets and the set would hence not be suitable for the respective case studies. Furthermore, due to extreme size of the data, the Euro-CORDEX domain has been split into 8 subdomains for EUCP but the number of model runs provided for each of the domains is inconsistent. For example, CS4 (which uses this data) has access to 9 models, as it uses the ALP-3 domain but CS1 would need data from NWE-3 (4 models) and CEU-3 (3 models) to cover its data needs and hence inconsistencies exist between the two study regions. This reflects some of the wider data challenges that exist beyond this project that have been considered in developing the internal harmonised data repository (see section 6 for further details).

3.2.1. Climate time-slices

Across the CSs impact model simulations are carried out using a pre-defined set of time-slices, with a 30-year time horizon (table 3). The baseline against which climate risk is measured is 1971-2000. In part this has been defined to account for the fact that multiple CSs are using Euro-CORDEX CMIP5 data (table 2). In this data the historical period ends in 2005, and the scenarios run from 2006. By ending the baseline period before 2005 it avoids mixing historical data with scenario data when calculating the reference period. This allows for risks to be estimated against a consistent baseline and aligns to the 30-year time horizon. It is very important to use longer-term time slices in the risk assessment to represent climate variability. These time slices also capture the specific years of 2030, 2050 and 2100 (see section 3.2.4 below).

Table 3: Climate time-slices

Time slice	Name	Timeframe	Socio-economic change modelled
1971-2000	Baseline	Present day	Reference Scenario (No climate change only SE change reflecting trends for the baseline, near-present, mid-century and end-of-century.
2011-2040	Near-present	2030s	Yes (capture climate and SE change)
2041-2070	Mid-century	2050s	Yes (capture climate and SE change)
2071-2100	End-of-century	2080s / end of century	Yes (capture climate and SE change)

One exception is CS4, which due to the use of CORDEX-FPSCONV will model the following three time slices with a 10-year time horizon: 1996-2005 (historical), 2041-2050 and 2090-2099. This reflects the specific needs of this case study, namely high spatial and temporal resolution data and a need to resolve convective processes to better simulate e.g. heavy rainfall. Whilst a limitation of using CORDEX-FPSCONV is that data is only available for the above time-periods they still align with the broader baseline, mid-century and end-of-century timeframes.

The second exception is CS1 which specifically aims to explore the unprecedently hot decade of 2010-2019 on the health sector and compare this to future projections. In this case a shorter time-slice of ten years will also need to be used for projected time periods. Future projections will sample 10-yr time horizons to allow for consistency when comparing across time and will be extracted from the time slices in table 3 above.

In addition, a reference scenario is defined that is a theoretical scenario where climate does not change. The reference scenario aligns to the baseline against which climate risk is measured. As such, the climate is kept at this baseline and the models will differ in their socioeconomic projections (SE-only). This allows for the contribution of different drivers of risk to be explored (climate versus SE change).

3.2.1. Climate model ensemble

As well as ensuring that uncertainties related to climate variability are addressed, CSs will use output from an ensemble of climate models, to also sample climate model uncertainty. Dynamical downscaling projects used the global climate output from GCM-simulations as inputs at its boundaries to provide finer resolution data to support regional risk assessment. Case studies select GCM/RCM pairs based on an analysis of the available data and variables required across CSs to establish a consistent set of regional climate projections. This supports the comparability of different risk-related outputs and will help inform stories relating to cross-sectoral impacts in different areas.

For example, CS2 (drought), CS5 (snow) and CS6 (Cross-sectoral multi-hazard risk) all make use of Euro-CORDEX CMIP5 data. Within the CSs different climate indices need to be calculated, which require different climate variables for their calculation. In particular, the indices needed for CS5 place greater demands on the availability of certain variables (e.g. snow depth, which is not always available from every model pair).

A further constraint on the selection of the GCM/RCM pairs is due to the availability of data hosted by different data centres/data distribution platforms. A final constraint is the requirement to select pairs that are available for both RCP4.5 and RCP8.5 emissions scenarios as highlighted as a requirement of CROSSEU (see section 3.2.3).

Table 4 outlines the nine GCM/RCM pairs that are recommended for use in CROSSEU. CSs will follow general best-practices of climate change impact modelling in using an ensemble size of at least 5 GCMs to sample model uncertainties. Equilibrium Climate Sensitivity (ECS) represents a measure of how much the Earth's surface temperature would eventually increase if the amount of CO_2 in the atmosphere were doubled and the climate system reached a new equilibrium, based on CMIP5 ECS Data.

Table 4: GCM/RCM pairs

Driving GCM	RCM	Ensemble member	ECS (°C)	Version-tag
CNRM-CERFACS-CNRM-CM5	KNMI-RACMO22E	r1i1p1	3.3	v2

ICHEC-EC-EARTH	KNMI-RACMO22E	r12i1p1	3.3	v1
ICHEC-EC-EARTH	KNMI-RACMO22E	r1i1p1	3.3	v1
ICHEC-EC-EARTH	DMI-HIRHAM5	r3i1p1	3.3	v2
MOHC-HadGEM2-ES	DMI-HIRHAM5	r1i1p1	4.6	v2
CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN63	r1i1p1	3.3	v2
MOHC-HadGEM2-ES	KNMI-RACMO22E	r1i1p1	4.6	v2
NCC-NorESM1-M	DMI-HIRHAM5	r1i1p1	2.8	v3
NCC-NorESM1-M	SMHI-RCA4	r1i1p1	2.8	v1

3.2.2. Climate warming levels

Whilst this climate data/scenario protocol outlines fixed climate-time slices to use (section 3.2.1), an alternative approach is to use average global warming levels whereby time slices are selected that centre on an average global surface temperature change of e.g. 1.5°C, 2°C, 3°C, or 4°C. In this approach the specific start and end points of each 30-yr time slice will vary for each of the climate models in the ensemble given they will reach warming levels at different points in time based on their parameterisation. However, it is possible to determine, for each GCM/RCM pair (table 4) and time-slice (table 3) the corresponding average global warming level this aligns to (relative to pre-industrial levels). Representative warming levels will be estimated and can also be used when analysing and reporting results from CROSSEU.

A benefit of this is that outputs can also be presented at warming levels which allow risks to be considered in a more policy-relevant manner. This is important given the current discourse on avoiding dangerous climate change and risks associated with 1.5°C and 2°C of global warming above pre-industrial levels (Adger et al., 2018) as defined via the UNFCCC Paris Accord (UNFCCC, 2016). The assessment of risks at higher levels of warming, such as 4°C can be used as a likely upper range that cannot be ruled out and encourages thinking and stress testing of systems considering what a 4°C world could look like for adaptation planning (Betts & Brown, 2021).

3.2.3. Representative Concentration Pathways (RCPs)

CROSSEU will facilitate different combinations of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) to highlight the differential effect of economic and climate drivers on socio-economic risks. The RCPs reflect the GHG concentration trajectories that drive the radiative forcing in the models. The scenarios cover very low emissions (reflective of strong and ambitious mitigation) to high risk pathways that reflect weak mitigation. The SSPs are plausible narratives that describe five different pathways about future socio-economic developments (Riahi et al., 2017).

CSs in CROSSEU will prioritise the provision of consistent results using RCP8.5 and RCP4.5. The only exception is CS4 as it is using CORDEX-FPSCONV and data is only available for RCP8.5.

In addition, there is potential for additional combinations of RCPs/SSPs to be captured by some of the CSs with three covering SSP1-RCP2.6 and two covering SSP3-7.0. Thus, the CROSSEU framework can represent the top priority scenarios indicated by CMIP and the IPCC.

3.2.4. Common reporting years

As highlighted in table 2 and table 3 CROSSEU will facilitate the assessment of risk across different sectors and for different policy-relevant timeframes of the 2030s, 2050s and end of century. Results will be presented to align with these common reporting years. Results will reflect mean values and uncertainty ranges across the 30-yr time-slices across the years and the ensemble of models capturing the uncertainty in the pattern of regional climate projection as well as the variability over the time slice.

3.3. Process for Harmonisation

Harmonisation refers to the process of aligning data from diverse sources to ensure consistency in structure, semantics and scale. In the context of impact data, the actual harmonisation step mainly involves three parts: standardisation of indicators, alignment of spatial and temporal resolutions, and the generation of shared ontologies and classification systems. But the overall process also involves additional pre- and post-processing steps, such as data sourcing and integration, quality assurance, generation of metadata, and distribution. The following section briefly describes the steps performed for the harmonisation of BGP and SE data within CROSSEU.

3.3.1. Data sourcing and integration

After identifying the data requirements for each Task and CS, available datasets were first identified and then trimmed to a subset which would best fit the requirements of the harmonisation protocol. The selected datasets where then obtained from various sources, which involved:

- Automated download from APIs, FTP servers, and open data portals.
- Manual download of structured datasets where access points for automated processing were not available.
- Initial validation to check for completeness, format compliance, and metadata availability

Subsequently, the raw data was further pre-processed in several steps, which included:

- Reprojection of spatial data to a common reference system.
- Temporal alignment to standard intervals (e.g. daily, monthly, annual).
- Unit conversions and normalisations (e.g. from Kelvin to Celsius)

3.3.2. Standardisation

Within harmonisation, the standardisation step usually follows on from data integration and refers to the process of transforming data into a common structure to ensure understandability, comparability, and integration across all systems. Examples of those transformations are:

- Generation of a consistent terminology to ensure the same terms are used to describe the same concepts across datasets.
- Conversion to uniform data formats, e.g. standard date format, units of measurements, or numerical precision.
- Checking for data type consistency, e.g. that fields such as age, or income are stored in the same data type.
- Normalisation of values to a common scale or range, especially in a statistical context.

3.3.3. Metadata

The generation and extension of metadata is an important part of the harmonisation process, as it records the provenance of the data and the transformations applied, ensuring transparency and reproducibility. As outlined in the data management plan (D1.6), each dataset is hence accompanied by detailed metadata covering provenance, licensing information spatial and temporal coverage, and further file level details.

3.3.4. Quality Assurance and Validation

The harmonised data are subject to a multi-step quality assurance process, which includes validation rules (range checks, missing values) and cross-referencing with independent sources prior to use in any analysis or distribution.

3.3.5. Data sharing

BGP and SE data are stored in an internal harmonised data repository via UEA. This repository is a purely internal collation, generated to facilitate initial data access and distributed processing within the CROSSEU consortium. Individual datasets hence currently mainly reside with the respective processing partner or the case studies directly working with the data. The main harmonised data is currently housed internally via UEAs HPC ("/CROSSEU/data/"). As an example, a smaller subset of data that has been shared via the CROSSEU SharePoint is available here: CROSSEU/Documents/WP2/CSA#2-Drought/Data/scPDSI.

As outlined in the data management plan (see deliverable 6.2) the internal harmonised data repository is a precursor to the HDR that integrates various types of data including BGP and SE modelling outputs and impact data retrieved from CSs. The data integrated in the internal harmonised data repository will feed into the HDR and IAF, hosted by DAFNI and further the CROSSEU DSS. Thus, all data derived from the raw datasets will eventually be made publicly available whenever licensing restrictions permit.

4. Data Sources and Types

The internal harmonised data repository (T1.2) integrates a wide range of datasets which originate from different sources, each with varying formats and resolutions. This data is being shared and utilised internally across CROSSEU partners. It will also feed into the external HDR (T1.5) with further details included in the DMP (see deliverable 6.2). This section provides a summary of the key data collated and generated.

4.1. Core Datasets

The initial data survey performed towards the start of the project, highlighted that there are core data requirements, shared by all case studies and the deliverables. These requirements mainly related to standard climatic variables (e.g. temperature, precipitation) used as direct model inputs or for geospatial analysis.

Table 5: Core datasets harmonised for internal use in CROSSEU.

Dataset Name	Description/Data Type	Primary Use	Link
EURO-CORDEX	CORDEX regional climate model (RCM) simulations for the European domain from 1951 to 2100 (depending on model).	Direct model input or used to estimate indicators required by the case studies.	https://www.euro-cordex.net/
ERA5	Global reanalysis dataset providing hourly estimates of atmospheric, land, and oceanic climate variables from 1940 to present.	Climate extreme detection, drought and flood modelling, long-term trend analysis globally.	https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download
ISIMIP	The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) provides data from a structured approach, uniformly assessing the impacts of climate change across various sectors and geographic regions	Direct model input where future projections are required globally.	https://www.isimip.org

4.2. Case Study Specific Datasets

In addition to the core datasets, most case studies required additional observational or reanalysis data specific to their regions and analysis. These data are hence not widely shared between the partners but mainly reside with the respective case studies. The datasets were mostly only harmonised according to the general protocol (time periods) but not for the entire European domain. The reason for this approach was that models and analyses were generally performed on gridded data, which require substantial storage space. To keep costs for data transfer and storage at a minimum, the data was hence only prepared if necessary and mostly limited to the domain of the case study.

Table 6: Case study specific datasets harmonised for internal use in CROSSEU.

Dataset Name	Description/Data Type	Primary Use	Link
CERRA (Copernicus regional reanalysis for Europe)	Spatially and temporally consistent historical reconstructions of meteorological variables in the atmosphere and at the surface.	Calculation of snow-related indicators (CS5)	https://cds.climate.copernicus.eu/datasets/reanalysis-cerra-single-levels?tab=overview
Combined drought indicator (CDI) from the European Drought Observatory	Used to detect and monitor areas that are affected by, or are at risk of, agricultural drought. The CDI combines anomalies of precipitation, soil moisture and vegetation greenness.	Direct analysis input (CS2)	https://drought.emergency.copernicus.eu/tumbo/edo/download/
E-OBS	Gridded meteorological data for Europe from 1950 to present derived from in-situ observations.	Calculation of 10-day cumulative precipitation and mean temperature over the Danube River basin (CS6).	https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php
ERA5-DROUGHT	Reconstruction of drought indicators from 1940 to present.	Detection of drought events globally (T1.3)	https://xds-preprod.ecmwf.int/datasets/derived-drought-historical-monthly?tab=overview
ESA CCI LC	Global landcover set (22 classes) providing data from 1992 to the near present.	Subsetting of indicators to agricultural or urban areas globally (T1.3)	https://cds.climate.copernicus.eu/datasets/satellite-land-cover?tab=overview
Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) from the	The fraction of the solar radiation absorbed by plants for photosynthesis. It refers only to the	Direct analysis input (CS2)	https://land.copernicus.eu/en/products/vegetation/fraction-of-absorbed-photosynthetically-

Copernicus Land Monitoring Service	green and living elements of the canopy.		active-radiation-v1-0-300m
Fire danger indices historical data from the Copernicus Emergency Management Service	Reconstruction of fire-favourable meteorological conditions from 1940 to present.	Estimation of wildfire risk globally (T1.3)	https://ewds.climate.copernicus.eu/datasets/cems-fire-historical-v1?tab=overview
Global Agro-Ecological Zoning (GAEZ)	Suitability and production potentials for individual crop types under specific input and management conditions	Model input (CS8)	https://www.fao.org/gaez/en
Land Surface Temperature (Synthesis and Thermal Condition Index) from the Copernicus Land Monitoring Service	Statistical overview of the land surface temperature over each 10-day compositing period.	Direct analysis input (CS2)	https://land.copernicus.eu/en/products/temperature-and-reflectance/10-daily-land-surface-temperature-thermal-condition-index-global-v1-0-5km
Leaf Area Index (LAI)	Useful input parameter for various primary productivity models.	Direct analysis input (CS2)	https://land.copernicus.eu/en/products/vegetation/leaf-area-index-300m-v1.0
Normalised Difference Vegetation Index (NDVI) from the Copernicus Land Monitoring Service	Standard 10-day synthesis (S10). NDVI is an indicator of the greenness of the biomes.	Direct analysis input (CS2)	https://land.copernicus.eu/en/products/vegetation/normalized-difference-vegetation-index-300m-v1.0
Soil water index (SWI) from the Copernicus Land Monitoring Service	10-day updates on the moisture conditions in the different soil layers.	Direct analysis input (CS2)	https://land.copernicus.eu/en/products/soil-moisture/soil-water-index-static-layers-v3-0-12-5-km

4.3. Indicators

A crucial part of the harmonisation was the generation of additional indicators that were not available in the core or case study specific datasets and for which no suitable pre-calculated alternative that adheres to the CROSSEU scenario protocol and the requirements of the case studies exists. Key examples of indicators calculated are highlighted in table 7.

Table 7: Indicators calculated (or in process to be calculated) as part of the harmonisation process of CROSSEU; the table presents key examples.

Indicator	Method	Primary Use
Cumulative 10-day precipitation	Direct calculation from E-OBS precipitation	Analysis input (CS6)
The greatest 3-day fresh snow accumulation	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)
Number of days with fresh snow ≥ 30 mm	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)
Number of days with fresh snow ≥ 50 mm	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)
Number of days with maximum temperature ≥ 0°C and snow depth ≥ 30 cm	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)
Maximum number of consecutive days (at least 3 days) with maximum temperature > 0℃, and snow depth ≥30 cm	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)
Rain-on-snow events (precipitation ≥1.0 mm in days with average temperature >0℃, when snow depth is ≥10 cm)	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)
Maximum number of consecutive days with strong winds (wind speed >10 m/s) and snowfalls (snowfall water equivalent over 1 kg/m2)	Direct calculation from EURO-CORDEX CERRA variables	Analysis input (CS5)
Number of days with strong winds (wind speed ≥ 10 m/s) and snowfall	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)

(snowfall water equivalent over 1.0 kg/m^2)		
Potential evapotranspiration (PET)	Application of Penman-Monteith equation to EURO-CORDEX data	Analysis input (CS2)
Rain-on-snow events (precipitation ≥ 1mm and median temperature ≥ 0°C and snow depth ≥ 10 cm)	Direct calculation from EURO-CORDEX and CERRA variables	Analysis input (CS5)
Self-calibrating Palmer-Drought-Severity-Index (scPDSI)	Application of modified ECA&D routine to EURO-CORDEX data	Analysis input (CS2)

5. Global indicators of climate hazards for SE modelling

To support the econometric modelling in task T1.3 further global indicators of climate hazard frequency and intensity have been developed. This supports econometric modelling exploring the extent to which effects of extreme weather events and their relationship to equity can be captured.

5.1. Indicators / brief methodology

To explore how climate extremes effect income inequality climate hazards need to be linked to economic data on a global level. Based on the ERA5 core datasets, frequency and severity of selected climate extremes – such as heatwaves, tropical nights, extreme rainfall days – were determined on national levels. Table 8 outlines the current indicators that have already been calculated, or that will be calculated going forwards, as part of the SE modelling. More detailed information on this task is provided in the interim deliverable D1.3 (Data on the sectoral impacts of selected mitigation and adaptation strategies at European level).

Table 8: Indicators calculated (or in process to be calculated) as part of the global SE modelling; the table presents key examples.

Indicator	Method
Coldwaves	Derived from the excess cold factor (ECF) calculated based on ERA5
Frost days (minimum temperature ≤ 0°C)	Calculated based on ERA5
Heatwaves	Derived from the excess heat factor (EHF) calculated based on ERA5
Heavy precipitation days (> 10mm precipitation)	Calculated based on ERA5
Hot days (maximum temperature ≥ 35°C)	Calculated based on ERA5
Icing days (maximum temperature < 0°C)	Calculated based on ERA5
SPEI over agricultural land	Direct calculation by combining ESA CCI LC with ERA5-DROUGHT
Tropical nights (minimum temperature > 20°C)	Calculated based on ERA5

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Very heavy precipitation days (> 20mm precipitation)	Calculated based on ERA5
Wet-bulb globe temperature	Direct calculation based on ISIMIP data
Wildfire risk	Direct calculation based on the Fire danger indices historical data from the Copernicus Emergency Management Service

6. Addressing Data Challenges and Limitations

The creation of a harmonised repository is complex and comes with many challenges and limitations. On the most fundamental level, data required for a specific analysis is often not available or exhibits gaps. This lack of coherent information for reporting hazards across the EU was the initial driver behind setting up the repository and has previously been highlighted by the H2020 ESPREssO project (Zuccaro et al., 2020). Going through the process of setting up the repository, however, highlighted additional issues which will be discussed in detail in the following sections.

6.1. Data availability and gaps

A key challenge in the harmonisation of datasets lies not in the absence of data per se, but in the asymmetry of data availability. Although Europe benefits from dense and high-quality data infrastructures, many datasets are region-specific and have no global equivalent. Conversely, there are global indicators that are not systematically reported within the EU framework. To address this issue, CROSSEU follows a multi-layer approach. Case studies predominantly rely on region-specific information, and global data is only sourced if necessary for the specific use case. This ensures data compatibility across the project while minimising the loss of detail and the introduction of further uncertainty.

The spatial availability problem was further compounded by mismatches in temporal availability. These, predominantly, stem from two main sources: a) indicators are estimated on different time scales (e.g. daily, monthly, annually) and b) data is only available for specific time periods (e.g. 1981-2020, 2050s). By developing a common data and scenario protocol in close collaboration with the case studies, issues arising due to the unavailability of data for specific time periods were minimised but not eliminated.

Furthermore, some indicators were absent altogether. Some impact dimensions are only relevant at very regional scale and hence not systematically collected or modelled on larger domains. This lack of availability limits the ability to perform fully harmonised, cross-regional analyses. In line with the multi-resolution framework necessitated by mismatches in spatial resolution, affected indicators were hence only included at the available level.

Consequently, a pragmatic approach, balancing the needs of the individual case studies with those of the data harmonisation process was taken. This results in some deviation from the protocols in six CSs as summarised in Table 2. However, it is noted that where value is added in harmonising this has been undertaken but in cases where this does not add value, or detracts from adding value, expert judgement is applied. This approach is required due to the very different nature of the CSs in terms of focus, questions asked, and areas over which the analysis takes place.

6.2. Inconsistencies across sources

Another persistent challenge in data harmonisation is the divergence in collection methodologies, definitions, and classification systems. These discrepancies manifest in divergent definitions of key concepts such as "affected population", "economic loss", or "vulnerability", which can vary not only between institutions but also across time and context. The result is an array of indicators which are nominally similar, but substantively incompatible, requiring careful ontological mapping and potentially, parallel representation, rather than integration. A prominent example is the land cover classification from Copernicus, which differs substantially from those used in global datasets like MODIS or ESA CCI. To keep parallel representation at a minimum, CROSSEU follows a "minimal data" approach. Across the project, the data is initially restricted to a limited number of sets (e.g. one land cover classification system) to ensure coherence across all case studies and analyses.

Even if an indicator is available for both the European and the global domain, the data often differs in spatial and temporal resolution. European datasets frequently offer high-resolution spatial data – such as 11km gridded climate data or NUTS-3 level socio-economic indicators, which are regularly updated. Global datasets, on the other hand, are often only available on coarser grids (0.25) or aggregated to national level and only updated annually or less frequently. Integrating these sets hence either requires aggregation of high-resolution data, which leads to a loss of information, or the disaggregation of coarse data, which introduces uncertainty and potential bias. Since most case studies performed their analysis on high-resolution grids, aggregation of data was often not directly required, but limited to the results. Notable exceptions are case study 8 and where Europe cannot, and should not, be decoupled from the global economy and task 1.3 where data was required at national or sub-national level instead of regular grids.

6.3. Technical and Computational Constraints

The integration of a wide range and large number of heterogeneous datasets into a harmonised repository imposes substantial technical and computational demands. The ingestion and processing of large-scale raster datasets – such as climate variables or land cover classifications – require significant storage capacity, parallel processing capabilities, and optimised data pipelines. These demands are further amplified when harmonisation involves spatial interpolation, temporal resampling or derivation of additional indicators. Within CROSSEU, the computational burden of accessing and preparing the datasets was shared between the partners and processing was regularly performed on a per case study basis to keep computational costs low.

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Beyond raw processing power, the harmonisation also requires a high degree of technical expertise in geospatial analytics. Integration of datasets with differing coordinate reference systems, spatial resolutions, and file formats involves complex transformations which need to be correctly executed to avoid the propagation of spatial distortions. Similarly, the temporal alignment of datasets with varying calendar conventions demands careful handling to preserve analytical integrity.

Despite substantial efforts, certain computational limitations remain difficult to overcome. For example, a lack of standardised APIs across data providers constrains efficient and semi-automated integration, and the need for downloading terra bytes of raw data incurs substantial costs, both in processing time and disk space. Overall, the constraints highlighted the importance of investment in cloud-based infrastructure, and a need for prioritisation: not all datasets can or should be harmonised at the same level of granularity, and trade-offs between resolution, timeliness, and analytical values must be explicitly acknowledged in the design and operation of the repository.

6.4. Institutional and legal barriers

CROSSEU mainly operates within an open data paradigm, but the integration of datasets from multiple institutional sources is constrained by a complex web of licencing conditions, attribution requirements, and institutional fragmentation. Although the datasets integrated into the repository – such as those from Copernicus Climate Data Store (CDS), ISIMIP, and Eurostat – are publicly accessible, they are governed by distinct usage policies and stewardship models. These differences complicate the redistribution and re-use of the harmonised repository. Some of the data are released under relatively permissible licences such as the Creative Commons Attribution (CC BY), while others use more stringent licences that include specific clauses on citation, redistribution and derivative works. These conditions must be respected not only in the metadata of the repository itself but also in any derived application and visualisation. For the repository, there is hence a trade-off between what can be included in a final public version and what needs to be kept restricted to internal use only.

While open access principles are increasingly embraced by many institutions, there are still instances where data have been produced as part of research projects but are not distributed due to licencing restrictions or embargoes. These instances slow down scientific progress and incur additional costs, because the exact same data processing must be repeated. Whenever possible, the regeneration of such datasets was avoided within CROSSEU, and data was sourced from openly available data.

7. Conclusions

This interim deliverable sets the foundation for a consistent and harmonised assessment of BGP data to enhance social value for climate adaptation. The climate data/scenario protocol presented here aims to ensure, as far as technically possible, key climate variables and modelled indicators are aligned to enhance comparability, integration, and the potential for upscaling to regional and European levels. Following this protocol a data needs assessment has supported the compilation of an internal harmonised data repository that is being used across tasks in CROSSEU. Existing data has been sourced from observational, reanalysis and climate model projections. Additional processing has generated national scale climate hazard indicators focus on the frequency and severity of events such as coldwaves and heatwaves. This provides an essential foundation for understanding climate-related threats to SE systems.

Building on the foundation of this interim deliverable, the next steps will focus on expanding the harmonised dataset which will evolve as modelling in WP1 and WP2 continues. Through this link the BGP data will support modelling and understanding of SE consequences of CC, including risks and opportunities through modelling effects on equity (T1.3), the STLs and CSs (WP2) and their coverage of different sector-specific climate policy and adaptation options. As such, the final deliverable will be able to reflect upon how the use of BGP data has supported the evaluation of strategic options for adaptation.

Next steps also include the integration of data into the HDR under T1.5 to support broader uptake across the CROSSEU project and beyond. This will be available for public use through the CROSSEU science-based DSS (WP3) that will ultimately support decision-making and contribute to a more climate-resilient and informed Europe.

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CROSSEU Partners

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