Interdisciplinary large-scale research to advance the science and management of drying river networks facing climate change

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Conflict of Interest

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Abstract

Drying River Networks (DRNs) are increasingly widespread due to climate change and human pressures, yet their ecological and societal importance has long been underestimated. This paper synthesizes the interdisciplinary outcomes of the DRYvER (Securing Biodiversity, Functional Integrity and Ecosystem Services in Drying River Networks) project, which developed an innovative framework for understanding and managing DRNs across multiple spatial scales. DRYvER integrated hydrology, biodiversity, ecosystem functioning, ecosystem services, and socio-economic dimensions through a cascading model linking physical drivers, ecological processes, and human well-being. The project applied a dynamic meta-system perspective across nine representative river networks in Europe and South America, encompassing diverse climatic, geological, biogeographical, and socio-cultural contexts. Using coordinated field sampling, modelling, and stakeholder co-construction approaches, DRYvER investigated how river drying affects biodiversity, ecosystem functions, and ecosystem services from local reaches to continental scales.

DRYvER demonstrated that DRNs are not marginal ecosystems but fundamental components of global river networks, requiring recognition in freshwater science, policy, and management. It provided new tools and strategies to support adaptive and cost-effective management of river networks prone to climate change. We identified key priorities for future research, including long-term monitoring programmes, improved assessment of anthropogenic drying, expansion of studies to larger river systems, and the development of predictive mechanistic models linking hydrological changes to ecological responses. Greater integration of DRNs into governance, legal frameworks, and restoration policies is urgently needed. We also advocate stronger adoption of international Nature-based Solutions standards and broader global collaboration. Overall, DRYvER establishes a robust scientific foundation for advancing the understanding, conservation, and management of DRNs worldwide in the face of accelerating environmental change.

Keywords.

Interdisciplinary, rivers, streams, transformative research, coconstruction, global scale, Horizon 2020

1. Introduction

River networks are among the most threatened hotspots of global biodiversity (Sayer et al. 2025, Tickner et al. 2020, Reid et al. 2018). They act as critical habitat and dispersal pathways for aquatic and terrestrial biota from local to continental scales (Tonkin et al. 2019). River networks contribute substantially to the carbon cycle by linking terrestrial and aquatic ecosystems down to the sea and emitting carbon dioxide into the atmosphere (Battin et al. 2023). They provide key ecosystem services that underpin human wellbeing, including provision of drinking water, climate regulation, and food production (Lynch et al. 2023). In river networks, ecosystem structure and functioning emerge from the interplay between local environmental conditions and regional fluxes of organisms and resources (Talluto et al. 2024). Their dynamics are fundamentally governed by the flow regime, which acts as a master variable structuring aquatic communities and regulating ecosystem processes. However, climate change and intensifying human water use are profoundly altering natural flow regimes worldwide (Gudmundsson et al. 2025). Disruptions of flow propagate through river networks, with cascading and often negative consequences for biodiversity, ecosystem functioning, and the services that rivers provide (Reid et al. 2018, Tonkin et al. 2019).

All river networks are composed of perennial river reaches (PRs, that flow year-round) and non-perennial river reaches (NPRs, that periodically stop flow or dry). Over 70% of the global river network, by length, is naturally non-perennial (Messager et al. 2021, Butler et al. 2026). As this proportion is increasing under global change (Tramblay et al. 2021, Zipper et al. 2021, Mimeau et al. 2025, Abbasi et al. 2026), many rivers must be considered part of drying river networks (DRNs, Datry et al. 2023). Historically, most river sciences have been developed for and from PRs, largely omitting NPRs (Datry et al. 2023). However, there has been a recent surge in NPR research since 2010 (e.g. Leigh et al. 2016, Stubbington et al. 2017, Bush et al. 2020), generating an immense amount of knowledge highlighting the significance of NPRs in various disciplines, from hydrology (e.g. Price et al. 2021) to ecology (e.g. Datry et al. 2014) and social sciences (e.g. Cottet et al. 2023). Nevertheless, how the dynamic assembly of PRs and NPRs in river networks shapes aquatic communities and ecosystem functioning remains poorly understood, limiting our capacity to understand and predict how climate change will alter the ecology of river networks in the near-future. Achieving such understanding would represent a fundamental breakthrough in river science and freshwater resource management.

The metasystem theory, that local- and regional-scale processes interact to influence the dynamics of environmental conditions and biota in a given landscape (Gounand et al. 2018), offers a relevant framework to explore the effects of drying. This is because drying typically has both local and regional effects on flow, solutes, sediments and organisms (Crabot et al. 2019, Gianuca et al. 2025, Lopez-Rojo et al. 2025). Locally, ecological processes and biological communities can differ substantially among hydrological phases, spanning flowing (lotic), standing pool (lentic), and dry riverbed (terrestrial) conditions (Larned et al. 2010, Datry et al. 2014). As the spatiotemporal dynamics of these abiotic conditions affect regional-scale transport and dispersal pathways, local drying generates cascading effects across entire DRNs regionally. This suggests that PRs and NPRs must be considered together and spanning multiple hydrological phases to thoroughly unravel how drying is altering and will alter the functioning of river networks at multiple scales.

This paper synthesizes the interdisciplinary results of an international effort to advance the science and management of DRNs (Securing biodiversity, functional integrity and ecosystem services in DRYing riVER networks (DRYvER); Datry et al. 2021). DRYvER pioneered a dynamic meta-system framework of DRNs, integrating hydrology, biodiversity, ecosystem functions and services and their values across multiple spatial scales, i.e., from local reaches to continental extents. By implementing a cascade approach linking physical and ecological processes with social dimensions, DRYvER has provided new knowledge and developed novel strategies and tools for cost-effective adaptive management of DRNs in the EU and worldwide. After presenting the main outputs of DRYvER, we discuss the success, limitations and challenges of such a large and ambitious project.

2. Methods

2.1 A cascading model to explore how climate change influences DRNs

To integrate the diverse disciplines involved in river research, from hydrology to social sciences, and to include both scientists and practitioners, we developed a 'cascading' model based on three guiding principles (*Figure 1a*). *The first guiding principle* is that a causal chain links physical drivers (e.g. climate, hydrology, geology) to ecosystem structure and processes that underpin biodiversity and functioning. These drivers also support ecosystem services that are key to human well-being (Haines-Young and Potschin 2010). Societal objectives and management actions feed back to physical drivers, and changes at any point in the system can propagate throughout the causal chain (**Figure 1a**). We investigated each component of this chain and linkages among components using common methods across nine contrasted focal DRNs, including 3 in South America, with the ultimate aim to support adaptive management of DRNs (**Figure 1b and c**). In the resulting project structure reflecting the causal chain from hydrology to management (**Figure 1a**), each disciplinary component was assessed through a similar approach (see section 3): we first conceptualised the possible effects of drying in hypotheses that were tested through an extensive and coordinated sampling effort, followed by upscaling at the regional and continental scales. *The second guiding principle* lies in adopting a dynamic meta-system perspective to study and manage DRNs. We translated climate projections into changes in flow intermittence patterns across in the nine focal DRNs, which were selected to represent a wide range of climatic, geological, and biogeographic contexts. This physical setting was used to implement a dynamic meta-system perspective to understand the cascading changes in biodiversity, ecosystem functions and ES. In short, each DRN was sampled in a representative way (spatially and temporally) to 1) quantify the regional processes underlying biodiversity, ecosystem function and service patterns as a result of fragmentation by drying and 2) examine how these spatial patterns varied across the hydrological year spanning between wet and dry phases (**Figure 1d**). *The third guiding principle* is to cover contrasted contexts through large-scale efforts. The DRYvER cascading model has been applied in nine focal DRNs in Europe (**Figure 1c**) and South America (**Figure 1d**) (Datry et al. 2021). These DRNs drained catchments of 100-300 km^2 comprising human-impacted and near-natural reaches, which were prone to drying or had perennial flow. This design allowed us to disentangle the respective effects of water quantity and quality. The focal DRNs were selected to represent six climatic zones (semiarid, Mediterranean, continental, tropical, temperate and boreal) and nine biogeographical ecoregions (Mediterranean, Alpine, Continental, Balkanic, Pannonian and Boreal for Europe; Pacific Lowlands, Central High Andes and Caatinga for South America). This selection serves several purposes. First, these regions are affected differently by climate change, allowing DRYvER to generate a wide and regionally relevant range of scenarios. Second, the biota have distinct evolutionary histories, which may result in contrasting responses to current and projected river drying. For example, in southern Europe, aquatic organisms have experienced drying phenomena for millennia, while those of central and northern Europe are only beginning to face such pressure. Third, besides biodiversity, socio-cultural contexts also vary substantially across the nine focal DRNs, which broadened the socio-economic scope of DRYvER.

Moreover, advancing the science of DRNs requires working closely with stakeholders because perception, consideration and definition of drying can differ widely across disciplines in academia and among stakeholders (Bush et al. 2020, Sarremejane et al. 2021, Cottet et al. 2023). In DRYvER, we developed a co-construction approach at multiple levels: within the consortium, at the DRN level, and at the European level. At each level, scientists and stakeholders interacted closely throughout the project (see section 3). Last, after implementing the cascading model at the DRN scale, the effects of predicted climate change on the biodiversity, ecological functions and services have been explored at the continental scale, using the contrasting DRN contexts for testing how generic and transferable the findings are across different environmental settings. The implied causal structure and meta-system conceptualization were considered to support upscaling and generalisation from single river reaches to DRNs and then to continental scales, thereby laying foundations for future management of DRNs.

2.2. Implementation of the five-component cascade model

In the first step, we defined the hydrological trajectories of DRNs under climate change (Work Package 1, WP1) for both the focal DRNs and the European and South American continents. In the second step, we explored the effects of drying on i. aquatic biodiversity (Work Package 2, WP2), ii. selected ecosystem functions related to carbon cycling (Work Package 3, WP3), and iii. key ES provided by DRNs (Work Package 4, WP4). We also evaluated the socio-economic impacts of changes in the provision of ES resulting from future drying patterns (WP4). In the third step, we developed a set of tools to support adaptive management of DRNs (Work Package 5, WP5). The data and information resulting from Steps 1 and 2 informed a participatory process with stakeholders to co-design and explore restoration actions, socio-technological mitigation and adaptation measures, including Nature Based Solutions (NBS). The resulting applied adaptive management framework resulting from this scientific and participatory process aims to support decision-making while explicitly accounting for uncertainty at the focal DRN (local-scale) and EU-scales (continental). It by coupling the model outputs from WP1-4 to Bayesian Belief Networks to derive a generic multi-criteria decision frameworktool .. Finally, a Europe-wide citizen science network was created to monitor river drying through an open-access smartphone application ('DRYRivers'). Its aim is to overcome the scarcity of data on drying, enhance hydrological model validation, and strengthen public awareness and engagement around DRNs.

2.3. Detailed flow within and among disciplines and work packages

WP1 modelled streamflow conditions to better understand and characterise spatio-temporal patterns of flow intermittence under climate change. Hydrological models were implemented to simulate dynamic flow intermittence at the six European DRNs, as well as for the entire European and South American continents. As complete drying of the river channel is difficult to reproduce with physically-based hydrological models, simulations of flow intermittence were obtained through hybrid modeling that coupled physically-based hydrological models with Random Forest models. We trained these models with observed flow time series for the continental scale (Döll et al., 2024), and flow intermittence data - collected through the DRYRivers application and DRyVER field campaigns - for the six European DRNs (Mimeau et al., 2024). Based on these hybrid hydrological models, we computed spatialized flow intermittence indicators in the river networks over a historical period (1960-2021 for the DRN scale and 1981-2019 for the continental scale) and until 2100 using an ensemble of climate projections (Abbasi et al., 2025; Mimeau et al., 2025). These projections considered three Shared Socio-economic Pathways (SSPs) with contrasting greenhiyse-gas emissions: SSP1-2.6 Sustainability, SSP3-7.0 Regional Rivalry, and SSP5-8.5 Fossil-Fueled Development (IPCC, 2023) and relied on tailored output of five different Global Climate Models (GCMs). Moreover, a continental flow intermittence model was achieved based on he global hydrological model WaterGAP, which accounts for human water use. We by 1) downscaleding the 0.5-arc-deg (~55-km) output of WaterGAP the global hydrological model WaterGAP, which accounts for human water use, to compute monthly streamflow time series at 73 million 15-arc-sec (~500-m) grid cells and 2) setting up a two-step Random Forest modeling approach with predictors derived from the simulated monthly streamflow time series. This random forest model was and trained and validated at 3706 gauging stations with daily streamflow observations (Abbasi et al., 2025).

In the South American DRNs, specific data collection and modelling protocols were carried out to better understand the processes underlying flow intermittence. Firstly, we collected isotopic, and geochemical data in the Ecuadorian DRN to infer streamflow generation processes in intermittent and perennial reaches (Mosquera et al., 2025). Secondly, we combined hydrological observations, citizen science, drone surveys, and satellite imagery to inform a Random Forest model to assess flow intermittence patterns in the Brazilian and Bolivian DRNs (Soares et al., 2024; Soares et al., 2026, Moya et al. 2026).

The choice of flow intermittence metrics produced by WP1 resulted from consultation with the other WPs to provide a common narrative and terminology, and to support quantification of the ecological and socio-economic impacts of flow intermittence. These metrics were designed to characterise intermittence at the scale of river reaches initially. For example, the metrics included the number of days without flow per month or per year, the duration of dry periods (number of consecutive days without flow), or the date of the first dry period in the year. A second set of spatially aggregated indicators was designed to characterise flow intermittence at the river-network scale by using, for example, the length of rivers exhibiting flow intermittence (per month or per year).

Work Package 2 (WP2) quantified the current and future effects of drying on the aquatic biodiversity of river networks. It considered multiple facets of biodiversity (e.g., taxonomic and functional diversity) and spatial components (local and regional diversity) at both the DRN and continental scales. To achieve this, WP2 combined empirical data and modelling approaches. First, a theoretical metacommunity model was developed based on a dendritic river network model that allows the user to simulate the effect of drying regimes with varying frequencies, spatial extents, durations and locations within the river network, and infer their consequences on the survival and movement of organisms. This allowed us to explore community trajectories under different spatio-temporal drying scenarios depending on species' drying resistance and dispersal strategies (drifting, swimming and flying) (Jacquet et al. 2022).

Second, extensive sampling campaigns across the nine DRNs characterised biodiversity patterns and dynamics along drying gradients for multiple taxonomic groups, including microbes (bacteria, fungi and diatoms), macroinvertebrates and fish. Sampling was conducted at 20–26 sites across each DRN and carried out approximately bimonthly over one year (starting in January 2021, Datry et al. 2021). Environmental variables describing geomorphology, hydrology, water chemistry and habitat characteristics were measured at each site during each campaign. Microbial communities were characterised by scraping cobbles for biofilm and by collecting sediment samples, macroinvertebrates were collected using quantitative samplers and fish were surveyed by electrofishing before and after the main dry period (Truchy et al. 2026). Microbial biodiversity was assessed using environmental DNA metabarcoding from sediment and biofilm samples targeting bacterial (16S) and eukaryotic (18S) markers, followed by high-throughput sequencing and bioinformatic processing to generate molecular operational taxonomic units used in subsequent biodiversity analyses (Taberlet et al. 2018). These data enabled assessment of how drying influences taxonomic and functional diversity and metacommunity assembly across different climatic and biogeographical contexts (Chalmandrier et al. 2025, Escobar-Camacho et al. 2026, Messager et al. 2026). We also conducted functional trait analyses to evaluate how drying affects functional diversity and to explore the potential role of functional redundancy in buffering biodiversity responses (Journiac et al. 2024).

Finally, based on the predictions of the metacommunity model, biodiversity patterns within each European DRN were assessed using empirically collected data. Regression models accounting for the spatio-temporal structure of river networks were designed to predict taxonomic and functional diversity of key functional groups in macroinvertebrate and microbial communities, calibrated using environmental and hydrological data from WP1 (Messager et al. 2026). The models were used to extrapolate community structure across space and time under current conditions and to project biodiversity changes under future (2100) environmental scenarios for each European DRN. These projections enabled the identification of vulnerable reaches and taxonomic groups, mapping of future biodiversity patterns, and provision of guidance for targeted restoration and management actions.

Work Package 3 (WP3) quantified how flow intermittence influenced carbon processing, storage and emission in DRNs and developed models for upscaling from reach to DRN scale given current

and future climate change scenarios. Empirical data collection included in-situ measurements of greenhouse-gas fluxes, leaf litter decomposition, and organic matter stocks and estimation of river metabolism (only in the French DRN, daily estimations for the whole sampling period), complemented with several environmental variables measured at both local and regional scales at the same sites as WP2 and targeting three hydrological phases (before, during and after drying) to capture seasonal variability in hydrology (March–June 2021, July–August 2021, October 2021–January 2022). Ecosystem functions and OM stocks were measured in the different habitats present: flowing water (at both PR and NPR reaches when flowing) and dry riverbed plus eventually occurring disconnected pools in non-flowing NPR reaches. Sampling for WP2 and WP3 was carried out as close as possible in time to discern the role of biodiversity on the control of ecosystem functioning.

Carbon dioxide (CO_2) and methane (CH_4) fluxes were measured using a chamber operated in closed loop mode directly coupled to an infra-red gas analyser (Dossa et al. 2015; Wilkinson et al. 2018) alongside measurements of a range of abiotic local variables. Random Forest models for each habitat and flow regime were used to identify drivers of CO_2 and CH_4 fluxes among local and regional variables, variables accounting for the effect of fragmentation by drying and, for NPRs, drying metrics. The Random Forest modeling approach was also applied to upscale reach-scale daily CO_2 flux to annual dynamics at the scale of the entire DRN. To achieve this aim, Random Forest models were fitted to calculate daily CO_2 fluxes from predictor variables available for all reaches and including climatic and land use variables (developed by WP4) and drying metrics (simulated by WP1). Daily dry and flowing surface area of each river reach over the year 2021 was calculated using the daily discharge modeled by WP1 and corresponding wetted width estimated by hydraulic geometry relationships. Total CO_2 fluxes of DRNs were calculated as the sum of dry riverbeds and flowing water. Finally, analog Random Forest models were used for upscaling CO_2 fluxes to the European scale. This effort was limited to river reaches with stream orders 1-4 given the absence of calibration data for larger rivers and the expected lower importance of drying in larger rivers. The final European river network used for modelling included almost 1.2 million river reaches, for which we achieved reach-scale predictions of monthly CO_2 emissions based on four RF models.

We calculated leaf decomposition at each site and date using coarse-mesh litter bags (1-cm mesh; 15 × 20 cm) filled with 4 g of air-dried *Populus nigra* leaves. One temperature logger (HOBO 8K Pendant logger, Onset, USA) was placed at each site to continuously record environmental temperature every 30 minutes during the incubation period because leaf decomposition is strongly affected by water temperature. Incubation lasted between 8 and 87 days, targeting an intermediate stage of litter decomposition (≈20–70% mass loss). After retrieval, litter bags were frozen, the remaining ash-free dry mass (AFDM) measured following standard procedures, and temperature-adjusted decomposition rates (degree-day^{-1}) were calculated as first-order decay coefficients by regressing the natural logarithm of remaining AFDM against accumulated degree-days (Bärlocher 2020). Leaf decomposition data were analyzed using structural equation modelling linking drying metrics at local and regional scales to taxonomic and functional descriptors of macroinvertebrate, fungal and bacterial communities and decomposition rates (del Campo et al. 2025). For South America, a simpler protocol was used to measure the effect of drying on decomposition. Briefly, this effect was tested among different leaf species, some of which known to be highly recalcitrant due to local xeric conditions (Rezende et al. 2026).

We estimated stream metabolism using the single-station open channel method (Odum, 1956), a mass-balance of dissolved oxygen as a function of light-dependent Gross Primary Production (GPP, g O_2 m^{-2} d^{-1}), constant Ecosystem Respiration (ER, g O_2 m^{-2} d^{-1}), and temperature and concentration-dependent gas exchange between the water and air. At each sampling reach of the French DRN, oxygen concentration (mg L^{-1}) and water temperature (°C) were recorded every 5 min, from April 2021 to February 2022 with an in-situ sensor (HOBO U26-001, Onset Computer Corporation, Massachusetts, USA or miniDOT® logger, PME, California, USA). Light intensity at the stream surface (lum ft^{-2}) was recorded every 10 min (HOBO Pendant® Temperature/Light 64 K Data Loggers). Hourly atmospheric pressure data—needed to estimate oxygen saturation—were extracted from the closest meteorological station. Daily stream depth was calculated using discharge data simulated by WP1 and hydraulic geometry relationships. We simultaneously estimated daily GPP, ER, and the gas exchange constant (K600 d^{-1}) using inverse fitting of oxygen dynamics with a state space approach and Bayesian inference with Markov chain Monte Carlo sampling (Appling et al., 2018). We then calculated metabolic fingerprints (*sensu* Bernhardt et al., 2018) of ER, GPP and net primary production (NEP), and used linear mixed effect models to test if stream metabolic regimes and known drivers differed between PRs and NPRs. Finally, Partial Least Squares Path Modeling approach (Henseler, 2017) was used to determine the effect of climate, land use, drying regime, local abiotic conditions and microbial community composition on ER and GP (Lopez-Rojo et al. 2025).

Work Package 4 (WP4) characterized, modeled, and valued a set of ecosystem services (ES) in the DRNs, both at the basin scale and at the European scale. The analysis of the effects of drying on ES was based on the characterization of connecting functional units (adjacent terrestrial land, riparian vegetation and aquatic ecosystems) associated with each river segment (Pérez-Silos et al. 2025). The meta-system perspective was considered as the basis of the separation between Service-Providing Areas (where the service is generated), Service-Connecting Areas (which link the sources to the users), and Service-Benefiting Areas (where the benefit is consumed) (Syrbe and Walz 2012). This distinction stressed that provision and delivery of ES may not spatially coincide. For instance, water provisioning happens when water produced in headwaters is delivered downstream. Further, the analysis considered the spatial and temporal differentiation of flowing reaches, disconnected pools and dry streambeds to identify services specific to each phase.

Several ES were considered. At the DRN scale, these included water provisioning (i.e., the amount of surface water available for domestic, industrial or agricultural use), flood regulation (the capacity to mitigate extreme precipitation events), erosion regulation (involving erosion control at the source and sediment filtering in riparian zones), drought mitigation (the potential capacity to store water and recharge groundwater, which sustains base flows during dry periods), thermal regulation (capacity of the riparian forest in mitigating summer water temperatures) and carbon emission regulation (the consideration of rivers as active components in CO_2 fluxes, particularly under drying).

The ES assessed at the scale of European river networks were largely identical to those estimated at the DRN scale. These included water provisioning, dilution capacity, flood regulation and drought regulation. Modelling these ES allowed detection of regional patterns and key service-providing areas. In particular, the dilution capacity service was considered under several present and future climate scenarios. It was assumed that climate change would affect the water flow of river networks and therefore the respective dilution capacity of both PR and NPR segments when receiving wastewater treatment plant effluents. This prognosis was performed under two different emission levels (mow RCP2.6 and high RCP8.5), and aimed to estimate how variations in river flow - especially under extreme drought conditions - could impact dilution and, consequently, water quality and the ecological health of river segments (Sepp et al. 2025).

As a final step, WP4 produced an economic valuation of several ES. This valuation paid particular attention to local populations (and visitors) engaging with the DRNs and gaining multiple benefits, including welfare, from them. The analysis was conducted for three of the project's DRNs (located respectively in Central, North and South Europe) and considered several ES which would be directly appreciated by stakeholders. These were recreation (e.g. benefits related to sightseeing, ability to swim in pools or go fishing), support to biodiversity (drying may affect sensitive biota but also may support flora or fauna that the public may value), and environmental regulation of floods or droughts. Valuation translated the predicted changes in ES delivery in service-providing areas (named as the "Degraded State" caused by climate change and its associated enhancement of drying) into monetary terms by measuring societal Willingness-to-Pay to limit those losses.

Work Package 5 (WP5) integrated outputs from WP1-WP4 to develop management strategies for drying river networks, based on iterative learning, monitoring and adjustment of management actions, Three complementary approaches were emphasized: stakeholder co-creation, evaluation of NBS as mitigation measures and citizen science.

Co-creation was implemented at three levels: (i) within the consortium through meetings and working sessions, (ii) at the DRN level through "Futures Thinking" co-creation workshops, and (iii) at the European level via a stakeholder committee. While early project phases were largely disciplinary, integration was strengthened in later stages through harmonization of datasets and models across work packages. Transdisciplinary elements were incorporated through stakeholder engagement, namely river managers, policymakers and local communities. This included continuous interactions with a dedicated Stakeholder Committee and different types of co-construction events. Differences in terminology, data types, methodological frameworks and standards of evidence across disciplines and stakeholders were explicitly addressed through iterative dialogue, feedback and knowledge exchange among participants. This approach aimed to support the integration of multiple knowledge types into the development of adaptive management strategies for DRNs.

NBS were assessed as measures to reduce climate change impacts on DRNs. Bayesian Belief Networks were developed for each European DRN using published studies, model outputs and monitoring data. Potential mitigation measures were identified through a systematic literature review and integrated into the models. The Bayesian Belief Networks represented probabilistic links between hydrological conditions, management actions and ecological responses. Outputs were aligned with policy-relevant biodiversity indicators, including Red List species and taxonomic richness. The models were parameterized with data collected between 2005 and 2022, and the results explicitly accounted for uncertainty: they revealed major knowledge gaps in restoration–hydrology–biodiversity relationships and identified monitoring priorities and future model improvements.

Spatial prioritization methods were further applied to identify river reaches where restoration would be most effective under current and future conditions (Lanzas et al. 2026). Using systematic conservation planning principles and optimization tools (Hanson et al., 2024), prioritization incorporated projections of biodiversity metrics, ecosystem functions, and services, as well as spatiotemporal connectivity patterns as prevalent in DRNs. Projected data for 1960-2021 were used to represent "current" conditions, while future conditions were derived from average projections across the five global climate models under the SSP370 scenario for the period 2040-2070. This approach captures interannual variability in future conditions. These inputs were used to develop a Shiny-based decision-tool, DRYvER-OptimApp, for spatial prioritization across the six European DRNs (Lanzas et al. 2026).

A citizen science application (DRYRivERS) was developed to address gaps in spatial and temporal hydrological monitoring in DRNs. The smartphone-based tool enables users to record georeferenced observations of flow conditions (flowing, isolated pools or dry), supported by photographs. Observations can be collected offline and later uploaded. A complementary web interface allows data visualization and management through an interactive map. By facilitating large-scale, low-cost data collection, the tool complements conventional monitoring datasets and improves understanding of drying dynamics across DRNs (Truchy et al. 2023).

Last, a Stakeholder Committee (SHC) was constituted as a key multi-actor platform designed to ensure strong linkages between scientists and stakeholders. The SHC brought together 13 members from national and local water authorities, river basin organisations, research institutes, and environmental management bodies from all countries in Europe with studied DRNs. The SHC's activities contributed to several core functions, including the co-design of policy-oriented recommendations, the co-development of NBS integrating hydrological, ecological, socio-economic, and governance perspectives, and the support of the citizen science network. It also played an active role in dissemination, including contributions to newsletters, thereby extending the outreach of project results to a broader stakeholder community. Overall, the SHC acted as a critical interface between scientific production and practical implementation, ensuring continuously that DRYvER outputs were aligned with the operational realities of water authorities and basin managers and transforming research into action.

Work Package 6 (WP6) played a key role in shaping communication, dissemination and capacity-building activities throughout the DRYvER project. Beyond supporting the day-to-day coordination of the consortium (e.g. regular meetings, steering Committee meetings, general assemblies, and structured digital communication channels), WP6 contributed to creating a shared project identity and ensuring that DRYvER's scientific outputs reached a broad range of audiences, including researchers, stakeholders, water managers and the wider public. A dedicated project website (www.dryver.eu) acted as the central communication platform, complemented by an active presence on social media. Together, these channels disseminated a set of communication products such as news updates, audiovisual materials and project outputs to both specialist and non-specialist audiences.

Among these initiatives, a travelling exhibition on NPRs — also made available in an online graphical format — played a key role in making the ecological relevance and management challenges of drying river networks more accessible and tangible to the wider public. Regular newsletters further sustained engagement with stakeholders and interested audiences throughout the project.

Capacity building represented another key pillar of WP6. The Forum of Young Researchers was established as a platform to connect early-career scientists across the consortium, facilitating networking and access to shared resources. In parallel, a Short Term Scientific Mission (STSM) programme promoted mobility and collaboration among partner institutions through a series of competitive calls supporting short research visits. Training activities were further strengthened through the organisation of a one-week training school, which offered intensive methodological and interdisciplinary training while reinforcing networking and integration among participants

Dissemination efforts focused not only on communicating scientific findings, but also on enhancing their practical relevance and societal uptake. Particular emphasis was placed on translating scientific results into concise policy-relevant formats tailored to water managers and decision-makers, ensuring that project results could effectively inform governance and management strategies.

3. Results

In this section, we are presenting the main results of the DRYvER for each of the 5 WPs. These key findings are illustrated on **Figure 2**.

3.1 Current and future flow intermittence patterns at DRN and continental scales

The hydrological simulations produced for the past-present period by the hybrid flow intermittence models showed seasonal and spatial patterns of drying in the six European DRNs (1960-2021) (Mimeau et al., 2024). The hydrological projections simulated for the SSP5-8.5 Fossil-Fueled Development scenario indicate an intensification of drying across the European DRNs, particularly during summer. For instance, in the Albarine DRN (France), the proportion of dry reaches during July to September is projected to rise from 15% in the reference period to 26% by the 2050s. Our findings also indicate an increase of drying duration in general, with drying events starting earlier in the year (by several weeks or even months, depending on the basin) and persisting longer until late autumn.

The evolution of the spatial pattern of flow intermittence was shown to be specific to each focal DRN. The spatial extent of flow intermittence will remain relatively stable for the Albarine (France) and Bükkösdi (Hungary) DRNs, whereas small tributaries of the Lepsämänjoki (Finland) DRN could become non-perennial by the 2050s. Likewise, the Butižnica (Croatia), Bükkösdi (Hungary), Genal (Spain, **Figure 3**), and Velička (Czechia) DRNs are projected to become largely non-perennial, including large tributaries and large section of the mainstem river in the longer term (Mimeau et al. 2025)

Flow intermittence was estimated for more than 1.5 million river reaches in Europe, expressed as the number of no-flow days grouped into five classes (0, 1–5, 6–15, 16–29, 30–31 no-flow days) for each month from 1981 to 2019 (Döll et al. 2024) and the 21st century under the impact of climate change (Abbasi et al. 2025). Of the observed perennial and non-perennial station-months, 97.8% and 86.4%, respectively, were correctly predicted. Interannual variations of the number of non-perennial months at non-perennial reaches were satisfactorily simulated and we estimated that 3.8% of all European reach-months and 17.2% of all reaches were non-perennial during 1981–2019, predominantly with 30–31 no-flow days (Döll et al. 2024). The impact of climate change on flow intermittence was estimated by replacing, in the Random Forest model, WaterGAP-based predictors reflecting historical climate conditions with those under future climate conditions, as computed by driving WaterGAP with the outputs of five global climate models. The generated monthly time series of intermittence status were used to calculate the change of five ecologically relevant indicators of streamflow intermittence change. In Europe, the number of non-perennial reach-months is projected to increase in the future, for both low (SSP1-RCP2.6) and high (SSP5-RCP8.5) greenhouse-gas emissions scenarios, in almost all climate zones, particularly in August and September (**Figure 4**). Under SSP1-RCP2.6, 3.8% of all reach-months may experience no-flow conditions in 2071–2100 - only a small increase from 3.5% in 1985–2014. Under SSP5-8.5, however, a larger increase to 4.8% of all reach-months is expected, with 2.8% of European reaches projected to shift from being perennial to non-perennial (**Figure 4**).

3.2. Current and future effects of drying on the aquatic biodiversity of river networks

Model simulations confirmed that the amount of connectivity lost during drying was the main driver of biodiversity recovery, regardless of where the drying occurs (Jacquet et al. 2022). Empirical data from European DRNs supported the results of the theoretical model by underlining drying duration as a major predictor of richness across river reaches. It negatively altered diversity of macroinvertebrates and diatoms, highlighting their sensitivity to drying events (Chalmandrier et al. 2025, Escobar-Camacho et al. 2025, Messager et al. 2026). Conversely, drying duration positively influenced bacterial and fungal richness in both sediment and biofilm habitats, likely due to fast colonization of terrestrial taxa during dry phases (Messager et al. 2026). However, functional richness seemed to be less impacted by drying, particularly in the South American DRNs (Escobar-Camacho et al. 2025).

The diversity of diatoms and macroinvertebrate, and particularly the Ephemeroptera, Plecoptera and Trichoptera, are predicted to markedly decline under high-emission scenarios (**Figure 5**). Increased drying duration and timing, rather than decreasing connectivity, seemed to be the primary drivers of aquatic biodiversity decline, although high context-dependency was found among the DRNs (Messager et al. 2026). For example, dramatic diversity decrease is predicted in the Hungarian DRN for macroinvertabrates, whereas smaller decreases are likely in the Mediterranean DRN (Spain and Croatia), where flow intermittence is already high (**Figure 5**, Messager et al. 2026).

The discrepancy between the fine-scale biodiversity sampling conducted at the DRN scale and the much coarser spatial resolution of the European-scale hydrological projections prevented a reliable upscaling of biodiversity responses to future drying conditions. Specifically, individual river reaches in the European hydrological models were often associated with multiple biodiversity sampling locations, generating a large number of pseudo-replicates. As a result, it was not possible to establish robust relationships between biodiversity metrics and modeled drying characteristics, limiting the extrapolation of biodiversity predictions from the DRN network scale to the European scale.

3.3 Current and future effects of drying on carbon processing, storage and emission in DRNs

Metabolic regimes of NPRs were characterized by greater ecosystem respiration (ER) than PRs. Growth Primary Production (GPP) differed minimally between reach types. The combination of similar GPP but greater ER indicates that NPRs are more heterotrophic than PRs. Only PRs exhibited increasing downstream GPP. In contrast, GPP or autotrophy did not increase downstream in NPRs but the decoupling of GPP and ER did, suggesting a distinctive metabolic regime of NPRs compared to PRs. Drying patterns were key determinants of stream metabolism in the network, both directly and indirectly through their influence on stream biota and abiotic structure. As a direct effect, drying prevalence and drying severity tended to increase ER and decrease GPP. Indirect effects from drying on metabolism were of equal importance to the direct effects of drying. NPR biofilms were dominated by diatoms, whereas more diverse PRs also supported red, green and brown algal taxa. Those differences in the autotrophic communities between PR and NPR reaches were evident all year, suggesting a long-term, or legacy, imprint of hydrology on reach structure and function (López-Rojo et al. 2025).

Drying controlled the rate of leaf litter decomposition in all DRNs. Even short drying events (≤ 6 days) decreased leaf litter decomposition by up to 50% (del Campo et al. 2025). Structural equation models revealed that negative effects of drying were primarily indirect, mediated by rapid shifts in the diversity and composition of decomposer communities occurring over short time scales (2–18 days). In PRs, decomposition was sustained by a balanced contribution of fungi, bacteria and detritivorous macroinvertebrates (del Campo et al. 2025). However, in NPRs, the onset of drying disrupted this balance: decomposition rates declined as detritivorous macroinvertebrates were rapidly lost, followed by a replacement of aquatic fungal and bacterial communities by dry-tolerant but less efficient bacteria.

At the DRN scale, hydrological connectivity partially mitigated the negative effects of local drying by facilitating the recovery of aquatic decomposers (del Campo et al. 2025). However, this buffering capacity depended on the drying regime and biogeographic context of the river network. For instance, stronger fragmentation in more arid networks in southern Europe constrained recolonization by aquatic decomposers after flow resumption. As a result, drying effects on decomposition can persist well beyond the return of flow, reflecting the limited recovery capacity of both microbial and macroinvertebrate communities. These findings show that drying not only alters decomposer communities and decomposition rates at the reach scale, but also disrupts diversity–function relationships across entire DRNs (del Campo et al. 2025). Notably, the identification of threshold responses—community shifts within 2 to 18 dry days and decomposition declines of up to 50% after only six dry days—suggests that even brief annual drying periods may have disproportionate consequences for carbon cycling in river networks.

Across the six European DRNs, the magnitudes of CO_2 and CH_4 fluxes within both flowing waters and dry riverbeds were similar in PR and NPR reaches (Lopez-Rojo et al. 2024). RF models identified drying severity (i.e., mean duration of dry periods) as the main driver in NPRs, suggesting a legacy effect of drying on gas emissions, even after flow resumption. Drying severity increased CO_2 emissions during subsequent flowing phases, whereas CH_4 fluxes were higher after short dry periods (Lopez-Rojo et al. 2024). In dry riverbeds, CO_2 emissions were primarily controlled by seasonal climatic conditions, increasing with precipitation, evapotranspiration and sediment temperature. The upscaling of the CO_2 fluxes to the entire DRNs revealed that dry riverbeds contributed substantially to total emissions, exceeding 50% in half of the networks and ranging from 14% to 77%. Even in the most perennial system, including dry riverbeds increased annual emissions by 14%. These results indicate that current global estimates of carbon emissions from streams and rivers are likely underestimated, as NPR reaches and specifically dry phases have largely been neglected.

The upscaling of CO_2 emissions to the European scale revealed that cumulative CO_2 emissions were higher in NPRs compared to the PRs. Temporal patterns showed that in most of the regions in Europe, CO_2 emissions were higher during the dry hydrological phase (July-August) than in pre-dry (March-April) or post-dry (November-December) phases. This pattern did not apply for the most northern regions of Europe (Iceland and Norway), where emissions were highest during the post-dry phase (November-December). During the dry phase (July-August), almost half (47%) of total CO_2 emissions from stream orders 1-4 for the whole European river network used in our modelling was from dry riverbeds. Even in Northern Europe, where the contribution from the proportion of dry-riverbed fluxes was lower, dry riverbeds were responsible for 40% of the total emissions during the dry phase. This confirmed previous findings (e.g. Datry et al. 2018, Silverthorn et al. 2023) that omitting non-perennial rivers from estimates of global- or continental-scale CO_2 emissions results in significant underestimation.

3.4. Current and future provision of ecosystem services in the DRNs

The modeling of ES in each DRN illustrated the relevance of drying both spatially and temporally, and also the respective land cover characteristics across different climatic regions. Overall, DRNs with more forested catchments exhibited significantly higher hydrological stability, reducing peak flows while maintaining greater baseflows. The role of hillslope forests, particularly mature stands, is critical because they function as ‘hydrological sponges’ by enhancing soil infiltration and reducing erosive runoff (Pérez-Silos et al. 2025). Conversely, their absence or degradation directly impaired the provision of several ES in the various DRNs, including flood regulation and drought mitigation. These services were further enhanced by active and well-connected floodplain-river channel systems (Pérez-Silos et al. 2025).

In this context, water provisioning was markedly lower in NPRs compared to PRs. In the Mediterranean DRN (Guadiaro, Spain), water availability declined sharply from wet to dry seasons, a trend expected to intensify under climate change. Projections showed that increased drying could reduce annual discharge across DRNs by more than 50%, particularly during summer. This highlights the importance of maintaining and restoring well-preserved forested headwaters, which support baseflows and reduce risk in the most vulnerable areas (Pérez-Silos et al. 2025).

Areas with steep slopes (such as the Albarine and Genal DRNs) showed the highest risk of erosion, and therefore the greatest need for ES that regulate erosion and sediment transport. However, these areas also exhibited high potential for ES provision through forest systems that enhance soil stability via root systems (Pérez-Silos et al. 2025). Riparian forests also play a critical role, as they could prevent up to 60% of sediment from reaching the river channel (Pérez-Silos et al. 2025). Furthermore, riparian vegetation along river reaches was a key driver of additional ES, such as thermal regulation. Pérez-Silos et al. (2025) hypothesised that this function becomes increasingly important as rivers undergo drying, helping to maintain lower water temperatures.

Drying fundamentally affects several compartments of the carbon cycle and derived services (Pérez-Silos at al. 2025). Although drying can temporarily increase terrestrial vegetation colonizing the riverbed and therefore carbon sequestration (Barthélemy et al. 2022), rewetting events can trigger massive carbon pulses and methane emissions (Sepp et al. 2024a). Modelling also showed that large quantities of CO_2 may be emitted by dry streambeds through sediment respiration (Sepp et al. 2024a). The relevance of this ES of carbon emission regulation differed among DRNs, influenced by their specific sediment moisture and temperature (Sepp et al. 2024a).

Drying led to the terrestrialization of riverbeds and the loss of human uses of freshwaters such as swimming or fishing, challenging some of these recreational ES. Willingness-to-pay to limit losses of recreational or provisioning ES differed among DRNs, and reflected both distinct local cultures and environmental conditions. Recreation (swimming in river pools) was valued more highly in Spain than other ES, whereas public preferences regarding a potential climate change adaptation programme in Southern Finland (Lehtoranta et al. 2026) showed that residents mostly valued flood mitigation and secondarily drought mitigation in the nearby streams. Fishing was the most preferred ES for the Hungarian DRN, while drying itself was not perceived to be important. Overall, drying was not among the highest concerns to stakeholders in the EU, except in DRNs that strongly suffer from periodic drying that affects both social activities and the ecological status of the river networks.

The provision of several ES was modelled at the EU scale and overall showed large differences between European regions and seasons (Sepp et al. 2024b). Water provision delivery was, as expected, higher in Northern Europe and lower in Southern Europe, differences being more acute during the dry summer months but still relevant in the pre-dry season (March-April). Southern and Western Europe had higher water provision in the post-dry season (November-December), reflecting climatic differences from other European regions. Flood regulation by forest cover was higher in mountainous areas (Alps, Pyrenees), which have greater capacity to regulate runoff and reduce downstream flood risk. Drought regulation was higher in areas with greatest local recharge (**Figure 7**), coinciding with regions of high annual precipitation (Ireland, Atlantic coast of Norway, southern Iceland). Regions with low local recharge also had low annual precipitation (e.g. the eastern part of Iberian peninsula) or higher proportions of agricultural areas (e.g. Denmark). The regions with higher percentages of forest cover (Finland, Sweden) were those having areas with the highest surface water storage capacity. This confirmed the role of forested areas in mitigating drying and flooding events at the EU scale (Pérez-Silos et al. 2025).

Based on the high-resolution hydrological data and modeling framework of Döll et al. (2024) and Abbasi et al. (2025), we analyzed the water purification and dilution services by considering the reception of wastewater treatment plant effluents at the reach scale (Sepp et al. 2025). Flow intermittence was strongly related to the dilution capacity of the network, and this was accounted for by the dilution factor, which on average was 4.6 times lower in NPRs compared to PRs (Sepp et al. 2025). This difference increased to 10.8 times in the driest summer month. The dilution factor was lowest in Mediterranean and semi-arid areas where NPRs prevail, indicating that NPRs are unable to efficiently dilute the concentrations of solutes and pollutants contributed by sewage effluents (Sepp et al. 2025). This effect would be enhanced under RCP8.5, particularly in Mediterranean and Central Europe. In this scenario, the decrease in dilution factor was more pronounced under extreme climate conditions (i.e., extreme dry months, or drier years), which affected both PRs and NPRs, although the latter were more vulnerable. However, under the low-emissions scenario (RCP2.6), the dilution factor remained stable or even increased slightly in more than half of the rivers.

3.5 Towards adaptive management of DRNs

Spatially-explicit projections of biodiversity, ecosystem functions and ES were used to run systematic conservation planning and optimize the allocation of conservation and restoration measures across DRNs, taking into account current and future conditions (Lanzas et al. 2026). NPRs were often selected as priority reaches for conservation and restoration purposes, including for implementing NBS. On average, 26% of the NPRs across the six European DRNs were selected for conservation and 55% for restoration (Lanzas et al. 2026). In the Genal River, the most intermittent DRN, 52% of the reaches selected for conservation purpose were non-perennial, highlighting the value of NPRs for ensuring the conservation status of biodiversity, ecological functions and ES. This is in spite of the negative perceptions that NPRs generally suffer from society. To visualise these modeling outputse, we developed a Shiny-based decision-tool, DRYvER-OptimApp, for spatial prioritization across the six European DRNs to allow exploration of customizable scenarios, with river reaches classified according to projected changes in ecological metrics (Lanzas et al. 2026). Reaches showing positive trends are prioritized for conservation, whereas those with negative trends are identified as restoration targets. The app enables stakeholders and researchers to run tailored optimizations and visualize outcomes under different assumptions.

The DRYRivERS smartphone application was developed with active involvement from water management stakeholders, including the *Syndicat de la Rivière d'Ain Aval et ses Affluents* (SR3A), which participated as a beta tester. It also contributed to tailoring the app and establishing a user network of local authorities to collect systematic observations of hydrological states. This co-design process ensured alignment with management needs and enhanced the applicability of citizen-generated data. Citizen science data collected through the DRYRivERS platform provided georeferenced observations, complementing conventional monitoring (e.g. gauging stations and field campaigns of WP2 and WP3). These observations were integrated with other data streams to support model evaluation and inform adaptive management at the network scale. In addition, the platform facilitates large-scale data collection and contributes to raising awareness of the ecological importance and vulnerability of intermittent river systems (Truchy et al. 2023). During the project, more than 3,500 registered users submitted observations from over 6,700 river locations, generating a large and spatially explicit dataset of hydrological states and drying events. Analyses of these citizen-generated observations demonstrated their capacity to capture real-time drying dynamics across diverse climatic regions and expand spatial coverage beyond that of traditional monitoring systems (e.g. gauging stations). At the continental scale, these data provided empirical support for model evaluation and highlighted regional patterns of intermittence that aligned with projected model outputs, reinforcing the value of combining citizen science with WP-derived projections. The scalable nature of the dataset also demonstrated the potential for linking participatory observation networks to broad-scale hydrological and ecological assessments.

This iterative interaction between scientists and stakeholders through the SHC ensured that research activities responded to management needs, enhancing both the relevance and applicability of project outputs. The SHC's participation in project discussions provided critical feedback that helped refine methodologies, prioritise topics of operational importance and orient some WPs towards actionable results. This experience highlights the essential role of structured collaboration between researchers and water managers in research projects. It demonstrates that addressing complex challenges, such as the management and protection of DRNs under increasing climate pressure, requires not only scientific excellence but also a strong integration of practitioner knowledge. Strengthening such collaboration frameworks is therefore crucial to ensure that research generates feasible, scalable and policy-relevant solutions capable of supporting competent authorities and water managers in tackling emerging hydrological and ecological challenges.

Collectively, the interactions among modelling outputs, participatory co-creation activities and citizen science demonstrated multi-directional linkages among work packages. However, differences in data types and methods across components of the project´s conceptual cascade highlighted ongoing challenges in fully harmonizing integrated knowledge for adaptive management (see section 7).

4. Discussion

A major achievement of the DRYvER project was to demonstrate the global relevance and ecological significance of drying river networks (DRNs), contributing to a paradigm shift in river science (Datry et al. 2023). By integrating research across European and South American regions, DRYvER helped establish that intermittence is not restricted to arid systems or isolated regions, but is instead a widespread and ecologically important feature of river networks worldwide (Messager et al. 2021, Datry et al. 2023, Botter et al. 2026). This shift in perspective has strengthened recognition of DRNs as critical socio-ecological systems that must be incorporated into future freshwater research, monitoring, conservation and management frameworks.

DRYvER achieved a high level of scientific productivity and visibility. To date, the project has generated 63 peer-reviewed publications (**SM1a**) and approximately 200 conference contributions, including oral and poster presentations across international scientific events (**SM1b**). These outputs reflect both the scientific quality of the project and the strong engagement of the consortium with the international research community. Importantly, publications continue to emerge from both individual DRNs and comparative analyses across subsets of study sites, illustrating the long-term scientific value of the project datasets and collaborations. Although not all datasets could be analyzed in full detail or within the project timeframe, the data generated constitute a valuable resource for future projects and analyses, and will constitute a unique baseline against which predictions from DRYvER can be tested in the future. This is reflected in the continued production of publications emerging either from individual DRNs that participated in DRYVER or from subsets of DRNs analyzed across the project. Moreover, DRYvER was very active with public outreach and communication with society (**SM1c**).

DRYvER was characterised by a high degree of interdisciplinarity, particularly through the strong integration of work packages focused on hydrology, biodiversity, ecosystem functioning and socio-ecological dimensions. Conceptual developments, methodological advances and data generated in upstream WPs supported downstream applications and synthesis activities, including conceptual modelling of ES (Pérez-Silos et al. 2025) and spatial prioritisation for conservation and restoration planning (Lanzas et al. 2026). Such integration enabled DRYvER researchers to move beyond individual disciplines and promote a more holistic understanding of the ecological and societal implications of drying.

DRYvER established strong and durable relationships with stakeholders, including river basin managers, scientific advisory bodies, regional institutions and European policy actors such as the Joint Research Centre (JRC) developing transdisciplinary actions. These interactions strengthened the relevance and applicability of project outcomes while facilitating dialogue among researchers, practitioners and policy communities. A particularly important achievement was the translation of scientific knowledge into applied and policy-relevant outputs. The project produced three policy briefs synthesising key findings into actionable recommendations for the recognition and management of NPRs within water policy and river basin management frameworks (**SM1d**). These briefs were complemented by seven thematic factsheets (**SM1d)** and six case study summaries (**SM1d**), provided in multiple languages to maximise accessibility and uptake among practitioners and regional stakeholders. Three online applications were developed to foster the uptake by stakeholders of DRYvER's outputs (**SM1e**). Together, these outputs contributed to bridging the gaps among research, management and policy implementation. Certainly, DRYvER fostered the scientific reputation of multiple scientists at various career stages. Their involvement in policy- and management- related planning activities at national and international levels (e.g. JRC, IPBES) and in panels entrusted with identifying river reaches to be restored under the EU`s nature restoration regulation ensures first-hand transfers of river-related knowledge into actionable recommendations.

Another major success was the establishment of an unprecedented open-access dataset combining hydrological modelling, biodiversity data and ecosystem functioning metrics across nine DRNs spanning contrasting ecoregions in Europe and South America (**SM1f**). Importantly, the dataset also incorporates a strong temporal dimension, encompassing multiple years of hydrological data and contrasting hydrological seasons (for data on biodiversity and ecosystem functions), which is essential for capturing the temporal dynamics of intermittence and ecosystem responses across DRNs. These datasets enabled novel cross-continental comparisons and substantially broadened understanding of the ecological consequences of drying under climate change (eg. Escobar-Camacho et al. 2025). Although the scale and complexity of the database meant that not all components could be fully analysed within the project's lifetime, the completion and harmonisation of these datasets by the end of the project created a lasting scientific legacy (**SM1f**). The resulting hydrological data infrastructure constitutes a unique resource for future analyses, synthesis studies and long-term monitoring efforts in ecohydrological contexts involving aspects of flow intermittence.

DRYvER had substantial impacts in terms of communication, outreach and public engagement, and capacity building. Coordinated dissemination activities generated broad visibility both within academia and among the general public, including more than 120 media items, 21 videos, six project newsletters and a travelling exhibition dedicated to NPRs (**SM1a-i**). Beyond dissemination, the project contributed significantly to training by research through the involvement of 19 PhD students, 14 postdoctoral researchers, 4 technicians and 14 local stakeholders across Europe and South America. The Dryrivers smartphone app, available to the general public to monitor drying patterns of rivers and build a participatory database, is also a legacy of the project that will contribute to public awareness and knowledge about drying river networks and support future research projects.

DRYvER made a major contribution to capacity building, training and methodological harmonisation across Europe and South America. The high share of researchers affiliated with tertiary institutions ensured fast integration of newly generated knowledge in up-to-date teaching curricula. The project also fostered the co-development and sharing of monitoring protocols, analytical approaches and ecohydrological tools across contrasting socio-environmental contexts (**SM1i**). Protocols for biodiversity monitoring based on environmental DNA metabarcoding and for measurements of ecosystem functions were shared across the consortium to obtain standardised inventories across river networks and study regions. In data-scarce regions, particularly in parts of Bolivia, Brazil and Ecuador, DRYvER contributed to the development of methodological approaches and tools that improved long-term data generation capacity for DRN research. This not only strengthened scientific expertise and local infrastructure, but also fostered new international collaborations and professional networks that are likely to persist well beyond the duration of the project.

Despite these major scientific achievements, we acknowledge a number of important limitations and challenges that we faced and which could inform further interdisciplinary efforts on DRNs. Many of these challenges were intrinsic to the ambition, interdisciplinarity and international scope of DRYvER. Others reflected broader conceptual and operational difficulties associated with emerging socio-ecological research fields. The major challenge relates to the coordination and integration of data and modelling outputs across WPs, to ensure flow along our cascading model. Indeed, downstream activities depended heavily on the timely delivery of harmonised datasets from upstream work packages, particularly WP1-WP4. Delays associated with data production and harmonisation - partly exacerbated by the COVID-19 pandemic - created delays and difficulties for the synthesis activities to be conducted in WP4 and WP5. Integrating hydrological, ecological and socio-economic information across scales and disciplines proved more complex than initially anticipated. In particular, discrepancies emerged between the feasibility of generating reliable high-resolution hydrological estimates at the continental scale in WP1 and the spatiotemporal resolution required by biodiversity analyses in WP2. As a consequence, robust large-scale upscaling of biodiversity responses to drying remained limited. Limited spatiotemporal resolution and limited quantitative explicitness of hydrological data (e.g. presented as metrics rather than hydrographs) also constrained modelling of ecosystem functions and forced respective upscaling efforts to make use of machine-learning techniques such as Random Forests instead of physically conclusive mechanistic models. These factors may also affect the robustness of the predictions.

The project revealed the persistent difficulty of moving from interdisciplinarity toward fully integrated transdisciplinary environmental research, that ideally also employs robust linkages among researchers, practitioners and stakeholders. DRYVER mastered the combination of expertise from multiple scientific disciplines, including hydrology, ecology, sociology and economics - likely in part by simply aligning the consortium through a common project context and narrative. However, deeper integration among the various scientific knowledge systems and stakeholder perspectives remained comparatively underdeveloped. This was most likely due to a scale gap between conceptual ideas of the project and their often only locally perceived relevance. In several DRNs, local managers and practitioners showed limited involvement because river drying was not yet perceived as a major management issue. The prevalence and significance of drying across river networks are still overlooked in some areas (Acuña et al. 2014, Leigh et al. 2019, Cottet et al. 2023). For example, interactions with participants involved in co-construction workshops often remained limited after the initial meetings, restricting longer-term knowledge co-production processes and broader engagement beyond the Scientific and Stakeholder Committees. These experiences highlighted the importance of sustained iterative dialogue, explicit recognition of differing epistemologies, more conscious selection of high-level knowledge intended to be relevant for local action, and overall stronger and more attractive mechanisms for maintaining stakeholder participation throughout project lifecycles.

Temporal limitations in ecological sampling also constrained interpretation of some results. Most field campaigns were conducted over a relatively short timeframe, usually only a single hydrological year. In spite of the massive sampling effort in space, this timeframe limited the ability to disentangle seasonal variability from drying-induced ecological responses and reduced the capacity to identify lagged effects, life-cycle dependencies and longer-term ecosystem trajectories. Such limitations are particularly important in DRNs, where ecological responses may occur over multiple years and depend strongly on hydrological history (Jones & Driscoll 2022, Lopez-Rojo et al. 2025). However, the availability of multiple drying metrics computed for each sampling site across different temporal windows (including the sampling year as well as the previous 10 or 30 years) provided an opportunity to partially account for hydrological legacy effects and to explore the influence of long-term drying history on ecological responses.

Another challenge concerned the implementation and interpretation of NBS. While DRYvER initially aimed to integrate NBS into hydrological modelling and management frameworks, we faced two challenges. First, we found there were widespread conceptual misunderstandings surrounding NBS among researchers, policymakers and the general public (**SM1i**). NBS were frequently interpreted as isolated conservation actions rather than as integrated socio-ecological planning frameworks. Researchers often applied divergent definitions, contributing to conceptual fragmentation, while policy frameworks sometimes promoted conflicting or impractical implementation strategies. These findings underscored the need for greater conceptual clarity and standardisation if NBS approaches are meant to effectively support DRN management and restoration (**SM1i**). Second, WP1 and WP5 were ultimately unable to operationalise NBS scenarios within the modelling approaches used. This was due to the conceptual misunderstandings of NBS, the lack of evidence in the literature supporting their implementation in DRNs and the technical challenges associated with their modelling through processed-based models. Therefore, we were unable to close the circular causality in DRYvER´s project cascade (**Figure 1a**).

Finally, DRYvER faced important practical trade-offs between scientific exchange, capacity building between Europe and South America, and environmental sustainability. The COVID19 pandemic forced a reduction of exchange activities, which was, however, also realized to be a chance to reduce the project’s carbon footprint. Project management thus partly deliberately constrained opportunities for in-person interaction among European and South American partners, including conference participation, research visits and PhD exchanges. Although remote collaboration proved effective in many contexts, reduced physical mobility likely limited some aspects of networking, training and intercultural scientific exchange. These are particularly valuable in international collaborative projects during the project as well as to facilitate long-term collaboration.

Collectively, these limitations provide valuable lessons for the design of future interdisciplinary and transcontinental research initiatives focused on DRNs and global change, and more largely, for all projects with a global scope.

5. Conclusions and agenda for future DRN research

With DRYvER, we substantially advanced understanding of drying river networks (DRNs) by demonstrating their widespread occurrence, ecological importance and societal relevance across contrasting climatic and biogeographic regions. By integrating hydrology, biodiversity, ecosystem functioning and socio-ecological perspectives, the project contributed to a major paradigm shift in freshwater science: DRNs can no longer be considered marginal or exceptional systems, but instead represent fundamental components of global river networks (Messager et al. 2021, Datry et al. 2023, Abbhasi et al. 2025). Moreover, we highlighted the considerable scientific, methodological and governance challenges that remain for understanding and managing river networks in a context of climate change.

A key priority for the agenda for future research is the development of long-term and multi-year monitoring programmes capable of capturing the temporal complexity of DRNs. The predominantly single-year sampling design adopted in many DRYvER study sites limited the capacity to distinguish seasonal variability from drying-driven ecological responses and to identify lagged effects, recovery dynamics and longer-term ecosystem trajectories. Extending ecological and biogeochemical monitoring over multiple hydrological cycles will therefore be essential to achieve greater temporal generality and improve predictive understanding of drying impacts on biodiversity and ecosystem functioning. This also requires stronger integration of DRNs into institutional and regulatory monitoring frameworks, where they remain underrepresented despite their prevalence and ecological significance.

Another key agenda item is to expand the research beyond minimally disturbed systems to better quantify the ecological consequences of anthropogenic drying caused by water abstraction, river regulation and land-use change and their climate change interactions. Although DRYvER included systems already affected by human pressures, the cascading effects of anthropogenic drying on biodiversity, ecosystem functioning and ES remain insufficiently quantified across environmental gradients and socio-economic contexts. Expanding research to larger rivers (stream order >4) will also be critical for improving regional and continental-scale predictions and enabling more robust upscaling approaches across Europe and beyond. Future drying is likely to be severe enough to expose quantitatively important dry riverbed surfaces in larger rivers.

Building on recent advances in hydrological modelling, an important next step in the research agenda will be the development of predictive models linking drying dynamics to biodiversity, ecosystem functioning and ES delivery. Although DRYvER substantially improved hydrological characterisation of DRNs, translating these advances into predictive ecological frameworks remains a major frontier. This is especially true when predictions are based on causally reliable and robust mechanistic modelling strategies instead of machine-learning algorithms. Integrating hydrological predictions with biological and functional indicators could support scenario analyses, vulnerability assessments and management planning, including systematic conservation, under future climate and land-use change.

The DRyVER project may be considered as having spearheaded research on DRNs; thus, the unveiled urgent need for translation of scientific advances into policy and management may be a consequence of inevitable delay. However, future projects should be conceptualized with stronger integration into governance and management frameworks. Future initiatives should move beyond conceptual recommendations and evaluate the real-world implementation and effectiveness of management measures and restoration strategies in DRNs. In parallel, systematic analyses of the legal recognition of non-perennial rivers, explicitly including rivers that may undergo a natural flow regime change due to climate change in the near future, are urgently needed. In many regions, limited institutional attention to DRNs partly reflects insufficient legal obligations for their monitoring and management. Addressing this gap will require closer collaboration not only between hydrologists, ecologists and social scientists, but also with jurists, policy specialists and river managers to develop governance frameworks that recognise DRNs as functionally connected river systems. Thus, the agenda for future research on DRNs must be extended to explicitly encompass water managers, policy makers and the general public so that scientific advances can be more swiftly translated into effective actions in DRNs worldwide.

The project also highlighted the need for greater conceptual clarity and harmonisation regarding NBS. The agenda for future work should support broader adoption of the IUCN Global Standard for Nature-based Solutions as a common international framework capable of reducing conceptual fragmentation and improving consistency across research, policy and implementation contexts. Aligning river-network river management policies and restoration strategies with internationally recognised NBS standards will improve both practical applicability and long-term effectiveness.

Finally, future research on DRNs should increasingly adopt a truly global perspective. DRYvER established strong foundations for international collaboration between Europe and South America, but broader integration with emerging global initiatives such as Aquatic Intermittency Effects on Microbiomes in Streams (AIMS, https://pure.psu.edu/en/projects/rii-track-2-fec-aquatic-intermittency-effects-on-microbiomes-in-s-2/) or StreamCLIMES (https://www.allenlab.org/research) could further strengthen comparative analyses across climatic, hydrological and socio-economic contexts. Expanding global collaboration, data sharing and methodological harmonisation will be essential to develop a predictive and management-oriented science capable of addressing the accelerating expansion of drying rivers worldwide.

Overall, DRYvER has provided a strong scientific and collaborative foundation for the next generation of research on drying river networks. Its legacy lies not only in the datasets, publications and conceptual advances it has produced, but also in establishing DRNs as a central frontier in freshwater ecology, hydrology and environmental management under climate change.

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Figures.

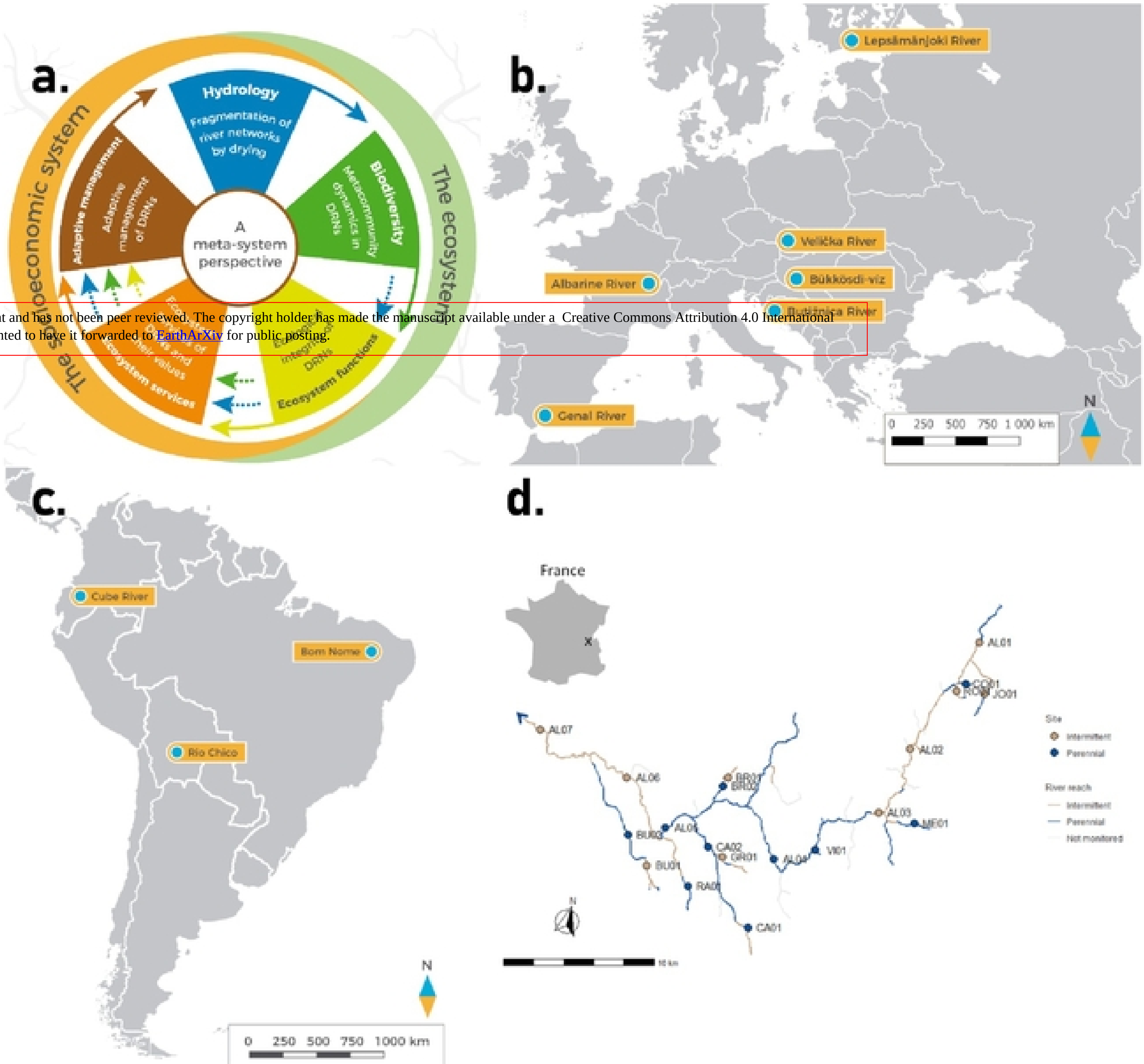

Figure 1. a. the cascading model of the project, from physical to social and economic sciences and river management through five disciplinary Work Packages (WPs, detailed in section 3). The arrows illustrate the flow of data and models among WPs, the color representing the sourced WP; b. the implementation of a dynamic metasystem approach with the example of the sampling design of one of the studied DRNs. There are 20 sites being samples multiple time, to document both the local and regional effect of drying. The codes indicates the sampling sites and codes; c. map of the six European DRNs; d. map of the three South American DRNs.

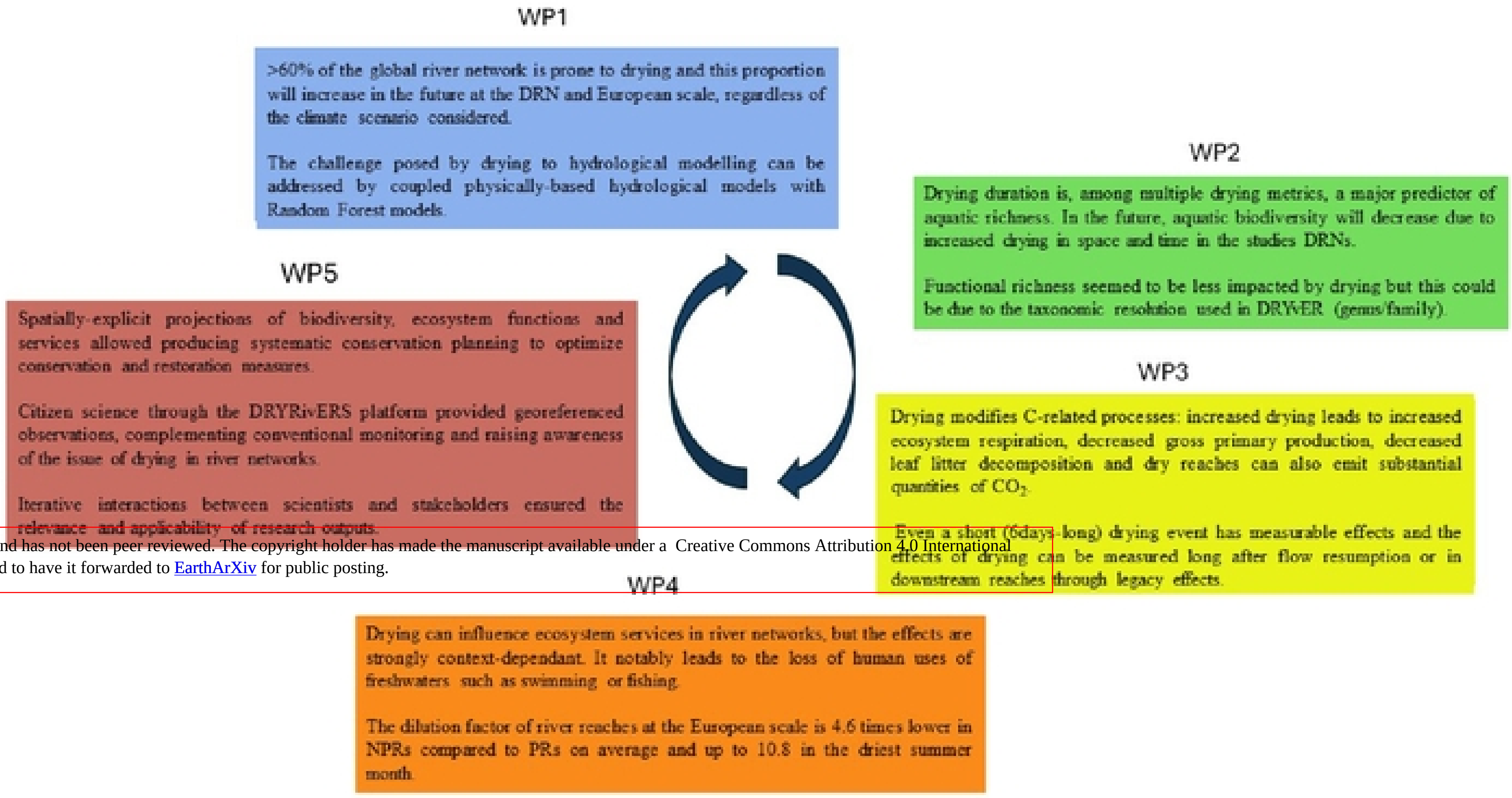

Figure 2. The main results and take home messages of DRYvER, organised by work-package, following the colours of Figure 1.

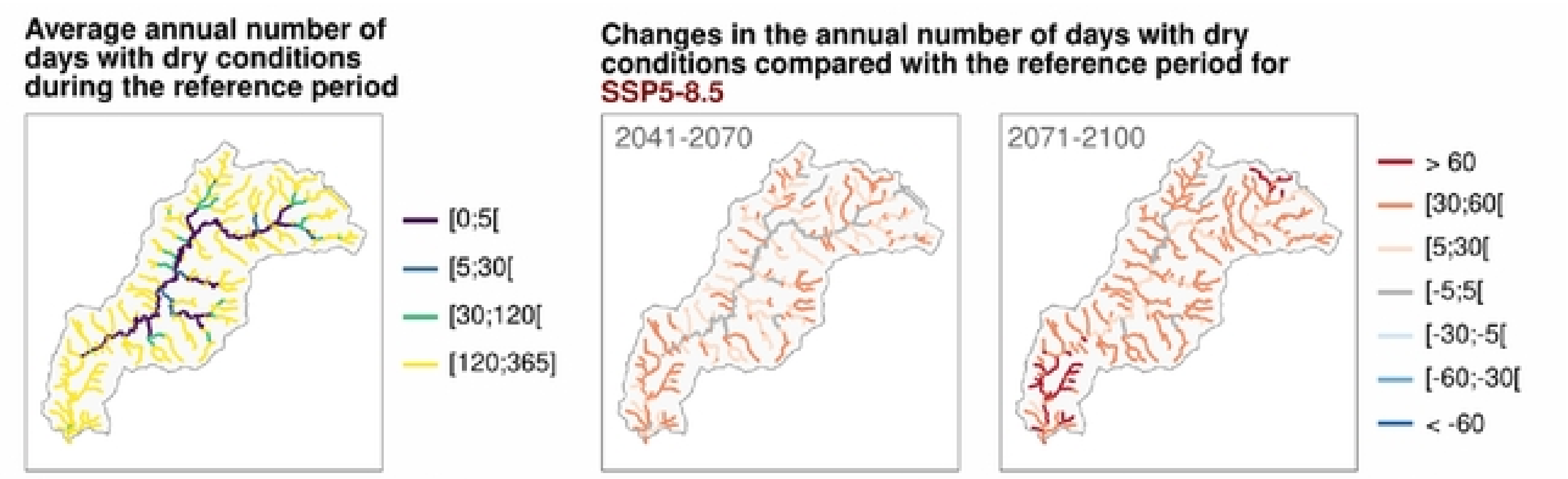

Figure 3. Evolution of the spatial pattern of flow intermittence under SSP5-8.5 climate change scenarios (median of 5 climate projections) at horizons 2050 (2041-2071) and 2080 (2071-2100) compared to the reference period (1985-2014) for the Genal river network in Spain.

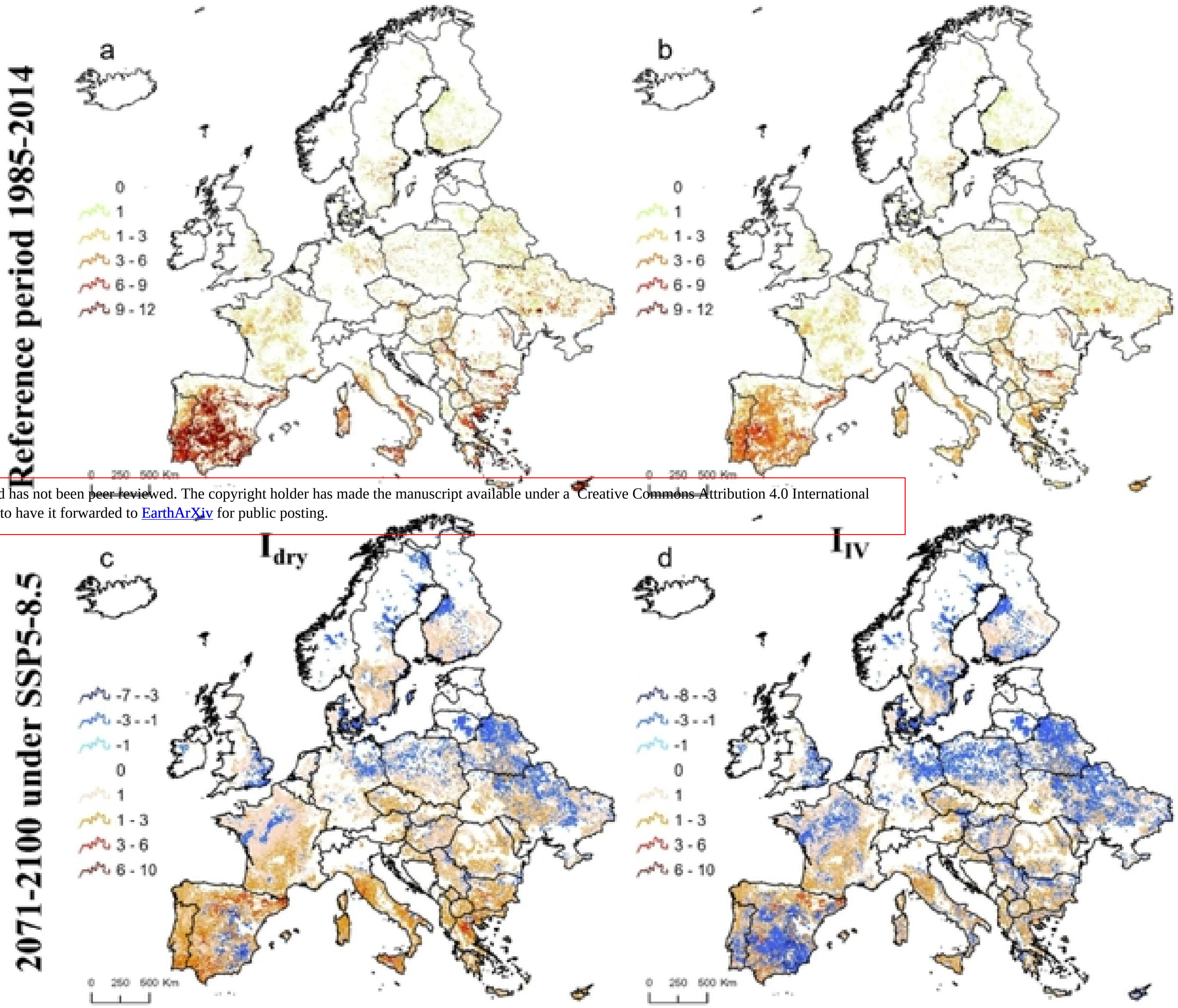

Figure 4. The number of non-perennial months in a dry year during the reference period (a) and the inter-annual variability of the annual number of non-perennial months during the reference period, represented by the difference between P90 and P10 of the annual number of non-perennial months (b). Changes in the number of non-perennial months in a dry year across the 30-year period (I_{dry}) (c) and change in the inter-annual variability of the annual number of non-perennial months (I_{IV}) (d) are shown for 2071–2100 under SSP5-8.5 compared to the reference period. The units are months. Class intervals are left-exclusive and right-inclusive (after Figure 8, Abbasi et al. 2025).

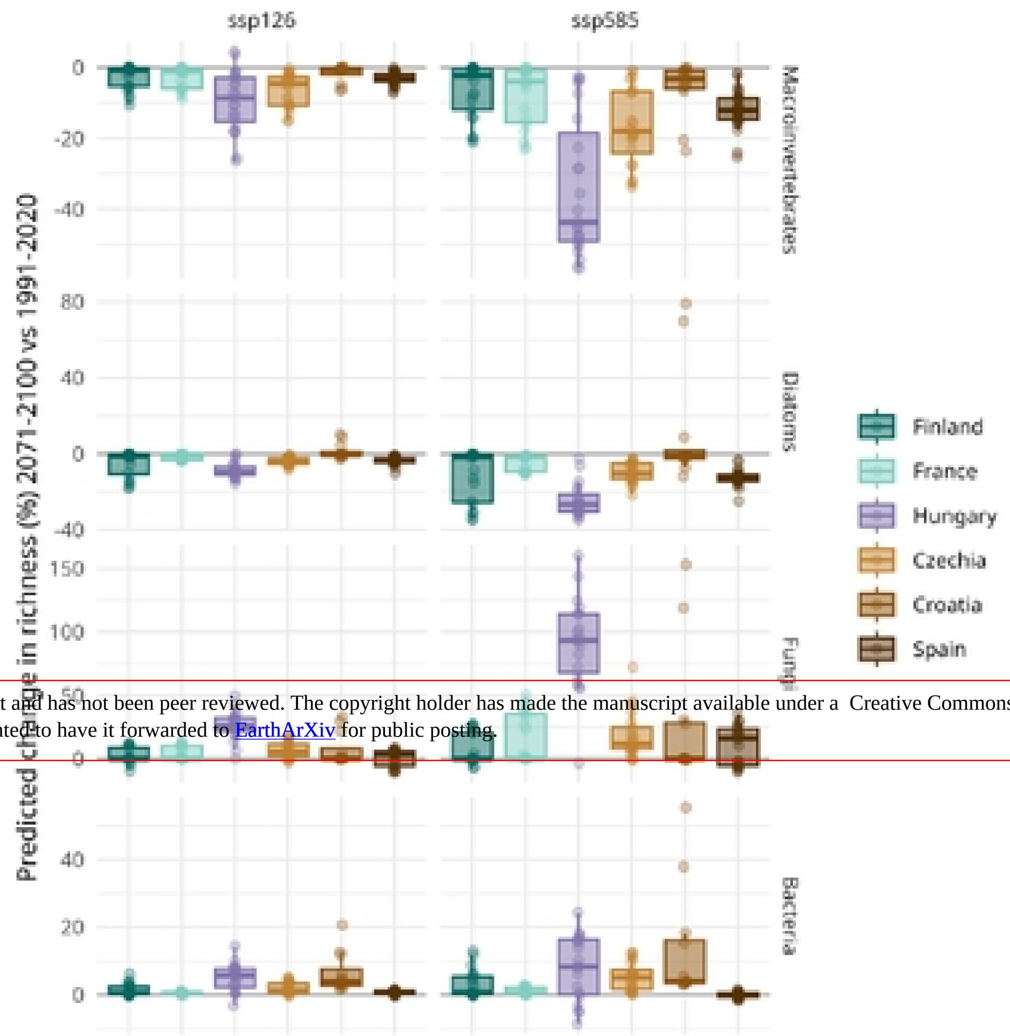

Figure 5. Predicted percentage change in mean annual richness in 2071-2100 compared to 1991-2020 across organism groups in six European DRNs. Boxplots with different colors show the distribution of sampled reach-level percentage difference in mean annual taxonomic richness in 2071-2100 compared to 1991-2020 for a given DRN (color), organism group (rows) and scenario (columns, SSP explained in the exte). Positive (negative) values reflect a relative increase (decrease) in mean annual richness in the future. Note that for microbial clades, we combined change in richness across biofilms and sediment. See Messager et al. (2026) for more details about the methodology.

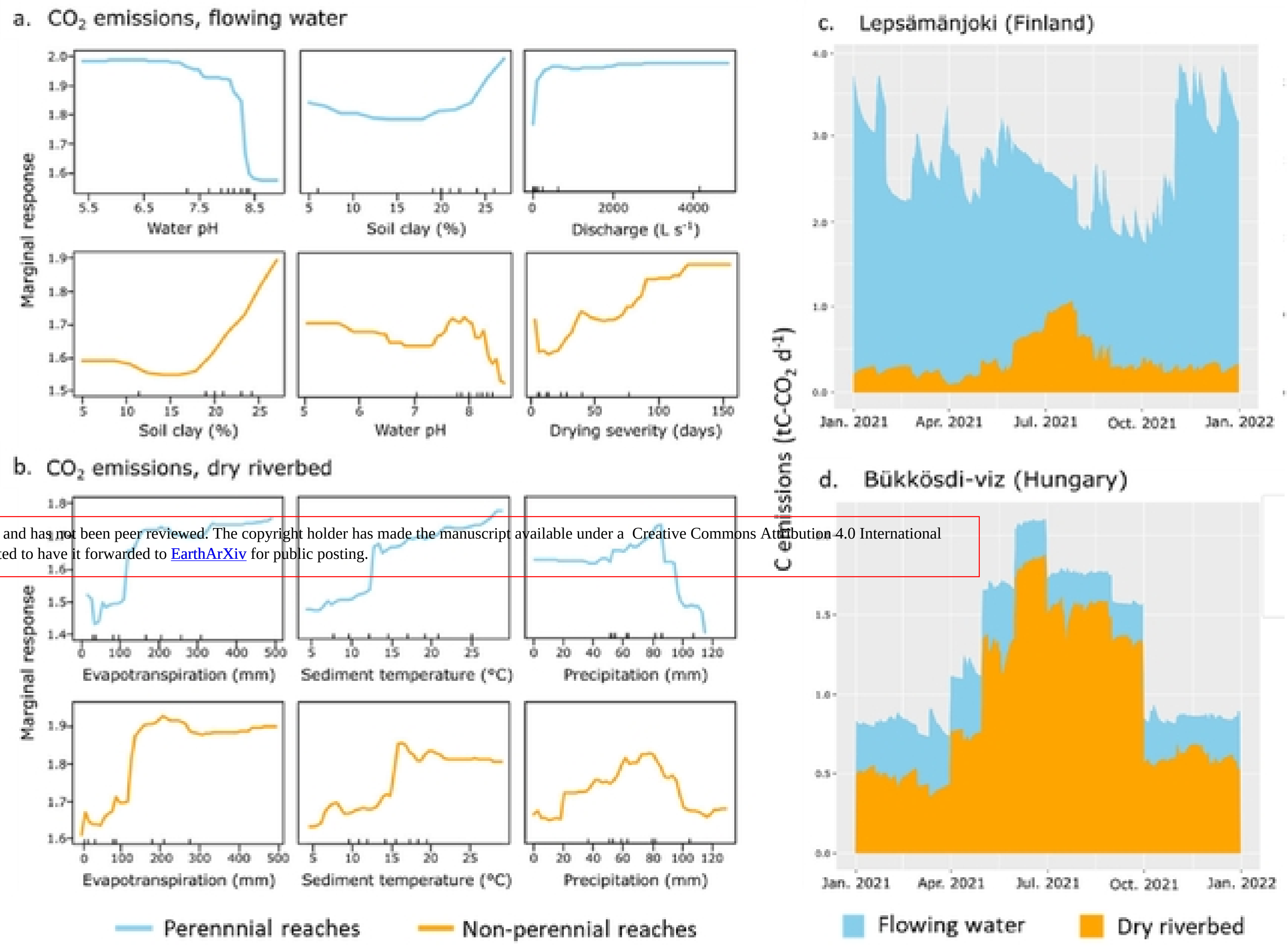

Figure 6. Drivers of CO_2 emissions in flowing waters (a) and dry riverbeds (b) for perennial and non-perennial reaches. Annual upscaling of C-CO_2 emissions for the Finnish (c) and Hungarian (d) DRNs, showing the contribution of emissions from flowing waters and dry riverbeds.

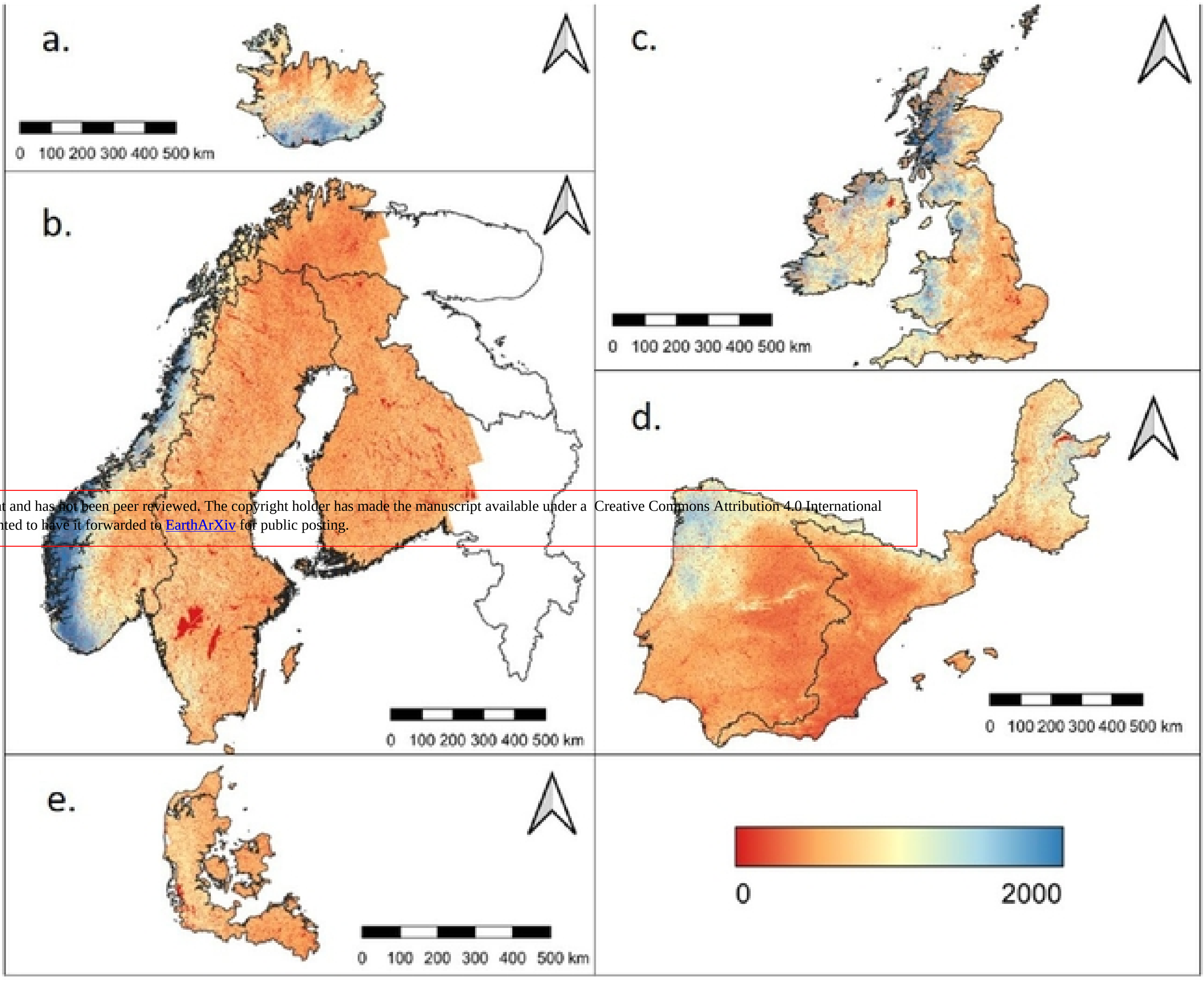

Figure 7. Local Recharge Index (LRI) is an estimation of the amount of water (mm) that infiltrates into the soil over a year and could potentially recharge groundwater. Regions in Europe with the highest LRI values are in Iceland (a), Norway (b), and Ireland (c). Regions with low LRI values are, for example, the eastern part of the Iberian peninsula (d) and Denmark (e).