Ecological Planning Strategies and Nature-based Solutions in the Context of Climate Change Resilience

Davide Geneletti, Chiara Cortinovis, Chiara Parretta, Simone Caridi, Giuseppe Formetta, Lorenzo Giovannini, Lia Laporta, Alfonso Vitti, and Jarumi Kato-Huerta

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1 Introduction

Climate change is a key challenge for urban areas, where its impacts affect a large number of people and assets. Increasingly frequent and extreme climate events—such as intense rainstorms, heatwaves, and droughts—pose risks to people's health and wellbeing, as well as to both green and grey infrastructure. Cities are thus priority areas for implementing strategies and actions aimed at strengthening climate resilience [1].

Among the available options for strengthening urban climate resilience, nature-based solutions (NBS) have gained traction in recent years, also due to strong endorsement from international institutions. By leveraging ecosystems' processes and functions, NBS can provide multiple co-benefits beyond climate adaptation. For instance, sustainable urban drainage systems and low-impact development techniques can manage stormwater runoff in near-natural ways [2], while street trees and

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D. Geneletti (✉) · C. Cortinovis · C. Parretta · S. Caridi · L. Laporta · J. Kato-Huerta
PLANES—Planning for Ecosystem Services and Urban Sustainability Lab, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, IT, Italy
e-mail: davide.geneletti@unitn.it

G. Formetta · L. Giovannini · A. Vitti
Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, IT, Italy

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green spaces can cool urban microclimates and reduce the Urban Heat Island (UHI) effect [3]. In addition to mitigating the impacts of a changing climate, these interventions support urban biodiversity and generate positive socio-economic benefits that contribute to the overall resilience of urban areas [4].

Scaling up the use of NBS in urban areas has strong potential for enhancing climate resilience [5, 6]. However, integrating NBS meaningfully into planning processes remains a challenge, largely due to the fragmented nature of urban governance, where multiple sectoral policies and plans operate at different spatial and temporal scales [7]. Spatial planning can play a key coordinating role by ensuring coherent interventions, optimal resource allocation, and equitable distribution of benefits and costs [8]. To be effective, individual NBS must be embedded within broader ecological planning strategies that consider cumulative impacts, synergies, and trade-offs across scales and sectors [9]. This integrated approach also helps bridge the disconnect between short-term interventions and long-term climate resilience objectives [10].

Modelling can be a valid tool to support integrated planning approaches, provided its assumptions and limitations are clearly acknowledged [11]. Modelling enables a deeper understanding of present and future climate-related challenges, allowing for the comparison of alternative scenarios at multiple scales. This is essential for both defining city-wide ecological planning strategies (i.e., at the urban scale) and designing context-specific, locally attuned NBS (i.e., at the local scale). Therefore, models working at different scales and producing useful inputs to inform different decisions must be integrated. Despite the growing recognition of this need in academic research, the practical, operational use of integrated modelling in planning remains limited [12, 13].

This chapter presents recent experience with multi-scale integrated modelling approaches applied in the city of Trento (Italy) to support different planning instruments linked to climate change resilience. Specifically, these include the drafting of Trento's Urban Greening Plan and the preparation of a Masterplan for river restoration. These initiatives were supported by two Horizon-funded projects, SELINA and BioValue, which aimed to integrate ecosystem service knowledge and biodiversity values into spatial planning. At the urban scale, modelling focused on identifying key climate-related challenges, particularly the UHI effect and the risk of urban flooding, and on exploring how they can be addressed through ecological planning strategies. At the local scale, a discussion on the potential use of NBS to enhance urban biodiversity and ecosystem health has sparked interest in exploring its climate-related benefits as well.

The following sections describe the modelling approaches adopted to assess climate-related priorities and inform ecological planning at both urban (Sect. 2) and local scales (Sect. 3). The discussion (Sect. 4) reflects on how the modelling outputs can be used in real-life planning processes, their added value for different policy instruments, and the broader implications for decision-making. We conclude by highlighting limitations and remaining challenges for both research and practice.

2 Defining Ecological Planning Strategies at the Urban Scale

Trento is a medium-sized Alpine city with a peculiar morphology. The most urbanized part of the city lies in the valley floor of the river Adige, where the majority of its 120,000 inhabitants live. Due to its location and the high share of soil sealing, this area is the most prone to urban flooding events. Furthermore, reduced air circulation and a high density of human activities and urban infrastructure make it the most vulnerable to the effects of summer heatwaves, with temperatures often comparable to those of other cities at much lower latitudes. To support the definition of ecological planning strategies at the urban scale, two spatially explicit models were applied to this part of the city (Fig. 1). The first focuses on the risk of flooding and measures runoff generation during an extreme rainfall event, identifying critical areas for stormwater management. The second examines spatial variations in exposure to extreme heat, thus capturing the intensity of the UHI effect.

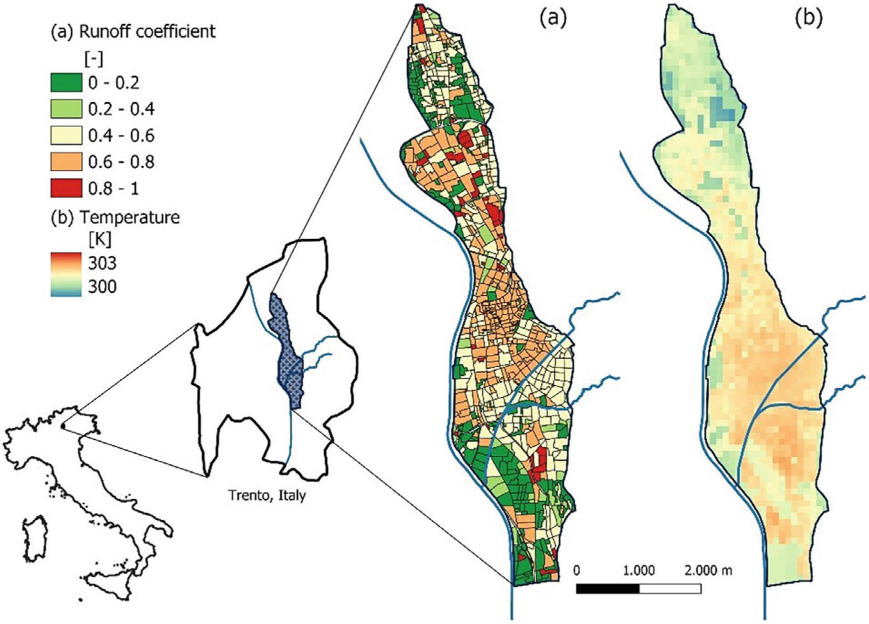

Fig. 1 Location of Trento in Italy and spatial distribution of the Runoff Coefficient (**a**) and average simulated temperature in the period 20–25 August 2023 (**b**) across the valley floor

2.1 Identifying Critical Areas for Stormwater Management

Areas most prone to generate surface runoff were identified for an extreme rainfall event of 15 min with a 100-year return period. The valley floor was divided into sub-catchments, the hydrologic units of analysis, based on the municipal land use map. For each sub-catchment, two complementary metrics were calculated to characterize how rainfall is transformed into runoff. The runoff volume quantifies the absolute amount of water flow generated by each sub-catchment during the selected rainfall event, because of its imperviousness and soil characteristics. This indicator is particularly useful for evaluating the cumulative load on the stormwater system and estimating the potential benefits of volume-reducing measures, such as NBS [14–16]. The Runoff Coefficient (RC) is a dimensionless ratio expressing the fraction of total precipitation that becomes runoff. It is particularly useful for comparing areas with different degrees of imperviousness and identifying zones where interventions to reduce runoff generation, such as green infrastructure or de-sealing, can be prioritized. As such, RC can be applied to identify priority areas for restoration [17] or to estimate the runoff reduction capacity of green infrastructure [18]. At the urban scale, both RC and runoff volume contribute to identifying critical areas for stormwater management and can jointly support the definition of integrated planning strategies [19]. These indicators can be derived using different modelling approaches, from simplified empirical methods (e.g., curve number) to more complex hydrologic models [20].

Figure 1a shows the spatial distribution of RC across the valley floor of Trento. High values (>0.6) are concentrated in the northern industrial-commercial area and in the central urban core, where impervious surfaces dominate. Intermediate values (0.4–0.6) are found in mixed-use zones surrounding the city center. Low values (<0.4) are located in the southern and peripheral northern areas, characterized by agricultural land and green spaces. The observed spatial patterns reflect the degree of imperviousness and provide an evidence-based foundation to support the definition of ecological planning strategies to address the risk of flooding.

2.2 Downscaling Meteorological Models to Assess Exposure to Extreme Heat

A modelling system composed of the Weather Research and Forecasting (WRF) [21] model coupled with a single-layer urban canopy parameterization scheme was used to perform high-resolution forecasts of the thermal field in the urban area of Trento. The WRF forecasts adopt initial and boundary conditions from the Global Forecast System (GFS) model, using three nested domains with a resolution of 9, 3, and 1 km, respectively. WRF forecasts in the inner domain were downscaled to a resolution of 100 m in the urban area of Trento using a single-layer urban canopy model [22], which calculates the energy exchange between the urban environment and the atmosphere, taking into account the physical properties of urban materials and the geometrical characteristics of the city, influencing the surface energy balance and heat trapping inside urban canyons with multiple reflections of longwave radiation. Local characteristics of the urban morphology are accurately taken into account, starting from a detailed land cover map and 1-m resolution Lidar data of building height. The single-layer urban canopy model is offline coupled with WRF, where its meteorological fields at the lowest model level serve as upper boundary conditions.

The modelling chain was applied to simulate meteorological conditions in the period 20–25 August 2023, characterized by a summer heat wave, with minimum temperatures above 20 °C and maximum temperatures above 35 °C in the urban area, reaching almost 40 °C on 23rd August. Figure 1b shows the average simulated temperature field, clearly highlighting the presence of the UHI effect. The temperature field on the valley floor displays a sharp increase at the edge of the city, whereas inside the urban area temperature is closely dependent on the local urban morphology and vegetation fraction. The UHI is stronger during nighttime, with intensities exceeding 2 °C in the core urban area, where the urban morphology is more compact and the vegetation fraction is lower. On the other hand, temperature tends to remain slightly lower in the compact city center during daytime, due to the reduced penetration of solar radiation inside urban canyons and the thermal properties of urban materials, which store heat during the day and release it during nighttime.

3 Designing Nature-based Solutions at the Local Scale

Two analyses were performed at the local scale to support the design of context-specific NBS. The area selected for the local-scale analysis is located on the valley floor, where the Fersina river–subject of the Masterplan for river restoration—flows into the Adige. It includes part of the urban core, as well as vacant lots and public services. The first analysis evaluates the hydraulic performance of the drainage network during an extreme rainfall event; the second analysis simulates the spatial distribution of mean radiant temperature over a hot summer period. Both analyses rely on a detailed map of land cover and vegetation structure characterized using a 30 cm-resolution Pléiades-Neo satellite image from June 2022. In QGIS (v. 3.34.2), non-vegetated and vegetated parcels were identified based on the Brightness Index. A sensitivity analysis was then performed on sample points to determine threshold values for trees and low vegetation [23]. Finally, the results were integrated with data layers on impervious areas, agriculture, and water areas from the municipal land use/land cover map.

3.1 Coupling Hydrologic and Hydraulic Modelling to Select Specific Areas of Intervention

The U.S. Environmental Protection Agency's Stormwater Management Model—SWMM [24] is a widely recognized tool for simulating stormwater runoff in urban areas and is commonly used in stormwater management design and planning (e.g., [25, 26]). It is a dynamic rainfall-runoff model that simulates both the quantity and quality of runoff by representing runoff generation from subcatchments and flow routing through underground drainage systems, which are composed of conduits, nodes, and outfalls [27]. By integrating hydrologic and hydraulic components, the model evaluates surface water flooding by simultaneously assessing runoff production and its downstream impacts on the drainage network.

Here we employed two modeling approaches provided in SWMM: (i) the SCS-CN method [28] for simulating spatially variable infiltration and runoff generation, and (ii) dynamic wave routing for modeling flow movement through the drainage system. The SCS-CN method accounts for variations in soil type and land use/land cover, which influence runoff production. We used high-resolution land cover data to define imperviousness and infiltration parameters for each sub-catchment. The dynamic wave routing method (e.g., [24]) captures complex hydraulic phenomena such as pressurized flow, channel storage, flow reversal, backwater effects, and entrance/exit losses.

The study area was divided into 80 sub-catchments with 76 junctions and 73 pipes. Each sub-catchment drains stormwater to its nearest junction. The drainage network of the study area was initially sized using a design rainfall event with a 15-min duration and a 10-year return period, ensuring that conduits operate at no more than 80% of their full capacity. Subsequently, the system was evaluated under a more extreme pluvial event of the same duration (15 min) but with a 100-year return period. Following [29], the hydraulic impact of this event was assessed in terms of node flooding and conduits' degree of fullness. Two synthetic indicators were derived from SWMM model outputs: (i) number of flooded nodes (defined as nodes with a flood volume greater than zero), representing the system's ability to manage inflows; (ii) conduit degree of filling, calculated as the ratio of the maximum water depth to the full depth of each conduit, indicating the extent of hydraulic loading.

The results reveal critical areas of the network experiencing significant hydraulic stress under extreme conditions. As shown in Fig. 2a, 60% of conduits exceed a filling degree of 0.8, with the most affected segments located in the downstream portion of the system. These conduits are particularly vulnerable to surcharging, primarily due to the accumulation of upstream flows. Additionally, 14% of nodes are identified as flooded, corresponding to junctions where critical conduits converge. These locations are prone to localized overflows, driven by limited drainage capacity and high internal pressure in the conduits.

Overall, the findings pinpoint sections of the drainage network where the system is likely unable to efficiently manage stormwater during extreme rainfall scenarios (conduits and nodes marked in red in Fig. 2a), underscoring the need for targeted

Fig. 2 Spatial distribution of flooded nodes and conduit degree of filling of the drainage network (**a**), and average simulated mean radiant temperature within the study area in summer 2023 (**b**)

mitigation measures to reduce runoff volumes and providing preliminary insights for NBS prioritization.

3.2 *Modelling Thermal Comfort to Inform the Strategic Siting of NBS*

Urban Multi-scale Environmental Predictor (UMEP) is a modular open-source QGIS extension developed to support urban microclimate analysis [30]. Among its modules, SOLWEIG (SOlar and LongWave Environmental Irradiance Geometry) is used to estimate mean radiant temperature (Tmrt) [31, 32], a comprehensive indicator of the radiative environment perceived by the human body, in contrast to air temperature, which is independent of radiative influence [33].

The model simulates a 2.5D urban environment through 1-m-resolution DEM, DSM, and land cover layers. It accounts for all visible surfaces emitting thermal radiation, including both direct and diffuse solar radiation as well as long-wave radiation emitted from buildings, ground surfaces, and vegetation [34], while also incorporating the effects of shading and multiple reflections. SOLWEIG integrates hourly meteorological data (ERA5, Copernicus Climate Change Service). These inputs enable fine-scale microclimate simulations and the production of high-resolution hourly maps of Tmrt (Fig. 2).

During the summer of 2023, average Tmrt values in the study area ranged from 18.6 to 27.8 °C. When considering only daytime hours, the average Tmrt reached up to 38.9 °C, with maximum hourly peaks exceeding 68 °C in the most exposed locations. The critical threshold of 55.5 °C, associated with a 5% increase in heat-related mortality risk for individuals over the age of 80 [33], was exceeded for almost 0.2% of the total daytime in several parts of the study area. These exceedances were primarily associated with high levels of solar exposure, the prevalence of impervious surfaces, and the limited presence of vegetation and shaded areas, all of which reduce the potential for radiative and evaporative cooling. Additionally, urban morphological features such as low sky view factor, the prevalence of heat-retaining materials, and the lack of tree canopy contribute to further exacerbating the radiative heat load on individuals.

In addition to its standalone relevance for assessing heat-related health risks, Tmrt plays a critical role in estimating the Universal Thermal Climate Index (UTCI), as it reflects the actual radiative thermal load on the human body. UTCI is an advanced biometeorological index that estimates the apparent temperature perceived by the human body based on air temperature, relative humidity, wind speed, and Tmrt [35]. Two points of interest (PoIs) were identified within the study area: the first (PoI 1) is located in an exposed urban setting characterized by impervious ground surfaces and surrounded by buildings, while the second (PoI 2) is situated within a residential green space, featuring trees and grass (see Fig. 2b). For both locations, Tmrt and UTCI values were calculated for a standing 80-year-old male subject over the period from 20 to 25 August 2023 (the same time frame used for the temperature modelling in Fig. 1b). The results are presented in Fig. 3. The Tmrt values observed at PoI 1 regularly exceeded the critical threshold of 55.5 °C, with frequent peaks above 60 °C. In contrast, Tmrt at PoI 2 consistently remained below the critical threshold throughout the observation period, confirming the moderating influence of vegetation evapotranspiration and shading on the local radiative environment. Regarding thermal comfort, UTCI values at PoI 1 generally exceeded 26 °C (a level typically associated with moderate heat stress) and reached values above 32 °C (strong heat stress) during the peak hours (12:00 and 14:00). At PoI 2, the overall diurnal pattern was similarly shaped, but the peak values were markedly lower, exceeding the 32 °C threshold only in isolated instances.

4 Discussion and Conclusions

The models applied in Trento, targeting urban flooding and thermal comfort, produced decision-relevant outputs at both urban and local scales.

At the urban scale, the two models applied to the most climate-vulnerable area of the city, i.e., the valley floor, provide valuable insights into the identification of the priority areas that ecological planning strategies should target. The runoff

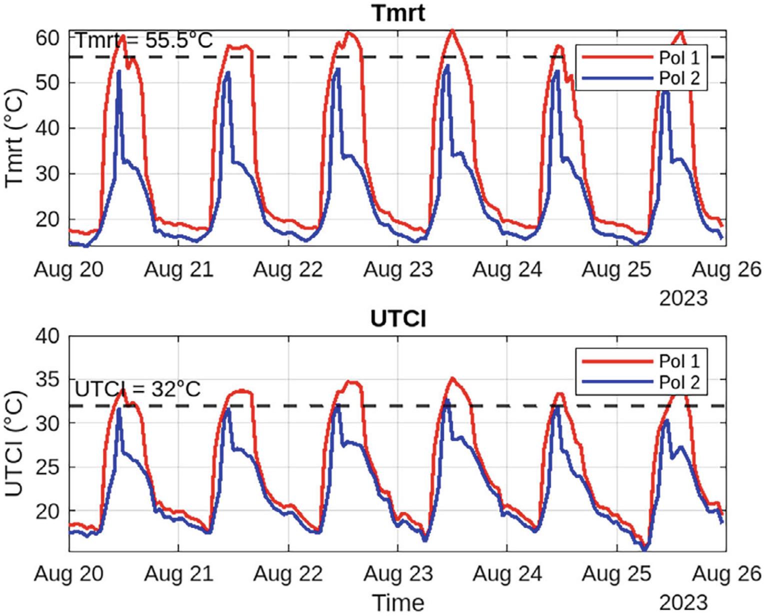

Fig. 3 Temporal evolution of Tmrt and UTCI at two selected points of interest: PoI 1 = impervious surfaces surrounded by buildings, PoI 2 = residential green space with tall trees and grassy areas

coefficient highlights sub-catchments that, due to their high degree of imperviousness, have limited capacity to infiltrate water. These areas produce relatively more runoff, which is ultimately responsible for urban flooding [36]. Similarly, the map of air temperature identifies areas of the city where temperatures are higher than those of the surroundings, due to their morphological and vegetational characteristics. Drawing on this knowledge, ecological planning strategies can guide actions to improve stormwater management, such as removing impervious surfaces or installing green roofs, primarily in industrial and commercial zones in the northern part of the city. Simultaneously, actions to enhance the local microclimate, such as tree planting, should preferably be directed towards the city center and the southern neighborhoods.

While models applied at the urban scale can inform strategic priorities, higher resolution models using more detailed inputs can be applied to guide the design of site-specific NBS. For instance, the two models run at the local scale served to identify locations where the implementation of NBS could be more beneficial for climate resilience. Crucially, higher spatial resolution enhances the capacity of models to capture the fine-grained spatial variability that often exists within broader priority areas. Compared to the use of models at the urban scale, these more localized applications not only relied on higher resolution input data to produce more detailed outputs, but also allowed for the simulation of more complex processes. For example, SWMM combines the analysis of the hydrologic processes described by the runoff coefficient with hydraulic modelling of the drainage network's performance.

This allows assessing the impact of proposed NBS not only in terms of reduced runoff, but also through other indicators more directly linked to NBS benefits, such as the reduction of flood volume (when nodes are flooded) or flood risk (associated with the conduits' degree of filling). Similarly, the thermal indices estimated using the UMEP model, such as mean radiant temperature and the Universal Thermal Climate Index, capture the level of thermal stress experienced by people in outdoor spaces. Unlike air temperature, these user-centered indicators are well-suited for evaluating the benefits of NBS from a human comfort perspective, thus being more informative for designing and assessing the potential impacts of NBS.

In practice, the models applied at both urban and local scales in Trento offered valuable inputs for different types of planning instruments. At the city scale, model results informed the development of the Urban Greening Plan. The plan responds to the objectives set by the EU Biodiversity Strategy for 2030, which calls on cities of at least 20,000 inhabitants to "develop ambitious Urban Greening Plans" (now "Urban Nature Plans") including "measures to create biodiverse and accessible urban forests, parks and gardens; urban farms; green roofs and walls; treelined streets; urban meadows; and urban hedges" [37]. Trento's Urban Greening Plan positions climate change as a central challenge to address through greening interventions and includes spatially-explicit modelling outputs, particularly on runoff generation and urban microclimate, to inform future greening and ecological planning strategies and interventions. These outputs can be used to prioritize specific types of NBS in different parts of the city, hence supporting a more targeted and potentially effective response. Modelling results further support the argument that the multifunctionality of urban green infrastructures and the synergies among multiple ecosystem services should be acknowledged and strategically leveraged in the design of ecological strategies for climate-resilient cities [10].

To be implemented at the local scale, such ecological planning strategies require the detailed design of context-specific NBS. This implies a preliminary analysis of the potential impacts of different solutions, to support decisions about their location and specific design characteristics (e.g., size, materials, species) [38, 39]. These potential impacts must be evaluated in conjunction with other parameters that define the feasibility of the proposed interventions, including the availability of space and resources [40]. In Trento, the ongoing development of a Masterplan for the restoration of the river Fersina offered the opportunity to reflect not only on the feasibility of specific interventions, but also on their benefits.

The limitations related to the use of the described models should also be acknowledged. Although we do not address the technical limitations of each model here (for which we refer to the relevant literature), we highlight key considerations regarding their use in policy processes. First, there is, in general, a trade-off between simplicity and accuracy, meaning that the more accurate a model is, the higher the risk that it is perceived by the actors involved in the process as a black box or an all-solving "Oracle" [41]. In the described applications, however, we have also observed that the complex models applied at the local scale produce indicators that might be more meaningful to a non-technical audience, as they focus on variables directly linked to people's perceptions. This suggests that when selecting the most appropriate model to use, it is essential to consider not only its assumptions, but also its outputs and how both can be effectively communicated to the actors involved in the process.

Second, the breadth and depth of analysis should be balanced by considering the type of decisions being supported. Ecological planning strategies and NBS are multipurpose and, beyond addressing the main challenge for which they are implemented, they produce several co-benefits. These co-benefits are rarely captured by modelling approaches such as the ones described above. Yet at the strategic level, it is especially important to consider and quantify them not only to justify the adoption of NBS over other (grey) solutions, but also to anticipate additional consequences that will emerge from the implementation of the proposed interventions, especially in terms of spatial equity and distributive justice [42]. For instance, many planning processes fail to assess how the benefits and burdens of NBS are distributed across different social groups in urban areas. This can lead to interventions that, while ecologically effective, reinforce existing spatial injustices [43]. As such, it is important to combine multiple assessments, which often implies a trade-off with the accuracy of analysis.

Finally, a multiscale approach, such as the one presented in this chapter, involves challenges in the application of the results in real-life decision-making processes. While having different types of indicators at different scales makes sense, it also implies that the results will not perfectly overlap across scales. Managing these inconsistencies and communicating the implications to stakeholders requires careful expectation management and a conscious effort to avoid overly technocratic interpretations of model results. As observed in similar planning contexts [44], the role of experts in mediating between modelling outputs and planning processes is crucial to ensure transparency, legitimacy, and shared understanding of results.

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