EcoViz: co-designed environmental data visualizations to communicate ecosystem impacts, inform management, and envision solutions

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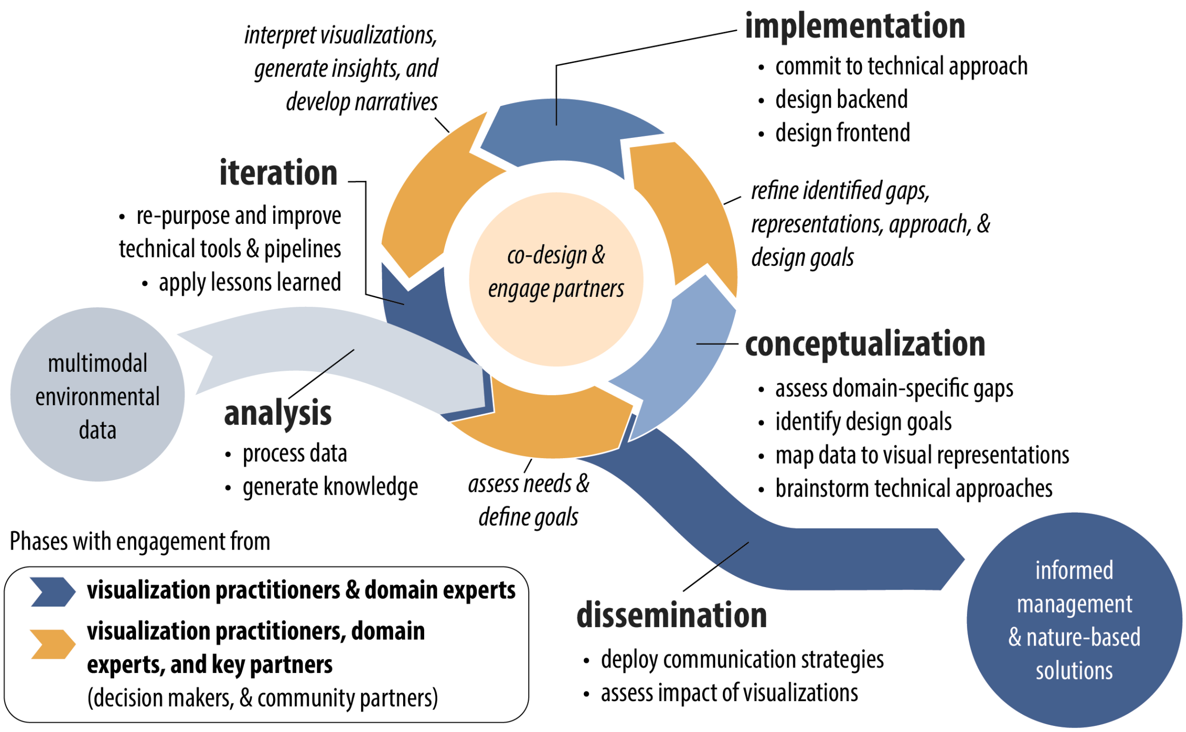

Figure 1: Process diagram for designing environmental visualizations that promote collaboration and communication between visualization practitioners, domain experts, decision makers, and community partners. These visualizations aim to transform knowledge into action through informed management and nature-based solutions.

Abstract

Climate change's global impact calls for coordinated visualization efforts to enhance collaboration and communication among key partners such as domain experts, community members, and policy makers. We present a collaborative initiative, *EcoViz*, where visualization practitioners and key partners co-designed environmental data visualizations to illustrate impacts on ecosystems and the benefit of informed management and nature-based solutions. Our three use cases rely on unique processing pipelines to represent time-dependent natural phenomena by combining cinematic, scientific, and information visualization methods. Scientific outputs are displayed through narrative data-driven animations, interactive geospatial web applications, and immersive Unreal Engine applications. Each field's decision-making process is specific, driving design decisions about the best representation and medium for each use case. Data-driven cinematic videos with simple charts and minimal annotations proved most effective for engaging large, diverse audiences. This flexible medium facilitates reuse, maintains critical details, and integrates well into broader narrative videos. The need for interdisciplinary visualizations highlights the importance of funding to integrate visualization practitioners throughout the scientific process to better translate data and knowledge into informed policy and practice.

Index Terms: Environmental visualization, coastal resilience, climate change, nature-based solutions, wildfire resilience, prescribed burns, and ecosystem management.

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1 Introduction

As climate change's impacts on ecosystems and coastal communities intensify, visualization of multifaceted environmental data is a critical tool for analysis, science communication, and decision making [40]. Across vast temporal and spatial scales, visualizations reveal pervasive but otherwise invisible environmental processes and phenomena [31]. Like the scientific process, data presentation can disproportionately reflect the narratives and perspectives of data storytellers and their scientific advisors [73]. Therefore, environmental data storytellers must also engage community members and policy makers in crafting these stories and designing future scenarios for climate mitigation and adaptation [68], [34], [49].

1.1 Related Work

Nature-based solutions incorporate natural features and processes to protect ecosystems while providing measurable co-benefits to people and nature [66]. Controlled burns and natural coastal protection via coral reefs and mangroves are well-quantified examples of nature-based solutions that can provide significant local benefits [13, 54, 35]. Nature-based solutions can aid with climate adaptation (reducing the negative effects of climate change) as well as climate mitigation (reducing greenhouse gas concentrations) through grey infrastructure replacement and ecosystem protection. While potentially powerful, the benefits of nature-based solutions are limited by local and regional environmental conditions and require active protection and management following implementation. Informed management of animals and ecosystems can similarly reduce the negative effects of climate change and other anthropogenic stressors. Healthy ecosystems also support natural processes that sequester carbon. Ultimately, nature-based solutions and informed management must be paired with climate mitigation policy and management to effectively curb global greenhouse gas effects. Famous climate visualizations such as Ed Hawkins' "Warming Stripes" graphic [33] have advocated for climate mitigation through official reports for the Intergovernmental Panel on Climate Change (IPCC). This paper and our visualizations aim to contribute to this body of work by illustrating pathways toward climate adaptation and resilience through informed ecosystem management and nature-based solutions that are tailored to specific domains, regions, ecosystems, and communities.

In crafting environmental narratives about climate change, we must avoid defeatism and powerlessness conjured by the "toxic sublime" and "climate doomism" that arise from considering the profound impacts of industrialization [57], [51]. Inspirational imagery that connects to an audience's emotions and concerns engages the public more effectively than fear-based messaging [56]. Interactive climate visualization tools showing meteorological datasets are gaining popularity, but rarely include impact-related datasets on drought, flooding, or wildfire risk [50]. Uplifting, action-oriented browsers are needed to evaluate and compare climate risks with informed management and nature-based solutions. These tools, often part of multi-institutional non-commercial partnerships, require continued input and engagement by visualization practitioners and key partners [50].

Co-design, collaboration, and communication benefit the entire research pipeline from participatory planning and data analysis to insight generation, science communication, community engagement, and informed decision-making [34], [65], [20], [19], [44]. Scientific visualization studios, such as NASA's Scientific Visualization Studio and UIUC's Advanced Visualization Lab, collaborate closely with scientists and benefit from the support of dedicated visualization engineers, communication specialists, and web designers. However, visualization practitioners are seldom engaged throughout the research life-cycle. Funding often limits their engagement to final presentation stages, after questions have been asked, data have been collected, and the interpretive narrative has emerged. Critically, this limits the analytical potential of data-rich visualizations to identify errors or anomalies, inform the analytical approach, or generate new insights [19], [44]. The lack of long-term funding for visualization projects also hinders user-centered design and collaborations between scientists, community members, and policy makers [52].

1.2 Contributions

This paper introduces *EcoViz*, a collaborative initiative to apply co-design principles to produce environmental visualizations with an interdisciplinary group of visualization practitioners, domain experts, community partners, and policy makers (Fig. 1). We present three bodies of work that arose from this cross-institution collaboration between University of California San Diego and University of California Santa Cruz, highlighting synergies in our technical approaches, practical challenges, and future opportunities for environmental visualization. This work spanned three domains and three core visualization types: narrative data-driven animation, interactive data browsers, and immersive experiences. We have created an online portal, the *EcoViz Explorer* to host all of the publicly available immersive tools, interactive browsers, and data-driven animations that have arisen from this collaboration [45].

In three climate-related research areas, our ongoing work adds to three-dimensional representations by visualizing additional data, modeled outputs, and alternative scenarios, depicting anthropogenic impacts on animals and ecosystems while envisioning nature-based solutions. These 4D visualizations (3D + time) facilitate visual analytics, science communication, and decision making. Our examples span three fields: marine science, coastal resilience, and wildfire resilience. In each case, we visualize multidimensional datasets to illustrate ecosystem changes above and below sea level as well as at the land-sea interface where coastal risks are rising. We tailored outputs for visual analytics by domain experts, decision support by policy makers, and science communication for broad impact. We developed products ranging from data-driven animations to immersive experiences in Unreal Engine and interactive data exploration tools for visual analytics and decision support.

A core subset of this group, consisting of visualization practitioners, some of whom were also domain experts, met weekly over the last two years to share technical approaches, provide design feedback, and lead high-level discussions about the role of visualization in environmental science. This weekly meeting served as a springboard for additional topic-specific hackathons, week-long workshops, grant-writing, and several ongoing mentorships. Despite differences in project timelines, project types, and implementation responsibilities, this collaborative structure allowed us to learn from each other, invited visualization experts, and other key partners. Figure 1 illustrates our design process, building off of the software development Agile framework [18] and incorporating well-established co-design principles. While Agile and related methodologies emphasize quick iteration between developers and clients, this co-designed approach between visualization practitioners and key partners helped engage end-users and audiences to address complex environmental issues with nature-based solutions and informed management.

To begin this iterative process, the needs and goals of key partners were assessed and defined. Then, we assessed domain gaps where visualization could play a role, identified design goals, mapped data to visual representations, and brainstormed technical approaches. Before implementation, visualization practitioners consulted partners to validate data representations and the appropriateness of their technical approach and design goals. Next, as practitioners implemented the visualization, they committed to a technical approach as they engineered the frontend and backend for the app, video, or immersive experience. Before dissemination, they worked again with domain experts and key partners to annotate the visualizations, generate additional insights, and develop narratives to integrate into disseminated products. The efficacy of environmental visualization was assessed during dissemination, where communication strategies were deployed to foster public engagement, raise funds in support of related work, and inform policy and practice. Finally, our collaborative meetings with visualization practitioners were key for iteration, where we re-purposed and improved the technical tools and pipelines used in each project and shared techniques with the broader public via educational materials.

2 Conceptualization: Gaps & Data Representation

To understand the potential decision-making impact of visualizations in each of these three fields, we briefly contextualize each use case and introduce each domain-specific data representation approach. Multifaceted data from each use-case included spatiotemporal data with multiple attributes (multivariate) that stemmed from different acquisition modalities (multimodal) and that involved multiple runs of a single model (multi-run) or combined models (multi-model) [40].

2.1 Life in the Deep

To assess the impact of human activities on marine ecosystems, we must establish baselines to track in the face of climate change. Characterizing these baselines involves tracking concurrent shifts in oceanographic conditions and the abundance, distribution, and behavior of marine organisms. In parallel to oceanographic shifts caused by global warming, humans have heavily impacted marine ecosystems through overfishing, coastal development, and pollution [30], [29]. In order to bring attention to multifaceted impacts on ecosystems, we aggregated global Argo data to visualize ocean heat accumulation with depth [64] and visualized 3D diving behavior of marine mammals and birds [44]. Visualizations of ocean heat content provide visible, concrete evidence of global change. To connect this change with its impact on marine animals, visualizations allow us to characterize baseline behavior and physiology in the face of acute and chronic human-caused disturbances [44], [24]. Short-term disturbances could include sound blasts from naval or seismic activity, while long-term disruptions to life-sustaining behaviors like foraging or sleep could be caused by disease or a lack of food due to over-fishing or shifts in prey distribution [58]. Data-driven visualizations of impacts on animals can inform dynamic management to minimize impacts on marine mammals [15], [36].

To visualize impacts on marine ecosystems, we used data from animal-borne sensors and autonomous profiling floats. *For animal behavior and physiology data,* we employed bio-logging devices to record ambient environmental variables, heart rate, brain activity, depth, and three-dimensional motion for northern elephant seals, blue whales, and emperor penguins [44], [46], [14], [60], [28], [43]. Electrophysiological data was sampled at 500 Hz for recordings lasting hours to days, while diving data was sampled at up to 50 Hz for hours or at intervals of 5–10 seconds for months. We primarily visualized diving data using 3D polylines of latitude, longitude, and depth, along with available 3D rotation, swimming behavior, sleep or behavioral state, EEG spectrograms, and heart rate graphs [44]. *For oceanographic data***,** we compiled data from the Argo float network (January 2004 to September 2023) to create a gridded product of temperature values for 0 to 2000 m along a meridional transect [12]. Temperature anomalies were calculated at monthly intervals and represented as heatmaps based on an average local temperature over January 2004 to December 2018 based on the Roemmich-Gilson Argo climatology model [64].

2.2 Coastal Resilience

In addition to supporting bio-diverse marine ecosystems, coral reefs and mangroves provide substantial flood protection benefits to coastal communities [13], [54]. These coastal protection benefits are increasingly important as sea levels rise and extreme weather intensifies [62]. Reefs provide comparable wave attenuation benefits to artificial defenses like breakwaters, but also provide significant value in the form of ecotourism and biodiversity [25]. Risk-transfer solutions that wish to cost-effectively eliminate environmental liability are now being used to insure nature. Using this technique, coral reefs can be restored in the wake of extreme weather events that surpass threshold storm intensity levels [47], [61]. To implement these nature-based solutions, decision-makers such as those from risk management agencies and government must be able to interpret, assess, and communicate the results of complex physics-based hydrodynamic models. Visualizations can contextualize benefit-cost analyses within ecosystems and coastal communities, allowing the viewer to witness flooded infrastructure but also the flood reduction from nature-based solutions.

To visualize flood impacts, we used hydrodynamic model outputs from 2D and 3D wave simulations and monetary quantifications of risks and benefits of nature-based solutions. For 2D wave model flood rasters, we used XBeach and SFINCS to generate data, indicating water height at fine resolutions (down to 5m) over large extents (up to 10 x 10 km). We visualized 2D outputs as 3D meshes alongside topobathy data, imagery, and land use/cover rasters, with a temporal resolution of 1 second. For 3D computational fluid dynamic simulations (CFD) of hybrid reef designs, we used OpenFOAM and Houdini SideFX [55], visualizing speed through motion and turbulence through opacity and color. Risks and benefits of nature-based solutions, such as reef and mangrove restoration, were quantified using 2D wave modeling [13], [54], comparing scenarios with and without natural defenses. For coastal study units (less than 5 km), risks and benefits were aggregated into statistics like risk reduction ratio and benefit per square kilometer. We visualized benefits with scaled bubble plots and risk reduction ratios with stacked 3D bar charts.

2.3 Wildfire Resilience

Ecologically-informed beneficial fires are another nature-based solution that can significantly reduce risk to property, lives, and livelihoods. Beneficial fires, i.e., cultural burns, have been a part of Indigenous land management strategies for thousands of years [53]. However, more recent century-old wildfire firefighting techniques have centered around suppression, where natural fires are extinguished as soon as possible. This has resulted in an accumulation of vegetation in the landscape, which in turn multiplies the impact of future wildfires, contributing to the megafires observed globally in recent years. Prescribed fires can reduce vegetation buildup, in addition to providing a range of benefits for the ecosystem [35], [39]. Planning and conducting these prescribed fires is a complex and difficult task with both safety and legal ramifications [72]. Decision makers have to infer risks from weather and fire models, coordinate strategy for conducting burns, manage public safety implications, and engage with community partners to respect the sovereignty of local Indigenous populations [53], [37]. Diverse partnerships required to sustainably manage land for wildfire resilience clearly illustrate the need for visualization to enable participatory research, risk assessment, community engagement, and effective communication across teams.

To visualize prescribed fire propagation models, we used physics-based fire simulations and LIDAR scans. *Physics-based fire simulations* were performed with FastFuels data and QUIC-Fire, employing cellular automata algorithms to model fire behavior and fuel consumption [48]. Inputs and outputs are three-dimensional volumes of "voxels," often visualized as 2D animations, except for fuel distribution, represented as a 3D point cloud. *Terrestrial Laser Scanning (TLS) LiDAR scans* were collected using handheld or vehicle-mounted sensors. As part of the Interagency Ecosystem LiDAR Monitoring (IntELiMon), these scans provide a 3D colorized point cloud, revealing structural information about vegetation [59].

3 CONCEPTUALIZATION: DESIGN PRINCIPLES

Each of these big datasets contains adequate volume, variety, and value to present significant challenges for visualization. To conscientiously represent this data, we maintained the following universal design goals outlined below, inspired by Harold et al. 2016 [32].

3.1 Strategically deploy visual attention

In each output, we used visual attributes like color, motion, orientation, and size to guide the viewer [75]. We matched colors to symbolic meanings, using blue for positive scenarios like cooler temperatures, reduced risk, or nature restoration [32]. We retained visual complexity when it could provide insights in an immersive context, such as using RGB color channels in forest scan point clouds to convey vegetation state. We minimized overlapping motion in animations, introducing elements sequentially to avoid missed cues. Although annotations can detract from immersion [38], we included them in most visualizations to prioritize analytical clarity and context over cinematic quality.

3.2 Distill complexity and preserve scientific integrity

To represent multivariate datasets, we often reduced dimensionality while maintaining temporal and spatial resolution. For example, in data-driven animations of marine animal behavior, we compressed over 10 independent time series representing an animal's neurological and physiological state, alongside its 3D movement and rotation, into a 2D video [46]. We used volumetric shaders for waves and smoke to represent multivariate data through color, opacity, and particle velocity, addressing scientists' "loss aversion" by creating interpretable graphics that distill complexity and retain scientific integrity [20, 32]. When scientific models lacked the resolution needed for seamless playback, we interpolated between time steps to enable smoother motion at 24 FPS for 3D rotations, marine animal positions, and wave model visualizations using Bezier curves or ML-frame generation and superresolution.

3.3 Support solution-oriented decision making

To enable decision makers to leverage nature-based solutions, we presented tangible options to combat climate change, emphasizing positive and actionable links to personal desires and concerns, as fear alone does not motivate genuine engagement [56]. To contrast scenarios effectively, users could view overall comparisons and then drill down into spatial variability and driving mechanisms, following Schneiderman's information-seeking mantra: "overview first, zoom and filter, then details-on-demand" [69]. However, the key information and technical approach varied for policy makers across disciplines, media, and situational contexts.

4 IMPLEMENTATION: TECHNICAL APPROACHES

While these three bodies of work emerged independently, we have converged on similar technical approaches to address the overlapping challenges of visualizing large, multifaceted environmental datasets. We discuss three strategies for visualizing these datasets along a spectrum of user engagement and autonomy from immersive environments in Unreal Engine and web-based interactive browsers to narrated, cinematic data-driven animations (Fig. 2).

4.1 Immersive data exploration tools

Immersive experiences can heighten audience engagement, empathy, and agency [11, 65, 23]. Our immersive data exploration tools, developed in Unreal Engine [27], allow practitioners, scientists, and the public an up-close view of fine-scale patterns in the data. Unreal allows for seamless real-time rendering of large datasets and model outputs, leveraging custom pipelines that mix automated methods with node-based programming.

4.1.1 Life in the Deep

The *Life in the Deep* Unreal app features an automated pipeline that ingests bio-logging data, allowing experts, policymakers, and the public to observe wild animals' behaviors, such as sleeping, foraging, and diving, and understand the impacts of human activity. High-fidelity playback enables users to interpret fine-scale changes in activity and movement, generating new insights and empathy for these animals. Bio-logging data is loaded locally or via a RestAPI compatible with the AwesomeDB semi-structured polystore database [21]. We created immersive scenes using the Cesium basemap for Unreal (WGS84 coordinate system) with Bing map tiles for geospatial and bathymetric data, using precise latitude and longitude coordinates for positioning marine mammal models [44], [46]. The RestAPI data fetching is coded in a custom C++ plugin, while most features are engineered using Unreal's visual scripting language, Blueprints. Blueprints manage data intake and user interaction for scene navigation, error handling, and displaying behavioral and physiological parameters. To integrate this viewer with analytical tools for data processing and AI-assisted time series segmentation, we are working on embedding the Unreal scene within a web-based framework through Pixel Streaming.

4.1.2 Coastal Resilience

Detailed depictions of 2D and 3D wave models using custom pipelines in Unreal Engine and SideFX Houdini aim to increase understanding of hydrodynamic models for domain experts and decision-makers. Two pipelines have been developed: (1) an automated Python pipeline for scenario comparison with 2D models (XBeach and SFINCS [26]), and (2) a flexible framework for cinematic visualizations of coral reefs using 3D models (OpenFOAM [5, 55]). The Python pipeline extracts topobathy and flood raster time steps from 2D wave models and prepares them for Unreal Engine alongside aerial imagery, structure data, and land use rasters. Unreal Engine tools intake meshes and textures, applying procedural-generation techniques to enhance playback smoothness for scenes lacking high temporal resolution. The scene can be manipulated to exaggerate elevation, view cross-sections, highlight flooded areas, compare scenarios, and control playback speed. The 3D pipeline visualizes CFD simulations of reef designs. Gridded 3D data from OpenFOAM is processed in Houdini into a volumetric format, with attributes like turbulence and velocity vectors driving color, opacity, and bubble movement. Motion vectors interpolate frames for smooth 24+ FPS playback. The data is visualized in Unreal Engine with real-time interaction and rendered using the engine's Path Tracer.

4.1.3 Wildfire Resilience

Immersive Forest visualizes the increasingly complex inputs and outputs of the vegetation and fire models used for fire management. As the models transition from 2D to 3D, new modes of visualization and interaction are needed to understand their behavior, and the effectiveness of a given treatment on the ecosystem. Scenes with real-time interaction display fire model inputs and outputs contextualized within public terrain, satellite imagery, and LiDAR datasets [71, 48]. This allows the user to explore scenes at multiple spatial scales. Data is cataloged in WIFIRE Commons [74] and stored with an S3 cloud object store, with tiles downloaded based on the user's camera or avatar location. Due to varying resolutions and coordinate systems in models and datasets, preprocessing is required to align geospatial layers in the visualization engine. While preprocessing is automated, developers must still choose datasets and program interactions like navigation, clipping, and recoloring. The application runs as a desktop or VR app using a head-mounted display (HMD).

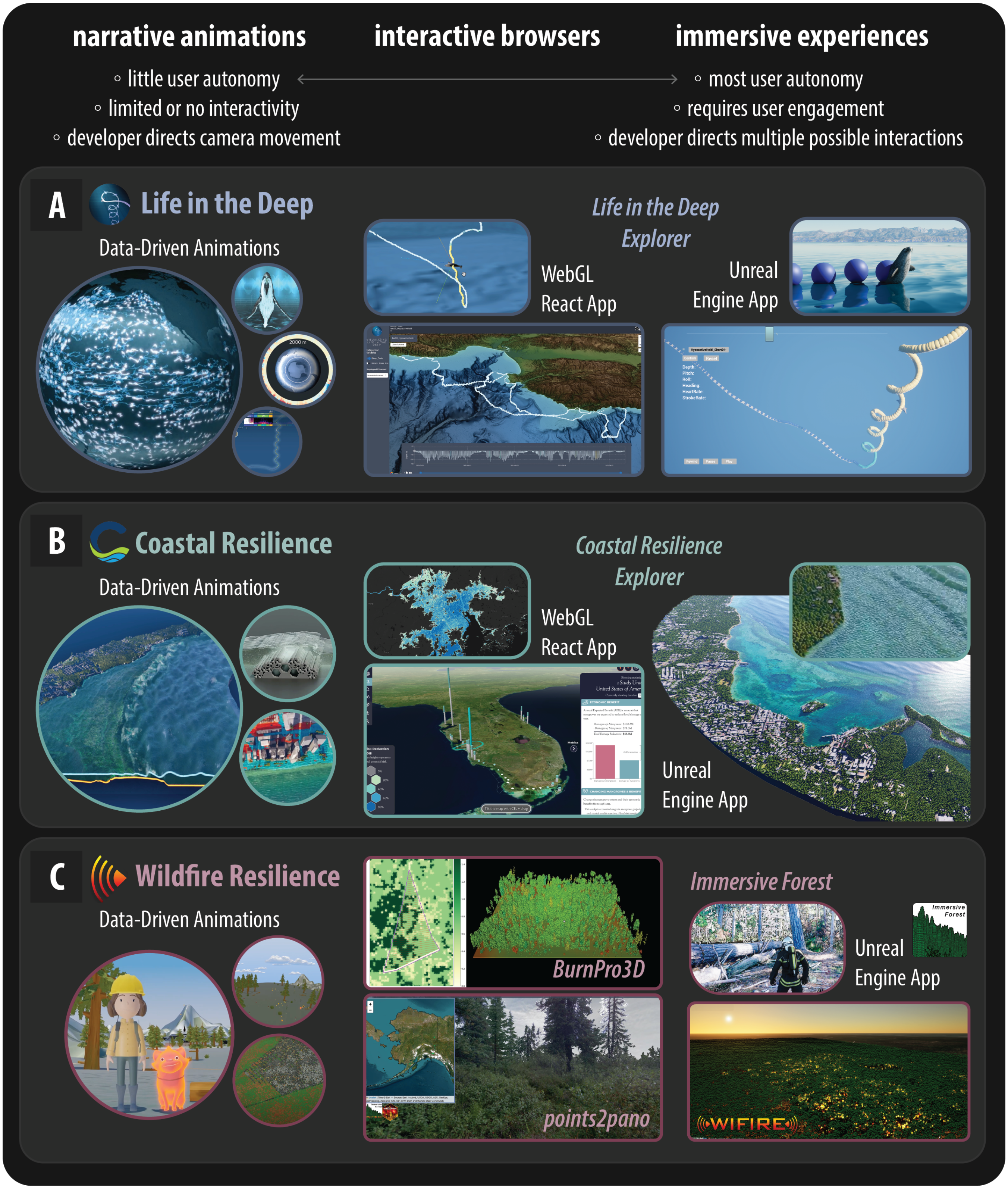

Figure 2: Diagram showing the three types of visualizations (narrative data-driven animation, interactive data exploration tools, and immersive data exploration tools) for each of the three use cases discussed in the paper: **(A) Life in the Deep:** visualizing impacts on marine ecosystems, **(B) Coastal Resilience:** visualizing nature-based solutions leveraging the flood protection benefits of coral reefs and mangroves, and **(C) Wildfire Resilience:** visualizing prescribed fire simulations to inform forest management and prescribed fires.

4.2 Interactive data exploration tools

At the interface of interactive and immersive tools, there are many opportunities to interactively alter immersive scenes using integrated editors as data browsing interfaces. Here, we describe web tools built for the explicit purpose of adjusting parameters to flexibly view data and analyses.

4.2.1 Impacts on marine ecosystems

The *Life in the Deep Explorer* interactive web portal displays marine bio-logging data in a geospatial context, visualizing 3D movement and behavior alongside physiology to understand marine mammals' responses to environmental stimuli. Researchers can submit biologging data, view it against other data sources, and gain insights into animal behavior. It has been used to study underwater sleeping dives by northern elephant seals and disturbance dives in response to predators [44], [67]. *Life in the Deep* uses WebGL for 3D bathymetric environments and includes a data server and API for browsing electrophysiological data via the National Research Platform's Nautilus system.

4.2.2 Coastal Resilience

The *Coastal Resilience Explorer* is a decision support tool developed by the Center for Coastal Climate Resilience at UC Santa Cruz to communicate the benefits of nature-based solutions for coastal risk reduction. It allows users to browse geospatial layers related to mangrove habitats and flood protection benefits. The tool helps users across various disciplines understand flood risk and adaptation options and is useful for insurance, risk reduction, and habitat conservation. Built with WebGL and MapboxGL, it uses custom geospatial servers to serve high-resolution climate data. Planned expansions include higher-resolution hydrodynamic models and coral reef benefit layers.

4.2.3 Wildfire Resilience

BurnPro3D is a decision support platform for prescribed fire planning, providing a web interface for configuring and running physical models of fuel and fire under varying conditions [2]. Coupled fire-atmosphere modeling using QUIC-Fire and FastFuels generates data and visualizations registered in WIFIRE Commons [48], [74]. Components stored in S3 buckets are accessible via a RestAPI through the CKAN data management system [9]. The modeling uses 3D volumes (voxels) visualized in 2D animations of fuel consumption and a 3D point cloud of fuel distribution post-burn. User inputs are used to schedule simulations, with results collected, cataloged, and visualized in an automated process. The same web interface used to set simulation parameters navigates the results with sliders and mouse controls. *points2pano* is a web app for generating 360-degree panoramic images from 3D point clouds and exploring scans with a map interface [6]. Written in Python using OpenCV-Python [4], it leverages a painter's algorithm to project points to an equirectangular format, tiled and stored in S3. Image data is cataloged in WIFIRE Commons by date and location, allowing users to select scans by location on a map. The image tiles are dynamically rendered with marzipano [10] as users navigate locations.

4.3 Data-driven animations

We carefully chose when to use immersive technologies to represent multifaceted data, despite their popularity [40]. Our immersive experiences enhance user autonomy in data exploration but are less scalable than videos, which can be easily embedded in various platforms. Even with primarily immersive outputs, we created demo reel MP4s for broader accessibility. For all projects, we exported cinematic sequences using Unreal Engine to illustrate our data integration approach. When exporting videos, we considered the camera's position and angle over time to improve cinematic quality, narrative flow, and interpretability of the visualizations.

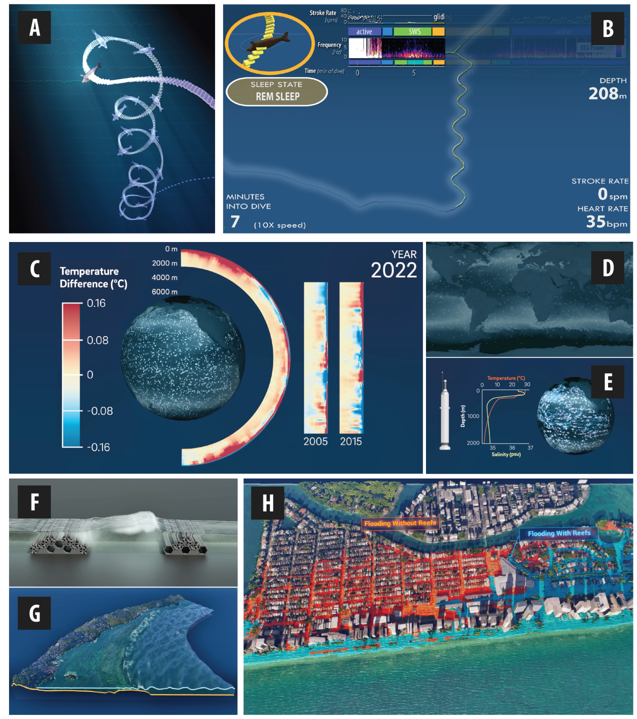

Figure 3: Scenes from data-driven animations produced in Autodesk Maya (A & B), Adobe After Effects (A-E), and Unreal Engine (F-H). Scenes A & B represent the sleeping patterns of northern elephant seals, C-E represent oceanographic data from autonomous profiling Argo floats, and F-H represent the coastal flood protection benefits of coral reefs.

4.3.1 Life in the Deep

We produced data-driven animations in Autodesk Maya and Adobe After Effects using Python and JavaScript to ingest tabular CSV data, driving motion, position, size, color, and text elements [44], [41]. We processed motion sensor data for 3D rotation and swimming behavior, generating tracks in Maya and adding text counters, line graphs, and spectrograms in After Effects. To depict northern elephant seals' sleeping patterns deep underwater, we used 3D-oriented rectangular prisms and "ghosting" techniques borrowed from animation, allowing experts to analyze animal rotation over time (Fig. 3A). Data-driven animations offer flexibility with camera angles and scale that demonstrate the narrative and illustrative power of these choices for cinematic visualization. Camera positioning, playback speed, and glow effects can highlight critical movements and scene dynamics (Fig. 3B). For example, a 35-minute elephant seal dive was played back at 10x speed, slowing at key transitions to accentuate changes.

We incorporate these data-driven scenes into fully-produced videos with footage, music, and narration [44]. One video explains machine learning model outputs that reveal population-level sleep patterns, improving AI transparency [46], [8]. Another shows the ocean's heat storage increase as measured by Argo floats since 2004 [7], displaying Argo temperature and salinity profiles alongside NASA's sea surface temperature visualizations [42] (Fig. 3D-E). We displayed heatmaps of temperature anomalies across depth in the Pacific Ocean (Fig. 3C), illustrating the vast heat energy contained in ocean volume— over 176 zetta-Joules since the 1980s, equivalent to 7 billion atomic bombs. Line graphs, sequential information introduction, and annotations provided scientific context and interpretive assistance for the data-rich visualizations.

4.3.2 Coastal Resilience

In addition to cinematic data-driven animations rendered in Unreal Engine (Fig. 3F-H), our group has produced short motion graphic animations to communicate scientific results. One animation used Adobe After Effects to represent flood impacts on coastal communities, comparing scenarios with and without coral reefs. Although simple, these animations effectively convey scientific findings. We also created videos to illustrate the research vision of the Center for Coastal Climate Resilience at UC Santa Cruz, highlighting its goals in linking economics, risk modeling, and natural ecosystems.

4.3.3 Wildfire Resilience

Associated with BurnPro3D and related fire modeling, we produced data-driven animations using Unreal Engine to demonstrate prescribed fire spread over time (Fig. 2C). The Wildfire Resilience group also led a design challenge with UC San Diego undergraduates, resulting in a 3D animation called "Who's a Good Fire?" featuring a spark named Flint who explains the benefits of mild-intensity fires for forest health. This narrated video effectively describes the rationale and management framework for prescribed burns.

5 Dissemination: Assessing Impact

We have had several opportunities to informally assess the impact of these visualizations through their ability to garner interest and support from domain experts, funders, media professionals, and the public. In the future, we plan to conduct more formal assessments including surveys and case studies to further investigate the efficacy of our visualizations. However, our practical experience in presenting this work to audiences of scientists, community members, industry professionals, federal agencies, and congresspeople has provided unique opportunities and anecdotal evidence that points to the valuable role of visualizations in decision-making arenas.

5.1 Research Insights

Exploratory visualizations of multimodal environmental data reveal mechanisms driving change, facilitating model refinement. Data-driven visualizations of northern elephant seal diving behavior helped identify how shifts in sleep states affect motion, leading to improved models for sleep identification [46]. These range-wide sleep maps help characterize human impacts on wildlife [43]. Visualizing ocean heat accumulation emphasizes temperature anomalies that surpass normal annual and multi-year cycles. Visualizations of model outputs for floods and fires can help ensure the accuracy of these models, which is critical for risk assessment. Decision support tools combined model outputs and structural data to assess impacts on infrastructure for vulnerable communities, helping to foster trust and transparency with decision-makers like risk managers and insurance modelers.

5.2 Science Communication Impacts

Formal studies on visualization efficacy in science communication are challenging, but Altmetric scores track media impact across social media, news outlets, and traditional citations [22]. Our data-driven animation of a sleeping seal was published as supplemental material for an article in the journal *Science* and was republished by major outlets like *The New York Times* and *The Atlantic*, reaching over 290 news outlets with an Altmetric score of over 2700, indicating wide public engagement [46]. The animation was remixed into a TikTok video viewed more than 2.6 million times [1]. This and other *Life in the Deep* animations have been presented to broad audiences, including the American Physiological Summit 2023 keynote lecture and at high-level meetings with the Office of Naval Research and the National Marine Mammal Commission. Data-driven animations and graphics representing the coastal protective benefits of coral reefs accompanied an article in the journal *Nature Sustainability* [70], [63]. This study was referenced by 21 news outlets and key images we produced were used directly in news outlets and then in two guidance documents developed by the US Army Corp of Engineers on the use of Nature Based Solutions for hazard mitigation [17, 16]. Evaluating media impact using Altmetric scores is an imperfect way to quantify the total reach of an article, due to the arbitrary weighting of different media categories and the inability to track outputs without explicit DOI mentions. A future study could investigate the Altmetric scores of research papers in similar fields on similar topics with and without data-driven animations as part of their science communication efforts.

5.3 Decision Support Impacts

Since their development, *Coastal Resilience* visualizations have been used in every presentation by the project's principal investigator to organizations like FEMA, USACE, and the World Bank. In 2023, *Life In the Deep* visualizations were showcased to the National Marine Mammal Commission and at COP 28 in Dubai. Our immersive tools have also reached the House of Representatives and various governing bodies, including the USGS, USDA Forest Service, US National Park Service, state land management agencies, local fire safety councils, and cultural burning organizations. The *Immersive Forest* prototype was demonstrated to the House and Senate AI Caucuses on Capitol Hill for a hands-on National Artificial Intelligence Research Resource Pilot (NAIRR) Pilot Demo by NSF (see Fig. 4). At this demonstration, practitioners stated that they wanted to see additional metrics and metadata alongside the immersive LiDAR point cloud data and observe the distribution of scenarios so that they could draw conclusions on their own, as opposed to having too much narration from the visualization tool. However, this same narration was appreciated by higher-level decision makers who did not have as much field experience, underscoring the importance of this user feedback and iteration.

5.4 Impact for Building Communities of Practice

Our collaborative network of visualization practitioners has also received support to foster collaborative communities of practice, especially around the challenges of increasing transparency and explainability of AI-assisted analysis. We hosted an international workshop in March 2024 called *EcoViz+AI: AI and Visualization for Use Cases in Ecology* where we developed visuals during hackathon sessions to increase the explainability of AI models and democratize access to AI methods for ecologists. In creating these visualizations, we prioritized creating reproducible visualization pipelines that could be implemented by others. For example, in an effort to make our work reproducible, we catalogued geospatial layers from experiments in WIFIRE commons [74], making use of CKAN [9] to publish and share the inputs, outputs, and parameters we used to achieve the visualization results. A future researcher can use this to validate our workflow or extend it to visualize models from another domain. Reproducibility also drove our decision to use Unreal Engine [27], as it is open-source and free to use for non-profit research projects. For teaching the methods implemented throughout these projects, we have hosted several workshops and created a freely available online Coursera course called *Data-Driven Animation for Science Communication* [3].

6 Discussion

We introduce a collaborative initiative, *EcoViz*, that gave rise to several environmental visualizations co-designed by visualization practitioners and key partners, including community members, domain experts, and policy makers. The three use cases apply visualization and co-design theory to develop impactful tools for science communication, research, and decision support. Our collaborative structure allowed us to leverage overlaps in technical approaches;

Figure 4: On May 22, 2024, the House and Senate AI Caucuses hosted NSF on Capitol Hill for a hands-on NAIRR Pilot Demo. Research partners from the National Artificial Intelligence Research Resource Pilot (NAIRR) demonstrated groundbreaking AI innovations from around the nation. Photo Credit: Charlotte Geary/NSF.

we each applied Unreal Engine to flexibly render large, 3D spatiotemporal datasets, created flexible web browsers to examine alternative scenarios and solutions, and produced data-driven animations to scalably share this work with others.

6.1 Lessons Learned

To facilitate this type of collaborative work in the future, we share some challenges and lessons learned in the design, design process, and visualization approaches for these visualizations:

Tradeoffs between visualization approaches: *Never underestimate the power of a video.* While we have developed immersive and interactive tools, we still rely heavily on videos to share our work. Videos are often more accessible and lightweight, making them preferable when time or connectivity is limited. Videos reach larger audiences at conferences and workshops but sacrifice individual interaction and feedback. However, principal investigators typically present videos in PowerPoint to policymakers, as interactive demos are less frequently requested.

Understanding our audience: *Domain experts preferred exploratory tools while decision makers preferred a succinct, evidence-based narrative.* Domain experts relied more on exploratory visualizations than decision-makers and community members. Scientists opted for exploratory visualizations to understand phenomena, verify mechanisms, and monitor for errors. In contrast, policymakers and stakeholders preferred clear, concise narratives that used data visualizations as evidence to support claims. Since the content consumer is often not the ultimate decision-maker, presenting clear and evidence-based claims is crucial for effective second-hand communication to decision makers.

Challenges for reproducibility and collaboration: *Document your process thoroughly and explore version control solutions.* Developing custom visualization tools that are reproducible and scalable presents challenges, especially with GUI-based and code-based tools. Unreal Engine's Blueprints offer visual scripting but are hard to debug and modify, while C++ is more flexible but difficult for non-technical users. Unreal's visual interfaces result in small design deviations, like camera parameters or button colors, that later hinder reproducibility. Perforce, a tool for version control, slowed development due to issues with read-write permission and was too heavyweight a solution for projects with a single Unreal developer. Web-based tools avoid concerns with obscure node-based programming and proprietary (like Autodesk Maya) or GUI-based software (like Unreal Engine). Nonetheless, the web development learning curve for non-technical users may be steeper than using Autodesk Maya with a single Python script. Project complexity compounded reproducibility challenges, so thorough documentation of technical and design decisions was essential. We plan to enhance our documentation with tutorials and educational materials, through modules similar to our previous Coursera course [3].

Flexibility is key: *Make peace with the fact that a better tool may come out tomorrow.* We often had to switch software solutions after significant time investment, such as redesigning the *Life in the Deep* web browser with MapBox and ThreeJS to React.js for better map integration, and now to DeckGL for camera control. Flexibility in our visualization pipelines was linked to project funding, timeline, and complexity. Short-term projects limited by time and funding often resulted in narrow, inflexible solutions, while long-term projects benefited from code reuse and developing generic tools. Our key takeaway is the importance of not relying on a single tool, as new technology can quickly become available. Flexibility and adaptability are crucial to optimize performance and leverage the latest technology.

Funding limitations: *Start collaborations early, write grants together, and allocate ample funding to support co-design.* While optimizing tool performance through formal assessment and user experience research is important, this is a time-intensive process that requires proper incentives and support. For domain scientists, dedicating time and resources to such assessments may be impractical given that they are under pressure to publish in their own fields and have little incentive to develop tools that fully meet users' needs. Therefore, we emphasize the benefits of cross-disciplinary collaboration between visualization practitioners, who are incentivized to conduct formal assessments, and domain scientists, who need these tools for their research. Funding availability varied greatly across individual projects and those where visualization practitioners were included in research group meetings early on benefited the most from their ability to understand domain experts and key partners. In the future, we will be focused on creating a more intentional structure to involve community members and decision makers into a subset of our visualization meetings.

In our future work, we plan to quantify and investigate the efficacy of immersive, interactive interfaces to improve the impact and usability of our visualizations. The interactive and immersive tools for *Life in the Deep* are still in their early stages, but the next step towards improving usability across users will be to curate datasets from different bio-logging devices as well as a unified method for manipulating 3D models for different species, created by different artists. In the next stage of development for the *Coastal Resilience* visualizations, we plan to integrate features that will accelerate and facilitate the domain scientists' use of the tool. As part of the FIRE-PLAN funding for *Immersive Forest*, we have secured funding to support future assessment plans for immersive fire planning tools. We are particularly interested in exploring the differences in motivation for using immersive tools among various audience members, both before and after tool use.

Our collaborative initiative, *EcoViz*, helped facilitate knowledge and skill transfer between domains, software expertise, and career levels. Our projects spanned data-driven animations of large scale heat accumulation in the ocean to immersive visualizations of nature-based solutions provided by prescribed burns, coral reefs, and mangroves. In working to visualize impacts on nature and present solutions in the form of informed management and nature-based solutions, it is important to craft narratives that recognize the subjective aspects of storytelling. Visualization practitioners can help inform decisions with the best available science, include diverse perspectives in shaping the questions we ask and the data we analyze, and engage the public in decisions that impact their lives and livelihoods.

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