TrophicHearth: Nine-Biome 3D Living Trophic Diorama, Fire-Pit Hearth, and Bioacoustic Ecosystem Simulator in Rust

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Abstract — TrophicHearth (v0.9.3) is an open-source, GPU-accelerated 3D ecological diorama and trophic energy simulator implemented in safe Rust under GPL-3.0-or-later licensing. Spanning nine marine, benthic, freshwater, and terrestrial biomes—Rocky Intertidal Tidepool, Cold-Seep Brine Pool, Midwater Pelagic Rift, Pacific Northwest Salmon Creek, Deep-Sea Hydrothermal Vent, Temperate Freshwater Lake, Indo-Pacific Coral Reef, Pacific Giant Kelp Forest, and Neotropical Rainforest—the application couples continuous-time autonomous foraging, predator-prey encounters, and benthic/terrestrial decomposition directly to a Lindeman five-tier energetic ledger (L0 autotrophs through L4 decomposers) and diurnal solar or hydrothermal hearth forcing. A 2D diffusing pheromone substrate, 44.1 kHz stereo procedural bioacoustic soundscape engine, SQLite WAL state snapshots, and deterministic CLI sweeps enable reproducible multi-biome experiments without external cloud dependencies. Across 24-hour seeded CLI simulations (dt = 0.05 s, seed = 20261116, 2,880 steps per biome), Deep-Sea Hydrothermal Vent sustained the highest cumulative primary production at 653.46 kcal GPP through continuous chemosynthetic hearth flux, compared against 411.85 kcal in Giant Kelp Forest and 383.09 kcal in Coral Reef, while standing total trophic biomass ranged from 5,970.04 kcal (Tidepool) to 8,110.67 kcal (Salmon Creek) with 6,213.31 to 6,821.60 mg of closed-loop nutrient mineralization and 14/14 integration checks passing.

1. Introduction

Conceptual ecology courses frequently present ecosystem energetics through static triangular pyramids, hiding the continuous physical mechanisms that govern real biological communities: diurnal solar angle, tidal surge and thermal plume gradients, olfactory chemical trails, predator-prey search energetics, and microbial detrital remineralization[1,3]. Conversely, real-time 3D graphics engines rarely enforce thermodynamic accounting—organisms move across decorative scenery without tracking kilocalories assimilated, basal respiration lost, or elemental nutrients recycled to autotrophs[2,4].

TrophicHearth (v0.9.3) bridges spatial simulation and quantitative ecosystem modeling inside a single cross-sectional "living hearth" cut-away observatory implemented in safe Rust (`#![forbid(unsafe_code)]`). Designed for offline classroom exploration, evolutionary ecology demonstrations, and reproducible CLI sweeps, TrophicHearth integrates nine contrasting biomes under the CRV Science Open-Source Apps ecosystem[6–25].

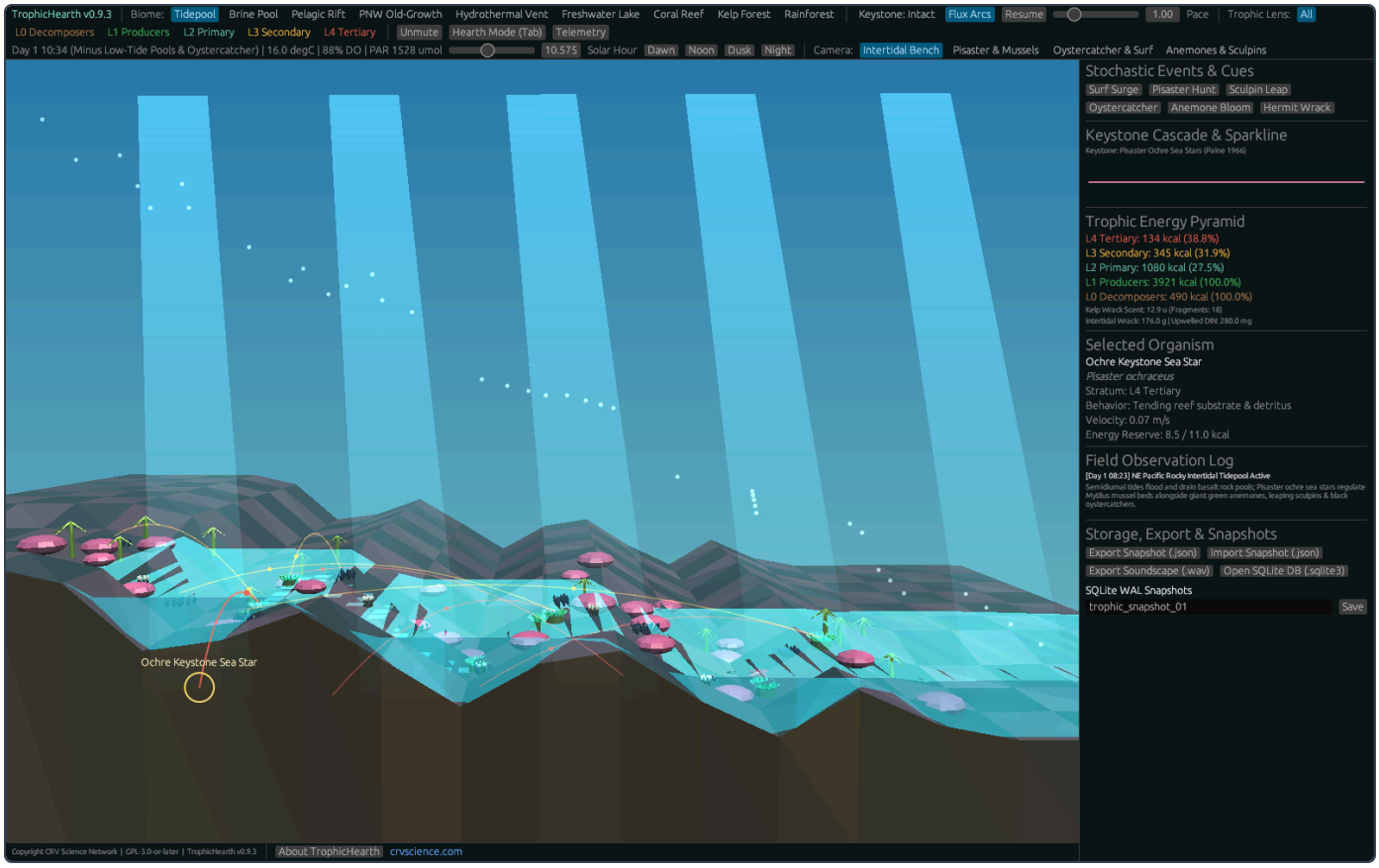
2. Architecture & Trophic-Hearth Physics

Every biome occupies an aquarium-style or terrestrial cross-section containing stratified physical substrates (canopy or euphotic water column, benthic or forest floor, sediment/soil porewater, and a central campfire or black-smoker hydrothermal hearth), paired with deterministic organism kinematics and stereo bioacoustic synthesis[5] (Table 1). Across the Lindeman hierarchy, autotrophic primary producers (`L0`) fix solar photosynthetically active radiation (PAR) in diurnal biomes or hydrogen sulfide / methane vent enthalpy in abyssal biomes. Primary herbivores and filter-feeders (`L1`) graze `L0` stocks and detrital snow, supporting mesopredators (`L2`) and apex consumers (`L3`), while detritivores and fungi (`L4`) remineralize organic detritus back into bioavailable inorganic nutrients.

Table 1. Core Rust Modules Inside crvscience-trophic-hearth v0.9.3

Source File	Subsystem Role
`src/trophic.rs`	Nine `BiomeKind` definitions, keystone guilds, five-tier (L0–L4) energy ledger, GPP/respiration & nutrient budgets.
`src/organisms.rs`	Species life-history catalog across terrestrial canopy, kelp, reef, lake, tidepool, brine seep, and abyssal vents.
`src/world.rs`	Fixed-step ecological integration loop, foraging decisions, predation, keystone removal scenarios, and event stream.
`src/pheromone.rs`	2D spatially diffused alarm, courtship, grazing, and detrital chemotaxis gradient fields on the habitat floor.
`src/physics.rs`	Diurnal solar irradiance, precipitation/foliage wetness, tidal surge, plume updrafts, and vegetated habitat geometry.
`src/audio.rs`	44.1 kHz stereo procedural bioacoustic soundscape synthesis and stereo WAV export synchronized to ecological events.
`src/models_3d.rs` & `src/renderer.rs`	Procedural anatomical 3D mesh builders and native wgpu HDR/offscreen framebuffer renderer (1600 × 1000 PNG capture).
`src/persistence.rs` & `src/main.rs`	Bundled SQLite WAL checkpoint slots, JSON simulation snapshots, and headless CLI `simulate` harness.

Figure 1. Offscreen Headless GPU Capture (1600 × 1000 RGBA): Rocky Intertidal Tidepool



Offscreen GPU capture showing NE Pacific Rocky Intertidal Tidepool (`RockyIntertidalTidepool`) with *Pisaster* sea stars, surfperch, kelp crab grazers, diurnal irradiance slider, and real-time L0–L4 energy bars.

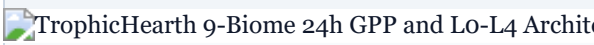
3. Multi-Biome 24-Hour Validation Benchmarks

Running compiled release CLI sweeps (`19_Trophic-Hearth.exe simulate --hours 24 --dt 0.05 --seed 20261116` , 2,880 integration steps per biome) quantifies divergent production regimes across aquatic, intertidal, deep-sea, and forested ecosystems (Table 2; Figure 2). Continuous chemosynthetic oxidation at the 2,600 m black smoker vent sustained **653.46 kcal** cumulative GPP over 24 hours without nocturnal photosynthetic shutoff, surpassing Giant Kelp Forest (**411.85 kcal**), Indo-Pacific Coral Reef (**383.09 kcal**), and Neotropical Rainforest (**360.12 kcal**). Closed-loop microbial and invertebrate decomposition mineralized **6,213.31 mg** to **6,821.60 mg** of inorganic nutrients per 24-hour cycle, supporting total standing community energy budgets between **5,970.04 kcal** (Tidepool, 46 organisms) and **8,110.67 kcal** (PNW Salmon Creek, 30 organisms).

Table 2. Deterministic 24-Hour Nine-Biome Benchmarks (dt = 0.05 s, Seed 20261116, 2,880 Steps)

CLI Biome	Ecosystem	Orgs / Spp	L0 (kcal)	L1 (kcal)	L2+L3 (kcal)	Total Biomass (kcal)	Cum. GPP (kcal)	Mineralized (mg)
`tidepool`	Rocky Intertidal Tidepool	46 / 8	490	3921.0	1425	5970.04	109.87	6213.31
`brine`	Cold-Seep Brine Pool (1,050 m)	49 / 8	640	4620.9	1370	6756.90	240.54	6213.31
`rift`	Midwater Pelagic Rift	48 / 10	540	4480.9	1510	6686.86	265.21	6213.31
`pnw`	PNW Old-Growth Salmon Creek	30 / 10	580	6422.7	1000	8110.67	282.73	6432.90
`vent`	Deep-Sea Hydrothermal Vent	45 / 10	620	5182.4	1300	7234.45	653.46	6382.93
`lake`	Temperate Freshwater Lake	40 / 14	440	4682.1	1085	6325.09	221.20	6449.64
`coral`	Indo-Pacific Coral Reef	45 / 14	460	4383.7	1275	6266.66	383.09	6821.60
`kelp`	Pacific Giant Kelp Forest	50 / 13	510	5624.0	1130	7388.98	411.85	6478.82
`rainforest`	Neotropical Lowland Rainforest	42 / 13	420	4852.1	850	6210.12	360.12	6701.21

Figure 2. Multi-Biome 24h Primary Production & Coupled L0–L4 Architecture

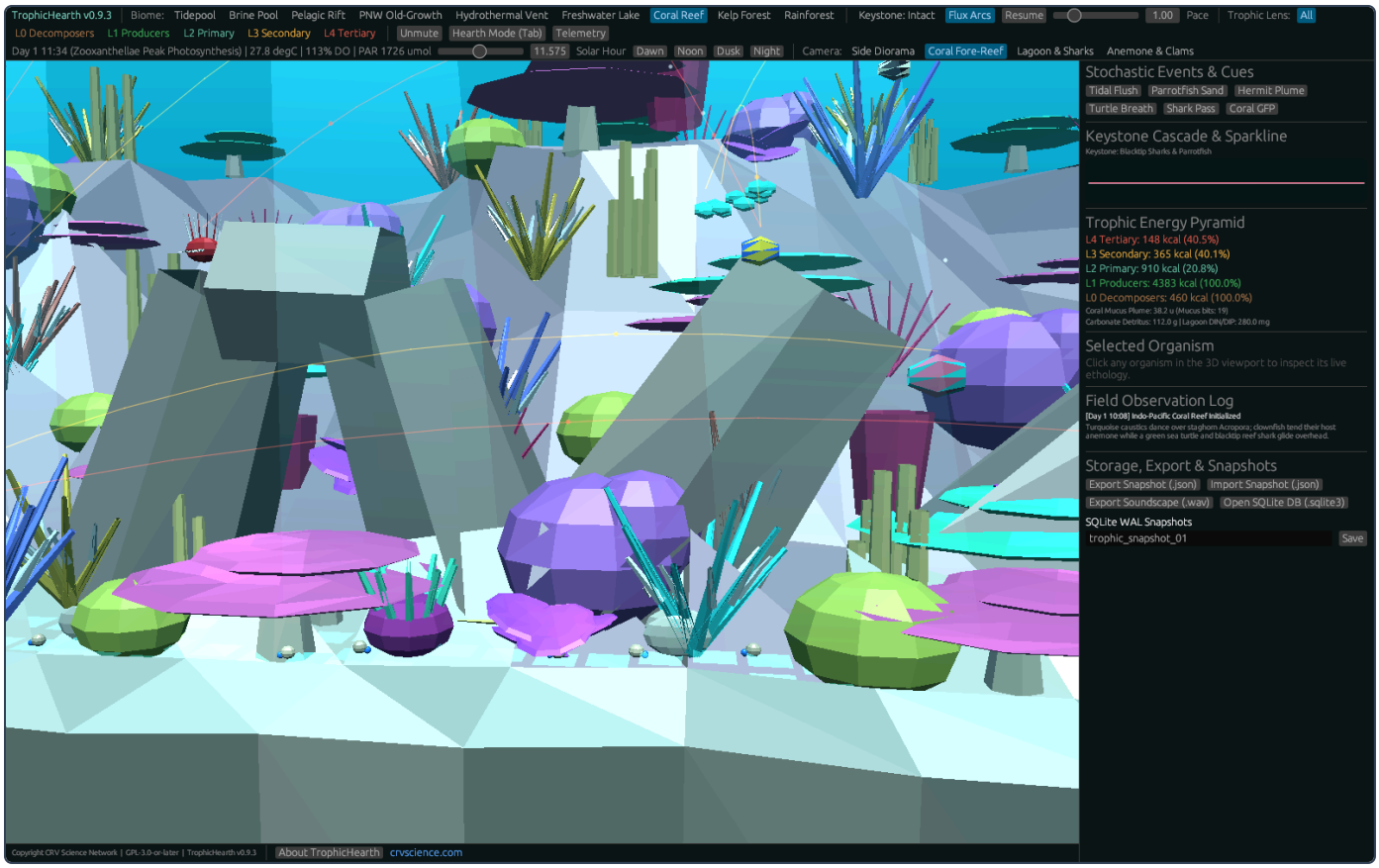


Left: Cumulative 24h GPP (kcal) and total standing biomass across all nine biomes from seeded CLI runs. Right: Closed-loop L0–L4 Lindeman cascade coupled to thermal forcing, pheromone diffusion, and 44.1 kHz stereo soundscapes.

4. Interactive Biome Gallery & Bioacoustic Synthesis

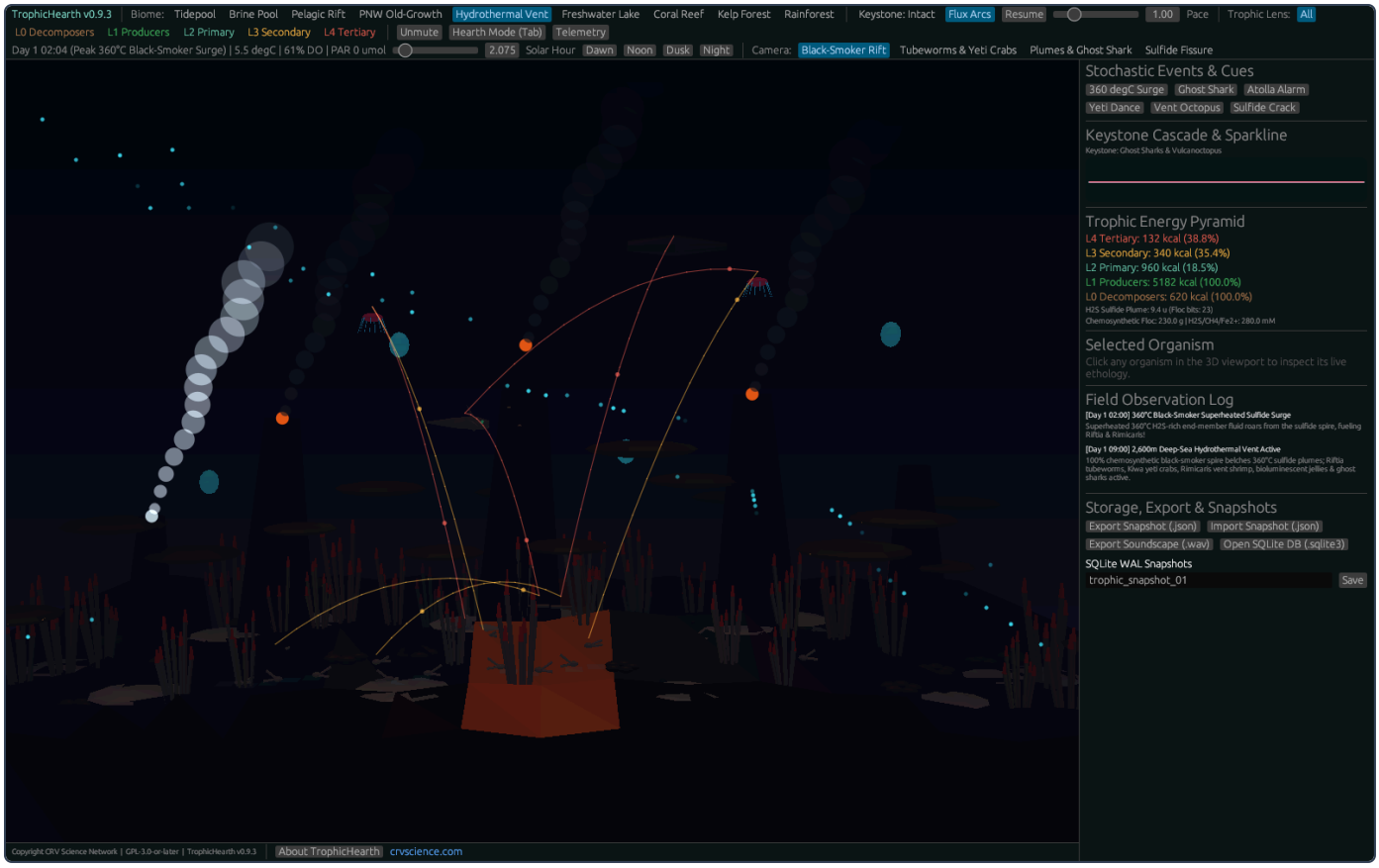
Two additional 1600 × 1000 headless GPU captures illustrate geometric and metabolic diversity across euphotic reefs and abyssal vents (Figures 3–4). In sunlit shallow lagoons (*Indo-Pacific Coral Reef*), GFP-fluorescent scleractinian heads anchor multi-guild herbivorous scraping by parrotfish alongside apex blacktip reef sharks, whereas 2,600 m black-smoker chimneys drive hydrothermal shrimp grazing, tube-worm mutualisms, and benthic chimaera patrols powered entirely by hearth geochemistry.

Figure 3. Headless Biome View: Indo-Pacific Shallow Fore-Reef & Lagoon



Indo-Pacific Coral Reef diorama featuring multi-species reef guild swimming paths, photic depth attenuation, bioerosion cues, and interactive inspection panel.

Figure 4. Headless Biome View: Deep-Sea Hydrothermal Vent (2,600 m Black Smoker)



Deep-Sea Hydrothermal Vent diorama illustrating mineral chimney plume convection, chemosynthetic primary producer beds (653.46 kcal/24h GPP), and benthic megafauna.

5. Discussion

Unifying 3D behavioral animation with strict kilocalorie conservation exposes trophic constraints often obscured in qualitative diagrams: in every simulated biome, herbivore and detritivore biomass (`L1` : 3,921.04–6,422.67 kcal) exceeds combined predator biomass (`L2+L3` : 850–1,510 kcal), while steady detrital remineralization stabilizes nutrient pools against premature washout[1,4]. All 14 integration tests in `tests/simulation_tests.rs` confirm deterministic state transitions, SQLite checkpoint serialization, WAV bioacoustic generation, and keystone-predator perturbation bookkeeping. Current parameterizations intentionally use compartmental guild pools rather than spatial reaction-diffusion biogeochemistry or multi-year life-history demography—domains explored dynamically alongside seasonal population fluctuations in companion CRV Science tools.

6. Software Availability & Network Integration

TrophicHearth (v0.9.3) is released in full safe Rust source under the GNU General Public License v3.0 or later (GPL-3.0-or-later) through the isolated CRV Science Open-Source Apps hub at https://crvscience.com/apps[6–25]. Within the twenty-application Rust network, TrophicHearth pairs naturally with PopBio-Studio for population elasticity and adaptive landscapes, SonoWing for spectrogram bioacoustics, OSABT for ecophysiology, AeroFlyway for nocturnal aeroecology, and ITME for deep-time macroevolutionary transitions.

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