CanopyForge: 3D Isometric Pacific Northwest Old-Growth Watershed Recovery and Ecological Stewardship Simulator in Rust

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Abstract — CanopyForge (v1.0.0) is a hardware-accelerated 3D isometric Pacific Northwest (PNW) old-growth watershed recovery and ecological stewardship simulator written in memory-safe Rust across core library modules under GPL-3.0-or-later licensing. Across a 16 x 16 spatial watershed lattice (256 sectors spanning five ecotypes: Remnant Old-Growth Core, Dense Second-Growth Plantation, Incised Salmonid Creek Corridor, Degraded Clearcut Edge, and Upland Oak-Conifer Meadow Ridge), autonomous restoration crews and canopy LiDAR drones execute budget-constrained treatments—variable-density crosscut thinning, prescribed underburns, invasive suppression, Beaver Dam Analogue (BDA) installation, native mycorrhizal underplanting, and snag cavity creation—while strict site-compatibility invariants guarantee mismatched interventions never degrade ecosystem state. The custom three-pass WGPU renderer renders sculpted continuous terrain over columnar basalt cliffs, 2048 x 2048 directional shadow maps, 4x MSAA HDR lighting, animated dual-wave creek water with woven-willow BDAs, and six articulated PNW fauna guilds (Northern Spotted Owl, Oregon Coast Coho Salmon, North American Beaver, Roosevelt Elk, Marbled Murrelet, and Northern Flying Squirrel). Across 8/8 passing tests and deterministic 15-year CLI sweeps (seed 2026), the watershed Ecological Recovery Index (ERI) rises monotonically from 40.42/100 (Year 1, annual grant USD 278,600) to 55.07 (Year 5), 66.92 (Year 8, replicated at 67.10 on seed 1994), and 77.17/100 by Year 15 (annual grant USD 484,800), with Oregon Coast Coho Salmon recovering to 413.0 / 420.0 K (98.3%).

1. Introduction

Industrial forestry, clearcut edge encroachment, stream incision, and summer drought vapor pressure deficit (VPD) interact across Pacific Northwest catchments in ways linear spread-sheet calculators rarely capture[1,3]. Rebuilding vertical old-growth structure—large multi-cohort conifers, cavity-bearing snags, native sword-fern and mycorrhizal understories, and reconnected Beaver Dam Analogue (BDA) off-channel salmonid wetlands[2,5]—requires decades of sequenced stewardship balanced against annual grant ceilings and wildfire ignition risk[4].

CanopyForge (v1.0.0) models these interacting forest-watershed mechanisms across a 16 × 16 sector terrain in standalone safe Rust (`#![forbid(unsafe_code)]` across core modules) with a hardware-accelerated three-pass `wgpu` renderer and headless CLI audit tooling inside the CRV Science Open-Source Apps ecosystem[6–27].

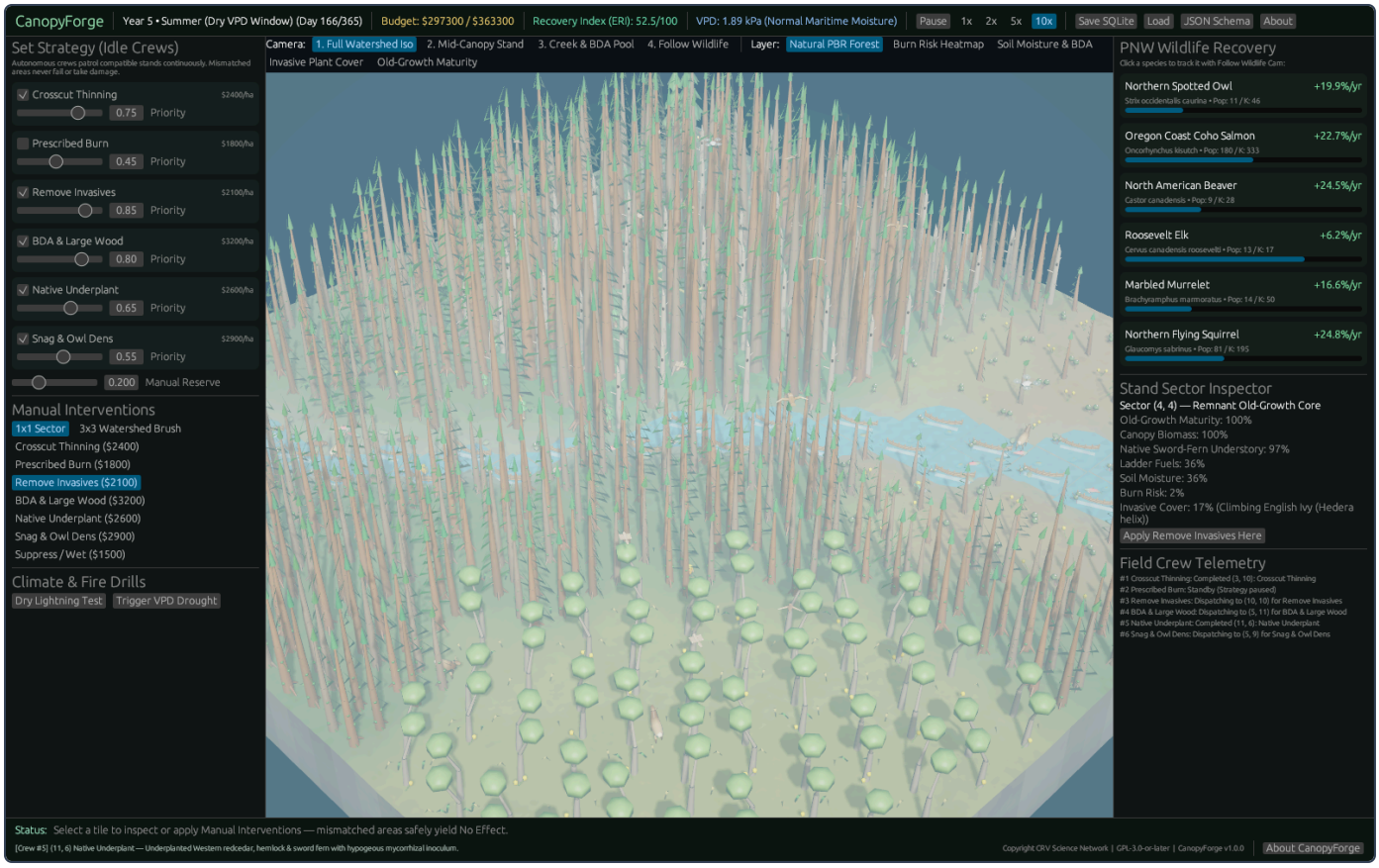
2. Architecture: Three-Pass WGPU Renderer & Zero-Harm Stewardship Rules

Eleven modular Rust files separate continuous-time forest/VPD/fire ecology, six articulated PNW fauna and steward crews, portfolio strategy enforcement, custom 3D mesh builders, GPU shaders, and SQLite WAL save state (Table 1). Each sector stores continuous fractions for old-growth maturity, canopy biomass, native understory, ladder fuels, soil moisture, three invasive species (Himalayan blackberry, Scotch broom, English ivy), riparian BDA/large-wood density, snag cavities, and mycorrhizal inoculation. A central validation invariant enforces **Zero-Harm Stewardship**: attempting incompatible actions (e.g., placing a BDA on an arid upland ridge) yields `No Effect` at zero cost and zero ecological penalty.

Table 1. Core Rust Modules Inside `crvscience-canopyforge` v1.0.0

Source File	Subsystem Role
`src/ecology.rs`	256-tile (16 × 16) 5-ecotype watershed state, seasonal VPD drought hydrology, invasive spread, and probabilistic wildfire dynamics.
`src/strategies.rs`	Six portfolio & manual interventions with strict ecotype compatibility rules and performance-scaled annual stewardship grants.
`src/agents.rs`	Six autonomous field crews, orbiting canopy LiDAR drones, terrain elevation sampling, and 6-species PNW wildlife demography.
`src/models_3d.rs`	Procedural 32 × 32 continuous terrain, columnar basalt cliff skirt, 6-species anatomical wildlife geometry (90+ verts each), conifers, oaks, and BDAs.
`src/wgpu_renderer.rs` & `src/shaders/`	Three-pass `wgpu` pipeline: 2048 × 2048 directional shadow map, 4× MSAA `Rgba16Float` HDR PBR, procedural 3D noise, and ACES tonemap.
`src/persistence.rs` & `src/app.rs`	SQLite WAL save slots, JSON schema export/import, interactive isometric HUD, and offscreen 1600 × 1000 GPU capture harness.

Figure 1. Offscreen Headless WGPU Capture (1600 × 1000 RGBA): Full 16 × 16 Watershed Isometric View



Year 5 summer full-watershed view displaying Remnant Old-Growth Core conifers, Upland Oak ridge in the foreground with foraging Roosevelt Elk, meandering Riparian Salmon Creek with installed BDAs, crew dispatch telemetry, and live wildlife carrying-capacity bars.

3. Multi-Year Recovery & Carrying-Capacity Benchmarks

Running compiled release sweeps (`22_CanopyForge.exe simulate --years N --seed S`) across 1-, 5-, 8-, and 15-year horizons demonstrates sustained ecological succession and multi-species population recovery (Tables 2–3; Figure 2). Under baseline portfolio weights on seed 2026, ERI climbs steadily from **40.42/100** in Year 1 to **77.17/100** by Year 15, scaling annual grant awards from **USD 278,600** to **USD 484,800**. Mean riparian BDA/LWD restoration reaches **100.0%** by Year 8 while mean watershed burn risk drops to **4.20%** at Year 15—even during a `SevereVpdDrought` summer oscillation—and an independent replicate sweep on seed `1994` yields nearly identical Year 8 ERI (**67.10/100**, burn risk **7.68%**, grant **USD 441,100**).

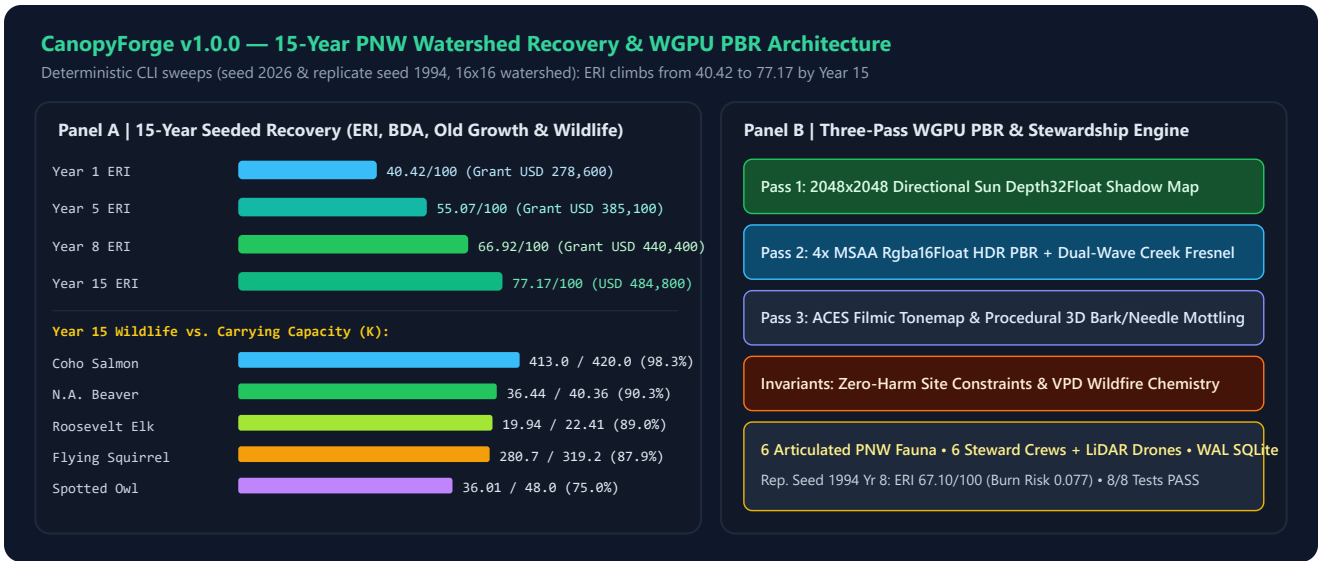
Table 2. Deterministic Multi-Year Watershed Trajectory (Seed 2026, Base Grant USD 140,000)

Horizon	ERI Score	Next Annual Grant	Mean Burn Risk	Old-Growth Maturity	Riparian BDA/LWD	Active Climate
Year 1 (End Y2)	40.42	USD 278,600	3.19%	42.5%	22.9%	WarmDrySummer
Year 5 (End Y6)	55.07	USD 385,100	6.32%	52.4%	78.4%	WarmDrySummer
Year 8 (End Y9)	66.92	USD 440,400	9.29%	59.9%	100.0%	NormalMaritime
Year 15 (End Y16)	77.17	USD 484,800	4.20%	76.9%	100.0%	SevereVpdDrought

Table 3. Year 15 PNW Wildlife Guilds vs. Carrying Capacity *K* (Seed 2026)

PNW Guild	Simulated Count	Carrying Capacity (*K*)	Percent of *K*	Net Trend
NorthernSpottedOwl	36.01	48.00	75.0%	+4.88%/yr
OregonCoastCohoSalmon	413.00	420.00	98.3%	+0.76%/yr
NorthAmericanBeaver	36.44	40.36	90.3%	+3.06%/yr
RooseveltElk	19.94	22.41	89.0%	+2.70%/yr
MarbledMurrelet	44.31	64.00	69.2%	+5.47%/yr
NorthernFlyingSquirrel	280.70	319.18	87.9%	+4.74%/yr

Figure 2. Multi-Year Restoration Trajectory, Wildlife Recovery & Three-Pass WGPU Architecture

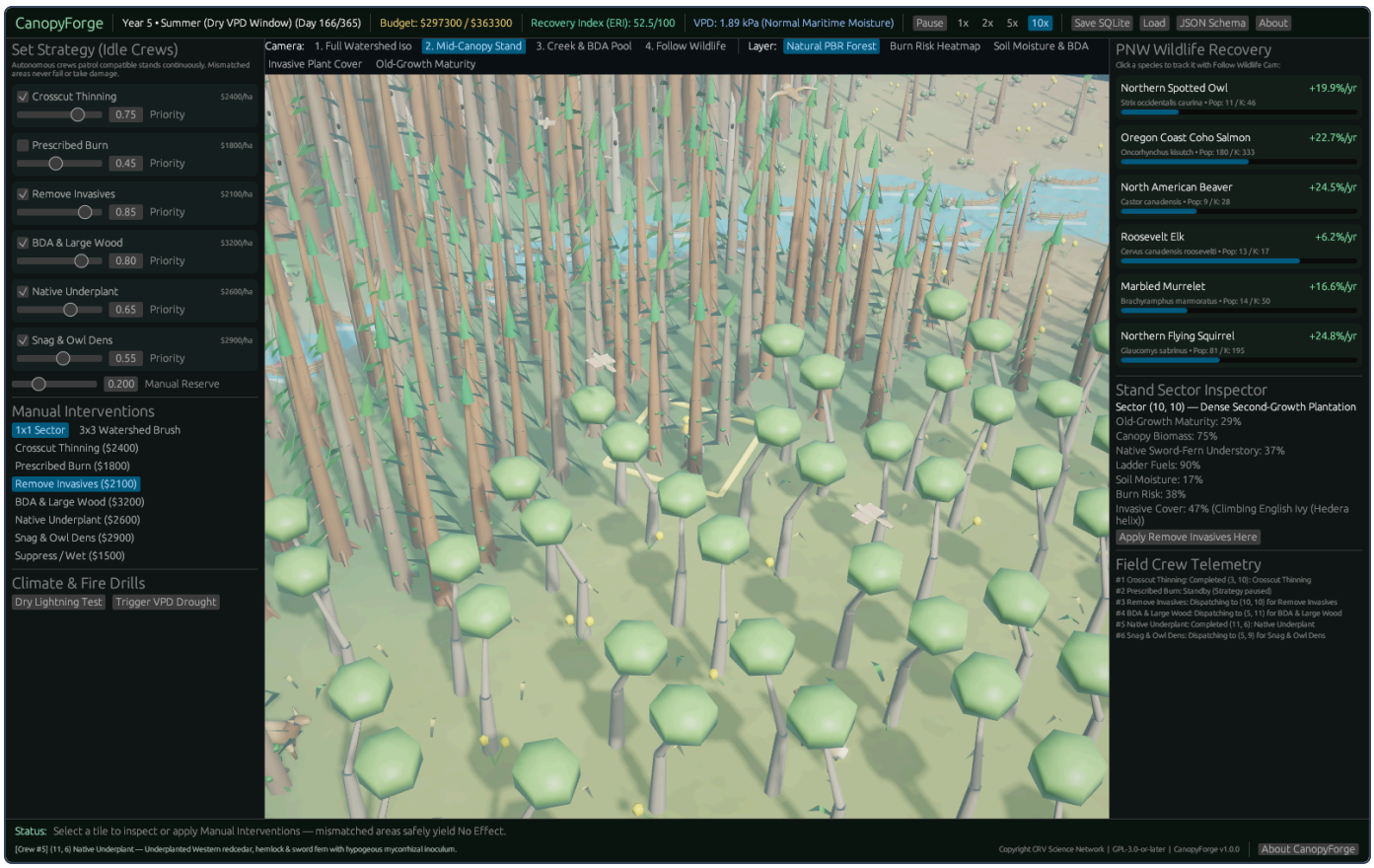


Left: Observed ERI trajectory across Years 1–15 paired with Year 15 wildlife carrying-capacity saturation. Right: Three-pass hardware WGPU PBR pipeline coupled to ecosystem succession and zero-harm stewardship guards.

4. Stand-Scale & Salmonid Creek Zoom Views

Zooming from basin scale into the Mid-Canopy Stand (Figure 3) and the Incised Salmonid Creek Corridor (Figure 4) exposes individual snag cavities, thinning crews, woven-willow BDA stakes spanning gravel bars, red spawning *Oncorhynchus kisutch* (Oregon Coast Coho Salmon), and drinking Roosevelt Elk alongside sectoral invasive and fuel telemetry.

Figure 3. Headless Mid-Canopy Stand Capture: Second-Growth Thinning, Oak Transition & Wildlife



Sector (10, 10) Dense Second-Growth transition showing selected sector rim, vertical canopy stratification, standing wildlife snag cavities, and steward field crew movement beneath an overhead conifer canopy.

Figure 4. Headless Creek & BDA Pool Capture: Woven-Willow Stakes, Spawning Coho Salmon & Riparian Elk



Close-up view of restored Sector (12, 3) Incised Salmonid Creek Corridor (100% BDA/LWD, 88% soil moisture, 1% burn risk) showcasing multi-stake woven-willow BDA structures, illuminated dual-wave pool water, spawning Coho salmon, and Roosevelt Elk along the riparian bar.

5. Software Availability & Network Integration

CanopyForge (v1.0.0) is distributed in full safe Rust source with compilation instructions, 8/8 passing cargo tests, SQLite WAL save support, and JSON validation summaries under GPL-3.0-or-later at https://crvscience.com/apps[6–27]. Together with TrophicHearth (nine-biome trophic energetics), PopBio-Studio (stage-matrix demography), SonoWing (avian/chiropteran bioacoustics), and PelagicGlobe (North Pacific climate forcing), CanopyForge completes an end-to-end Pacific Northwest land-to-ocean modeling suite.

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