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Compounding Crises: Moving Beyond the "Single Stressor" View of Forest Health

Biology * Environment * Climate Change

Introduction: The New Reality of Forest Disturbance

For much of the twentieth century, forest ecology studied disturbance agents -- discrete events that disrupt ecosystem structure and redistribute resources -- in isolation. Fire ecologists characterized burn severity; entomologists mapped bark beetle life cycles; pathologists traced fungal epidemiology; and climatologists modeled meteorological drought. In the Anthropocene, however, these stressors increasingly collide. Synthesizing over 160 recent studies in the Annual Review of Ecology, Evolution, and Systematics, Dudney, Edwards, Harvey, and Seidl (2025) demonstrate that the defining dynamic of modern forest health is the interaction of multiple disturbances, building on broader syntheses of novel disturbance regimes.[1][2]

As anthropogenic climate change shifts thermal and hydrological baselines, it dissolves the buffers that once separated disturbance events. Drought acts as a physiological pre-conditioning event that compromises tree defense chemistry against beetles while lowering ignition thresholds for wildfire; windstorms reorganize fuel loads and microclimates, catalyzing subsequent insect outbreaks or severe burns.[1][3] Whereas natural landscapes historically featured antagonistic (dampening) feedbacks that stabilized forests, current warming overwhelmingly favors synergistic (amplifying) feedback loops.[1][4] From pyrocumulonimbus megafires in western North America to moisture-recycling breakdowns in the Amazon, interacting disturbances push forests past recovery thresholds toward shrublands or non-analog communities.

A Unifying Framework for Disturbance Interactions

To standardize cross-biome modeling, Dudney et al. (2025) classify disturbance interactions into seven structural categories.[1] Linked disturbances occur sequentially when Disturbance A alters the likelihood or severity of Disturbance B -- such as windthrow transferring canopy biomass to the forest floor or western spruce budworm defoliation depleting carbon reserves years before a bark beetle attack.[4][5] Compound disturbances coincide closely in space or time and multiply ecosystem recovery failure, exemplified when post-fire drought kills regenerating conifer seedlings.[6][7]

At the outcome level, synergistic effects occur when combined mortality exceeds the additive sum of individual stressors, such as hotter droughts elevating atmospheric vapor pressure deficit (VPD) alongside soil moisture depletion.[8] Conversely, antagonistic effects buffer subsequent events -- when a severe burn consumes canopy fuel and restricts subsequent fire spread, or when blowdowns remove large-diameter host trees required by beetles.[9] Over time, self-feedbacks describe a disturbance modifying its own recurrence: negative self-feedbacks historically stabilized

forests as fires consumed fuel or insect epidemics exhausted hosts,[10] whereas invasive annual grasses like Bromus tectorum invert this into a runaway positive grass-fire cycle.[11] Finally, bidirectional coupled feedbacks (such as drought and fire mutually reinforcing canopy loss)[6][12] and multi-agent disturbance networks (where cyclones, beetles, fire, and landslides interact nonlinearly)[1] govern landscape regime shifts.

| Interaction Class | | Structural Definition | | Ecological Example | | Climate Change Implication |

| Linked | | Disturbance A sequentially alters Disturbance B. | | Windthrow or defoliation alters fuels or host defenses. | | Shorter intervals erode recovery buffers. |

| Compound | | Closely timed events multiply recovery failure. | | Wildfire + post-fire drought kills regenerating seedlings. | | Frequent heatwaves and fires maximize overlap. |

| Synergistic | | Combined impact exceeds additive sum of agents. | | Hotter drought + bark beetles drive exponential mortality. | | Thermal extremes trigger megadisturbances. |

| Antagonistic | | Disturbance A dampens severity of Disturbance B. | | Prior burn consumes fuel and limits crown fire spread. | | Invasive grasses and extreme weather erode buffers. |

| Self-Feedback | | Disturbance alters its own future likelihood. | | Fire promotes invasive grass that accelerates re-burning. | | Shifts stabilizing negative loops into positive cycles. |

| Coupled Feedback | | Bidirectional loop between two distinct agents. | | Canopy loss and reduced transpiration dry the Amazon. | | Drives tipping points toward savanna states. |

| Disturbance Network | | Multi-node web of cascading causal pathways. | | Drought -> pathogen/beetle -> wildfire -> landslide. | | High connectivity requires causal network modeling. |

Physiological Mechanisms: Hydraulic Failure and Carbon Starvation

The shift from dampening to amplifying interactions is rooted in the xylem hydraulic architecture and carbon defense allocation of individual trees. Process-based models such as SurEau-Ecos-FMC show that Live Fuel Moisture Content (LFMC) is dynamically coupled to leaf water potential ( ).[13][14] As soil moisture depletes during drought, xylem tension becomes increasingly negative until leaves cross their species-specific turgor loss point (TLP), where cellular turgor pressure collapses. Although stomata close to limit desiccation, prolonged heat and high VPD cause rapid foliar dehydration.[13] Once TLP is breached, the canopy transitions nonlinearly from a fire-resistant heat sink into a highly flammable fuel layer.

Simultaneously, stomatal closure halts photosynthesis, forcing conifers to draw down stored Non-Structural Carbohydrates (NSC). Conifers rely on carbon-intensive terpene resins and pressurized resin ducts to expel boring bark beetles.[15] Under protracted drought or repeated defoliation, NSC depletion induces carbon starvation

and collapses resin duct pressure.[15] Empirical studies in sugar pine (Pinus lambertiana) confirm a threshold response: stands appear resilient until water stress crosses a key physiological tipping point, collapsing resin defenses and enabling eruptive beetle mass attacks.[15] Moreover, carbon deficits from western spruce budworm defoliation can persist for a decade, predisposing visually recovered stands to lagged beetle mortality.[5]

| Physiological Trait | | Biological Function | | Role in Disturbance Interaction | | Climate Sensitivity |

| Water Potential ( ) | | Tension of water column in xylem. | | Governs cavitation and canopy fuel moisture. | | Driven by soil drought and atmospheric VPD. |

| Turgor Loss Point (TLP) | | Threshold where leaf cells lose rigidity. | | Triggers rapid LFMC drop and crown flammability. | | More negative values indicate drought tolerance. |

| Resin Duct Pressure | | Physical and terpene barrier in bark. | | Pitches out colonizing bark beetles. | | Collapsed by acute drought and prior defoliation. |

| Non-Structural Carbohydrates | | Stored mobile sugars and starches. | | Energetic reserve for tissue repair and defense. | | Depleted during stomatal closure (carbon starvation). |

| Serotiny & Bark Thickness | | Resin-sealed cones; cambial insulation. | | Post-fire seed release; surface fire survival. | | Short fire intervals cause immaturity risk. |

Biome Trajectories and Methodological Frontiers

Across global forest biomes, these physiological thresholds drive distinct regime-shift risks. In Western North American conifer forests, drought acts as a master driver of the beetle-fire nexus.[16][17] Rather than a static "beetle bomb," linked beetle-fire interactions evolve across outbreak stages: during the 1-3 year Red Stage, desiccated needles and foliar terpenes elevate crown fire potential,[16] whereas in the multi-decade Gray Stage, needle drop reduces crown fire continuity even as fallen snags intensify surface fire heating and soil damage -- a buffer overwhelmed under high-extremity fire weather.[16]

In the Amazon Basin, deforestation, rising VPD, and agricultural fire leakage drive a coupled feedback loop.[18][19] Because tropical trees lack thick bark, low-intensity surface fires kill up to 50% of stems, opening the canopy, increasing understory solar radiation, and weakening the transpired "flying rivers" that recycle regional rainfall.[12] Exceeding 20-25% forest loss risks a self-reinforcing savannization tipping point.[11][12] In high-latitude Boreal forests, serotinous conifers like black spruce (Picea mariana) and jack pine (Pinus banksiana) require 15-25 years to build cone seed banks.[10] When warming shortens fire return intervals below 15 years, immaturity risk obliterates conifer regeneration, shifting stands toward deciduous broadleaf species or open woodlands and destabilizing the boreal carbon cycle.[6][10] Similarly, temperate and boreal windthrow cascades into spruce beetle epidemics and subsequent high-severity burns.[4][8]

| Biome | | Primary Disturbance Agents | | Dominant Interaction Class | |

Regime-Shift Risk |

| Western US Conifer | | Hotter drought, bark beetles, wildfire | | Synergistic & Linked: Drought primes beetles; stage-dependent fuels. | | Moderate-High: Conversion of dry margins to shrubland. |

| Amazon Rainforest | | Drought, fire leakage, deforestation | | Coupled Feedback: Canopy loss weakens moisture recycling. | | High: Savannization tipping point and grass-fire hysteresis. |

| Boreal Forest | | Short-interval crown fire, wind, beetles | | Compound: Re-burning prior to cone maturity (immaturity risk). | | High: Shift from conifer sink to deciduous or lichen woodland. |

| Mediterranean & Temperate | | Heatwaves, drought, windthrow, pests | | Linked & Network: TLP breaches and wind-to-beetle cascades. | | Moderate: Compositional turnover and grass-fire cycles. |

Untangling these non-linear webs requires advanced analytical frameworks. Ecologists use Directed Acyclic Graphs (DAGs) to isolate causal pathways from shared confounders -- separating direct fuel links between beetles and fire from their shared dependence on drought.[20][3] At the landscape scale, network analysis maps forest patches as nodes and disturbances as edges to pinpoint high-centrality hubs where targeted management can sever contagion.[6] Finally, Process-Based Models (PBMs) such as LANDIS-II, FireBGCv2, and iLand simulate mechanistic photosynthesis, hydraulics, and seed bank dynamics under non-analog future climates.[6][21]

Conclusion: Managing for Adaptive Resilience

Interacting disturbances compel a shift from static resistance toward adaptive resilience and managed transition.[1][2] By targeting mechanisms linking stressors, managers can decouple amplifying chains: prescribed burning and thinning reduce fuel connectivity after windthrow and alleviate water competition before beetle outbreaks,[5][15] while assisted migration introduces drought-tolerant genotypes where compound events preclude recovery.[10][22] Sustaining forest biodiversity and carbon storage requires managing forests as dynamic networks.

Updates... (Nov 22, 2026): Replaced HTTP 403-blocked NOAA Institutional Repository link (Ref [7]) with the underlying peer-reviewed Tamm Review paper (Falk et al., May 2022, Forest Ecology and Management, doi:10.1016/j.foreco.2022.120129), clarified online Dec 9, 2022 vs. Feb 2023 print publication on Ruffault et al. (Ref [13]), and retained verified DOIs across Annual Reviews, BioScience, New Phytologist, Forests, Global Change Biology, and Forest Ecology and Management.

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