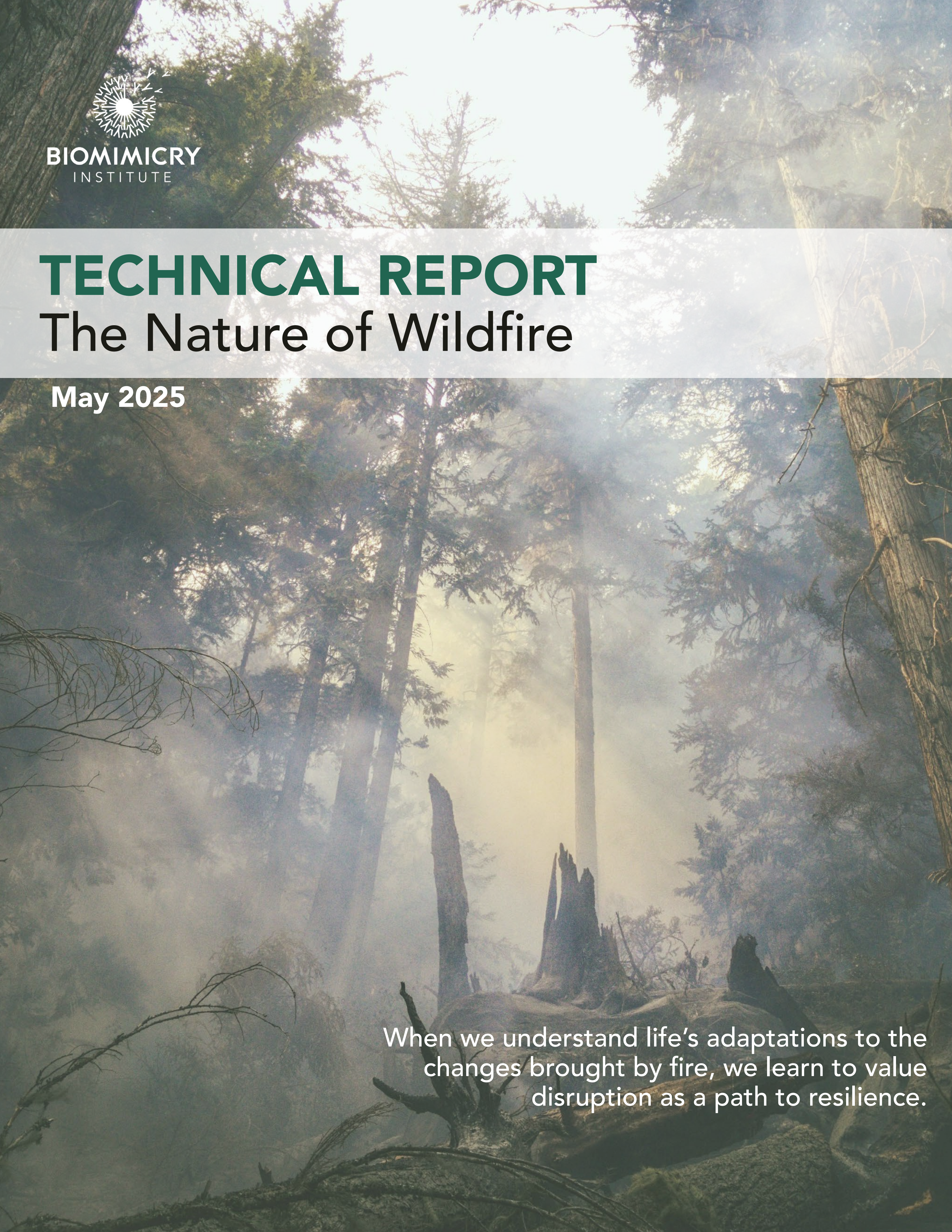
BIOMIMICRY
INSTITUTE

TECHNICAL REPORT
The Nature of Wildfire

May 2025



When we understand life’s adaptations to the changes brought by fire, we learn to value disruption as a path to resilience.

WILDFIRE AS A MODEL, MENTOR, AND MEASURE

In many of Earth's ecosystems, wildfires dance as both destroyer and creator, embodying a cycle of destruction and renewal that is fundamental to many landscapes. Fires are fundamentally a natural force, shaping and rejuvenating ecosystems by clearing debris, enriching soils, and stimulating new growth in newly transformed geographies. For hundreds of thousands of years, humans have intentionally set or controlled fires both small and large to manage the openness of landscapes, the growth of plants, and the movements of animals, often promoting overall ecological stability and biodiversity.

Around the globe, intensive management practices aimed at total suppression of wildfires to protect human interests have inadvertently disrupted this natural balance, including recent and devastating examples in the communities present in Lāhainā in the island of Maui in Hawaiʻi, the communities affected by the various fires in Southern California and Los Angeles, and the communities in New Jersey affected by recent fires, just to name a few. By extinguishing smaller, regular fires, forests have grown denser, accumulating more combustible materials. When fires do occur, they burn hotter and more intensely, often leading to catastrophic outcomes for humans and the rest of nature in wild, rural, and even urbanized areas.

Wildfires are not merely isolated events; they are deeply embedded within complex socio-ecological adaptive systems, which are intricate networks where ecological and social components interact dynamically, adapt to changes, and evolve over time. They can be analyzed through adaptive cycle models that interpret the dynamics of complex ecosystems in response to disturbance and change, where ecosystems move through phases of growth, conservation, release, and reorganization.

Drawing inspiration from these insights, a diverse group of nature-inspired scientists, engineers, designers, artists, and architects have embarked on a journey to reimagine their disciplines through the lens of wildfire resilience. They look to nature's resilient species—such as serotinous pine cones releasing seeds after intense hear, thermophiles surviving heat shock, giant squoias shielded by thick insulating bark, fire beetles laying eggs in burned wood, echidnas reducing body temperature during burns, and gopher tortoises creating fire-resistant burrows—as models for fire-inspired technology, design and systems.

These remarkable adaptations have inspired numerous innovations that benefit humans: biomimetic materials that resist fire and insulate living tissue from heat, architectural designs that integrate fire-resistant materials and natural ventilation systems, and urban planning strategies that embrace green corridors and fire-resistant landscaping.

Beyond technology, there are broader lessons to be learned. Long-lived rituals surrounding fire speak to a deeper connection with the natural world, emphasizing respect, balance, and community stewardship. These enduring practices offer a framework for fire-suppressing societies to reevaluate their relationship with fire, moving from fear and control towards understanding and collaboration.

As the world grapples with the increasing threat of wildfires in a changing climate, embracing wildfire resilience means not just adapting technology and management practices, but fostering a cultural shift. It entails honoring the role of fire in natural ecosystems, applying Indigenous wisdom and practices, and fostering a collective responsibility to coexist with wildfire as a natural phenomenon. [73, 74]

This wildfire-inspired examination is part of a greater understanding where humanity looks to nature as model, as mentor, and as measure. Embracing wildfire resilience requires recognizing that we are an integral part of the ecosystems we inhabit. Our actions, decisions, and technologies must reflect an understanding that we are not separate from nature but deeply a part of it.

In telling the story of wildfire's lessons, the contributors, advisors, and editors of this report—including experts who have studied, researched, and lived with fires—seek not just to innovate, but to inspire a paradigm shift towards a future where human and ecological systems thrive in harmony with fire's regenerative power. Their collective wisdom suggests that this journey extends beyond disaster mitigation to rekindling our connection with the natural world, acknowledging that human well-being is inextricably linked to ecosystem health.

TABLE OF CONTENTS

INTRODUCTION **2**

STUDY CONTEXT **4**
- Biomimicry Launchpad program 4
- Fire-ecology, a primer 4

WILDFIRES AS A MODEL PART 1 .... **6**
- Complex Socio-Ecological Adaptive Systems 6
- Nonlinearity 6
  - Temporal Circularity 7
  - Adaptive systems and ecological succession 7
  - Panarchy 8
  - Pathways of Transition 8
  - Emergence 8
  - Scale 9
  - Self-Organization 9

WILDFIRES AS A MODEL PART 2 .... **9**
- Biological Strategies 9
  - Cellular 10
  - Organismal 10
  - Ecosystem 12
  - Timescales 13
- Emulation and Innovations 13
  - Chemical 13
  - Sensing 14
  - Material 15
  - Built Environment 16
  - Community 16
  - Society 17
  - Organizational 18

WILDFIRE AS MEASURE **20**
- Life's Principles 20
- Adapt to Changing Conditions 20

WILDFIRE AS MENTOR **21**
- Key Takeaways 22
- Conclusion 23
- Acknowledgements 24
- Endnotes 25

CONTEXT OF THIS STUDY

BIOMIMICRY LAUNCHPAD PROGRAM

A group of multidisciplinary and creative individuals came together in the spring of 2024 to learn what they could from wildfire (you can read more about this convening in **this reflection**). This group was not initially aware that they would study this particular phenomenon—they were brought together under the pretext of exploring their individual biomimetic research and design projects in the Biomimicry Institute's Launchpad Program. None of them were experts in fire ecology—they consisted of environmental engineers, fashion designers, and biochemists. The Institute runs multiple programs like this designed to maximize collaborative discovery. Essential to this process is the immersion of diverse and multidisciplinary individuals in untamed environments, prioritizing relational dynamics over task-oriented approaches, and facilitating diverse experiences. These collaborators were gathered in a larch forest in the Northern Rockies, an ecosystem shaped by centuries of wildfire. The insights gained from this collaboration extend beyond individual research projects, offering crucial lessons for global wildfire adaptation and ecosystem management. To frame these lessons, the group turned to a powerful paradigm for understanding nature's wisdom: Biomimicry.

In an epigraph to her book, "Biomimicry: Innovation Inspired by Nature," Janine Benyus puts forward three fundamental principles for our relationship with nature [1]:

1. Nature as model. Biomimicry is a new science (and ancient practice) that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems (e.g., a solar cell inspired by a leaf).

2. Nature as measure. Biomimicry uses an ecological standard to judge the "rightness" of our innovation. After 3.8 billion years of evolution, nature has learned what works, what is appropriate, and what lasts.

3. Nature as mentor. Biomimicry is a different way of viewing and valuing nature. It guides us towards an era based not on what we can extract from the natural world, but what we can learn from it.

Armed with these principles, the group approached wildfire through Benyus's triple lens—as model, mentor, and measure—while adapting the framework to their unique context. Given the complexity of wildfire systems, they first stepped back, examining fire's role across scales: from cellular adaptations to global ecosystems.

FIRE-ECOLOGY, A PRIMER

Fire holds a significant role in nature. A complex phenomenon, it is a catalytic process needed to cycle energy through an ecosystem [2]. Fire defines ecology. Even low-fire frequency is an important categorization indicator in ecologies. Fire is a vital evolutionary enabler, accelerating adaptation processes across species and biomes. Analogous to an herbivorous consumer, fire stands as one of Earth's most transformative forces. As a bioregion-defining phenomenon, it has sculpted landscapes, directed the evolution of species, shaped economic trajectories, and influenced the rise and fall of civilizations [3, 4].

The words we ascribe to fire are significant. The term "wildfire" itself—popularized in English-speaking countries—implies fire operating beyond human control, reflecting a Western paradigm that often frames natural fire as a force to be tamed rather than an essential ecological process [4]. Often the type of landscape being burned is used when categorizing fires, as in "forest fire" or "brush fire." The ecosystem-specific names of fire portray their endemic importance; each bioregion has a different relationship to fire. The communities within these bioregions coevolve with fire, creating unique lived experiences. This is seen in the way Aboriginal communities coexist with fire, even working with it to shape the terrain, optimize food production, and strengthen their endemic relationships to land [3]. Fire science has developed its own precise and

Image Credit: Jen Fredette, The Biomimicry Institute

anthropomorphic vocabulary to understand fire, and breaks fire and its aspects down anatomically for our own equivalences. The "head" of a fire is the area of highest burning intensity often occupying the windward side of the burn. The "flank" and "heel" of the fire extend to the sides and back of the "head", with lower temperatures and voracity. A "fingers" are long and narrow extensions that create spot fires through ember transport and heat transfer ahead of the primary burn area. The flame front advances as the fire spreads to available fuel. A surface or ground fire burns the fuels on the forest floor, while a crown fire ignites the canopy of the forest, consuming aerial fuels. The fire regime refers to the cyclical occurrences of fires within an ecosystem. High-frequency fire regions experience one fire every five years, while low-frequency fire regions experience fires every fifty years [2].

Understanding fire's role in ecosystems requires us to think in systems and cycles. Fire within an ecosystem exemplifies an adaptive cycle—a framework for understanding how systems respond to disturbance and change. This cycle moves from growth toward conservation, marked by increasing biomass accumulation. When stored energy reaches a critical threshold, disturbance triggers a release phase, freeing energy and enabling system reorganization before growth begins anew [5]. Fire acts as a disturbance whose impact depends on both intensity and scale. In ecosystems where fire regimes operate naturally, periodic burns maintain system resilience, allowing recovery without triggering major reorganization. However, when fire regimes face suppression, fuel accumulation increases potential fire severity, transforming what might have been a maintaining force into a potentially catastrophic disturbance.

Fire succession highlights the dynamic nature of ecosystems and their ability to regenerate through a series of predictable and adaptive stages, as seen in the graphic above and described below:

1. It begins with the initial disturbance of the fire, which clears away vegetation and alters the soil.

2. In the immediate aftermath, pioneer species such as grasses and fireweed quickly colonize the bare, nutrient-rich soil, stabilizing it and preparing the ground for more complex plant communities.

3. Over time, shrubs and small trees establish themselves, leading to the gradual reappearance of a mature plant community.

4. This progression continues until the ecosystem reaches a stable, climax state, where species composition and structure resemble those present before the fire, but often with enhanced biodiversity and ecological resilience.

Fire has shaped evolutionary pathways across temporal and spatial scales throughout Earth's history [4]. Just as different communities have different relationships to fire, so do organisms within the ecosystem. Species experience fire with vastly different perspectives and scales, with fire-suppressing human cultures seemingly unique in their goal of extinguishing its existence [2]. Some species rely on fire to trigger life-cycle events like germination and reproduction, while others take advantage of the post-fire regrowth and low competition for food sources. Others have adapted to fiery landscapes through heat-resistant scales, hides, and barks. While communal species build fire-proof tunnels and mounds, clonal plants develop underground root systems ready to regrow once the blaze has passed. This diverse roster of adaptations shows us not one right way to relate to fire, but many—as diverse and unique as the bioregions, communities, cities, and civilizations present on Earth.

The interactions between human societies and wildfires are complex and often reciprocal. Human actions such as deforestation, land use change, and fire suppression can alter natural fire patterns, increasing the likelihood of severe wildfires. Conversely, wildfires can have profound social and economic impacts, influencing land use policies, community planning, and emergency response strategies. For instance, aggressive fire suppression techniques, while aimed at protecting human assets, can lead to an accumulation of combustible materials in forests, setting the stage for larger and more intense fires in the future. This illustrates a harmful cycle, where short-term solutions create greater long-term risks.

These relationships demonstrate how human and other systems continuously influence each other. The adaptive cycle, described by Holling in 1986 [6], helps us understand how communities and ecosystems they belong to respond to major changes like fire. Through this perspective, wildfires aren't isolated events but part of a larger pattern, where human decisions and natural processes affect each other in ongoing cycles. Understanding wildfires this way reveals the deep connections between human communities and the landscapes they inhabit.

WILDFIRE AS A MODEL PART 1

COMPLEX SOCIO-ECOLOGICAL ADAPTIVE SYSTEMS

Complex socio-ecological adaptive systems are characterized by the interconnectedness and interdependence of social (human) and ecological (natural) components. These systems are complex because they involve multiple interacting components that can lead to unpredictable behaviors and outcomes. They are adaptive because they respond to internal and external changes through feedback mechanisms, learning, and adjustments. Consider a forest ecosystem and its neighboring communities: residents harvest timber, manage recreation, and make fire management decisions that directly affect forest health. In turn, the forest's condition influences community safety, economic opportunities, and quality of life. These ongoing interactions create cycles of influence between human decisions and natural processes.

In these systems, resilience and adaptability are key concepts. Resilience refers to the system's ability to absorb disturbances and still retain its basic function and structure, while adaptability is the capacity of actors within the system to manage resilience through learning, flexibility, and self-organization. The dynamic interactions within these systems mean that changes in one component can have cascading effects on others, making management and prediction challenging.

Some defining characteristics of these complex systems include nonlinearity, emergence, scale, and self-organization [7]. The following offers a look at wildfire through these four lenses.

NONLINEARITY

In the context of complex adaptive systems, nonlinearity refers to the idea that relationships between elements within the system are not proportional or straightforward. In other words, a small change in one part of the system can lead to disproportionately large or unexpected effects elsewhere, and vice versa. This nonlinearity makes complex adaptive systems unpredictable and challenging to manage or control using traditional linear approaches, where cause and effect are assumed to be directly proportional.

Nonlinearity was a concept that first appeared in this study when examining the ecological succession associated with wildfire. Ecological succession is the process of change in the species that make up an ecological community over time, and disturbances like wildfire play a defining role. But as we will explore later through the lens of scale, complex systems include subsystems nested within larger subsystems, and phenomena at each level of the scale tend to have their own properties, as well as feedback loops that inform one another.

TEMPORAL CIRCULARITY

Throughout human history and around the world today, different cultures think of time in various ways. While Western societies often emphasize a linear view of many traditions—including Hindu philosophy and various Indigenous cultures of the Americas. Many view time as a series of repeating cycles: the changing of seasons, the phases of the moon, the cycles of birth, death, and rebirth. This cyclical view is often rooted in observable natural patterns, where the end of one cycle naturally leads to the beginning of another. [71, 72, 73, 74] It's a worldview that emphasizes renewal, repetition, and balance rather than linear progress or decline. [71, 72] This cyclical view can be seen in mythologies, religious rituals, and agricultural practices where the focus is on recurring seasons, harvest cycles, and natural regeneration. [55] It has influenced human communities and their fire-management and fire-related practices around the world. In North America for example, the Anishinaabe have cultivated their habitat in collaboration with fire to discern the best moment to harvest blueberries, while the Lakota have used larger fires to drive and hunt bison and clear campsites seasonally. Industrialization brought standardized time measurement to many societies. However, numerous cultures maintain different relationships with time, integrating both cyclical and linear concepts. Aboriginal Australian, many Asian, and various Indigenous peoples continue to embrace temporal frameworks that don't prioritize linear progression. In fact, intergenerational thinking emphasized in Indigenous communities may be seen as both a cause and effect of their ability to consider and interpret these cycles and adaptive structures over longer timescales.

ADAPTIVE SYSTEMS AND ECOLOGICAL SUCCESSION

Understanding the cyclical aspects emphasize a linear view of time can profoundly influence how we perceive natural processes such as wildfires and ecological succession. In the linear view, wildfires are often seen as disasters—devastating interruptions that push us backwards from the progress we've made. This perception fuels a desire to prevent, control, and suppress fires at all costs, aiming to maintain a constant state of growth and stability that aligns with a linear progress narrative.

Wildfires are a critical disturbance that exemplifies the complexity of socio-ecological adaptive systems. They are influenced by various factors, including climate conditions, vegetation types, land management practices, and human activities such as urban development and fire suppression efforts. Wildfires can act as a natural regulator within ecosystems, promoting biodiversity, nutrient cycling, and habitat renewal. However, when situated in a human context, wildfires can also pose significant threats to lives, property, and livelihoods.

If we adopt a cyclical perspective, wildfires can be seen as a necessary and natural part of ecological renewal. Just as time cycles through seasons, ecosystems cycle through stages of growth, disturbance, and regeneration. Wildfires, in this context, are not aberrations but integral phases that clear dead material, return nutrients to the soil, transport microbes vast distances through the atmosphere as part of the aerobiome, and trigger the growth of fire-adapted species like the Western larch. This cyclical understanding aligns closely with the concept of ecological succession, where an ecosystem moves through a series of stages after a disturbance—starting with pioneer species, advancing through intermediate stages, and eventually reaching a mature community. This process is not a straight line of progress but a loop that can be reset by disturbances like fire. These cycles have been well studied and generalized within complex adaptive system theory. In the following sections we'll dive into technical details and terminology useful for fully exploring these concepts.

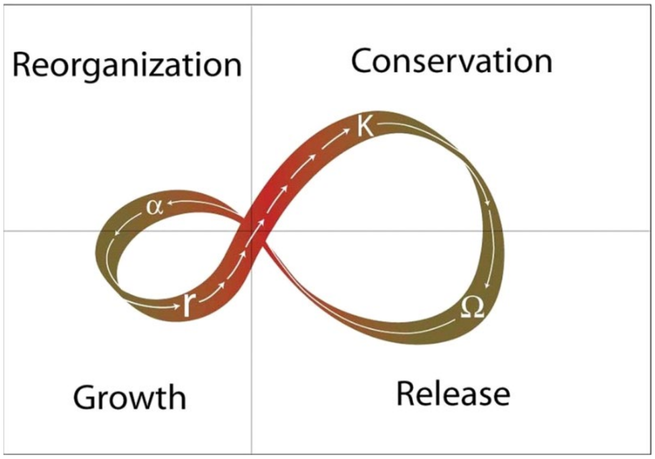
PANARCHY

Panarchy is a framework that describes the interconnected, dynamic cycles of growth, accumulation, restructuring, and renewal in natural and social complex adaptive systems [54]. It emphasizes that systems operate at multiple scales and are constantly adapting and evolving through interactions between these scales. Panarchy provides a way of understanding how complex systems—whether ecological, economic, or social—behave over time. It is built around the adaptive cycle, which includes four phases:

1. **Growth (r-phase)**: Rapid growth and colonization
2. **Conservation (K-phase)**: Slower growth with accumulation of resources and increased stability.
3. **Release (Ω-phase)**: A disruptive phase where

resources are released through disturbance (e.g., fire, financial collapse).

4. **Reorganization (?-phase)**: A creative phase where new opportunities emerge, allowing the system to reconfigure and adapt.



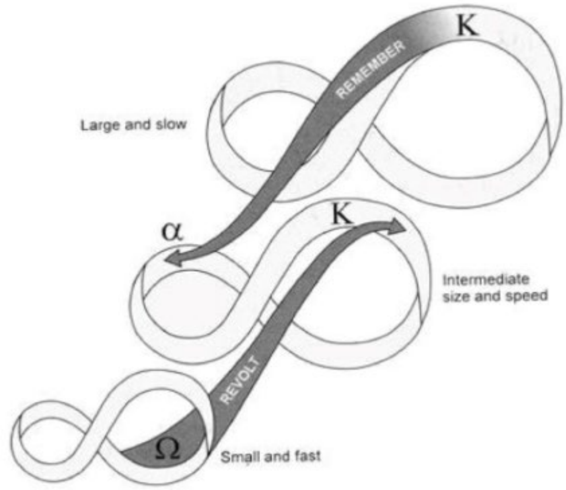
These phases are not linear but cyclical, and they occur across multiple scales. A key insight of panarchy is that the resilience and adaptability of a system depend on its ability to navigate these cycles at different scales—both temporal and spatial.

Panarchies themselves, including multiple nested systems, are dynamic and change as system processes and structures at different scales move through the adaptive cycle [8]. This change can come about through two primary pathways of transition: revolt and remember.

PATHWAYS OF TRANSITION

The revolt pathway occurs when a system at a smaller, faster scale (e.g., a local ecosystem) experiences a rapid release or collapse (the "release" phase of the adaptive cycle) and disrupts a connected system at a larger, slower scale (e.g., a regional or global system). This pathway represents a bottom-up influence where smaller-scale changes trigger broader, often destabilizing impacts on larger systems. For example, a local wildfire (small scale) can escalate into a regional crisis affecting larger landscape management policies. Revolt is characterized by cascading effects that can destabilize higher scales, potentially leading to larger systemic shifts or collapses.

The remember pathway involves the influence of larger, slower scales on the reorganization of smaller, faster scales. After a collapse or release phase, the smaller system can reorganize by drawing on resources, knowledge, and structures from the broader system. This pathway represents a top-down stabilization influence where the memory of the larger system (e.g., seed banks, institutional knowledge, or species pools) helps the smaller system to reorganize and recover. The remember pathway helps maintain resilience by ensuring that despite disturbances at the lower scale, the system can reorganize in a way that reflects and retains the broader context and legacy of the larger, stabilizing system [8].



[5]

These pathways illustrate the dual forces of connectivity and hierarchy in complex adaptive systems, showing how systems can either destabilize larger structures through revolt or recover and stabilize through remembering. Understanding these pathways aids in managing resilience and adaptability in socio-ecological systems.

EMERGENCE

One consequence of nonlinearity is emergent behavior, where the collective outcome of interactions among system components cannot be simply deduced from the behavior of individual parts. Emergent properties are a hallmark of complex adaptive systems, such as the emergence of traffic jams from the individual actions of drivers or the spread of wildfires due to the interaction of weather, vegetation, and human activities. Emergent properties, which are system-level behaviors that arise from interactions at lower scales, often depend on scale. What appears as noise or random at a small scale may reveal patterns or stability at a larger scale. For instance, the collective behavior of a swarm of insects emerges from simple rules followed by individual insects at a smaller scale [56].

SCALE

In the context of complex adaptive systems, scale refers to the levels or dimensions of analysis that can be used to examine and understand the system. These levels can be spatial, temporal, or organizational, and they represent the different sizes, timeframes, or hierarchies within which a system operates. Understanding scale is crucial because complex adaptive systems exhibit different behaviors, dynamics, and interactions at different scales, and changes at one scale can influence outcomes at others.

Spatial scale refers to the physical size or extent of the system being studied, ranging from local to regional, global, or even broader scales. Temporal scale involves the timeframe over which processes and interactions occur, ranging from short-term (seconds, days, or years) to long-term (decades, centuries, or millennia). For example, a single tree's fire resistance through its bark structure operates at a local scale, while heat and smoke-triggered seed germination across a landscape works at a regional scale, and fire-driven weather patterns function at continental scales. Temporal scale involves the timeframe over which processes occur, from immediate responses (seconds to days) to long-term changes (decades to millennia). Organizational Scale refers to the hierarchical levels within a system, from individual components (e.g., cells, individuals) to groups, organizations, or entire ecosystems and societies.

Scale plays a critical role in the resilience and adaptability of complex adaptive systems. A system's ability to absorb disturbances, adapt, and continue functioning can depend on the interactions and feedback across different scales. Adaptive management strategies often involve recognizing how resilience at one scale (e.g., a local community) can contribute to or detract from resilience at a broader scale (e.g., a regional ecosystem).

SELF-ORGANIZATION

Self-organization in the context of complex adaptive systems refers to the process by which a system spontaneously forms ordered and coherent structures, patterns, or behaviors without centralized control or external direction. In self-organizing systems, order and complexity emerge from the interactions among individual components or agents following simple rules, often leading to higher-level coordination or organization.
In wildfire ecology, self-organization refers to the way ecosystems naturally reorganize and adapt after a wildfire without centralized control. This process involves various species and environmental factors interacting locally to create new patterns of growth, structure, and function within the ecosystem [23].

WILDFIRE AS A MODEL PART 2

For our launchpad group, after situating wildfire within the context of complex adaptive systems across scales of space and time, it was time to slow down and listen to the lessons that wildfire had to teach. We begin at the smallest spatial scales, examining biological adaptations that emerged over evolutionary time—from cellular responses to organism-level strategies for fire survival. The group was searching for insights directly from fire-ecology, but also from related phenomena like heat resistance. Here, we will start by examining the small spatial scale, and look next at emergent properties that evolved over long periods of time, biologically speaking.

BIOLOGICAL STRATEGIES

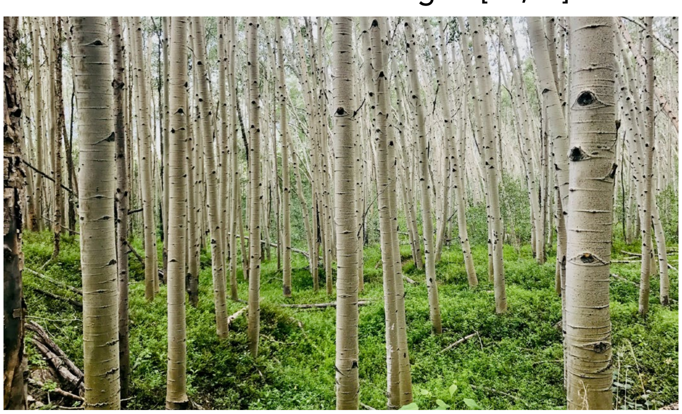
Complex socio-ecological adaptive systems are characterized by the interconnectedness and interdependence of social (human) and ecological (natural) components. These systems are complex because they involve multiple interacting components that can lead to unpredictable behaviors and outcomes. They are adaptive because they respond to internal and external changes through feedback mechanisms, learning, and adjustments. Consider a forest ecosystem and its neighboring communities: residents harvest timber, manage recreation, and make fire management decisions that directly affect forest health. In turn, the forest's condition influences community safety, economic opportunities, and quality of life. These ongoing interactions create cycles of influence between human decisions and natural processes.

CELLULAR

At the cellular level, a variety of biological adaptations are known to confer unusual heat tolerance to certain organisms. Thermophiles are species known to live or survive at high temperatures, many examples of thermophiles are microorganisms, such as archaea and bacteria [9], [10]. Adaptations that enable these species to live under these extreme conditions impact the entire organism including a reduction in genome size, the acquisition of genomic and protein characteristics that increase molecular stability at higher temperatures, as well as changes to the cell membrane and much more [9], [10].

Beyond thermophiles, many species can temporarily survive unusually high temperatures through heat shock response—a well-studied biological survival mechanism. When exposed to high temperatures, cells activate specific genes that help them cope with heat stress. For example, cells produce heat shock proteins that act like molecular "bodyguards," protecting other proteins and RNA from heat damage [11,12,13]. This protective response has been maintained throughout evolution and activates not only during heat stress but also during other types of cellular stress [11,13]. Recent research shows that during heat shock, cells not only increase production of protective proteins but also reduce the production of non-essential proteins to focus cellular resources on survival [12].

While cellular heat shock responses help organisms cope with temperature stress, surviving actual wildfire is a good bit more extreme and requires robust adaptations—the intense heat of flames far exceeds what most cells can tolerate, even with heat shock proteins activated. Species have evolved various strategies to survive fire, particularly in fire-prone ecosystems. Plants showcase diverse adaptations: ponderosa pines develop thick, insulating bark; serotinous cones protect seeds until fire triggers their release; and plants like aspen maintain underground rhizomes that can sprout new growth after fire passes [14, 15]. However, these fire adaptations often come with trade-offs. For example, some fire-adapted plants show reduced drought tolerance, suggesting that species must balance different survival strategies [14,15].



ORGANISMAL

Many organisms have evolved to either depend on fire or exhibit remarkable resilience to it, making fire a critical element in their life cycles or survival strategies. These species, whether they are plants, trees, animals, or microorganisms, have adapted to thrive in environments where wildfires are a natural and recurring phenomenon.

Some of the most striking examples of fire-dependent organisms are trees and shrubs. Serotinous trees, those with heat-triggered seed release, like the lodgepole pine [22], have cones that remain sealed tightly until exposed to the heat of a wildfire. When fire comes, the intense heat triggers the cones to open, releasing seeds into the nutrient-rich, newly cleared landscape [21, 22]. Similarly, eucalyptus trees, with their fire-activated seeds and resprouting capabilities, take advantage of post-fire conditions to regenerate [45]. Many shrubs in Mediterranean climates rely on fire to crack their hard seed coats, ensuring germination only happens after fire has cleared away competition [15]. Grassland species have also adapted to fires. Bluestem grasses [49] have deep root systems that can withstand fire, and the burning of old growth fertilizes the soil, encouraging new growth.

Trees in fire-prone ecosystems often exhibit impressive fire-resilience rather than fire-dependence. Giant sequoias, for instance, are protected by thick, insulating bark that shields them from intense heat and flames. Not only do they survive fires, but the fires help to clear away smaller trees and brush that would otherwise compete for sunlight and water, creating the perfect conditions for new sequoia seedlings to thrive. Similarly, the ponderosa pine has adapted to survive in a fire-maintained ecosystem. Its thick bark and high branches help it withstand low-intensity fires, which in turn help reduce competition and maintain the health of the forest. Cork oaks, native to the Mediterranean, are another fire-resilient species, with thick bark that can regenerate even after being charred by fire.

Animals, too, have found ways to adapt to life in fire-prone ecosystems. Large mammals such as elk, bison, and deer have the mobility to flee from fire, but they also benefit from the new growth that follows in its wake. Fires clear away old vegetation, making room for fresh grasses and shrubs, providing a rich food source for these animals. Some birds, such as the red-cockaded woodpecker and the black-backed woodpecker, depend on recently burned forests for nesting and feeding. They take advantage of the fact that fire clears the way for easier access to insects hidden in dead trees. Even insects have adapted to fire; certain beetles, like the fire beetle of the *Melanophila* genus, are actually drawn to the heat of a fire. They lay their eggs in burned wood, where their larvae can feast on the weakened or dead trees.

Beneath the soil, a world of microorganisms also plays a critical role in fire-adapted ecosystems. Mycorrhizal fungi, which form symbiotic relationships with plants, help plants re-establish after a fire by improving their ability to take up nutrients from the soil. These fungi are key to the rapid recovery of ecosystems following fires. Nitrogen-fixing bacteria, particularly those associated with leguminous plants, thrive in the aftermath of fire. They enrich the soil by converting atmospheric nitrogen into forms that plants can use, accelerating the regeneration process.

In the first wave of recovery after a fire, pioneer plants such as forbs, like fireweed and lupine, emerge to colonize the burned areas. These fast-growing species stabilize the soil and create habitats for other organisms, paving the way for the entire ecosystem to recover and rebuild.

Together, these fire-adapted and fire-resilient organisms form a complex web of life that not only survives fire but, in many cases, depends on it to maintain balance and health in their ecosystems. The following is a non-exhaustive categorical list of fire adapted species, with linked references

Fire adapted species

Reproduction
Black-Backed Woodpecker (*Strix occidentalis*)[16]
Red-Cockaded Woodpecker (*Leuconotopicus borealis*)[17]
Kirtland Warbler (*Setophaga kirtlandii*)[18]
Fire Chaser Beetles (*Melanophila acuminata*)[19]
Prairie Mole Crickets (*Gryllotalpa major*)[20]

Germination & Seed Release [21]
Lodgepole Pine (*Pinus contorta*)[22]
Pinyon Pine (*Pinus edulis*)[23]
Monterey Pine (*Pinus radiata*)[24]
Sugar Pine (*Pinus lambertiana*)[24]
Longleaf Pine (*Pinus palustris*)*[25]
Giant Sequoia (*Sequoiadendron giganteum*)[26]*

Hunting with Fire & Feeding on Post-Fire Vegetation
Black Kite (*Milvus migrans*)[27]
Whistling Kite (*Haliastur sphenurus*)[27]
Brown Falcon (*Falco berigora*)[27]
Black bear (*Ursus americanus*)[28]
American Bison (*Bison bison*)[29]
Elk (*Cervus canadensis*)[30]
Western Swallowtail Butterfly (*Papilio rutulus*)[31]

Fire Resilient Species: How is nature resilient to fire?

Heat Resistant & Self-sacrificial Tree Bark[32]
Sequoia (*Sequoiadendron giganteum*) [58]
Ponderosa Pine (*Pinus ponderosa*)[33]
Lodgepole Pine (*Pinus contorta*)[34]
Sugar Pine (*Pinus lambertiana*)[35]
Longleaf Pine (*Pinus palustris*)[36]
Red Pine (*Pinus resinosa*)[37]
Cork Oak (*Quercus sp.*)[38]
Eucalyptus Trees (*Eucalyptus sp.*)[39]

Fire Resistant Anatomy
American Bison (*Bison bison*)[40]
Echidna (*Tachyglossus aculeatus*) [41]

Fireproof Infrastructure
Gopher tortoise (*Gopherus polyphemus*)[42]
Termites (*Family Termitidae*)[43]
Ants (*Family Formicidae*)[44]

Clonal Root Systems & Lignotubers
Aspen (*Populus tremuloides*)
Eucalyptus Trees (*Eucalyptus sp.*)[45]
Banksia Tree (*Banksia sp.*)[46]
California Chaparral Shrubs (*Adenostoma fasciculatum*)[47]
Kangaroo Grass (*Themeda triandra*)[48]
Bluestem grasses (*Andropogon sp.*) [49]
Switchgrass (*Panicum virgatum*)[50]

Heat resistant
From giant worms [51] that inhabit 150-degree pockets of the deep ocean to desert snails with optimally shaped shells [52] for self-cooling, nature offers numerous examples of heat-resilient creatures from which we can learn lessons in adaptation.

ECOSYSTEM

At the ecosystem level, the relationship between fire and life is a fascinating dance of adaptation and resilience, where wildfires are integral to the health and function of many landscapes [4]. Ecosystems that have evolved in fire-prone areas exhibit a remarkable array of adaptations, allowing them to not only endure but thrive in the presence of periodic fires [14].

In these ecosystems, fire is often a driving force behind ecological succession and regeneration. For instance, certain trees, like the lodgepole pine [22], have developed serotinous cone sealed by resin until opened by fire's heat. This mechanism ensures that their seeds are released into a post-fire environment, where competition is reduced [21, 22]. Similarly, eucalyptus trees have evolved both fire-activated seeds and remarkable resprouting capabilities after fire [45].

Shrublands and grasslands also showcase impressive fire adaptations. In Mediterranean climates, shrubs such as manzanita and ceanothus rely on fire to crack their hard seed coats, allowing them to germinate and take advantage of the post-fire conditions. Grasslands, too, benefit from periodic fires. Many grass species have deep root systems that survive fires, and the burning of old growth helps to fertilize the soil and clear away excess biomass, making room for fresh, healthy growth.

The resilience of ecosystems is not limited to plants. Many animals, including humans, have evolved strategies to cope with fire. Large mammals like elk, bison, and deer have the mobility to escape fires and take advantage of the new, nutrient-rich vegetation that emerges afterward. Birds such as the red-cockaded woodpecker and the black-backed woodpecker thrive in the post-fire environment where they can find an abundance of insects in dead trees. Insects like the fire beetle are drawn to the heat of fires, using the burned wood as a habitat for their larvae.

Beneath the surface, microorganisms also play crucial roles in post-fire recovery. Mycorrhizal fungi, which form symbiotic relationships with plant roots, help plants reestablish themselves by improving nutrient uptake from the soil. Nitrogen-fixing bacteria associated with leguminous plants enhance soil fertility, accelerating the recovery process by converting atmospheric nitrogen into forms usable by plants.

As fires move through landscapes, they create a mosaic of habitats—a patchwork of burned and unburned areas that fosters biodiversity. This spatial diversity supports a range of species, from those that thrive in the early stages of succession to those that prefer more mature environments. This patchwork effect helps maintain a balance within the ecosystem, allowing it to adapt and recover more effectively from disturbances.

Ecosystems also develop feedback loops that regulate fire behavior. For example, some fire-adapted species, like certain types of eucalyptus, produce flammable oils that not only help them survive but also encourage frequent fires. This creates a cycle where fire maintains the habitat structure that these species depend on, ensuring that the ecosystem remains balanced and resilient.

Functional redundancy is another key adaptation. Many ecosystems feature a variety of species that can perform similar ecological roles. This diversity means that if one species is impacted by a fire, others can step in to fulfill critical functions such as pollination, seed dispersal, and nutrient cycling. This redundancy ensures that the ecosystem remains functional and stable, even in the face of disturbances.

Finally, the concept of adaptive fire regimes highlights the importance of fire patterns in maintaining ecosystem health. Different ecosystems have evolved with specific fire regimes—patterns of frequency, intensity, and timing—that are crucial for their balance. Grasslands, for example, often need frequent, low-intensity fires to prevent woody encroachment, while some forests may require less frequent but more intense fires to clear out older trees and promote regeneration. Deviations from these natural fire regimes, whether due to human intervention or climate change, can disrupt the delicate balance of these ecosystems and lead to degradation.

In essence, the interplay between fire and ecosystems is a dynamic and intricate relationship. Fire-adapted ecosystems use fire as a tool for renewal, ensuring that they remain vibrant and resilient through cycles of destruction and regeneration. These adaptations are a testament to the remarkable ability of nature to not only survive but flourish in the face of natural disturbances.

TIMESCALES

Human intervention can significantly alter the natural timescales of complex adaptive systems, especially in the context of fire. For instance, present-day fire suppression policies prevent the regular, low-intensity fires that many ecosystems rely on for nutrient cycling and biodiversity maintenance. This suppression disrupts the adaptive cycle, causing fuel buildup that leads to more intense, catastrophic fires when they do occur [2,4]. Such interventions compress the adaptive cycles, causing accelerated shifts in ecosystem dynamics and selective pressures, ultimately driving rapid, and often maladaptive, evolutionary responses in fire-adapted species.

The Pyrocene is a term proposed by environmental historian Stephen J. Pyne to describe a geological epoch shaped significantly by fire, paralleling the influence of the Anthropocene. This fire-driven era has transformed how fire functions in ecosystems [2, 4], from traditional ecological knowledge that embraces fire as a management tool [3] to present-day fire suppression and land use changes that have altered fire regimes worldwide [4]. These shifts influence everything from local species adaptation [14] to broad-scale ecosystem processes [4], highlighting how fire has become a dominant ecological force through human intervention.

Animals exposed to fire-prone environments show unique evolutionary responses, such as behavioral changes, adaptations in physical traits, and even shifts in coloration [4]. For example, the Peppered moth developed dark morphs to adapt to soot-covered environments during industrial pollution [59]—a phenomenon paralleled in fire-prone areas where color morphism enhances camouflage on charred landscapes. Similarly, certain pygmy grasshoppers have evolved darkened morphs after fires [60], while Temminck's tragopan eggs exhibit fire-influenced coloration to blend in with fire-altered habitats [61]. These adaptations demonstrate how fire exerts selective pressures, leading to rapid evolution as species adjust to survive and thrive amid frequent burns [4].

EMULATIONS AND INNOVATION BY HUMANS

CHEMICAL

Chaperone proteins: Self-Degrading Plastics Inspired by Cellular Processes — Innovation — AskNature

Hero Proteins: A widespread family of heat-resistant obscure (Hero) proteins protect against protein instability and aggregation

Innovative chemicals inspired by fire-dependent species could leverage the unique adaptations these organisms have developed to survive and thrive in fire-prone environments. Here are a few potential examples:

Fire-Activated Germination Compounds: Some fire-adapted plants, like the Australian Banksia or certain pines, release seeds only in response to fire. Chemicals that mimic this fire-triggered germination process, such as compounds activated by heat or smoke (e.g., karrikins, found in smoke), could inspire innovative agricultural or reforestation methods for regenerating crops in harsh environments. [62]

Natural Model:
- Banksia [46] and serotinous pines [21, 22]

use smoke/heat-triggered seed release

Active Applications:
- Seeding Victoria: Smoke-water treatments for restoration
- Kings Park Innovation: Synthetic karrikins for agriculture

Heat-Resistant Protective Coatings: Many fire-adapted species, such as the bark of the giant sequoia, have evolved protective layers that resist high temperatures. Inspired by these natural heat shields, innovative heat-resistant chemicals could be developed for use in building materials, protective clothing, or coatings for electronics that need to endure extreme temperatures. [63]

Natural Model:
- Sequoia and other thick-barked trees' thermal protection [34, 37, 38]

Active Applications:
- Prometheus Materials: Bio-inspired heat-resistant building materials
- Cypris Materials: Biomimetic thermal protective coatings

Fire-Resistant Resins or Polymers: Certain plants produce resins that are not only fire-resistant but can seal wounds or protect the plant after a fire. Inspired by this, fire-resistant polymers or resins could be engineered for industrial applications, such as creating more durable, fire-resistant construction materials or paints.

Natural Model:
- Plant resins for post-fire protection and wound sealing

Active Applications:
- Humble Bee Bio: Developing fire-resistant biomaterials based on native bee biochemistry

Post-Fire Soil Regeneration Chemicals: Some fire-dependent species have evolved to enrich the soil with nutrients after a fire. For instance, leguminous plants that fix nitrogen could inspire the development of chemical fertilizers that mimic this natural process, accelerating soil regeneration in areas affected by wildfires.

Natural Model:
- Leguminous plants' nitrogen fixation [25]

Active Applications:
- MyLand Company: Living soil treatment using biomimetic soil regeneration
- Biome Makers: Soil microbiome solutions for post-disturbance recovery

Thermally Stable Biochemical Signals: Many fire-dependent species use biochemical signals to respond to fire cues (like heat or specific smoke compounds). These signals could inspire the creation of advanced chemical sensors or detectors for fire management systems that respond to heat or smoke at early stages, improving fire prevention or early-warning systems.

Natural Model:
- Fire beetle heat detection [19]

Active Applications:
- Breeze Technologies: Bio-inspired environmental sensors
- N5 Sensors: Advanced chemical detection inspired by natural systems

SENSING

Fire sensing: Fire-chaser beetles are rarely found in forests under normal conditions but are attracted to forest fires in large numbers [19]. They travel great distances, often over 20 km to the fires to mate and lay eggs in burnt conifer trees. They respond to the fires via a pair of specialized sensory organs located next to their legs. This example could inspire: early fire detection systems, distributed sensor networks mimicking beetle sensitivity, long-range fire detection for remote areas, and/or heat pattern recognition systems, infrared sensor technology, ultra-sensitive thermal imaging, low-power consumption detection systems and/or compact sensor design.

Verified Active Applications:
- Dryad Networks: Bio-inspired forest fire detection system using distributed sensors
- Pyri: Bio-inspired and bio-based early wildfire detection system using organic electronics
- Breeze Technologies: Environmental sensors incorporating natural detection principles

MATERIAL

Innovative materials inspired by fire-dependent species could take advantage of the unique adaptations these organisms have developed to withstand or utilize fire in their life cycles[53]. Here are some potential material innovations:

Fire-Resistant Bark Insulation: Inspired by the thick, fire-resistant bark of trees like the giant sequoia or cork oak, new insulating materials could be developed for use in buildings or protective gear. These materials could provide enhanced thermal resistance and protection against high temperatures or flames.

Citations:
- Tree bark fire resistance [34]
- Thermophysical properties of pine bark [37]
- Cork bark characteristics [38]

Verified Active Applications:
- Prometheus Materials: Bio-inspired building insulation
- Thermocork: Natural cork-based fire-resistant insulation

Self-Healing Polymers: Certain fire-adapted plants, such as some pine species, produce resins that help seal and protect wounds caused by fire. Mimicking this natural self-repair mechanism, materials with self-healing properties could be created for industrial applications, such as in coatings, infrastructure, or electronics, where damage repair is crucial.

Verified Active Applications:
- Speck & Speck: Bioinspired Self-Repairing Materials [53]
- Autonomic Materials: Self-healing coatings

Heat-Activated Seed Dispersal Materials: Plants like serotinous pines release seeds only after exposure to the heat of fire. This could inspire smart materials that change their structure or release substances (e.g., medicines or nutrients) in response to heat, useful in controlled-release systems or packaging that reacts to environmental triggers.

Citations:
- Serotinous pine mechanisms [21, 22]
- Seed characteristics [24]

Verified Active Applications:
- ThermoSeed Global: Heat-activated delivery systems

Smoke-Activated Sensors or Coatings: Some fire-adapted species are triggered by chemical compounds in smoke, leading to seed germination or other survival responses. Materials that react to specific smoke chemicals could be developed for fire detection, creating advanced smoke-activated sensors or coatings that respond to early signs of fire.

Citations:
- Fire beetle detection [19]
- Plant smoke response [15, 25]

Verified Active Applications:
- N5 Sensors: Advanced chemical detection
- Dryad Networks: Early forest fire detection

Fire-Resilient Structural Components: The unique structural integrity of fire-surviving trees, such as eucalyptus or fire-resistant proteas, could inspire the development of resilient structural materials that maintain their strength and stability after exposure to high temperatures, ideal for building in fire-prone areas.

Citations:
- Eucalyptus adaptations [45]
- Bark characteristics [34, 38, 39]

Verified Active Applications:
- Prometheus Materials: Bio-inspired building materials

BUILT ENVIRONMENT

Innovations in the built environment inspired by fire-dependent species could enhance fire resistance, resilience, and sustainability. Here are a few examples:

Fire-Resistant Building Materials: Inspired by the thick, insulating bark of fire-resistant trees like giant sequoias, new fire-resistant construction materials could be developed. These could include heat-shielding cladding, insulation, or structural components that protect buildings from wildfires and extreme heat.

Natural Model Citations:

- Tree bark fire resistance [34]
- Thermophysical bark properties [37]
- Bark characteristics and fire resistance [38]

Verified Active Applications:

- Prometheus Materials: Bio-inspired building materials
- Thermocork: Natural cork-based construction materials

Heat-Activated Ventilation Systems: Mimicking the serotinous cones of pine trees that open in response to fire, buildings could incorporate heat-activated ventilation systems that open when exposed to high temperatures, improving air circulation during a fire and reducing smoke damage.

Natural Model Citations:

- Serotinous pine mechanisms [21, 22]
- Pine cone heat response [24]

Self-Healing Facades: Inspired by plants that use resins to seal fire wounds, building facades made from self-healing materials could repair minor damage after exposure to fire or heat. This innovation could extend the lifespan of buildings in fire-prone regions and reduce maintenance costs.

Natural Model Citations:

- Bioinspired self-repairing materials [53]

Verified Active Applications:

- Autonomic Materials: Self-healing coatings

Smoke-Triggered Fire Suppression Systems: Drawing inspiration from fire-adapted plants that respond to smoke chemicals, buildings could be equipped with smoke-activated fire suppression systems. These systems would detect specific chemical compounds in smoke to activate sprinklers or release fire-retardant materials early, improving fire response times.

Natural Model Citations:

- Fire beetle detection [19]
- Plant smoke response [15, 25]

Verified Active Applications:

- N5 Sensors: Chemical detection systems
- Dryad Networks: Early detection networks

Post-Fire Regenerative Landscaping: Inspired by ecosystems that regenerate after fire, built environments could incorporate regenerative landscaping designs with fire-adapted plants and materials. These landscapes would help control post-fire erosion, improve soil health, and create fire-resilient green spaces in urban areas.

Natural Model Citations:

- Plant life-history in fire regimes [46]
- Beaver dams [70]
- Fire ecology principles [4]
- Legume germination post-fire [25]

Verified Active Applications:

- Seeding Victoria: Post-fire restoration
- MyLand Company: Soil regeneration systems

COMMUNITY

"Fire-adaptation is central to the concept of defensible space, which promotes 'morphological changes' to properties such as non-flammable exteriors. However, in nature this concept works only at the landscape level or above. For example, individual fire-adapted Pinus ponderosa trees mixed in with fire sensitive tree species (like *Abies* spp.) are more likely to die than a landscape comprising solely *P. ponderosa* trees. Similarly, an entire community built with defensible space is more likely to survive fire than a single home amidst a community of fire-sensitive structures." Smith 2018

Over millennia, plants, animals, and many early human communities have developed the ability to thrive in fire-prone regions. In trying to answer the question of how humans can learn to coexist with natural fires, the team of scientists sorted biological species into different categories of fire driven existences. According to Dr. Alistair Smith and his colleagues, these approaches include those that avoid fire, those that adapt to better tolerating fire, and those that have become dependent on fires.

In fire-prone ecosystems, certain species provide natural refuges for other animals during wildfires, a phenomenon exemplified by the gopher tortoise in North America [42, 63]. Known as a "keystone species," the gopher tortoise digs deep burrows that serve as fire-resistant shelters, providing protection not only for itself but also for a diverse community of animals [42, 63]. During fires, these burrows offer safe harbor for small mammals, reptiles, amphibians, and insects that would otherwise struggle to survive the heat and flames [42]. By inadvertently creating a multi-species refuge, gopher tortoises play a critical role in preserving biodiversity and supporting ecosystem resilience [4]. This interspecies protection reflects a larger community-based resilience found in nature, where individual species contribute to the survival and adaptability of the larger ecosystem [4].

Such natural fire shelters emphasize the importance of mutual aid in resilience strategies. They illustrate how communities, both human and ecological, can benefit from interconnected structures that allow them to weather disturbances together. Inspired by the tortoise's role, human communities might design shared refuge areas or incorporate resilient infrastructure that similarly supports collective protection during natural disasters. In doing so, we create ecosystems and societies that are better equipped to face environmental challenges with a collaborative approach [42].

SOCIETY

Societies around the world have long relied on principles of resilience, flexibility, and renewal that mirror natural ecosystems' responses to wildfire [3, 4, 64]. One powerful approach is the circular economy, which emulates nature's cycles of decomposition, regeneration, and resource reuse [1, 64]. This model encourages industries to design products for longevity, reuse, and eventual recycling, much like ecological nutrient cycles that return energy and materials to the system [1, 5, 62]. By designing products for disassembly and re-use, companies mimic natural processes, reduce waste, and minimize the need for virgin materials, creating a self-sustaining economic cycle that supports resilience at the societal level [7, 65].

Indigenous fire management practices provide another example of resilience, built on a deep understanding of natural cycles and the role of fire in ecosystem health, resulting in thousands of years of accumulated knowledge and technology. [3].

Aboriginal fire stewardship in Australia, for instance, uses "cultural burns"—controlled, low-intensity fires—to manage vegetation, prevent large-scale wildfires, and promote biodiversity [27, 66]. These practices are guided by knowledge passed down over generations, embodying the "remember" pathway in panarchy, where memory and tradition stabilize and support recovery [5, 7]. Similar methods have been used by Indigenous tribes in North America, where fire is seen as an integral tool for land management [3, 67, 71, 72], supporting ecosystems that thrive under regular, controlled disturbances [4].

In a lot of current urban planning, green infrastructure is inspired by the natural resilience of fire-adapted landscapes [4, 68]. Cities like Singapore incorporate rooftop gardens, urban wetlands, and green corridors that absorb excess rainwater, reduce heat, and support biodiversity [7, 69]. These natural elements provide a buffer against extreme weather, much like how fire-adapted ecosystems contain diverse species that each play a role in withstanding and recovering from fires [4, 5]. This approach exemplifies panarchy's adaptive cycle by integrating flexible, ecological solutions that help cities absorb shocks and maintain functionality during times of stress [5, 7, 54].

The "revolt" pathway in panarchy can inform societal resilience by valuing localized changes that push for broader transformations [5, 7]. These cross-scale interactions mirror ecological systems, where small-scale changes can trigger larger system transformations [5, 54]. After experiencing extreme wildfires, regions have implemented stricter building codes and fire-resistant landscaping practices [4], influencing broader urban planning policies and resilience efforts [7]. This pattern of local adaptation leading to systemic change demonstrates how smaller-scale responses to environmental challenges can drive larger-scale transformations [5, 8].

In many ways, societies that maintain or incorporate nature-inspired resilience–such as circular economy practices, cultural burning, green infrastructure, and grassroots activism–develop to a dynamic model where disturbance leads to innovation. These approaches encourage resilience not as rigid stability but as the capacity to adapt, recover, and transform, creating societies that can navigate an uncertain future with greater cohesion and flexibility.

Circular Economy Models: The release and reorganization phases in panarchy align with circular economy principles, where waste becomes a resource, and products are designed for disassembly and reuse. This mirrors natural nutrient cycles and promotes sustainable production and consumption.

ORGANIZATIONAL

The principles learned from complex adaptive systems, panarchy, and wildfire ecology offer valuable insights for organizations seeking resilience in an ever-evolving world. Embracing adaptive cycles, organizations can incorporate lessons from nature that go beyond efficiency and productivity, instead focusing on fostering structures that are flexible and responsive to change. For instance, in agriculture, understanding how ecosystems recover from disruptions [4, 5] can inspire sustainable practices that emphasize cycles of growth, renewal, and fallow periods [7], enhancing long-term soil health and biodiversity [25, 29]

Diversity and redundancy are fundamental to both ecological and organizational resilience [5, 7]. Panarchy demonstrates how systems maintain stability through multiple pathways for absorbing and adapting to disturbances [5, 54]. This principle can guide organizational design, where structures mimicking nature's redundancy [1] - such as distributed networks and modular systems - create resilience through flexibility and multiple backup systems [7, 8]. Just as ecosystems maintain function through diverse species performing similar roles [4], organizations can build resilience through overlapping capabilities and adaptable structures [7].

Cross-scale interactions are another key feature of panarchy that can inform organizational design [5, 7]. Just as ecological systems benefit from connections across scales [4, 54]—from soil microbes to forest canopies—organizations can enhance resilience by fostering adaptability and collaboration at multiple levels [7, 8]. Urban planning, for instance, can draw on panarchy's insights [5] to design infrastructure that promotes cross-scale interactions [7], benefiting not just individual components but the broader system [4]. This interconnectedness reinforces the stability of the whole, as local innovations reverberate through larger systems [5, 54], creating a resilient network that can withstand stress [7].

The release and reorganization phases of panarchy remind us that resilience is more than stability—it's a dynamic ability to reorganize and innovate. Unlike traditional approaches that aim to maintain a constant state, adaptive systems benefit from change and transformation. Organizations can apply this by creating products or systems designed to be repairable, recyclable, or upgradable, reflecting how natural systems break down and repurpose materials. By adopting this approach, they become more adaptable, capable of responding fluidly to disruptions, and primed for innovation.

Ultimately, the reorganization phase in nature shows that disruption can be a source of creativity and renewal [5, 8]. After ecological disturbances, nature finds new equilibrium [4], often introducing novel species and relationships [7]. Similarly, organizations that embrace reconfiguration [1, 7] gain the flexibility to meet shifting demands. This adaptive approach mirrors the natural world [1], where renewal is a fundamental pathway to resilience [5, 54].
In drawing these lessons from panarchy and wildfire ecology, organizations learn to approach challenges as natural stages in a continuous cycle, transforming them into opportunities for renewal and evolution.

Fire ecology provides valuable insights into the revolt and remember pathways in the conceptual model of panarchy, a framework that explains the dynamic interplay between systems across scales and their cycles of growth, collapse, and renewal.

Revolt Pathway:
The revolt pathway in panarchy describes how disturbances at smaller, faster cycles can destabilize or "revolt" against larger, slower cycles, potentially triggering a collapse or transformation of the larger system [5, 7, 8]. Fire ecology exemplifies this through wildfires [4], where a local disturbance (fire) can cascade upwards and affect the broader ecosystem, landscape, or even human systems [4, 5, 54].

In many fire-prone ecosystems, small wildfires act as disturbances that clear out underbrush and dead vegetation [2, 4]. When these fires are frequent and small-scale, they help maintain balance and prevent the build-up of fuel that could lead to catastrophic fires [3, 4]. However, if fire suppression policies or environmental changes disrupt this balance [4, 33], larger, uncontrollable fires can occur, leading to ecosystem-wide collapse or transformation [5, 8]. This reflects the revolt pathway [5, 7], where a localized disturbance escalates to affect the larger system [54].

The lesson here is that small, contained disturbances are often necessary to prevent larger, system-wide crises. In human systems, this could be seen as embracing smaller disruptions (innovations, organizational changes, or market shifts) to prevent larger, destructive collapses. The absence of small-scale revolts can lead to the build-up of tensions or risks that result in a more devastating breakdown.

Remember Pathway:
The remember pathway describes how larger, slower cycles can influence the recovery and reorganization of smaller, faster cycles following collapse [5, 7, 8]. In fire ecology, this is seen in how ecosystems "remember" their history of fire disturbances and regenerate accordingly after a fire [4, 5]. The soil [25], seeds [21, 22], and surviving species [14, 15] carry the legacy of past fires, guiding the system's recovery and renewal [4, 7].

For example, fire-adapted species such as serotinous pines, which release their seeds only after exposure to the heat of fire [21, 22], rely on the memory of fire disturbances to regenerate the forest [4, 14]. Similarly, nutrient cycling in the soil, enriched by ash from the fire [25], fosters the growth of new plant communities [4, 15]. These regenerative processes reflect the remember pathway [5, 7], where the larger system's memory (the ecosystem's evolutionary adaptations and nutrient dynamics) guides the recovery of the smaller, disturbed area [4, 5, 8].

In human systems, the remember pathway emphasizes the importance of institutional memory, tradition, and learned experiences in guiding recovery after crises [5, 7]. For example, after a system disruption, recovery is often shaped by lessons learned from the past and strategies that have proven effective [7, 54]. This principle is demonstrated in traditional ecological knowledge [3], where generations of experience guide resource management and recovery practices. In this sense, the larger system's memory can act as a stabilizing force [5, 8], ensuring that recovery doesn't occur in a vacuum but is informed by prior experiences [7].

Integration of Revolt and Remember in Fire Ecology: Fire ecology shows that the revolt and remember pathways are interconnected [4, 5]. After a wildfire (revolt) [4], the recovery (remember) is shaped by the larger system's memory of past disturbances [5, 7] and its ability to reorganize in a resilient way [8]. These pathways highlight the dynamic balance between destruction and renewal [4, 5], where smaller disruptions can lead to transformation [54], but recovery is often rooted in the legacy of the larger system [7, 8].

Fire ecology teaches that the revolt pathway allows smaller disturbances to catalyze larger systemic change, while the remember pathway ensures that the system's recovery is informed by its history and capacity for resilience. Both pathways are essential for understanding how systems, whether ecological or human, adapt and transform in response to disturbances.

[54]

Just as ecosystems have adapted complex responses to wildfire, human systems can measure and refine resilience by examining these strategies, applying the natural resilience framework to assess our own adaptive capacity.

WILDFIRE AS MEASURE

LIFE'S PRINCIPLES

When looking to Nature as Measure, we can use [Life's Principles from Biomimicry 3.8] [1] as a framework to assess how well an innovation aligns with nature's proven strategies for sustainability. These principles and deep patterns found across all of life on Earth were developed to serve as metrics, guiding innovators to create solutions that are adaptable, efficient, and supportive of life [1]. By measuring a design against these criteria, we can ensure that it not only fulfills its purpose but also respects and sustains the natural systems it affects [1, 7].

This framework offers innovators a way to assess the "rightness" of their inventions by providing nature-inspired criteria for sustainability. When judging an innovation, designers can use these principles to determine whether their creations align with the strategies that have supported life on Earth for billions of years. This alignment ensures that solutions are not only effective in function but also beneficial—or at least non-disruptive—to ecological and social health over time.

Life's Principles are fundamental strategies observed in nature that help living organisms survive and thrive in their ecosystems [1]. At their core is a central idea that life creates conditions conducive to life [1]. The six principle strategies include:

- Evolve to Survive – adapt and embody resilience [1, 5].
- Adapt to Changing Conditions – remain flexible and responsive [7, 8].
- Be Locally Attuned and Responsive – leverage local resources and conditions [1, 4].
- Use Life-Friendly Chemistry – use safe chemistry for life and environment [1].
- Be Resource-Efficient – maximize efficiency with minimal waste [1].
- Integrate Development with Growth – align structure and function, creating optimized designs [1, 53].

It's easy to see how wildfire and fire ecology exemplify Life's Principles [1] and illustrate how fire-adapted ecosystems maintain resilience and optimize growth, embodying life's strategies for enduring in dynamic conditions [4, 5]:

- Evolve to Survive: Fire-adapted plants, like lodgepole pines, evolve traits such as serotinous cones that release seeds only after fire [21, 22], ensuring regrowth in cleared, nutrient-rich soil.
- Adapt to Changing Conditions: Fire-dependent ecosystems adapt to fluctuating fire regimes [4], with species that can withstand periodic fires, promoting long-term resilience and biodiversity [14].
- Be Locally Attuned and Responsive: Different fire regimes emerge across bioregions [4]. For example, fire-adapted communities rely on periodic fires to maintain health [2, 4], with specific adaptations unique to local conditions.
- Use Life-Friendly Chemistry: Fire's nutrient-recycling role exemplifies natural chemistry [4, 25], transforming organic material into bioavailable nutrients that promote regrowth without harming the soil long-term.
- Be Resource-Efficient: Fires clear excess biomass, cycling nutrients back into the soil [4, 25] and creating conditions for new life with minimal waste, allowing ecosystems to thrive post-disturbance [7].
- Integrate Development with Growth: Fire ecology maintains balance by structuring ecosystems around adaptive cycles of disturbance and renewal [5, 8], supporting species diversity and sustainable ecosystem growth [4, 7].

ADAPTING TO CHANGING CONDITIONS

Fire-adapted ecosystems illustrate how natural systems flexibly respond to disturbances over time [4, 5]. Species within these ecosystems have developed specific traits that allow them to thrive despite periodic fires [14]—like the thick bark of ponderosa pines [33, 34], which protects them from low-intensity burns, or the rapid resprouting capacity of plants after fire [45]. This adaptability reflects principles of complex adaptive systems [7, 8], where components (species) continuously interact with and respond to environmental changes [4], producing dynamic patterns at multiple scales [54].

In a complex adaptive system, each component affects and is affected by others, creating feedback loops that make the system resilient to disturbances [5, 7]. In fire ecology, the adaptive cycle models this process [5, 8], where ecosystems move through phases of growth, conservation, release, and reorganization [4, 5]. For example, frequent, low-intensity fires may prevent excess fuel buildup [2, 4], preserving ecosystem stability [3]. However, if these fires are suppressed (a disturbance to the system's typical feedback loop) [4, 33], fuel accumulates, making the system more vulnerable to large, destructive fires [2, 4].

These ecosystems also illustrate the importance of "emergent behavior," where ecosystem-level resilience and biodiversity emerge from local species interactions [4, 7]. The collective responses of fire-adapted plants [14, 15], animals [16, 17], and soil organisms [25] create a system that is both flexible and enduring [4, 5], embodying how adaptive cycles and cross-scale interactions [5, 54] enable resilience amid ongoing environmental fluctuations [7, 8].

In order to examine the Wildfire as Measure concept more fully, it can be helpful to think about examples of innovations that would not measure up.

A potential biomimetic innovation inspired by wildfire might be a highly efficient, heat-activated fire suppressant that releases chemical compounds in response to heat, inspired by the serotinous cones of pine trees [21, 22, 1, 57]. However, if this suppressant were made using persistent, synthetic chemicals that accumulate in the environment and harm soil microbes [25] or water sources, it would conflict with Life's Principles [1]. Specifically, it would violate "Use Life-Friendly Chemistry" and "Be Resource-Efficient" [1] due to toxic residues and lack of degradability, making it unsustainable despite its wildfire-inspired design [1, 7].

Another potential biomimetic innovation inspired by wildfire could be a heat-resistant building material modeled on the bark of trees [34, 37, 38]. This material might aim to create structures that survive extreme heat [1, 53]. However, if it relied on non-renewable materials or energy-intensive production, it would conflict with Life's Principles [1], specifically "Be Resource-Efficient" and "Use Life-Friendly Chemistry" [1]. The innovation, while inspired by nature, would ultimately be unsustainable if it consumed excessive resources or introduced harmful substances into the environment [1, 7].

WILDFIRE AS MENTOR

Lessons from fire ecology offer profound insights that can be applied to human endeavors like innovation, policy-making, and organizational structures [4, 7], particularly in the areas of adaptability, resilience, and the management of disruption [5, 54]. Just as fire-dependent ecosystems use disturbance as a force for renewal [2, 4], human systems can also benefit from embracing challenges and disruption as opportunities for growth and regeneration [7, 8].

In wildfire-prone ecosystems, fire is often a necessary and natural part of the cycle [2, 4], clearing out dead vegetation and making space for new growth [4]. Fire-adapted species thrive on this process [14, 15], illustrating the power of resilience through renewal [5]. Similarly, in human systems, disruptions can catalyze innovation and creative problem-solving [7, 54]. Rather than fearing or avoiding disruption, organizations can design systems that are not only resilient to change but that thrive because of it [5, 7]. Disruption, when properly managed, becomes a driver of long-term growth and creativity [7, 8], much like the role of fire in maintaining ecosystem health [3, 4].

Fire-adapted ecosystems also demonstrate the critical importance of flexibility and adaptability [4, 5]. In nature, species that can regenerate after a fire, such as plants with heat-activated seeds [21, 22] or those capable of resprouting [45], show how diverse strategies contribute to survival [14]. In human systems, this translates to the need for flexibility in organizations and policies [7, 54]. The ability to respond to changes dynamically, rather than relying on rigid structures, can enhance resilience and ensure long-term success [5, 7]. Much like ecosystems that evolve through diverse survival mechanisms [4, 8], organizations that promote a wide range of approaches are more likely to adapt successfully to new challenges [7, 54].

Diversity plays a central role in both ecological and human systems [4, 7]. In fire-dependent ecosystems, biodiversity increases the system's resilience [4]. Species with different strategies for surviving fire—from serotinous seeds [21, 22] to protective bark [34] to resprouting capabilities [45]—help stabilize the ecosystem and ensure its recovery [4, 14]. For human endeavors, this lesson underscores the importance of fostering diversity in approaches and solutions [7, 54]. Just as ecosystems rely on multiple species and strategies to weather disturbances [4, 5], diverse systems are better equipped to navigate uncertainty and change [7, 8].

Fire ecology also illustrates the importance of understanding nonlinearity and complexity [4, 5]. Wildfires follow nonlinear dynamics, where small changes in conditions can lead to disproportionately large effects [2, 4]. Human systems operate under similar principles of complex adaptation [7, 54], where changes can trigger cascading effects across different scales [5, 8]. This understanding of cross-scale interactions [7] and feedback loops [4, 5] makes it crucial to recognize that complex systems do not always behave in linear, predictable ways [54]. In fire-dependent ecosystems, the concept of self-organization is evident as ecosystems naturally recover and reorganize after fire without external control [4, 5]. Species interactions [14], nutrient cycling [25], and succession [4] all contribute to the emergence of new patterns and structures [7]. Similarly, in social-ecological systems [7], decentralized responses can lead to more effective adaptation to challenges [5, 54]. This capacity for reorganization [8] mirrors how ecosystems naturally restructure post-fire [4], demonstrating how complex systems can adapt through distributed responses [7, 54].

Another important lesson from fire ecology is the emphasis on long-term sustainability [4]. Fire-prone ecosystems have evolved to balance cycles of destruction and renewal [2, 4], with some species relying on fire for regeneration [21, 22] and others adapting to persist through varying fire intervals [14, 15]. Sustainable social-ecological systems [7] similarly need to account for long-term cycles rather than short-term responses [5, 8]. Systems that prioritize long-term resilience [54] are more likely to endure, just as ecosystems thrive by evolving with natural fire regimes [3, 4].

Feedback loops are central to both fire ecology and human systems [4, 7]. In ecosystems, fire affects vegetation [4, 14], which in turn influences future fire behavior [2, 4], creating a cycle of feedback that regulates the system [5, 8]. In human endeavors, feedback loops are equally important in shaping outcomes [7, 54]. Policies, for example, create feedback through incentives and consequences [7], which either reinforce or discourage certain behaviors. Understanding how actions and decisions reverberate through a system [5, 54] helps avoid unintended consequences and encourages positive, self-reinforcing outcomes [7, 8].

Finally, fire ecology teaches the value of controlled disruption [4]. Prescribed burns, used to manage wildfires, mirror natural fire cycles and prevent larger, more destructive fires [2, 3]. This principle can be applied to innovation and organizational management [7], where controlled experimentation or phased projects allow for testing new ideas with minimal risk [7, 54]. By introducing change in a managed way [5, 8], organizations can foster innovation and growth [7], much as prescribed burns maintain ecological health [3, 4].

In summary, fire ecology offers valuable lessons for human endeavors by highlighting the power of adaptability, diversity, resilience, and the strategic use of disruption. Just as ecosystems balance destruction and renewal, human systems can learn to embrace change, foster innovation, and build structures that endure and thrive over the long term.

KEY TAKEAWAYS

Through the lens of fire ecology, human systems gain a new perspective on resilience, using the dynamics of wildfire to evaluate strategies for adaptation, self-organization, and community-wide stability

First and foremost: **Embrace Change**

Adopt a cyclical view of time. For much of human history, time was a wheel rather than an arrow—a series of interconnected cycles rather than a relentless forward march. This cyclical perspective can greatly enrich our understanding of natural processes like wildfires and ecological succession. By viewing these phenomena as integral parts of a natural cycle rather than disruptions to be suppressed, we can develop more nuanced, sustainable approaches to ecological management. In the grand cycle of life, fire is not the end; it is merely a necessary beginning.

Consider the broader socio-ecological system. This conceptual model offers a valuable framework for analysis by emphasizing the importance of adaptive cycles, cross-scale interactions, and resilience. By understanding and mimicking these deeper patterns of natural systems, biomimicry can move beyond imitating static forms or processes to creating dynamic, adaptable solutions that are resilient to change and disturbance. This approach aligns human innovation with the sustainable principles that have governed natural systems for millennia, fostering a harmonious relationship with the environment that is crucial for the challenges of the future.

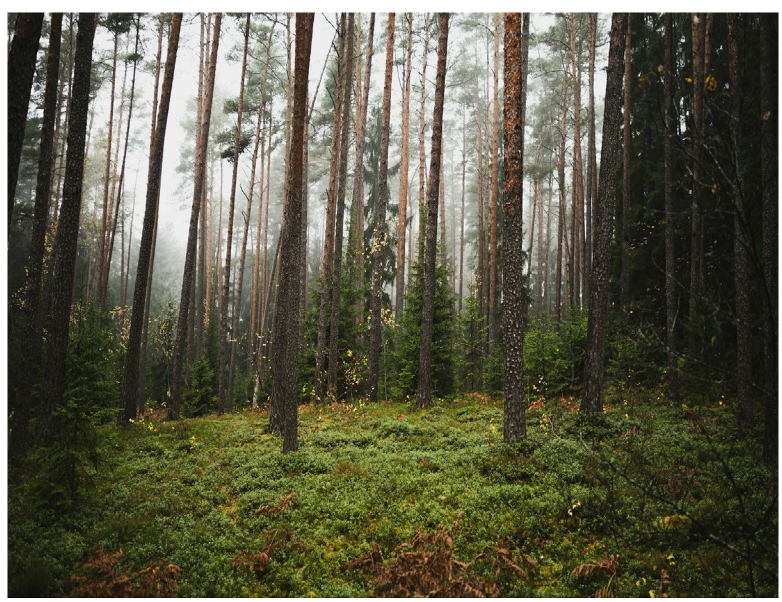
Complex systems must be considered across scales. Effective management and study of complex adaptive systems require multi-scale approaches that consider the interactions and feedbacks across different scales. Governance strategies need to be flexible and responsive to scale dynamics, ensuring that policies and actions are appropriately aligned with the scales of the ecological and social processes they aim to influence. Being aware of the scale at which observations are made or interventions are applied helps in avoiding oversimplification and mismanagement of complex systems.

Disturbances help maintain diversity, resilience and adaptability. Panarchy offers a valuable lens for organizational structures by highlighting how systems adapt and transform through interconnected cycles of growth, collapse, reorganization, and renewal. This model can inform organizational resilience by encouraging flexibility, adaptation, and strategic evolution. Applying panarchy in organizations can mean developing structures that support creative destruction (innovating even at the risk of existing models) and fostering interdependent teams that adapt based on broader market and internal feedback cycles. Ultimately, panarchy helps organizations balance stability with the agility to respond to change, crucial for sustainable growth.

Adaptive management parallels the adaptive cycles found in wildfire ecology, particularly through panarchy's insights on navigating collapse and renewal. By mimicking nature's balancing act, organizations can evolve, remaining resilient amid the pressures of both ecological and economic change.

CONCLUSION

In examining life's responses to fire, we observe a model of resilience rooted in adaptability, diversity, and renewal. As the world faces escalating environmental challenges, learning from fire-prone ecosystems offers a blueprint for developing resilient, interconnected communities. This report is a starting point. Observations and eco-technological management strategies especially from many Indigenous cultures express the key concepts and others more fully. By integrating ecological principles, we can foster systems that don't merely survive disturbances but use them as catalysts for sustainable growth. This journey back to resilience, informed by nature's wisdom, calls for a profound shift for many humans, individually and collectively: to recognize ourselves as part of an adaptive, living world where we thrive not by control but by collaboration.



ACKNOWLEDGEMENTS

This technical report is written and based on foundational work by the 2024 Biomimicry Launchpad cohort, especially Rae Lewark, Joe Cardielo, and Dave Hutchins.

It was edited by Andrew Howley and Camilo Garzón.

Indigenous advisors were Daniel Kinzer and Michael Painter.

Science review by Jenélle Dowling and Lily Urmann.

And it was designed by Jen Fredette.

ENDNOTES

1. Benyus, J. M. (2009). *Biomimicry: Innovation inspired by nature* (Nachdr.). Perennial.
2. Whelan, R. J. (2005). *The ecology of fire* (1st ed., transferred to digital printing). Cambridge University Press.
3. Kimmerer, R., & Lake, F. (2001). Maintaining the mosaic: The role of indigenous burning in land management. *Journal of Forestry, 99*(11), 36–41. https://doi.org/10.1093/jof/99.11.36
4. Kobziar, L., et al. (2024). Principles of fire ecology. *Fire Ecology, 20*. https://doi.org/10.1186/s42408-024-00272-0
5. Sundstrom, S. M., & Allen, C. R. (2019). The adaptive cycle: More than a metaphor. *Ecological Complexity, 39*, 100767. https://doi.org/10.1016/j.ecocom.2019.100767
6. Clark, W. C., Munn, R. E., & International Institute for Applied Systems Analysis (Eds.). (1986). *Sustainable development of the biosphere*. Cambridge University Press.
7. Berkes, F., Colding, J., & Folke, C. (Eds.). (2002). *Navigating social-ecological systems: Building resilience for complexity and change*. Cambridge University Press. https://doi.org/10.1017/CBO9780511541957
8. Holling, C. S., & Gunderson, L. H. (2002). *Resilience and adaptive cycles*. Island Press. Retrieved October 29, 2024, from http://hdl.handle.net/10919/67621
9. Somayaji, A., et al. (2022). An insight into the mechanisms of homeostasis in extremophiles. *Microbiological Research, 263*, 127115. https://doi.org/10.1016/j.micres.2022.127115
10. Wang, Q., Cen, Z., & Zhao, J. (2015). The survival mechanisms of thermophiles at high temperatures: An angle of omics. *Physiology, 30*(2), 97–106. https://doi.org/10.1152/physiol.00066.2013
11. Feder, M. E., & Hofmann, G. E. (1999). Heat-shock proteins, molecular chaperones, and the stress response: Evolutionary and ecological physiology. *Annual Review of Physiology, 61*, 243–282. https://doi.org/10.1146/annurev.physiol.61.1.243
12. Mahat, D. B., Salamanca, H. H., Duarte, F. M., Danko, C. G., & Lis, J. T. (2016). Mammalian heat shock response and mechanisms underlying its genome-wide transcriptional regulation. *Molecular Cell* 62*(1), 63–78. https://doi.org/10.1016/j.molcel.2016.02.025
13. Lindquist, S. (1986). The heat-shock response. *Annual Review of Biochemistry, 55*, 1151–1191. https://doi.org/10.1146/annurev.bi.55.070186.005443
14. Dickman, L. T., et al. (2023). Integrating plant physiology into simulation of fire behavior and effects. *New Phytologist, 238*(3), 952–970. https://doi.org/10.1111/nph.18770
15. Granström, A., & Schimmel, J. (1993). Heat effects on seeds and rhizomes of a selection of boreal forest plants and potential reaction to fire. *Oecologia, 94*(3), 307–313. https://doi.org/10.1007/BF00317103
16. Nappi, A., & Drapeau, P. (2009). Reproductive success of the black-backed woodpecker (*Picoides arcticus*) in burned boreal forests: Are burns source habitats? *Biological Conservation, 142*(7), 1381–1391. https://doi.org/10.1016/j.biocon.2009.01.022
17. Sparks, J. C., Masters, R. E., Engle, D. M., Payton, M. E., & Bukenhofer, G. A. (1999). Influence of fire season and fire behavior on woody plants in red-cockaded woodpecker clusters. *Wildlife Society Bulletin, 27*(1), 124–133. References (APA Style)
18. Probst, J. R., & Donnerwright, D. (2003). Fire and shade effects on ground cover structure in Kirtland's Warbler habitat. American Midland Naturalist, 149(2), 320–334.
19. Israelowitz, M., Rizvi, S. H. W., & von Schroeder, H. P. (2007). Fluorescence of the 'fire-chaser' beetle Melanophila acuminata. Journal of Luminescence, 126(1), 149–154. https://doi.org/10.1016/j.jlumin.2006.06.017
20. Walker, T. J., & Figg, D. E. (1990). Song and acoustic burrow of the prairie mole cricket, Gryllotalpa major (Orthoptera: Gryllidae). Journal of the Kansas Entomological Society, 63(2), 237–242.
21. Mason, L. (2013). Pine. Reaktion Books.
22. Lotan, J. (1976). Cone serotiny - Fire relationships in lodgepole pine. Tall Timbers Fire Ecology Conference Proceedings, 267–278.
23. Redmond, M. D., Urza, A. K., & Weisberg, P. J. (2023). Managing for ecological resilience of pinyon–juniper ecosystems during an era of woodland contraction. Ecosphere, 14(5), e4505. https://doi.org/10.1002/ecs2.4505
24. Johnson, M., Vander Wall, S. B., & Borchert, M. (2003). A comparative analysis of seed and cone characteristics and seed-dispersal strategies of three pines in the subsection Sabinianae. Plant Ecology, 168(1), 69–84. https://doi.org/10.1023/A:1024470224134
25. Wiggers, M. S., Kirkman, L. K., Boyd, R. S., & Hiers, J. K. (2013). Fine-scale variation in surface fire environment and legume germination in the longleaf pine ecosystem. Forest Ecology and

Management, 310, 54–63. https://doi.org/10.1016/j.foreco.2013.07.030
26. Lutz, E. (2017). Living with fire: Surviving the forest wildfires of California. American Scientist, 105(6), 328–330.
27. Bonta, M., Gosford, R., Eussen, D., Ferguson, N., Loveless, E., & Witwer, M. (2017). Intentional fire-spreading by 'firehawk' raptors in Northern Australia. Journal of Ethnobiology, 37(4), 700–718. https://doi.org/10.2993/0278-0771-37.4.700
28. Baldwin, R. A., & Bender, L. C. (2009). Foods and nutritional components of diets of black bear in Rocky Mountain National Park, Colorado. Canadian Journal of Zoology, 87(11), 1000–1008. https://doi.org/10.1139/Z09-088
29. Raynor, E. J., Joern, A., & Briggs, J. M. (2015). Bison foraging responds to fire frequency in nutritionally heterogeneous grassland. Ecology, 96(6), 1586–1597. https://doi.org/10.1890/14-2027.1
30. Spitz, D. B., et al. (2018). Fire history influences large-herbivore behavior at circadian, seasonal, and successional scales. Ecological Applications, 28(8), 2082–2091. https://doi.org/10.1002/eap.1797
31. Powers, B. F. (n.d.). Butterfly and flower community composition among prairie-oak ecosystem habitats in the Willamette Valley, Oregon.
32. Wilde, W. P. D., Wilde, W. P., & Brebbia, C. A. (2008). High performance structures and materials IV. WIT Press.
33. Fitzgerald, S. A. (2022). Fire ecology of ponderosa pine and the rebuilding of fire-resilient ponderosa pine ecosystems. In Ritchie, Martin W., Maguire, Douglas, Youngblood, Andrew (Tech. Coord.), *Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management*, October 18–21, 2004, Klamath Falls. Gen. Tech. Rep. PSW-GTR-198, Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, 197–225. Retrieved October 31, 2024, from https://research.fs.usda.gov/treesearch/27269
34. Fire Research and Management Exchange System. (n.d.). Bark characteristics and fire resistance: A literature survey. Retrieved October 31, 2024, from https://www.frames.gov/catalog/20051
35. Slack, A. W. (n.d.). Large sugar pine (Pinus lambertiana) vigor and mortality in a fire-excluded forest of the central Sierra Nevada.
36. Slack, A. W., Zeibig-Kichas, N. E., Kane, J. M., & Varner, J. M. (2016). Contingent resistance in longleaf pine (Pinus palustris) growth and defense 10 years following smoldering fires. Forest Ecology and Management, 364, 130–138. https://doi.org/10.1016/j.foreco.2016.01.014
37. Reifsnyder, W., Herrington, L., & Splat, K. (1967). Thermophysical properties of bark of shortleaf, longleaf, and red pine. Yale School of Environment Bulletin Series, (70). Retrieved from https://elischolar.library.yale.edu/yale_fes_bulletin/80
38. Dehane, B., Madrigal, J., Hernando, C., Bouhraoua, R., & Guijarro, M. (2015). New bench-scale protocols for characterizing bark flammability and fire resistance in trees: Application to Algerian cork. Journal of Fire Sciences, 33(3), 202–217. https://doi.org/10.1177/0734904114568858
39. Lawes, M. J., & Neumann, M. (2022). Variation in eucalypt bark allometry across Australia. Australian Journal of Botany, 70(3), 215–230. https://doi.org/10.1071/BT21150 References (APA Style) 40–69
40. Peters, H. F., & Slen, S. B. (1964). Hair coat characteristics of bison, domestic × bison hybrids, cattalo, and certain domestic breeds of beef cattle. Canadian Journal of Animal Science, 44(1), 48–57. https://doi.org/10.4141/cjas64-009
41. Nature Index. (n.d.). Cool echidnas survive the fire. Retrieved October 31, 2024, from https://www.nature.com/nature-index/article/10.1098/rspb.2016.0382
42. Kinlaw, A., & Grasmueck, M. (2012). Evidence for and geomorphologic consequences of a reptilian ecosystem engineer: The burrowing cascade initiated by the Gopher Tortoise. Geomorphology, 157–158, 108–121. https://doi.org/10.1016/j.geomorph.2011.06.030
43. Avitabile, S. C., Nimmo, D. G., Bennett, A. F., & Clarke, M. F. (2015). Termites are resistant to the effects of fire at multiple spatial scales. PLOS ONE, 10(11), e0140114. https://doi.org/10.1371/journal.pone.0140114
44. Parr, C. L., Robertson, H. G., Biggs, H. C., & Chown, S. L. (2004). Response of African savanna ants to long-term fire regimes. Journal of Applied Ecology, 41(4), 630–642.
45. Turnbull, T. L., Buckley, T. N., Barlow, A. M., & Adams, M. A. (2014). Anatomical and physiological regulation of post-fire carbon and water exchange in canopies of two resprouting Eucalyptus species. Oecologia, 176(2), 333–343. https://doi.org/10.1007/s00442-014-3032-5
46. Miller, R. G., Enright, N. J., Fontaine, J. B., Merritt, D. J., & Miller, B. P. (2024). Plant life-history data as evidence of an historical mixed-severity fire regime in Banksia woodlands. Australian Journal of Botany, 72(5). https://doi.org/10.1071/BT23098
47. Hellmers, H., Horton, J. S., Juhren, G., & O'Keefe, J. (1955). Root systems of some chaparral plants in Southern California. Ecology, 36(4), 667–

678. https://doi.org/10.2307/1931305
48. Butler, G. (2020). Some fire retardant native plants for the Southern Highlands region. Journal of the Australian Native Plants Society, Canberra Region, 20(4), 10–15. https://doi.org/10.3316/informit.274314621489672
49. Fire Research and Management Exchange System. (n.d.). Burning bluestem range. Retrieved October 31, 2024, from https://www.frames.gov/catalog/10178
50. Hartman, J. C. (2011). Responses of switchgrass (Panicum virgatum L.) to precipitation amount and temperature. Kansas State University.
51. AskNature. (n.d.). Worm tolerates temperature gradient of 140 Deg F — Biological Strategy. Retrieved October 31, 2024, from https://asknature.org/strategy/worm-tolerates-temperature-gradient-of-140-deg-f/
52. Spatial Experiments. (2016, September 20). Learning from the desert snail. Retrieved October 31, 2024, from https://spatialexperiments.wordpress.com/2016/09/20/learning-from-the-desert-snail/
53. Speck, O., & Speck, T. (2019). An overview of bioinspired and biomimetic self-repairing materials. Biomimetics, 4(1), 26. https://doi.org/10.3390/biomimetics4010026
54. Kharrazi, A., Fath, B. D., & Katzmair, H. (2016). Advancing empirical approaches to the concept of resilience: A critical examination of panarchy, ecological information, and statistical evidence. Sustainability, 8(9), 935. https://doi.org/10.3390/su8090935
55. Aveni, A. (1989). Empires of time: Calendars, clocks, and cultures. Tauris.
56. Camazine, S., Deneubourg, J. L., Franks, N. R., Sneyd, J., Bonabeau, E., & Theraulaz, G. (2003). Self-organization in biological systems. Princeton University Press.
57. Baumeister, D., et al. (2013). Biomimicry resource handbook: A seedbank of best practices for integrating nature's strategies into design. Biomimicry 3.8.
58. Noss, R. F. (2000). The redwood forest: History, ecology, and conservation of the coast redwoods. Island Press.
59. Cook, L. M. (2018). Records of industrial melanism in British moths. Biological Journal of the Linnean Society, 125(4), 862–866.
60. Forsman, A., et al. (2011). Rapid evolution of fire melanism in replicated populations of pygmy grasshoppers. Evolution, 65(9), 2530–2540.
61. Kong, X. H., et al. (2020). Evolution of eggshell structure in relation to nesting ecology in birds. Ecology and Evolution, 10(17), 9104–9113.
62. Ellen MacArthur Foundation. (2019). Circular economy and nature-inspired design.
63. Lips, K. R. (2016). Overview of gopher tortoise (Gopherus polyphemus) ecology and its role in ecosystems. Herpetologica, 72(1), 13–28.
64. Ellen MacArthur Foundation. (2019). Circular economy and nature-inspired design.
65. McDonough, W., & Braungart, M. (2002). Cradle to cradle: Remaking the way we make things. North Point Press.
66. Gammage, B. (2011). The biggest estate on Earth: How Aborigines made Australia. Allen & Unwin.
67. Lake, F. K., et al. (2017). Indigenous fire stewardship: Federal/tribal partnerships for wildland fire research and management. Ecological Society of America.
68. Tan, P. Y., & Jim, C. Y. (2017). Greening cities: Forms and functions. Springer.
69. Newman, P., & Matan, A. (2021). Green urbanism in Asia: The emerging green tigers. Springer.
70. Fairfax, E., Whipple, A., Wheaton, J. M., Osorio, B., Miller, J., Kirksey, K., Perez, N., Gilbert, J. T., & Jordan, C. E. (2024). Impacts of beaver dams on riverscape burn severity during megafires in the Rocky Mountain region, western United States. In J. L. Florsheim, A. P. O'Dowd, & A. Chin (Eds.), Biogeomorphic Responses to Wildfire in Fluvial Ecosystems (Geological Society of America Special Paper 562, pp. 131–151). Geological Society of America. https://doi.org/10.1130/2024.2562(07)
71. U.S. National Park Service. (2024). Indigenous Fire Practices Shape our Land. U.S. National Park Service. https://www.nps.gov/subjects/fire/indigenous-fire-practices-shape-our-land.htm
72. Save the Redwoods League. (2024). Banned for 100 years, cultural burns could save sequoias. Save the Redwoods League. https://www.savetheredwoods.org/redwoods-magazine/autumn-winter-2024/banned-for-100-years-cultural-burns-could-save-sequoias/
73. Mason, M. E. (2012). A rapid assessment of riparian vegetation condition along the Big Sur Wild and Scenic River. USDA Forest Service, Rocky Mountain Research Station.
74. Bradstock, R. A., Kenny, B. J., Williams, R. J., & Clarke, P. J. (2013). Contrasting fire ecology of coniferous and broadleaf forests in Australia. Wildlife Research, 40(6), 487-506.