An Evaluation of Biotechnology Approaches to Wildfire Resilience - and recommended research and development to advance feasible solutions

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California faces a range of threats to its critical ecosystem services, including climate change, non-indigenous species encroachment, natural resource exploitation, and human development. Novel pathogens, warmer waters, extreme climate events, and rapid habitat changes are exacerbating these threats. Genomics tools, such as translocation and gene editing, offer potential solutions to accelerate species adaptation and protect carbon stores, but also raise novel risks and governance challenges. This report explores the opportunities for genomic technologies to address wildfire resilience in the arid west, including both early stage research and applied product opportunities - and recommends research to advance in service of near term applied value for wildfire resilience in the arid west.

The objective of this report is two fold - first, to offer prioritized research + development recommendations for genomic technologies to address wildfire resilience, and second, to provide a place-based, values-driven case-study for the advancement of biotechnology research in the dual context of urgent ecological challenges and technological uncertainties. To that end, the report includes:

I. Evaluation methodologies used to: identify critical ecological threats related to wildfire resilience, categorize technology capacities, prioritize intervention points best-suited for genomic sciences, and refine potentially approaches which are simultaneously ecologically critical, technologically feasible, and socio-economically viable.
II. Pathways for advancing R+D in the context of uncertainty - aiming for ethical, effective and applied outcomes, weighing tradeoffs and unknowns in the context of knowledge gaps and regulatory ambiguity - including, potential co-benefit markets which could be leveraged to advance applied outcomes from the proposed biotechnology research opportunities.
III. And, lastly, a resulting set of recommended wildfire resilience biotechnology R+D areas which merit advancement in the near term - with priority placed on (A) those that replace or improve upon existing fire fighting or post-fire resilience methods and products, and (B) those that deliver critical and precise insights to improve future wildfire resilience management.

Below are considered R+D pathways by wildfire resilience intervention point - those in bold are those the Lab to Land Institute recommends prioritizing for advancement in the near term but all are worthy of further exploration.

INCREASE BENEFICIAL FIRE	REDUCE RISK OF HIGH INTENSITY FIRE	BOLSTER RESILIENCE TO SEVERE FIRE
utilize native species to create biological burn perimeters for beneficial burns ⟶ advocate for policy shifts to decrease reliance on fire fighting rigs and crews to be present during beneficial burns alongside the burn crews. *TRL[1]: high; sociocultural: high; political: low; econ: low*	improve lignan processing capacities + use-cases for 'biomass campus' models ⟶ improve carbon-negative and economically viable use-cases of this low-value byproduct *TRL: med; sociocultural: high; political: high; econ: TBD*	**reduce nutrient-loading from commonly used aerial fire retardants without requiring significant shifts in current fire fighting equipment.** ***the precursor to this is testing of existing methods in-use in ag sector today with native species in the target bioregion; an important pathway to tech-transfer between industry sectors which can be tested/modeled through this approach*** *TRL: high; sociocultural: med, political: med; econ: high*
determine if a heat 'dampening' retardant, or additive, is feasible ⟶ fire fighting crews can manage active wildfires to increase low-heat intensity burned acres *TRL: low; sociocultural: low; political: low; econ: low-med*	speed in-situ composting of cut and piled, but unremoved, small diameter timber and slash waste *TRL: med; sociocultural: low; political: low-med; econ: med-high*	**develop a soil amendment using natively occurring bacteria and microbes ⟶ speed ecological succession b ~8 yrs following high severity fires** ***the precursor to this is the time-resolved metagenomic analysis of post-fire soils, a substantial contribution to scientific knowledge of itself*** *TRL: med-high; sociocultural: med; political: med; econ: low-med*
	manage flammability and/or presence of cheatgrasses in 'high risk' regions ⟶ mitigate risk of fire ignition + reduce use of preventative retardants along highway corridors *TRL: low, sociocultural: low; political: low, econ: low*	develop non-mineral biological fire retardants and/or non-PFA surfactants to replace current retardants *TRL: low; sociocultural: high; political: high; econ: high*

[1] TRL = technology readiness level, a scale of 1-10 where 'high' indicates the successful demonstration of this technology in a relevant ecology; 'med' indicates prototype demonstration in a laboratory or non-relevant ecological environment; and 'low' indicates concept or application is formulated and feasible in a laboratory environment but as-yet unproven.

Ecological context. California faces a range of threats to the critical ecosystem services on which the state and its population relies - from global issues, like climate change, to more local challenges, like non-indigenous species encroachment, natural resource exploitation, and human development. Novel pathogens threaten critical species such as the California Oak. Warmer waters decrease salmon populations, with myriad knock-on ecosystem effects from biodiversity-loss to water quality decreases. Extreme climate events such as megafire and drought exacerbate water contamination and groundwater loss. The rapid pace of change to California's habitats outpaces species' ability to adapt (Catullo et al 2019, Hoegh-Guldberg et al 2018). California's forests have lost the ability to store an estimated >400 million tons of carbon dioxide due to factors including deforestation and wildfires (CNRA, 2020). Preserving and supporting these ecosystems is a critical need for the State's climate goals.

Historical land-use practices, including the removal of native peoples' from traditional territories, establishment of the USFS as an economic-driver for timber production in the United States, the practice of comprehensive fire suppression and the lack of economic value placed on the ecological stability of forest lands - have led to increasingly severe fires and high risk landscapes throughout the arid west. The prioritization of economic interests like timber and grazing have led to fuel accumulation and more severe wildfires over the 20th century (Westerling et al. 2011). Additionally, urban expansion has increased ignition sources and invasive grass spread; and climate change is exacerbating this trend. Federal and state agencies disproportionately prioritize funding for wildfire response, rather than risk mitigation and resilience, leading to a gap in capital for pre-fire resilience efforts and a back-log of critical forest restoration efforts which might mitigate risk and help to reverse this trend. As a result, there has been a significant rise in wildfire number, size, and severity has occurred over the past 40 years, especially in the Sierra Nevada and southern Cascades regions. Coordinating an effective statewide wildfire management approach is challenging due to the involvement of multiple agencies with different funding and cultural practices, as well as the complex web of public, private, and indigenous lands impacted with competing socio-economic stakeholder goals. Developing a deeper understanding of the changing wildfire conditions, the impacts of fire on soils and biodiverse landscapes, and the opportunities to improve both pre-fire risk reduction and post-fire resilience requires creative, cross-disciplinary thinking, including deliberate consideration of new technologies.

In the coming decades, we will see increasing severity in wildfires as a result of climate change, vapor pressure deficit effects (VPD effects) and failure to meet ambitious goals for ecological thinning and prescribed burning in overcrowded and unhealthy forest landscapes. To be more precise, we estimate an increase of 2-3 degrees celsius by 2100, much of that before 2050 - and a significant (50%+/-) increase in fire intensity, frequency and severity. These hotter and drier conditions will lead to the 'VPD' effect (Vapor Pressure Deficit), a negative feedback loop between climate change and wildfire - where drier hotter conditions absorb more moisture from forests and landscapes and exacerbate the potential of hazardous wildfires. A few impacts relevant to the capacities of biotechnology that result from this anticipated increase in fire between now and 2050: We will see more fire retardant dropped before we see less - and are highly unlikely to see PFAs or mineral loads shift in fire retardants within the next few years, despite substantial DOD investment in PFA replacement. Further, VPD effect and soil conditions will worsen and we may see exacerbated vegetation-climate mismatch among post-fire regrowth, which could have the effect of worsening risk of fire or increasing the vulnerability of important ecosystem services to the impacts of wildfire.

Biotechnology Context. New genomics tools, such as translocation and gene editing, offer the potential to accelerate species adaptation (Phelps et al 2019, Novak et al 2019). These same tools can help replenish and protect soil, plant and microbial carbon stores (Thakur et al, 2023), and provide us with refined methods for a more accurate, time-delimited understanding of complex conservation challenges. Genomics sciences, synthetic biology, and precision engineering hold the capacity to accelerate the adaptation of our ecosystems to changing climatic conditions, restore degraded habitats, develop green infrastructure mitigating the need for gray infrastructure such as water filtration facilities, enabling crop production to catch up with climate strains, enabling sustainable industrial processes and waste management – science which will enable us to bolster the resilience of vital ecosystem services on which our communities and economies depend. Further, while renewable energy, electric vehicles, and modular nuclear power may drive mitigation efforts, genetic tools may be among the only solutions that can address adaptation and resilience at the pace and scale required to combat the unfolding catastrophe.

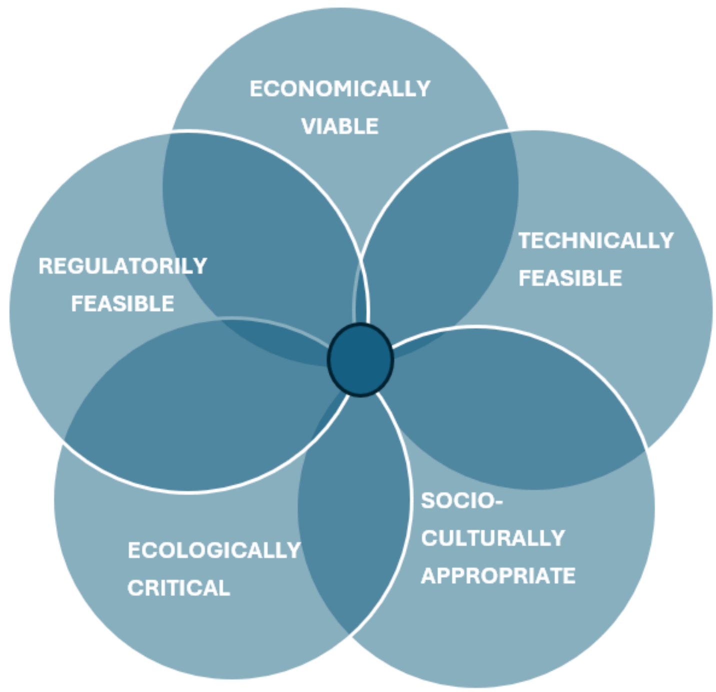
However, while promising, these approaches raise novel risks, many of which are still unknown or poorly understood (Barnhill-Dilling and Delbornel 2021, Burgiel et al 2021). This uncertainty has led to concerns about their adoption (Brister et al 2021), governance challenges (Rabitz et al 2022), and environmental justice issues (Lau et al 2021). Although a new suite of tools for biodiversity conservation is on the horizon, and despite the inevitability of these technologies' emergence, there is currently no established policy directing their practical use in California. So the question is less if, or whether, these technologies will come to bear for climate applications - but rather how, and for what purpose. Our effort is to ensure that the full scope of potential ethical, ecological, and social implications of environmental biotechnologies are carefully and proactively considered, and to ensure that environmental biotechnology approaches are not left unexplored while investments soar elsewhere in the bioeconomy.

Field trials in biotechnology solutions have been very limited - due to the nascency of the technology, the lack of precise focus on ecosystem resilience research within the biotechnology discipline (particularly outside agriculture), and socio-political concerns about biocontainment and uncertainties. As a result, the nearest term opportunities for biotechnology R+D to deliver clear and measurable applied outcomes will be in those areas where the economic, political and cultural license to operate is the highest: leveraging existing regulation and known markets to demonstrate viable approaches and, through these demonstrations, de-risk policy change and investment in replicable and scalable solutions. Importantly, R+D in the 'deeper understanding' category can and should be driven by precise inquiries which aim for applied solutions to discrete problems. For example, time-resolved metagnomic understanding of post-fire soil microbiomes can deliver insight into natively occurring microbes and bacteria which can speed ecological succession and consume naturally occuring chemical toxins which proliferate following high heat fires. The first step, however, is a better understanding of what species are present, and what functions they are serving, and under what pressures and conditions do those functions shift or fail.

Market context. Over the past two decades since the completion of the human genome project, the biotechnology sector has witnessed remarkable growth. By the end of the decade, syn-bio could be used extensively in manufacturing industries that account for more than a third of global output—a shade under $30 trillion in terms of value. Alternative meats developed through synbio techniques could result in conventional meat consumption in the US dropping by 33% by 2040. The global bioeconomy is projected to reach at least $3.4 trillion by 2030, driven largely by innovations in healthcare, agriculture, and industrial processes like cosmetic and textile inputs. This presents opportunities for new technologies to leverage adjacent/aligned markets which might drive growth and financial stability for products outside the wildfire context - enabling wildfire applications to be less profitable or run at a loss - relying on public and philanthropic investment, at least primarily.

Carbon markets are unlikely to drive near term development of solutions for wildfire management given the volatility of voluntary carbon markets (VCMs) coupled with current policy which prohibits the USFS from participating in VCMs. The new announcement of US Federal Government involvement with VCMs as a buyer won't meaningfully affect this, as the USFS is still not able to participate as a seller of credits. And biodiversity markets are a long way farther off. Today, the primary capital sources focused on megafire resilience are focused on emergency response and community preparedness, with some increasing efforts to kick-start market based approaches for ecological thinning - and these spaces provide the most clear pathways to scale new solutions and innovations through private and public investment.

SECTION I. METHODS



Our goal is to identify and recommend those potential solutions which are economically viable, technically feasible, regulatorily feasible, ecologically critical and socio-culturally appropriate. The following section outlines the methodologies we used, the criteria we landed on, and the resulting indicators that surround our recommendations - all with an effort to most closely seek the intersection of the venn diagram above - and where a solution was off-center but still recommended, to articulate why.

Prioritizing solutions is an imprecise science - and necessarily involves a variety of disciplines and a systems approach to considering the potential opportunities and roadblocks of any one approach. Given the nacency of the environmental biotechnology field, rigor and inclusiveness in the methods used to determine priorities is critical - as is candor and transparency where there are unknowns and challenging tradeoffs.

The following high-level criteria emerged as the most important in our evaluations - each of which is articulated in further detail throughout section I of this report:

- Ability to meet context-specific definitions of ecological appropriateness and acceptable risk
- Economic viability driven by primary applications in existing markets, as compared to developing markets, e.g. voluntary carbon
- Ability to utilize data sovereignty methods which place structure and rigor surrounding biological data and indigenous knowledge
- Demonstrable potential to replace or improve harmful processes and products in current use
- Scientific research value in generating broadly applicable insights beyond the immediate application, particularly for understudied or high-leverage mechanisms relevant to ecosystem resilience, future credit markets, or necessary inputs to recommended policy shifts
- Degree of reversibility and adaptive capacity to adjust or phase out interventions if negative consequences arise, avoiding lock-in to singular approaches
- Ability to empirically measure and attribute impacts to biotechnology interventions through counterfactuals and calculable harm reduction, even where comprehensive monitoring, measuring, reporting and verification (MMRV) remains challenging
- Sociopolitical palatability and alignment with public values, perceptions, and priorities as identified through proactive opinion research, media narrative analysis, and deliberative dialogues

A. METHODS SNAPSHOT

SNAPSHOT OF ROBUST AND MULTIDISCIPLINARY METHODS TO ENABLE DECISION MAKING AND PRIORITIZATION IN THE CONTEXT OF UNCERTAINTY

Literature review: We conducted a rigorous review of literature in biotechnology, synthetic biology approaches to climate impact, wildfire resilience and the surrounding economics, policies, and land management pressures which drive decision making and outcomes for fire resilience in the west. In the biotechnology field, there are a few select biotechnology reports which have paved the way for environmental biotechnologies and articulated priorities and focus areas for research, application and product development. The EBRC, the Schmidt Futures, BCG and the Federation of American Scientists are among the bodies leading these efforts - alongside newer field-building organizations like the Homeworld Collective and Revive + Restore.

Biotechnology toolset analysis and tech-readiness level evaluation: To identify potential biotechnology innovations applicable to each ecological threat, a suite of solutions were taken from Corlette (2016), which categorizes solutions by the specific conservation issue they are used to address. Through structured expert elicitation, we are then able to qualitatively evaluate the level of Development (i.e., technology readiness level), Effectiveness, and associated Risks of various biotechnology solutions for each conservation issue. Level of Effectiveness is defined as a measure of the extent to which a proposed biotechnology solution can deliver substantial, scalable, durable and cost-efficient positive impacts in resolving the targeted conservation issue while providing potential co-benefits. The Level of Risk refers to the potential negative ecological, economic, social, ethical and regulatory ramifications that could arise from the research, development, deployment or long-term existence of the proposed biotechnology solution in the environment.

Expert insight solicitation: We aggregated expert perspective through a direct outreach survey sent to biotechnologists and ecologists which resulted in dozens of 1:1 discussions and technical insights. A full list of those consulted and who advised this work is included as Appendix 2.

Hard science in-lab fellowship: In-lab postdoctoral researchers were simultaneously supported to advance wildfire soil genomic databases through the Innovative Genomics Institute via a grant from the Kohlhard Family Foundation, providing consistent feedback and insight on early-stage estimates of post-fire soil resilience and microbiomes which delivered compelling insights and hypotheses into the prioritization process.

Refinement of wildfire resilience challenge areas to target: We mapped the resilience challenges in three 'buckets' - reducing the risk of extreme fire, improving the outcomes/methods of active fire response, and increasing resilience following fire. Within each of these, we articulated a variety of vulnerabilities to ecosystems, ecosystem services, communities, infrastructure and climate. To clarify which of these might be most addressable through biotechnology R+D and applied solutions, we compared biotechnology tools to the precise ecological vulnerabilities - for example, the type and degree of harm (erosion, contamination, etc) or the ecosystem service at risk (water availability, etc). And, finally, we considered where there are opportunities to improve or bolster resilience - not just to respond to precise vulnerabilities.

Multidisciplinary stakeholder working groups: Over 15 months, Lab to Land held 4 gatherings on privately-stewarded grass, coastal, and Sierra mountain lands in Northern California. These intimate, highly-curated working groups brought together remarkable thinkers across dimensions of climate, wildfire, land stewardship, cultural fire, geochemistry, biotechnology, climate investors, biodiversity, fire fighting, Federal Forest management, quantitative modeling, synthetic biology, science communications, philanthropy, bioethics, entrepreneurs, biomanufacturing, data sovereignty, governance and environmental justice. The goal of these working groups was to support precise inquiries while encouraging strategy, creativity, and collaboration. Further, the gatherings helped to build trusted relationships between resourced organizations and actors around potential solutions - such that this effort delivered not just a set of R+D with advancing, but also with coalitions of actors poised and ready to advance it.

Economic analysis and industry engagement: Using the industries and stakeholders identified through literature review and stakeholder analysis, we invited biomanufacturers, early-stage biotechnology start-ups, biomanufacturing industry collectives, and investors in start-up biotechnologies to our working groups to provide candid insight into the challenges and opportunities associated with field testing, production, and scaling applied solutions.

Indigenous Futures Fellowship for hard and social scientists: In partnership with Lab to Land Institute Scientific Co-Director, Keolu Fox, we launched the Indigenous Futures Fellowship to bring hard and social scientists' of indigenous background to convenings and to support their scientific inquiries in climate biotechnology through writing grants. This increased the diversity of perspective in our working groups and amplified the lessons learned through the writing and publications of the fellows following the working groups.

Development of a rigorous climate biotechnology decision model: Given the socio-cultural and political concerns surrounding the use of biotechnologies in the context of climate resilience and ecosystem services support, we recognized the need for a usable tool that would provide the conservation and environmental communities with a rigorous and trusted method to evaluate the use of biotechnologies. This tool is published separately, and the fire work outlined here is provided as a case study in that publication. The tool is modeled on a decision method used today by large environmental NGOs - in order to ease the barriers to uptake and increase trust and comfort with the idea of biotechnology for environmental resilience.

B. TECHNOLOGY READINESS ASSESSMENT

ANALYSIS AND CATEGORIZATION OF AVAILABLE BIOTECHNOLOGY TOOLS AND CAPACITIES

Biotechnology is an ever-evolving field characterized by rapid advancements and increasing capacities across a wide range of applications. Tools such as genome sequencing and CRISPR gene editing are at the forefront of these innovations, continually enhancing our ability to manipulate and understand biological systems. **The following table (Table 1) provides a high-level overview of current biotechnological tools and their applications. This includes both established technologies and emerging solutions poised to make significant impacts in the near future.**

For each, there is a qualitative measure of readiness - though we did not limit our thinking to solely the higher readiness categories, rather this metric comes more to bear when considering timelines to potential applications and weighing that against potential impact for wildfire resilience. We include a comment on market segments driving innovation and growth as this informs whether there is a current sector with corollary tools in application today which might be interested in providing those tools to ecological resilience applications, and drove our thinking on what industries and investment sectors to engage in our research and analysis of prioritized R+D to advance.

In order to simplify the process of considering biotechnology tools for wildfire resilience, we binned the tools into three general categories of technology and four general areas of impact on an ecosystem or ecosystem threat. In this way, we could focus ourselves on potential impact and outcomes without limiting our creativity as to what tools could accomplish these outcomes - backing up from the end goal to determine if there were scientific pathways worth exploring.

Biotechnology technology functions:

1. Biobanking, Monitoring, Environmental Dna (Edna) And Bioinformatics: This category involves collecting, analyzing, and storing DNA from environmental samples (such as soil, water, or air) to monitor biodiversity, detect species presence, and track ecosystem changes over time. These tools are essential for assessing the health of ecosystems and identifying shifts due to environmental stresses like wildfires.

2. Editing Genomes To Enhance Or Decrease A Particular Function Or Ecosystem Interaction: Genome editing technologies allow for precise modifications of an organism's DNA to enhance desired traits, such as disease resistance or adaptability to environmental changes. These tools can be used to create organisms better suited to withstand and recover from wildfire-related stresses.

3. Novel Technologies Which Integrate Multiple Scientific Fields: This category encompasses innovative technologies that integrate various scientific fields, such as genomics, robotics, and machine learning, to develop advanced solutions for ecosystem management and resilience. These tools can create new functions within ecosystems or specific taxa to mitigate the impacts of wildfires.

Areas of application and impact:

4. Monitoring Environmental Shifts and Species Response: Technologies like environmental DNA (eDNA) banking and monitoring are essential for tracking ecosystem changes and species responses, helping to identify biodiversity shifts and manage wildfire impacts.

5. Accelerating Adaptation to Environmental Threats: Genome editing tools such as CRISPR and gene drives can speed up species adaptation to changing environments, enhancing disease resistance in plants and animals crucial for maintaining ecosystem functions amid increasing wildfires.

6. Creating Novel Ecosystem Functions: Integrating genomics with robotics and machine learning can create new ecosystem functions, such as engineering fire-resistant plants or developing microorganisms that restore soil health after fires.

7. Managing Invasive Species: Biotechnology can effectively manage invasive species, reducing their impact on native ecosystems. Genetic modifications can target and control these species, aiding in wildfire risk reduction and recovery.

TABLE 1.1 Biotechnology: Tool, Readiness Levels, Example Applications, Market Segments Driving Innovation

Genome Sequencing *Example Tools:* Next-Generation Sequencing (NGS), Sanger Sequencing.[2] *Example Environmental Applications:* Understanding what is present today, how it changes over time as a result of environmental and climate pressures, and which natively occurring species are capable of digesting or transforming toxins and minerals - and which are capable of speeding and supporting ecological succession following climate or polluting events. *Technology Readiness:* Mature - Widely used in research and clinical settings. *Market/Investment Sectors:* Healthcare, pharmaceuticals, agriculture, and academic research. Driven by the need for precision medicine, personalized treatment plans, and advancements in agricultural genomics.	**Bioinformatics** *Example Tools:* BLAST, Clustal Omega, RNA-Seq *Example Environmental Application:* Genomic data analysis, protein structure prediction, systems biology. *Technology Readiness:* Highly Mature - Widely used in research and clinical settings. *Market/Investment Sectors*: Biotechnology, pharmaceuticals, academic research. Companies like Illumina, IBM Watson Health, and academic institutions are major players.
Gene Editing and Transgenic Species Creation *Example Tools:* CRISPR-Cas9, TALENs, Zinc Finger Nucleases - tools used to precisely edit genes, allowing researchers to knock out, knock in, or modify specific genes; Gene cloning, microinjections, agrobacterium-mediated transformation (a method of introducing foreign DNA into plant cells). *Example Environmental Applications:* Gene drives to address mosquito or other invasive species proliferation, supporting the resilience of threatened species to environmental or climate pressures, crop resilience, functional genomics[3]; transgenic: enable species to resist pests or pathogens through 'splicing' with other native species such as the transgenic American Chestnut tree. *Technology Readiness:* High Readiness - Clinical trials and agricultural applications in progress. *Market/Investment Sectors:* Biotechnology, pharmaceuticals, agriculture. Significant investments from: Editas Medicine, Monsanto, CRISPR Therapeutics, others.	**eDNA and Microbiome Analyses** *Example Tools:*16S rRNA sequencing, metagenomics, metatranscriptomics. PCR amplification of DNA from environmental samples, qPCA for detecting and quantifying DNA sequences, high-throughput sequencing platforms for sequencing from mixed environmental samples *Example Environmental Applications*: understanding microbial communities, environmental microbiology, biodiversity monitoring, microbiome analysis, species detection, population studies. *Technology Readiness:* Established - Widely used in research; growing in conservation and environmental monitoring. *Market/Investment Sectors:* Healthcare, environmental science, agriculture, conservation biology.
Proteomics *Example tools*: Mass spectrometry, protein microarrays *Example Environmental Applications:* understanding protein function and interactions, identifying biomarkers for diseases, determine protein/heat interactions to address fire-focused applications where heat sensitivity is critical *Technology Readiness:* Mature - Advanced in research; emerging in clinical diagnostics. *Market/Investment Sectors:* Healthcare, pharmaceuticals, academic research. Companies like Thermo Fisher Scientific and Bruker lead the market.	**Gene expression analysis** *Example Tools:* Microarrays, RNA-seq *Example Environmental Applications:* measuring gene expression level, identifying regulatory mechanisms within genes, understanding disease pathways *Technology Readiness*: Mature - Widely adopted in research and diagnostics. *Market/Investment Sectors:* Healthcare, pharmaceuticals, academic research. Investments from companies like Affymetrix and Illumina.

[2] Restriction site-associated DNA sequencing (RAD-seq) has been a popular tool for genotyping and studying genetic diversity in non-model organisms due to its cost-effectiveness and efficiency in generating high-density SNP data. However, its usage has declined in favor of more advanced and comprehensive techniques.

[3] (a field of molecular biology that aims to understand the complex relationship between an organism's genome and its phenotype. It involves the comprehensive study of gene functions and interactions, focusing on dynamic aspects such as gene transcription, translation, and protein-protein interactions rather than static aspects like DNA sequence or structure alone.)

Metabolomics *Example Tools:* Gas chromatography-mass spectrometry (GC-MS), liquid chromatography -mass spectrometry (LC-MS), Nuclear magnetic resonance (NMR) *Example Environmental Applications:* metabolic profiling, ID disease biomarkers *Technology Readiness:* Advanced - Widely used in research; growing in clinical and environmental applications. *Market/Investment Sectors:* Healthcare, environmental science, nutrition. Companies like Agilent Technologies and Waters Corporation drive advancements.	**RNAi (RNA interference)** *Example Tools:* SiRNA, shRNA, miRNA - technologies in which RNA molecules inhibit precise gene expression by neutralizing targeted mRNA molecules, preventing production of specific proteins. *Example Environmental Applications*: gene silencing, study of gene function, taxa-specific vaccines (eg - a rodenticide that won't kill other species accidentally), therapeutic applications *Technology Readiness:* Established - Widely used in research; emerging in therapeutics with some FDA-approved treatments. *Market/Investment Sectors:* Pharmaceuticals, biotechnology, academic research. Investments driven by companies like Alnylam and Ionis Pharmaceuticals.
Synthetic Biology: *Example Tools:* DNA synthesis, genetic circuits, biosensors *Example Environmental Application*: biomanufacturing, environmental biosensors which could deliver real time insight on conditions or, one day, perhaps carbon levels in soils, development of synthetic alternatives to pharmaceutical inputs *Technology Readiness:* Emerging - Growing applications in research and industry. *Market/Investment Sectors:* Biotechnology, pharmaceuticals, environmental management. Companies like Ginkgo Bioworks and Amyris are key players.	**Single-cell analysis:** *Example Tools:* single-cell RNA sequence (scRNA-seq), flow cytometry, single-cell proteomics *Example Environmental Applications*: To understand how microbial communities contribute to soil health and nutrient cycling, particularly in the context of agricultural practices and environmental changes *Technology Readiness:* Advanced - Widely used in research; emerging in clinical applications. *Market/Investment Sectors:* Healthcare, pharmaceuticals, academic research. Leading companies include 10x Genomics and Bio-Rad Laboratories..

C. ECONOMIC VIABILITY

RELEVANT TRENDS (MARKET, PUBLIC, PRIVATE) AND ASSOCIATED CRITERIA FOR PRIORITIZATION

Carbon markets and wildfire resilience: The last two years have seen a series of challenges in voluntary carbon markets in California - and with a particular focus on forestry. Concerns range from measurement and verification issues to price uncertainty and market volatility. There is also a propensity for 'long duration' carbon which particularly stymies nature based solutions that offer near term in-and-above-ground measurable carbon but are often seen to be less durable over time as natural systems are less permanent - however, with policy and economic frameworks that placed value on reliable ecosystem services and avoided nature loss this would change. In the near term, it's unlikely that carbon markets will be the driving force behind any of the technologies we evaluated - as a result we focused our efforts on those areas where the near term value of the product is highest, and the potential for applied outcomes is greatest. Further, current federal law prohibits USFS from directly participating in carbon credit markets (VCM). Notably, there are policy trends which may affect the viability of carbon markets as a driver for wildfire resilience technologies - most substantially, the Biden administration's recent announcement that the US Federal Government will become a buyer in VCMs.

Decreasing or repurposing existing costs: Any new innovation must be considered in juxtaposition to alternative solutions available today or on the near horizon. What else is available? How expensive is it (as measured in carbon and dollars)? Who is paying for that and is that money sustainable? What are the risks and benefits of it? In general, this results in the following basic indicators of viable funding, replication and/or scale - if an approach has the potential to do one or more of the following:

- Replace Current Harmful Products and Practices: This takes advantage of existing markets, existing supply chains and applications and offers improvements which might drive cost reductions, public funding shifts, and more, in addition to ecological benefit.
- Free Up Labor and Equipment: Innovations that reduce the need for manual labor or heavy machinery.
- Provide An Improved Alternative To Current Public Sector Methods: Where there are public funds - federal, state or regional - which focus on, for example, the remediation of soil toxins, there is a compelling economic case for the research and development of improved and less costly (as measured in carbon or dollars) methods.
- Build Understanding of Soil Carbon and Health: Enhancing knowledge in these areas to support broader ecological resilience - this is important not only climate and biodiversity in the context of wildfire resilience; but also in that improved monitoring, reporting and verification (MRV) of soil carbon and other components of soil nutrient density as a critical factor in enabling soil carbon in carbon credit markets. For this reason, there may be non-traditional donors/investors in the wildfire space who are interested in improved MRV or scientific understanding.
- Leverage an adjacent and aligned market to drive adoption: By strategically aligning with existing markets, where wildfire-oriented biotechnologies can provide value and achieve growth, biotech innovators can access new resources to accelerate progress.

Capitalizing on co-benefits: Markets don't often place value on ecological health - but concessionary capital and public dollars do - and any approach to wildfire resilience is going to have additional co-benefits for other ecosystem functions. While this is not always easy to quantify and capture, it's critical to evaluate as this can provide access to non-traditional investors and partners to drive research, testing, early stage implementation and iteration. The following ecological co-benefits are present in nearly every biotechnology approach considered -

- Carbon Sequestration and Storage: Contributing to state and corporate net-zero goals.
- Water Quality Improvements and Watershed Protection: Aligning with the CA Water Resilience Portfolio.
- Habitat Restoration and Biodiversity Conservation: Supporting 30x30 and similar nature-positive targets.
- Sustainable Forest Products and Biomaterials: Expanding climate-smart wood utilization markets.
- Public Health Benefits: Reducing smoke impacts and exposure to firefighting chemicals.
- Green Jobs and Economic Resilience: Boosting employment in rural, forest-dependent communities.
- Enhanced Recreation and Aesthetic Values: Promoting healthy, fire-adapted landscapes.

Key take-aways:

There is substantial investment and public capital seeking improvements, replacements and beneficial additives to wildfire retardants. Recent legal restrictions placed on the use of some chemical additives in fire retardants underscores the pressure to innovate. And, there is a $180M+ markets, ripe for disruption, providing a clear exit for new products.

The transfer of existing techniques and tools - such as those already in use in the agricultural, mining or pharmaceutical sectors – to homologous applications in the wildfire resilience is technologically feasible and economically smart. This is particularly true where existing IP holders - or even bio-manufacturers - might be enticed to pursue wildfire applications themselves, perhaps at below market rate returns where public and philanthropic capital can de-risk the investment. For example, post-mining remediation currently uses microbial techniques for soil regeneration, these likely have applications in upper watersheds where heavy metals contaminate water and soil following extreme fires.

Wildfire resilience solutions which have additional market applications beyond fire can scale through those applications, leaving the wildfire application as a 'lost leader'. For example, native grass seed markets are growing, and native grass seeds altered to thrive in drought might have applications for both wildfire resilience (outcompeting flammable/encroaching cheatgrasses) and native seed markets (carbon, water, and soil-nutrient density improvements through, for example, *stipa pulchra* native grasses).

Biotechnologies can and should deliver Nature Positive outcomes, the field is nascent, field trials of viable products are limited and funding to advance them is hard to acquire without proven and demonstrated technologies**.** This means not just mitigating harm, but providing net benefits in the context of climate and extreme weather pressures like wildfire. Nature positive refers to actions and outcomes that contribute to the restoration and enhancement of biodiversity, leading to a net positive impact on nature (Nature Positive, 2022). This frame provides a useful methodology as a north star for environmental biotechnology approaches. In short, it aims for the increasing health, abundance, diversity and resilience of species, populations, and ecosystems so that by 2030 nature is visibly and measurably on the 'path of recovery'. This is measured by balancing metrics across GHG emission reductions, species and ecosystem biodiversity increases, soil fertility increases, and freshwater quality and availability (Baggaley et al, 2023).

Evaluating the intended and unintended consequences of biotechnology is challenging. We don't truly understand the risk of new innovations until we try, fail and iterate - both in the lab and through field trials. At present, in fact, we only truly understand the risk of inaction - which is all too often an insufficient understanding to ignite interest and funding, particularly in the face of concerns over technology risk, understandable socio-political wariness, and unintended consequences. Our effort here is to evaluate potentials within this uncertain context - and, ultimately, to make the case for advancing research and field trials where the anticipated outcomes appear feasible, near, and beneficial.

TABLE 1.2, Goals, Tools and Examples for Monitoring, Measurement and Reporting of Environmental Biotechnologies.

Monitoring	**Measurement**	**Reporting**
Goal: continuous monitoring systems to track the performance of biotechnologies in real-time - with a focus on direct and indirect impacts[4].	Goal: Standardized protocols for accurately measuring the impact of biotechnological solutions on ideal outcomes including GHG, Carbon, biodiversity or more precise outcomes such as soil resilience post-fire.	Goal: transparent reporting to communicate results to relevant stakeholders (policy makers, investors, land stewards, community members, researchers, project developers, the public) - and the significance of those results[5].
Potential tools: biosensors, remote sensing	Potential tools: mass spectrometry, chromatography, biosensors.	Potential tools: reports, central repositories, an aggregated central body like a climate biotech task force
Example: use of cell-free biosensors to detect the presence + concentration of GHGs or pollutants and any genetic shifts in ecosystems	Example: Masspec or chromatography to ensure carbon levels in soil and biomass are not shifting, biosensors to determine biocontainment or spread.	Example: Public regular reports that detail outcomes, possible flexible research funding to pivot where results are other than anticipated and affect research still in progress.

Key Takeaways:

There is a need for <u>decision tools which de-risk the consideration of biotechnologies</u> as part of the suite of ethical, effective and viable tools available to conservation and land management organizations among the suite of tools available for ecosystem resilience. In fact, we found this challenge to be so prevalent that we will soon be publishing an independent decision model for environmental biotechnologies.

Upper and lower bounds determinations (ie: uncertainty thresholds, what are we comfortable knowing and not knowing) should be defined with the <u>explicit goal of later using these to inform policy and governance recommendations.</u>

Field Trial Parameters should have advance agreement on rigorous <u>testing and monitoring of ecological impacts at relevant time and ecological scales.</u>

<u>Mitigation plans</u> (both to decrease unintended consequences, and to create replicable blueprints for policy and governance) <u>should be built in concert with multidisciplinary stakeholders</u>. For some approaches, there are clear risk mitigation methods, such as the incorporation of engineered safeguards and 'kill switches' – which cause a gene function to effectively turn off in the presence of certain environmental conditions or over a series of reproductive generations. This is a very reliable methodology, but requires genome editing (which is not always socio-politically feasible) and creates some vulnerability to 'picking the right indicator'. The mitigation plans we propose instead prioritize alternate methods to reach the same conclusion: mitigate unintended consequences to the best of our abilities, prioritize early stage research and create redundant and replicated field trials, aim for Nature Positive outcomes, not just harm reduction, move first into those areas where the risk of *inaction* is the highest.

[4] *Although it is generally easier to measure direct impacts and those tend to be a higher priority, biological solutions may impact other parts of ecosystems - where possible, metrics should consciously include non-target systems to evaluate unintended consequences.*

[5] *Regulatory agencies will set thresholds of 'significance' for ecosystem shifts over time, and in the absence of those today, we have to evaluate each potential approach based on tradeoffs and the best judgment of technical experts as to the net impacts and the significance of those impacts in the context of extreme wildfire.*

E. REGULATORY FEASIBILITY

REGULATION AND GOVERNANCE TRENDS, CHALLENGES AND OPPORTUNITIES

This field is nascent, and the most effective pathways to nimble governance - capable of grappling with uncertainty and tradeoffs while spurring innovation under limited risk conditions - will be to include governing bodies and regulatory agencies in the planning and development of field trials and implementation plans for any proposed biotechnology solutions. As articulated in the Introduction, we believe that early stage, and 'sub scale' demonstrations will be the most meaningful contributions to understanding risk, risk mitigation, and policy in the context of environmental biotechnology. As such, our effort here is to (a) provide insight on current regulation and governance as it relates to biotechnology R+D with a specific focus on wildfire resilience application (b) outline trends - enabling and disabling conditions - which inform prioritization of R+D hypotheses for advancement in the near term and (c) provide recommendations on governance principles, and mechanisms through which they can be developed and advanced, that might meaningfully unlock environmental applications of biotechnology innovations.

Regulatory bodies with existing interest in potential biotechnology solutions for wildfire resilience[6] to be involved in planning + implementation:
We evaluated and categorized Federal and State agencies with an interest in the application of all considered biotechnology approaches to wildfire resilience - with the goal of determining which among these agencies and organizations were most necessary to include in convenings and discussions during the trade-offs evaluation and hypotheses development phase, such that the R+D approaches were meaningfully informed by the agencies most responsible for enabling or disabling field testing and implementation over time. A full list of agencies and visual tables showing 'interest levels' is available in Appendix 1 of this report. From this analysis we concluded to include the USFS first and foremost, and to gain a clear understanding of field testing processes and timelines to reference during the process of prioritizing R+D approaches and recommendations. We further recommend that during the research and development of follow-on activities from this report, CalFire, Department of Fish and WIldfire and the California Natural Resources agency be included as partners and colleagues in development governance, risk, measurement and monitoring, and regulation methods for all proposed solutions.

Data Sovereignty and the Governance of Data and Knowledge under Advanced Biological Research and Development, use of CARE model:
Environmental biotechnology solutions will, we believe, be an increasing tool in how we approach the resilience of ecosystem services on which our communities, economies and ecosystems rely. With that emergence comes an important opportunity to inculcate the use of methods which track, categorize and utilize data in ways that provide meaningful sovereignty over the use of data, and benefit-sharing in the use of data, to Indigenous peoples and land stewards. We recommend the use of the CARE model, relying on the proposed methods for its use outlined by Jennings et al in 2024, which describes specific tools to use in integrating data sets between academic samples and Tribal contributions to data, knowledge, field assistance, and advisory services. This is particularly important in the context of wildfire resilience - where much of the affected land is Tribal land, where the root source of the challenge stems from the removal of Native Peoples and cultural burning from the land, and where much of the effort to build resilience relies on Indigenous scientific, governance and ecological practices. Additionally, the White House recently called for the increased use of CARE and OCAP models, further underscoring the recommendation to use these specific methods in evaluating R+D priorities.

Governance Guidelines in the Context of Risks and Uncertainties

1. <u>Develop MMRV plans which intentionally aim to de-risk policy changes</u> - if the technologies work, they should be able to meaningfully demonstrate what is possible through biotechnology solutions, and de-risk decision making and regulatory shifts to enable that potential.
2. <u>Pilot community-led governance models,</u> such as regional stewardship councils, to guide context-appropriate use of biotechnologies for shared ecological and social benefit. Importantly, governance strategies must remain adaptive and iterative, with built-in mechanisms for monitoring effectiveness, incorporating new knowledge, and adjusting course as needed.
3. <u>Strive for reflexive and regenerative policy approaches</u>, rather than overly restrictive or reactive ones, can create an enabling environment for game-changing solutions. Key actions could include:
    i. Establish a multi-agency working group to identify regulatory gaps, clarify jurisdictional authorities, and develop streamlined permitting pathways for low-risk, high-potential biotechnology applications. This is something the Aspen INstitute's Energy and Environment Program is actively pursuing in partnership with the Lab to Land Institute.
    ii. Invest in regulatory science and capacity-building to improve risk assessment capabilities and keep pace with emerging technologies - a leader in mapping this field is the Federation of American Scientists.
    iii. Develop guidance and best practices for transparent, inclusive public engagement and societal dialogue around biotechnology use in natural resources management - the Lab to Land Institute and Harvard Connecting Genomics to Climate organization are both focusing in these areas.
    iv. Create incentives and funding mechanisms for responsible biotech innovation, such as public-private partnerships, startup incubators, and results-based financing. Leaders in this space include the EBRC, Revive and Restore, and the Lab to Land Institute.
    v. Incorporate biotechnology considerations into existing planning processes, such as the California Wildfire and Forest Resilience Action Plan and the Climate Smart Strategy for Natural and Working Lands

[6] Full list provided in detail in appendix 1.

The following table, TABLE 1.3, summarizes the refined, precise areas of intervention where ecosystems and ecosystem functions are most vulnerable, and where biotechnologies can feasibly enable resilient and healthy, fire-adapted forests in the arid west.

TABLE 1.3 Developing Precise Problem Statement and Intervention Points for Biotechnologies to Address Wildfire Resilience

DECREASE THE RISK OF EXTREME FIRE	INCREASE BENEFICIAL FIRE	INCREASE FIRE RESILIENCE
THE CHALLENGE		
Problem: California is not meeting targets for acres treated by either prescribed fire or ecological thinning - both of which are necessary activities to decrease the risk of extreme fire. Factors which limit the State's ability to meet target include policy, regulatory, and economic challenges - including lack of access to over-crowded acres (for example, because current policy limits access to slopes of 30% or steeper) and lack of capital for ecological thinning at the pace and scale necessary.	Beneficial fire is a critical land management tool in fire-adapted landscapes. In California, only a fraction of acres that need beneficial fire each year receive it. Contributing factors include - workforce and equipment availability, permitting timelines, opportunity costs for high-demand crews, perceived risk, aqi regulations. Failure to meet target acres increases severe fire risk, and, over time, increases the number of acres which need ecological thinning.	Because there will be more high severity fire in the west before there is less, a critical focus area for any new technology is the resilience of our landscapes, communities and ecosystems to the impacts of high heat fires. Without resilience, we further exacerbate the potential risk and the vulnerability of ecosystems to future climate and fire impacts.
ASSESSMENT CRITERIA TO DEVELOP AN EXPANDED LIST OF ASSOCIATED ECOSYSTEM VULNERABILITIES		
- Type and degree of harm caused (erosion, contamination, species loss, etc) - equity and ethical considerations of who/what bears the bulk of that harm - degree of concern to State of California (based on budgets and anticipated costs/ramifications of failure to address)[7] - spatial scale of the threat - frequency of its occurrence and speed/scale of threat exacerbation - functional impact of the ecological threat - resistance of ecosystems to the ecological concern - recovery times of ecosystem functions (in juxtaposition to specific species recovery times)		
RESULTING REFINED, PRECISE INTERVENTION POINTS		
- Decrease arid, oily grasses in high-ignition regions - Enhance carbon + water storage in watershed soils - Improve lignan use in biomass processing - Decrease risk due to in-situ standing biomass	- Dampen the heat of high severity fires - allowing for extreme fires to become conscious/active beneficial burns. - Decrease reliance on firefighting rigs/crews for policy-mandated risk mitigation	- Improve existing fire retardants - Mitigate harm from existing retardants - Replace existing retardants - Enhance ecological succession post-fire - Enable resilient water quality/quantity
RESULTING AREAS OF INQUIRY FOR INITIAL HYPOTHESIS DEVELOPMENT		
➔ Lower cheatgrass resilience (soil inoculant) ➔ Stop cheatgrass growth (gene drive) ➔ Enhance native grass growth (enhance seed) ➔ Increase soil's resistance to fire (inoculant) ➔ Carbon-negative lignan uses (TBD) ➔ Compost biomass, in-situ (inoculant)	➔ Heat 'dampening' retardants (TBD) ➔ Natural burn barriers (fire resistant fungi)	➔ Speed recovery (soil amendment) ➔ Consume post-fire toxins (soil amendment) ➔ Remediate contaminated water (microbial) ➔ Replace PFAs (TBD) ➔ Low-nutrient loading retardants (additive) ➔ Rapid pollutant biosensors ➔ Engineered heat/burn resistant microbes
ENABLING FACTORS + BASIC RESEARCH NEEDS[8] ; Robust biocontainment strategies, improved biosensor capacities (with machine learning integration)		

[7] detailed in Appendix 1
[8] Excellent list of research needed to advance environmental biotech across applications: *Addressing the Climate Crisis through Engineering Biology* (Aurand, et al 2024)

SECTION II.
ALTERNATIVES AND RECOMMENDATIONS

SUMMARY OF RECOMMENDATIONS BY IMPACT AREA

Overall, we recommend advancing research on (1) the time resolved post-fire metagenomics of soil microbiomes with a goal of (a) better understanding the post-fire microbiome, it's natural make-up and toxin-digestion capacities, and providing public data on this improved understanding; and, (b) developing a soil amendment made of natively occurring species which may substantially speed beneficial ecological succession post-fire. (2) development of a drop-in additive to existing phosphorus-based wildfire retardants which would mitigate nutrient loading in sensitive and economically-critical upper watersheds and (3) developing a fire-science steering committee to harness learnings from goals (1) and (2) while simultaneously exploring (a) the potential of a 'heat-dampening' additive/alternative to existing retardants, (b) additional pathways to risk reduction and post-fire resilience through natively occurring species as informed by the soil amendment and drop-in nutrient load-mitigation and (c) literature reviews and expert insight gathering to inform improved lignin use and the potential for in-situ composting of lignin and slash waste.

Below are the hypotheses which emerged from this process - and in the following section each is explored in greater detail, resulting in the above summary recommendation.

INCREASE BENEFICIAL FIRE	REDUCE RISK OF HIGH INTENSITY FIRE	BOLSTER RESILIENCE TO SEVERE FIRE
biological burn perimeter during beneficial fire	improved carbon-negative lignan processing	reduce nutrient-loading from fire retardants
heat 'dampening' retardants during severe fire	in-situ composting of high hazard fuels	biological fire retardants + PFA replacements
	mitigate risk of cheatgrass ignition	speed ecological succession - from 10yrs to 1.

Each hypothesis was evaluated across the core categories laid out at the top of section I: (a) economic viability (b) technological feasibility (c) socio-cultural appropriateness (d) political viability (e) ecological/climate value. This visual shows a comparative analysis of each, using a 1-5 ranking system where 1 is low and 5 is high.

The following section lays out greater detail on the target impact area, biotechnology opportunity set, considered hypotheses, available or anticipated alternatives, economic viability and impact potential for each considered hypothesis. For some, we include recommended metrics and measurements - for others the phase of research is too early to offer clear parameters for measurement. For each we also discuss the above components which are not effectively visualized in a summary graph but are critical components of final recommendations. And, for each, we conclude with a short set of recommended near term actions to further understand and/or advance that particular hypothesis or set of hypotheses.

FIRE RESILIENCE CONCEPT: REDUCE NUTRIENT-LOADING FROM HIGH-USE PHOSPHORUS-BASED AERIAL RETARDANTS

Target Impact Area

Increased usage of phosphorus-based wildfire retardants exacerbates its harmful side-effects.
Phosphorus-based fire retardants are being deployed at increasing rates - as much as 18M gallons in the landmark 2020 fire season alone. Yet the increasing volumes of retardants (e.g., Phos Chek) are not matched with a proportional increase in acres burned. Rather, the volume of fire suppressant use is associated with fire severity, not acres burned, and the product lacks efficacy at higher severity rates. Further, we estimate a significant (50%+/-) increase in fire intensity, frequency and severity between now and 2050 or beyond. These hotter and drier conditions will exacerbate the Vapor Pressure Deficit (VPD) effect: a negative feedback loop between climate change and wildfire where drier hotter atmospheric conditions absorb more moisture from forests and landscapes and further exacerbate the potential of hazardous wildfires. In short - it's going to get worse before it gets better; and that will only require more fire retardant until and unless there are alternate retardants or a decrease in aerial fire fighting. The residue from the retardant sticks to trees, plants, and surface soils until removed by wind or rain - often weeks or months; and restricted areas like endangered species habitat and waterways receive highly concentrated doses[9]. Yet, there are no fire retardants in use at scale which are not phosphorus based. Nor are there nearterm potential replacement products which might meaningfully decrease reliance on high concentration of phosphorus in aerial firefighting[10].

Reduction in forest and grassland ecosystem resilience due to phosphorus nutrient-loading.
California soils are often low in phosphorus naturally, and native plants are adapted to this. Key life cycles and ecosystem processes - like flowering in plants, nutrient levels to support native wildlife, and more - are adapted to the balance of nitrogen, phosphorus and potassium in native soils (the NPK ratio of soil). When NPK ratios are thrown out of balance, (e.g. through phosphorus nutrient-loading), these processes are critically disrupted. Just as phosphorus heavy wastewater is a trigger for significant contamination in estuaries and oceans, so too is the consistent and high-volume use of phosphorus for wildfire suppression. The deployment of aerial fire retardants at such volumes is shifting nutrient profiles of sensitive forests altering the resilience of ecosystem function specific to wildfire severity reduction - causing algal blooms, water contamination, risks to endangered species, genetic shifts in forest landscapes, and regrowth of more arid and flammable species.

Biotechnology opportunity

Advance biological alternatives and/or additives which might mitigate the harm from - or fully replace - chemical and mineral fire retardants with biological alternatives. Options for research might include the below.

Sprayable Mycelium: Mycelium, the root structure of fungi, has adhesive properties that can bind together organic matter such as dead leaves, twigs, and other debris on forest floors. When sprayed onto these surfaces, mycelium creates a protective layer that inhibits the ignition and spread of wildfires (Dhawan et al. 2023).
Phytic Acid / Dry Water Nanomaterial: Phytic acid, also known as "dry water nanomaterial", is a naturally occurring compound found in plant seeds, and has been identified for its potential as a fire retardant due to its ability to form stable complexes with metal ions (Jiang et al. 2021). When incorporated into a dry water nanomaterial, phytic acid can be dispersed as a fine mist onto forest litter and other combustible materials, creating a protective layer that inhibits ignition and slows the spread of wildfires.
Hydrogels: Hydrogels are water-absorbing polymers capable of retaining large amounts of water while maintaining a gel-like consistency. The hydrogel is a carrier, phosphorus recovery and chelating agent, and nutrient source for biologicals. When applied to forest litter and other combustible materials, hydrogels create a moisture barrier that reduces their flammability and slows the spread of wildfires.
Struvite Crystals: Struvite crystals, composed of magnesium ammonium phosphate, have shown potential as a fire retardant due to their ability to absorb and retain moisture.
Chitosan: Chitosan, derived from chitin found in the shells of crustaceans like shrimp and crabs, can form a protective coating on the surface of combustible materials, and when combined with certain strains of bacteria, can bind to phosphorus and prevent contamination.

Hypothesis #1: There are natively occurring biological materials that consume and convert phosphorus to different forms. This conversion would lessen the impact of phosphorus nutrient-loading on soil microbiomes and waterways. The soil microbiome data required to complete these three research needs is very limited. Additionally, what data does exist, has also been relatively siloed as integrating data sets presents privacy, sovereignty, and equity concerns. However, there are environments in California with high phosphorus where extremophile microbes have adapted to consume high levels of phosphorus such as Pinto Lake (Watsonville, Central Coast)- which have yet to be characterized and sequenced. A deeper understanding of these extremophiles, coupled with advances in nature-positive delivery mechanisms for biological materials (pioneered in agricultural industry), may offer new pathways to mitigating nutrient-loading while delivering value to California's Sierra Nevada ecosystems.

[9] USFS enacted "exclusion zones" in ecologically sensitive areas where retardant is not meant to be used, and established a 300-ft buffer when applying retardant around surface water by plane, and a 100-ft for helicopter + fire engine. But, there are exceptions to these buffer requirements when human life and public safety are threatened - and this is a common, and increasing exception. USFS is now required to report these accidental "intrusions," which amount to dozens every year.
[10] Currently, there are no widely used meaningful alternatives to phosphorus-based fire retardants like Phos-Chek on the market. Recent innovations like Fortify and GreenFire attempt to address some of the harmful impacts, but are new, untested over time, and do not yet offer comprehensive solutions, particularly for the regenerative needs of ecosystems following extreme fires. And, while some advocate for alternatives to aerial fire fighting altogether, this is unlikely to change in the near-term given reliance on these techniques and lack of viable substitutes.

. → Innovation need**:** This will require (a) characterization of the functionality of local, native biological materials to determine which species most effectively convert phosphorus and (b) of those, determination of ecosystem benefits provided by each and (c) development of a carrier technology to get a live protein/microbe mix using native species to the target cite.

*Hypothesis #2***:** Develop biological alternatives to wildfire retardants that would rely on naturally occurring biological materials *in lieu* of minerals and chemicals. → Innovation need**:** There are some formulations in lab research - all will require field trials and testing, substantial equipment improvements and improvements in manufacturing infrastructure to meet the scale/demand of retardants (there need to be large volumes at the ready during fire season).

Research to achieve hypothesis 1 will meaningfully contribute to research efforts to achieve hypothesis two, and can be achieved on a shorter timeline.

Alternatives Consideration: These materials are increasingly deployed, yet the increasing volumes of retardants (e.g., Phos Chek) are not matched with a proportional increase in acres burned. Thus the volume of fire suppressants is associated with fire severity and as such indicates an ineffectiveness of the abilities of modern fire suppressants in achieving less "bad fire", and establishing more "good fire" on the landscape. And yet there are no meaningful alternatives to phosphorus-based wildfire retardants used at scale.

Economic Viability: There are products in-use with homologous applications in agriculture today. Further, improving wildfire fire fighting materials and methods is a federal priority under the USFS - and budgets have been allocated to this - which will speed timelines to field testing. The key shift from products used in agriculture today is the proposed bioaccumulation and conversion of phosphorus to beneficial biomass that can enable effective soil regeneration and resilience over time. Further, inputs to the carrier/stability agent (hydrogel inputs), relies on existing waste streams (chitosan waste, for example, from shrimp and crab waste). Lastly, the combination of state of the art proteomics and eDNA to develop a method by which the protein/microbe mix can be delivered, alive, to a target delivery site may have additional applications, and economic value, beyond wildfire.

Impact potential If proven out, this could:
- Effectively mitigate the nutrient-loading impacts through the use of natively occurring biological materials,
- Offer a solution without requiring additional equipment or workstreams for fire fighting or land management teams
- Leverage existing knowledge and product development capacity within the agricultural sector
- Introduce a nature positive solution with biotechnology which can provide key insight for regulators across the environmental biotech field
- Contribute to core scientific understanding of Sierra Nevada soils in the context of wildfire
- Mitigate the harmful impacts of fire retardants and pursue pathways to replace harmful products altogether in the long run - a 'nicotine patch' approach to mitigate harm while non-mineral (or better mineral) products are developed (which is a long-term research effort).

Metrics Recommendations

Efficacy compared to current methods (e.g., fire control / knockdown time, duration of fire retardation, reduction in flame height or heat release)	Environmental impact + persistence over time (e.g., biodegradability, toxicity, bioaccumulation)	Potential for unintended consequences (e.g., direct mortality, species / functional diversity, nutrient cycling)	Ease of integration with existing firefighting infrastructure and practices (e.g., techno-economic analysis, supply chain assessment, regulatory compliance, application rates)

Measurement feasibility - Evaluation across scales of direct v indirect impact, temporal impact from immediately post-fire to longer term microbiome impacts and the degree of significance for each of these impacts is feasible for all of the above - which further underscores the potential of this particular approach as one of near term and high value both for it's ecological implications and for the opportunity to demonstrate viable environmental biotechnology approaches to the broader academic, investment and land-stewardship communities.

Recommended pathways for pursuit in the near term: Develop a proof of concept for an additive to existing fire retardants which will both digest phosphorous overloads immediately post-fire and leave behind beneficial value for arid forest soils - do this via partnership with existing agricultural biotechnology producers, University of California laboratories, and individuals with capacity to advance CARE methods in tandem with biotechnology R+D. For an expanded outline of research proposed and partners aligned and poised to advance this work, please reach out to the authors of this report who aim to advance this work within the 2024. Here is a summary:
- Develop CARE methodology and implementation plan to align with sampling, sequencing and product development research
- Characterize natively occurring microbes in high-phosphorus and post-fire fighting environments
- simultaneously develop a material to encapsulate target biological materials
- Characterize phosphorous processing capacities in naturally occurring target microbes
- Identify target protein for use inn modulating heat intensity
- Refine encapsulation material for target microbe/protein mix.
- Explore soil depth penetration alongside microbial digestion pathways to optimize beneficial impact
- Research impacts on: shifts in water contamination, shifts in biodiverse regrowth, soil contamination, beneficial fire return targets, aridity
- Further research the 'base case' for use of today's retardants over time on the same above criteria.

FIRE RESILIENCE CONCEPT: BOLSTER ECOLOGICAL SUCCESSION POST FIRE, REMEDIATE POST-FIRE TOXINS

Target Impact Area

Severe wildfires have significant short-term and long-term impacts on soil microbiomes, leading to reduced diversity, altered nutrient cycling, increased carbon loss, and diminished ecosystem services. Fire can reduce microbial biomass by up to 96% shortly after fires, disrupting nutrient cycling and exacerbating vulnerability to erosion (Nelson et al, 2022). Burn severity influences the types of bacteria and fungi present in post-fie soils - and the higher heat fires tend to result in the highest and most lasting shifts in soil microbiome functional capabilities (Dove et al, 2022). It is clear that after high-severity wildfires, bacterial and fungal diversity is greatly reduced, including a loss of ectomycorrhizal fungi, tree-root symbionts. Severe fires also exacerbate the risk of landslides - caused in part by the creation of hydrophobic soils by volatilizing lipid and was materials in soils which then condense in upper soil layers and decrease the capacity of soils to soak up water and increase susceptibility to erosive forces (Timmis and Ramos, 2021). Soil erosion and post-fire landslides can release significant amounts of carbon stored in forest soils - increasing 'carbon fluxes' by disturbing large amounts of soil organic matter which can then decompose more rapidly in the presence of oxygen, releasing CO2. In fact, studies have shown that severe wildfires can lead to long-term changes in soil carbon storage, with recovery taking several decades (Dove et al, 2022).

There may be opportunities to mitigate this impact, and speed resilience and restoration, however, there is too little high-resolution temporal analysis to understand microbial dynamics post-fire. Natively occurring species or groups with desired ecological traits - capable of swiftly consuming chemical toxins present in soils post fire, for example - can be reintroduced to regenerate damaged ecosystems and speed ecological succession. If used in advance of fire, these soil treatments could enhance natural microbial community resilience to the harmful impacts of severe fire. Through robust soil sampling, metagenomic analysis, and computational modeling, target species or functional traits can be identified and used to develop cost-effective soil treatments, similar to practices used to support agricultural soil health. A strikingly small body of research has used metagenomic techniques to analyze microbes present at a higher taxonomic level, and elucidate the metabolic potential of these organisms[11]. In fact, there is, to date, no time-resolved metagenomic information on post-fire ecological succession that offers an in-depth view to ecological shifts over time post-fire – and, as a result – our knowledge as to how to bolster and support beneficial succession is limited to changes in bacteria and fungi at the phylum level, and singular points in time approximately 1-2 years post wildfire. Most current research on post-fire soil dynamics relies on singular snapshots in time, typically at a minimum of 11 months or more post-fire, due to the high costs associated with frequent sampling.

Biotechnology opportunity

Given the anticipated increases in high-severity fires in the coming decade[12], it is not only prudent to gain a deeper understanding but may be feasible to develop applied approaches to speeding post-fire ecological succession through the use of natively occurring species which create the enabling conditions for biodiverse regrowth and digest post-fire chemical toxins.

Hypothesis #1: Develop a probiotic application to post-fire soils using natively occurring species with the capacity to digest chemical toxins which emerge post-fire and to enhance post-fire ecological succession. Perhaps it is then possible to increase dispersal of beneficial bacteria, fungi and their associated proteins, to aid in shifting heavily burned soil to healthy soil. Effectively 'acting like the wind' by increasing the speed and scale of the most beneficial subsets of biodiversity soil microbiomes immediately post-fire. → Innovation need**:** Refine understanding of target species most closely associated with post-fire regeneration, advance and replicate multiple field studies simultaneously to speed understanding and testing, leveraging the existing burn studies taking place on the Blodget Research Station through the UC Berkeley Innovative Genomics Institute.

Additional Hypotheses, deprioritized in review - development of growth accelerants via the use of plant growth hormones as a treatment to accelerate recovery; introduction of specialized or engineered fungi and bacteria with desired ecological traits, such as plant growth-promoting rhizobacteria (can include biosurfactants) through the use of CRISPR-Cas9 genetic engineering. These were deprioritized due to technical readiness, political feasibility, and socio-cultural feasibility especially when compared with timeline to impact and economic viability.

Alternatives Considerations: At present, there are strategies to improve the resilience of seedlings planted during post-fire restoration activities, and there are companies aimed at increasing the speed (and decreasing the cost) of seed dispersal post-fire. Innovators in this space include Funga, who provide bespoke fungal mixes to speed the growth and bolster the resilience of loblolly trees and could very feasibly expand this application to western nurseries focused on mixed conifer forest restoration - and Mast Reforestation, who leverage voluntary carbon markets to drive seed dispersal in post-fire restoration and other marginal land restoration activities through the use of aerial seeding via drones. These innovations can and should deliver value for western fire-prone landscapes, but are not directly aimed at the swifter ecological succession post-fire of biodiverse microbiomes, nor do they provide unique insights into the ability of natively occurring bacteria and microbes to consume and repurpose chemical toxins and other post-fire contaminants - information which could be used to inform other research and development on the horizon for wildfire resilience.

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[11] The majority of research on post-wildfire soils is conducted using 16S sequencing

[12] An estimated increase of 2-3 degrees celsius by 2100, much of that before 2050 - and a significant (50%+/-) increase in fire intensity, frequency and severity. These hotter and drier conditions will lead to the 'VPD' effect (Vapor Pressure Deficit), a negative feedback loop between climate change and wildfire - where drier hotter conditions absorb more moisture from forest and landscapes and exacerbate the potential of hazardous wildfires.

Additionally, there are organizations focused on post-fire restoration through the application of natively occurring fungi which facilitate regrowth, such as CoRenewal, a project of Maya Elison and UC Santa Cruz which educates communities and land managers on the power of fungi to aid in post-fire restoration and watershed resilience. Working with CoRenewal and similar regional organizations in other fire-prone landscapes might be a very valuable pathway to building sociocultural understanding and acceptance of the power of intentionally dispersing native species to speed renewal - and this might provide the enabling conditions to address resilience with more proactive methods - such as a soil amendment - down the road. However, today, this work is so bespoke to the precise geography and requires such hands on effort that it is hard to see this scale meaningfully as a post-fire restoration tool in the absence of clear, easy, replicable methods for fungal application that CalFire, USFS and other large land owners can easily implement.

Banfield Laboratory Researcher and Lab to Land Institute Fellow, Dr. Elliot Weiss, has studied post-fire soil microbiome shifts through field tests at the Blodgett Research Station since early 2023. Dr. Elliot Weiss' innovative research, unique in its high-resolution temporal analysis, tracks changes in soil microbiomes and chemistry from just 2 weeks post-fire out to 2 years - and in direct comparison to adjacent, unburned lands. This approach captures the seasonal changes and successional dynamics of post-fire soil recovery in unprecedented detail, providing a critical foundation for developing targeted interventions to accelerate soil resilience. Results are just emerging and being evaluated over the next 5 months. Early findings include:

- identification of species which proliferate in post-fire conditions (employ a combination of life strategies including heat tolerance and fast growth), and, it appears. then die off before most eDNA samples have been taken in the past.
- a subset of these species express genes which break down pyrogenic organic matter, including aromatic compounds + chemical toxins creating during fire.
- Viral activity may result in the lysis of these microbes, liberating a diversity of carbon compounds bioavailable to a broader diversity of bacteria and fungi.
- Microbial communities in soils subjected to high-severity fire may take as much as several decades to resemble their unburnt state despite the early presence of these toxin-remediating and scorched-soil tolerant species.

The early colonization of soils by these microbes is likely facilitated by wind, and migration from adjacent unburned soils. It is therefore likely that human-assisted dispersal (i.e. a natural probiotic, akin to a fecal transplant) could accelerate ecological succession of microbes, decreasing the time to recovery - possibly speeding the time to restoration of soil microbiomes by as much as 8-9 years.

Economic Viability: This soil amendment could have applications in nursery management for reforestation seedlings, and perhaps also in pre-fire soil conditioning to prepare high risk regions for greater resilience in the event of fire. It could also have applications outside fire, in both agriculture and community preparedness or home hardening. If applied at scale, this could feasibly decrease reforestation costs - particularly if such an amendment can speed beneficial ecological succession from a decadal scale to an annual or 1-3 year scale as currently estimated.

Impact Potential:

- Target Highest Risk Landscapes: Target forest acres where restoration has been particularly delayed or unsuccessful first relying on AI mapping
- Earlier & Increased Carbon Sequestration: Accelerating the growth of native species can lead to substantial CO_2 sequestration. For example, in the western US, an estimated 1.5 MT CO_2/acre across 2 million acres/year could result in up to 24 million MT of CO_2 captured over 8 years.
- Improved Soil Health & Erosion Control: Degraded soils exacerbate erosion and lose up to 80% more than healthy soil. Assuming 5 tons/acre/year of erosion in degraded soils, faster restoration could prevent ≤64M tons of soil erosion over 8 years, enhancing water quality + availability.
- Biodiversity Benefits: swift biodiverse regrowth and enhanced ecosystem resilience significantly benefits a diversity of core ecosystem services
- Cost and Time Efficiency: Developing a successful probiotic could reduce the costs and time required for forest restoration activities, streamlining planning and implementation of land management plans.

Metrics Recommendations - comparing treating and untreated areas -

Speed and extent of ecosystem recovery (e.g., percent vegetation cover, soil nutrient content, water quality)	Ability to restore soil health, prevent erosion, and contribute to soil regeneration (e.g., water infiltration rate, microbial activity, soil compaction, species / functional diversity)	Long-term improvement in ecosystem resilience (e.g., species richness, functional diversity, primary productivity)	Adaptation to changing climate conditions (e.g., community composition, shifts in VCM from anticipated #s, functional gene abundance, mycorrhizal associations)
Ability to establish and persist in the environment without causing harmful unintended ecological consequences (e.g., half life, bioaccumulation, toxicity)		Long-term impact on biodiversity and ecosystem health in treated areas (e.g., species richness, functional diversity, primary productivity)	

Recommended Pathways for Pursuit in the Near Term: Expanded research and replication of field trials in the immediate term will deliver swifter results and a higher potential of near-term applied value. Further, this expansion will provide valuable public data through UC Berkeley, demonstrating the importance of time-resolved metagenomics in addressing extreme climate events and increasing wildfire threats - an important contribution to both wildfire resilience and environmental biotechnologies.

Expand Field Trials:

- Replication: Conduct additional field trials in 3-5 different ecosystems, soil types, and burn severities; assess the generalizability of the findings.

- Optimization: Test various concentrations + formulations of microbial inoculants; determine the most effective approach to accelerate soil recovery, aiming for the smallest possible amount of living material over the largest possible space and time.

Data Analysis and Integration:

- DNA and RNA Sequencing: Continue DNA and RNA sequencing to monitor changes in microbial community composition and gene expression.
- Chemical Analysis: Conduct chemical analyses to track pH, nutrient levels, and the presence of toxic aromatic compounds.
- Preserved Samples: Analyze preserved samples using mass spectrometry; detect changes in soil chemistry and the breakdown of toxic substrates.

Develop Predictive Models and Tools:

- Integration with Vegetation Surveys: Combine soil microbiome + chemistry data, vegetation surveys + remote sensing to
- Understand and identify linkages between soil health and ecosystem recovery.
- Develop predictive models and decision support tools to guide post-fire management and restoration efforts based on research findings.

FIRE RISK REDUCTION CONCEPTS: IN SITU COMPOSTING OF PILED BIOMASS and IMPROVED LIGNAN USES FOR REMOVED BIOMASS

Target Impact Area

CalFIRE estimates that 6-9m acres of forest land in California are overcrowded and in need of thinning efforts. For context, California completes ecological thinning on approximately 200k acres/year – but has a goal of 1m acre/year by 2025. Removal of hazardous fuels is delayed for a variety of reasons: permitting delays, trained staff + contractor availability, weather windows for thinning operations, regulatory limitations which prohibit thinning activities on slopes of 30% or greater, technical/engineering challenges in accessing thinning locations (notably, the technical access challenges often do not align with the 30% slope regulatory access limitation), and the cost of biomass removal compared to the minimal economic value these materials then have. One result is the prevalence of standing biomass piles in California forests - small diameter timber, pine needles and oak leaves which are piled and unremoved throughout the Sierra Nevada and Cascades. The USDA estimates that there are about 100,000 piles of 'slash' waste or biomass piles in the Sierra Nevada at any given time. The federal government has committed nearly $5 billion in the Inflation Reduction Act and Bipartisan Infrastructure Law to thinning forests on about 50 million Western acres over the next 10 years. Standard thinning costs somewhere around $3,000 per acre, about a third of which is spent hauling out or burning the slash. Materials which are unremoved are often burned in place. Open burning of biomass piles is estimated to release about 1MT of CO_2 per metric ton of piled woody biomass (varies depending on moisture content and species). Additional impacts of open burning of a biomass pile include PM2.5 air pollutants and related human health impacts. Carbon dioxide release estimates[13] for biomass pile burns, whether in extreme fire or through planned open burns, vary.

Biotechnology opportunity

It is possible that biotechnology solutions can aid in shifting the economics of this equation - either by increasing the value of end-markt products or by enabling in-situ composting of hazardous materials. We explored three pathways. (1) biological degradation accelerants: microbial inoculants, enzymes, or other chemical treatments that might speed up the rate or natural decay of biomass; (2) ex situ conversion of biomass into natural products: small diameter timber and slash are used to create structural, agricultural and energy products - including biochar, biofuels, biocomposites, biogas, and chemicals - all areas where biotechnology may improve end-products and/or increase efficiencies. And, (3) in situ conversion of biomass into natural products: modified and mobile reactors, digesters, or other conversion systems to process and convert fuels onsite. We eliminated the onsite conversion of biomass due to access concerns and economic viability and refined to two hypotheses.

Hypothesis #1: **Enable the in-situ composting of cut and piled biomass** while also providing beneficial value to soil microbiomes over time using natively occurring microbes and enzymes. → innovation need: robust biocontainment strategies to enable existing composting slurries to be applied in forest lands under reasonable regulation and management, increased scale and capacity of existing innovations for in-situ composting, and improved formulations that can be less bespoke to the vegetation on which they are applied, or have some other efficiencies in the system such that it's easier to create bespoke formulations and distribute effectively, safely and at scale.

Alternatives evaluation: The most viable pathways forward may be to evaluate and support existing innovations through techno-economic analysis, basic research support, and through bridge capital to de-risk the choice to focus their work on western wildfire. For example, Wildfire Alliance, a start-up organization building a compost accelerant (US Patent US 11,603,495 B2[14]), to be applied ahead of advancing flames - focusing on fire resistance rather than pre-fire resilience/risk reduction. For such an innovation, formulations have to be quite bespoke to the vegetation on which they are applied, and it's expensive, slow and complex - particularly given the regulatory preference for natively occurring and regionally-sourced species in any biological formulation. The company is currently undergoing a series of tests to determine which combinations of ingredients are the most effective in stopping embers from igniting plant material. Homeowners may, for example, one day be able to use the product to reduce fire risk and thereby maintain insurance. Or, another example: Boulder Mushroom, developed by mycologist Zach Hedstrom, which uses fungi to transform wood piles to nutrient-rich soil - a process through which saprophytic fungi break organic material into carbon compounds and mycelium secrete digestive enzymes that release nutrients from the substrates they consume. (Where flames destroy nearly all organic nitrogen, mycelium can fortify nitrogen where it's needed in the forest floor). Scientists are figuring out a way to scale deployment (i.e. brewing mycelium into a liquid that can be sprayed across hundreds of acres) but there remain production, formulation and scale challenges.

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[13] A UC Davis study found that standing biomass piles can release ≤ 20x more CO_2 than live trees when burned in a fire. However, other studies have found that the net C emissions from burned biomass piles is relatively small (e.g. USFS found that burned biomass piles release only ~10% of the C that burned live trees do).

[14] The patent broadly covers compositions containing: Compost accelerators, which speed the decomposition of dead plant material; Deliquescents, substances that pull water from air; Plant-based polymers, which help healthy plants retain moisture and aid in decomposition of dead material; Plant nutrients.

Economic Viability: The public benefit of any of the above alternatives - or new innovations - would be substantial if the solutions were applied at scale. The challenge will be governance, risk mitigation and biocontainment, regulation and socio-cultural acceptance of these solutions - which will require substantial and wide-spread field trials in multiple ecosystems and political jurisdictions to demonstrate, learn, iterate, improve - and, importantly, to bring the community and the forest managers along in the process.

Recommended Pathways for Pursuit in the Near Term: These approaches may also be effective complements to prescribed burns and aerial retardants over time. It is therefore worth further effort to support the enabling conditions for these innovations to iterate and improve - which include: .

- Basic research to build robust, widely-tested biocontainment strategies
- Techno-economic analysis, permit navigation, field trial set-up support, and partnership generation to expand the safe and effective use of existing innovations into western wildfire context

FIRE RISK REDUCTION CONCEPT: CARBON NEGATIVE LIGNIN PRODUCTS/USES

Target Impact Area

Ecological thinning in the western United States, particularly the removal of high hazard fuels, is a critical but costly endeavor. According to the Joint Institute for Wood Products Innovation, forest thinning efforts aim to mitigate wildfire risks by removing small diameter trees, brush, and other forest debris. These efforts are substantial, with around 2-5 million tons of biomass removed annually. However, the economics of these operations are challenging. The cost of removing biomass ranges from $1,000 to $3,000 per acre, heavily influenced by terrain and accessibility. Unfortunately, the end market value of these materials, such as biomass for energy production or mulch, often does not cover these costs. For example, processed biomass might fetch only $20 to $50 per ton, which is insufficient to offset removal expenses. Federal and state funding, including provisions from the Inflation Reduction Act, aim to bridge this economic gap by subsidizing these essential activities, recognizing the long-term benefits of reduced wildfire risks and healthier forests (Suresh aet al 2023; Martins et al, 2022)

Biotechnology Opportunity

Lignin, a complex organic polymer found in the cell walls of plants, can be used as an input to air filters, water filters, a catalyst for chemical reactions, an input to resins, adhesives, bioplastics, and biomass derived energy and bio-oils. However, today, it is often burned for on-site energy in waste-to-value biomass campuses, which may not be the most economically advantageous use. It is possible that advances in energy, chemical and materials science industries may offer improved uses that could increase the value of this byproduct and potentially shift the economics of wood utilization campuses.

Hypothesis: Chemical, materials science, and energy sectors are driving innovation in lignin use such as phenols, aromatic compounds and other uses as adhesives resins and plastics (chemical industry); carbon fibers, bioplastics and other composite materials (materials sciences, e.g. aerospace); bio-oils and syngas (energy). It is possible that conversion techniques like breaking down lignin into useful monomers and intermediates which can be inputs to high value chemicals could provide additional value to the biomass campus. However, current technologies for lignin extraction and conversion are not always efficient or economically viable on a large scale. High costs associated with advanced processing techniques limit the amount of lignin that can be feasibly converted into valuable products. → Innovation need: Identify lower cost, on-site conversion testing capacities; perhaps through partnership with universities or others with a vested interest in innovation for lignin use and/or the outputs of potential lower-cost/more-efficient lignan processing.

Recommended near term actions: Economic analysis and literature review are needed to determine the net benefit of improved lignan use; it may be that the economic opportunity is too limited to warrant the shift to an alternative end-market use for lignan byproducts (eg onsite heat may still be the most logical use case; but it is worth considering alternative and creative pathways that might shift economics, particularly given increasing investments in alternative energies, and improved production pathways for high value chemicals).

FIRE RISK REDUCTION CONCEPT: REDUCE RISK OF WILDFIRE IGNITION VIA CHEAT GRASSES ALONG HIGHWAY CORRIDORS

Target Impact Area

Cheatgrasses have increased in California by over 180% in the past fire years as a result of fire suppression activities in high hazard regions, overgrazing, drought and warming conditions. Cheatgrasses are highly flammable and swift growing, and also outcompete more deep rooted, perennial native grasses for water and nutrients[15]. Approximately 50-80% of annual wildfires in California are started in cheatgrass habitats. CalFIRE estimates that ~10% of annual wildfires in California are started along highway corridors, where the combination of vehicles and cheatgrasses pose a particularly potent threat - this percentage is increasing and estimated to reach 25% by 2030, owing, in part, to VPD effect increases. Carbon emissions from just that 10% of wildfires would be about 9m MTof CO2, equivalent to the annual emissions from 2 million cars. What's more, cheat grasses outcompete native grasses; in the last 5 years, the State has lost an estimated 50% of native grasses which are important for soil stabilization, water conservation and habitat stability. Stipa Pulchra, for example, is 60% less flammable than cheatgrass, has about 15% higher moisture content, and produces about 40% less volatile oil. Cheatgrass is a warm-season grass that thrives in dry, disturbed areas. It is a prolific seed producer, and its seeds can remain dormant in the soil for many years. Further, forest management crews use chemical spray to mitigate cheat grass growth and reduce the flammability of cheat grasses along highway corridors - alternative solutions would not only mitigate the need for these sprays, but feasibly free-up workforce for other activities during early season restoration and beneficial burn windows.

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[15] Cheatgrasses can store ~10% more carbon per unit of biomass than Stipa Pulchra grasses; however, because cheatgrasses are annuals and Stipa Pulchra is perennial, the full volume of stored carbon in cheatgrasses are released back into the atmosphere each year.

Biotechnology opportunity

Biotechnology solutions might be capable of either mitigating cheatgrass encroachment, replacing the materials with which we address cheatgrass flammability along highway corridors, or shifting soil conditions such that cheatgrasses are less likely to outcompete species which provide greater ecosystem benefits. We considered the following potential approaches:

Hypothesis #1: Enable soil microbiomes to support native grass proliferation despite cheatgrass competition - this is an unlikely strategy as any increase in nutrient or water density in soils will only increase the growth and stability of the most competitive grasses, this would have the opposite impact and bolster cheatgrasses. → Innovation need: soil inoculant which could also selectively support the growth of precise species through engineered microbiome.

- Bottom line: Viability and impact potential is low for near term wildfire risk mitigation. This is not a technology which is available today - or in the anticipated near term - and thus the impact for fire mitigation is low. However,

Hypothesis #2: Establish a native grass seed with a biological encasing to bolster competition, using technology widely available in agriculture today, enabling resilience to arid and degraded soil conditions. This is technologically feasible - but requires a deeper understanding as to the interaction of hardier perennial grasses with cheatgrasses and other highly-competitive annuals; as well as other potential unintended consequences. Socio-politically, given the risk cheat grasses pose along highway corridors and the potential reduction in use of preventative retardants that might result from decreased flammability (due to improved soil conditions and less flammable grasses) this might indeed be feasible. Economically, it's more challenging and would rely on the native grass seed market[16] as a root source for capital and scale - alongside early stage philanthropy. The native grass seed market is ~$8.5B and growing. There are a number of drivers for native grass seed: Soil erosion protection - native grass has longer deeper roots and decreases erosion (The global erosion control technologies market should reach $5.8 billion by 2025 from $4.4 billion in 2020 a 5.8% growth rate, which might also provide economic incentive to pursue this route. Regenerative and 'carbon farming' agriculture programs promote cover cropping, which requires native grasses and legumes to be planted between off-seasons to hold soil and provide nitrogen fixing benefits, decreasing fertilizer needs the following year; and Conservation - planting of native grasses protects water resources. → Innovation need: low cost, and highly resilient native grass seeds.

- Bottom line: this is technically feasible today, and already in use in agriculture - but - the pathway to implementation is very challenging to imagine in the absence of robust research indicating that the proliferation of (eg) purple needle grasses would also lower ignition of severe fires in the region, this would be extremely hard to 'A B' test, and so the impact potential of this approach is low relative to other feasible pathways.

Hypothesis #3: Replace materials and methods used to address fire resilience along highway corridors. These are the same source materials as fire retardants evaluated in approach one - and incorporate PFAs, which the Department of Defence is currently heavily invested in replacing. We therefore focused our efforts and research on pathways to mitigate cheat grass encroachment through biological techniques to decrease it's competitive edge relative to California native grasses. Ultimately, we find that the value of research in this area will be most important as a basic contribution to biotechnology research - moreso than as an applied approach to wildfire resilience in the near term. → Innovation need: a self-proliferating and bio contained replacement for fire retardants currently used on highway corridors.

- Bottom line: Given that we have not seen scalable and heavily field tested alternatives to wildfire retardants through biologicals - if we do, this will certainly be an important use case, but it's unlikely to be the driving reason.

Hypothesis #4: Explore biocontrols for cheat grass species. Another pathway for genomic tech to address cheat grasses may be to determine if there is a role of manipulation of nutrient cycling to make the cheat grass less competitive. If self-limiting gene-drives have the capacity to limit highly flammable and ecosystem degrading species such as cheat grasses, then there is substantial value to conducting the basic research to better understand this approach. However, importantly, technology readiness is low, the cost of research may be high, and the socio-political viability of gene drives for plant species in landscapes that do not have natural geographic limitations (such as lake, islands) is very low.

- Bottom line: The reason to advance this research, therefore, would be less with the ambition to meaningfully reduce wildfire risk through cheatgrass limitation - and more simply to leverage the interest in fire and the public benefit of wildfire risk reduction to drive philanthropic capital toward a body of research in plant genomics that could contribute substantially to the field of environmentally biotechnology for invasives management in generally - using cheat grass as an entry point for a very important body of work on self-limiting plant gene drives. This would be a high risk / high reward body of knowledge for the future (eg $432B is estimated cost of invasive species management, and this does not include the impact of these species on extinctions).

Recommended near term actions:

- Literature review and landscape assessment to determine the first and highest value applications for plant biocontrols. Incorporate cheat grasses (and other California species which might exacerbate long term climate resilience in the fire-prone regions, such as mustard grasses).
- Support Basic research in plant biocontrols utilizing the cheatgrass as first exemplary focus species - aiming next for biocontrols in other invasive species. Today, most, if not all, of the research in this field is focused on non-plant species such as case toads, mosquitos, and asian carp.

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INCREASE BENEFICIAL FIRE CONCEPT: FIRE RESISTANT FUNGI, PERMITTED AS 'BURN BARRIER' FOR BENEFICIAL FIRE

Target Impact Area

Low-intensity fire in mixed conifer forests in California initially provides a 60 percent reduction in risk of catastrophic fire (Wara et al, 2023). This reduced risk lasts for a period of time - often 5-7 years depending on the vegetation and landscape - and then there is a need for more beneficial fire. California landscapes need this low-intensity fire to remain resilient, healthy, and biodiverse. As a result of mismanagement, the forced removal of cultural fire, and the failure of policy and regulation to catch up with the pace and scale of the need - California is now woefully behind in achieving it's goal of 1.1M acres of low intensity fire/year - in fact, estimates for annual beneficial burn acers are around 50k/year (Wu et al, 2023) - wildly insufficient to the goal.

One limiting factor is the reliance on wildfire crews and rigs to mitigate the risk of 'escape' flames during burns. Of the average annual 4000-5000 prescribed burns that are conducted annually on federal lands, around 0.16%, or 6 burns, have escaped the planned region. Notably, less than 1% of prescribed burns have escaped the planned burn area - roughly 0.16%, or around six burns for every 4500 burns. Reports also indicate about a 1.5% escape rate over 20 year period for landowner-led associations. In short, the risk of escape is very low. However, because the potential damage of a significant escape is large, the risk mitigation requirements for prescribed burns are very high. Overcoming reliance on wildfire fighting rigs and crews to be present alongside prescribed burn crews would increase the number of acres that can receive low intensity fire in a year, particularly during limited burn windows.

Biotechnology Opportunity

Natively occurring fire resistant microbes, fungi and bacteria may provide fire barriers which are native, biological, reduce reliance on added workforce and reduce the need for diesel rigs at prescribed burn sites.

The pathway to returning cultural fire to the land has been - and continued to be - a long, and hard-won effort to educate the public on the value of low intensity flames, to provide the legal and management authorities to Tribal lands for cultural burns at the pace and scale necessary, and to increase the air quality management limits to allow for more low intensity fires in order to mitigate high intensity fires. Any approach to shifting the risk mitigation measures has to be very careful not to become deleterious to these efforts - it has to be clear, simple and valuable so as not to muddy the waters of this education and policy work.

Recommended near term actions:

- It is worth further bioinformatics to understand and characterize the fire resistance capacities of natively occuring fungi, microbes and bacteria. With this information, it would likely be possible to develop biological risk mitigation strategies using natively occurring species - and to test and demonstrate this capacity with a targeted storytelling and policy change goal.

INCREASE BENEFICIAL FIRE CONCEPT: MANAGE FIRE INTENSITY WITH PRECISION 'HEAT DAMPENING' RETARDANTS

Target Impact Area

Low-intensity fire in mixed conifer forests in California initially provides a 60 percent reduction in risk of catastrophic fire (Wara et al, 2023). This reduced risk lasts for a period of time - often 5-7 years depending on the vegetation and landscape - and then there is a need for more beneficial fire. California landscapes need this low-intensity fire to remain resilient, healthy, and biodiverse. As a result of mismanagement, the forced removal of cultural fire, and the failure of policy and regulation to catch up with the pace and scale of the need - California is now woefully behind in achieving its 1.1M acre/year goal for low intensity fires - achieving around 50k/year at present (Wu et al, 2023) - wildly insufficient to the goal.

At the same time, high severity fires have increased in intensity and size - In California, the need for more low-intensity fires has become increasingly critical for maintaining healthy ecosystems and reducing the risk of catastrophic wildfires. These fires contain low heat patches which can be managed as beneficial burns. IN fact, firefighters sometimes strategically manage fires to allow these low-intensity flames to burn, taking advantage of the opportunity to achieve necessary low-heat fire coverage even during high-severity events.

Biotechnology opportunity

While researching drop-in additives to existing aerial wildfire retardants, research also the feasibility of a heat-sensitive encapsulation and thermosensitive polymer such that the mineral components of a retardant (ammonium phosphate, etc) could effectively coat vegetation and prevent burning only at the highest severity heats - and would degrade at a lower heat to enable 'heat dampening' rather than 'fire fighting', so to speak.

Recommended near term actions:

Consciously including this line of learning alongside the pursuit of a nutrient-loading mitigation additive to aerial retardants - which could be done through a coworking group that meets on a bimonthly or quarterly cadence to consider additional adjacent research and implications of results as they emerge, for example - would be meaningful. Achieving a heat dampening additive or alternative would be very challenging - and may not be technologically feasible - but it's worth continued consideration.

FIRE RESILIENCE CONCEPT: REPLACE PFAs WITH BIOLOGICAL ALTERNATIVES

Target impact area

PFAS is an umbrella term for a family of thousands of manufactured organic chemicals with extremely strong carbon-fluorine bonds used in industry and consumer products since the 1940s. Among their useful properties, PFAS-containing materials are surfactants and resistant to water, oil, grease, stains, and fire. As a result, PFAS have been used pervasively in consumer goods (e.g., apparel, cosmetics, cookware, carpeting, electronics, food packaging), industrial processes, firefighting foams, soaps, and much more.

The cost of PFAS is high and growing. Scientific studies have shown that high levels of exposure to PFAS can lead to reproductive defects, developmental effects or delays, increased risk of some cancers, weakened immune systems, hormone disruption, and other health impacts.10 For example, researchers at the New York University Grossman School of Medicine found statistically significant PFOA- and PFOS-attributable increases in 13 medical conditions, including low birth weight, kidney and testicular cancer, and type 2 diabetes, resulting in disease costs in the United States in 2018 of between $5.5 billion and $62.6 billion.11 The effects on human health from low levels of PFAS exposure, including over long periods of time, are still uncertain, and research is underway to better understand those effects.12 Researchers have estimated PFAS exposure to be associated with more than 6.7 million deaths of U.S. adultsU between 1999 and 2018, including from heart disease and cancer.13 In Europe, researchers estimated the annual health related costs across the continent due to PFAS exposure to be between €52 billion and €84 billion.14

The pathways we see for PFA mitigation generally fall in these categories - Curb Production, Create Alternatives, Mitigate Impact, Remediate Contamination. In all categories, the solutions on the table today are insufficient. Regulation as recent as April 2024 aims for no more than 4 parts per trillion in water; no remediation technology available at present successfully achieves this on its own.

Biotechnology opportunity

As part of its expected 2024 phase-out of purchasing PFAS-containing firefighting foams, the U.S. DoD is in the process of approving the use of fluorine-free foams to be used to fight fires. Researchers are proactively analyzing and testing the proposed fluorine-free replacements. Further, the Sustainable Groundwater Management Act in California provides substantial funding where solutions might be found for remediation - in short, this is an area ripe for research though in our exploration we were not able to find biological alternatives that warrant near term consideration, particularly given the DOD investment.

Recommended near term actions

- Ongoing participation in national PFA replacement dialogues and coalitions to prioritize the replacement in fire-fighting contexts and provide insight on application and system-dependencies that have to be solved for in that unique use-case.
- Use of machine learning to determine the characteristics of known microbes and bacteria that might have components which can address either full or partial replacement of PFA capabilities in fire fighting foams.

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Appendix 1: Full List of California and Federal Agencies with Regulatory and Governance Interest in Biotech Approaches to Wildfire Resilience

Stakeholder	Mission / Directive / Incentive
Government Orgs	
CA Wildfire and Forest Resilience Task Force (State)	The Task Force is a collaborative initiative involving multiple state agencies, local governments, tribal nations, and other stakeholders. It aims to address the broader, long-term challenges related to wildfires and forest health across California. Includes CalFire, CNRA, CalEPA, CPUC, CDFW, and CARB.
US Forest Service (Fed)	Wildfire management, prescribed fire and fuels management, ecosystem restoration, community engagement and education, research and innovation
US Department of Agriculture (Fed)	The United States Department of Agriculture (USDA) oversees a wide-ranging role in fire management across its various agencies, notably the U.S. Forest Service (USFS) and other entities. Wildfire prevention and suppression, ecological restoration and resilience, community engagement and partnerships, research and innovation.
CA Department of Forestry and Fire Protection (CalFire) (State)	CalFire is a state agency specifically dedicated to firefighting, fire prevention, and managing emergency response to wildfires within California. CalFire's primary focus is on wildfire prevention, early detection, rapid response, and suppression of wildfires.
Tahoe-Central Sierra Initiative (TCSI)	The Tahoe-Central Sierra Initiative (TCSI) involves multiple government agencies at various levels working collaboratively to address the ecological challenges in the Central Sierra region. Includes USFS, CalFire, Tahoe Regional Planning Agency (TRPA), CNRA, and Local government agencies.
CA Natural Resources Agency (State)	The California Natural Resources Agency plays a pivotal role in coordinating and overseeing fire management strategies across the state. The Agency focuses on integrating efforts among various state departments, such as CalFire, to enhance wildfire prevention measures, promote community resilience, and safeguard California's diverse ecosystems.
EPA (Fed)	The Environmental Protection Agency (EPA) primarily focuses on addressing air quality and environmental impacts related to wildfires. Its scope involves monitoring and regulating air pollutants emitted during wildfires to mitigate their adverse effects on air quality and public health.
California Air Resources Board (State)	The California Air Resources Board (CARB) plays a crucial role in addressing the air quality impacts caused by wildfires in California. Its scope involves monitoring and regulating air pollutants, particularly those emitted during wildfires, to safeguard public health and mitigate environmental damage.
CA Department of Toxic Substances Control (State)	The California Department of Toxic Substances Control (DTSC) primarily focuses on managing hazardous substances and materials to prevent their release or spread during fire incidents.
Office of Planning and Research (State)	The Office of Planning and Research (OPR) in California oversees land use planning and policy coordination statewide. Concerning fire management, OPR's scope involves providing guidance and support to local governments and agencies in incorporating wildfire risk assessment, mitigation strategies, and resilient land-use planning into their policies.
CA Department of Insurance (State)	The California Department of Insurance oversees insurance-related matters within the state. Regarding fire management, its scope involves regulating insurance practices, ensuring fair and effective coverage for homeowners and businesses affected by wildfires, investigating claims related to fire damage, and advocating for policies that promote fire risk reduction and resilience.
CA Public Utilities Commission (State)	The California Public Utilities Commission (CPUC) regulates utilities, including electric and gas companies, within the state. Concerning fire management, its scope involves overseeing wildfire mitigation measures by utilities, ensuring compliance with safety regulations, and investigating incidents involving utility infrastructure that might contribute to or cause wildfires to prevent future occurrences and protect public safety.
CA Energy Commission (State)	The California Energy Commission focuses on energy policy, research, and planning across the state. In terms of fire management, its scope includes evaluating and promoting fire-resilient energy infrastructure, such as considering wildfire risks in the planning and implementation of energy projects.

CA Department of Water Resources (State)	The California Department of Water Resources (DWR) primarily manages and protects the state's water resources and infrastructure. Concerning fire management, its scope involves assessing the impact of wildfires on watersheds, ensuring water availability for firefighting purposes, and implementing measures to protect water quality and availability in areas affected by wildfires.
CA Division of Mines and Geology (State)	The California Division of Mines and Geology, now known as the California Geological Survey, focuses on geologic and seismic hazards, including wildfire-related risks. Its scope involves assessing and mapping wildfire hazards related to geology and providing geological information to aid in wildfire risk assessment, land-use planning, and emergency response strategies across the state.
Local / County Government Agencies	Local and county governments lead fire protection, prevention, and emergency response efforts, overseeing firefighting operations, land use planning for fire-prone areas, and community education.
Private / Public Orgs	
FireWise Communities	FireWise Communities is a national program focused on community-based wildfire risk reduction. Its scope involves educating and empowering communities to take proactive measures.
Tribal Organizations	Tribal organizations often have a multifaceted role in fire management, particularly in areas where their lands intersect with federal, state, or private properties. Their scope involves preserving traditional ecological knowledge, implementing culturally sensitive fire management practices, and collaborating with governmental agencies to manage wildfires, protect tribal lands, and promote ecosystem health.
Private Landowner Associations	Private landowner associations typically focus on implementing fire management practices to protect their properties from wildfires and reduce associated risks. Their scope involves coordinating efforts among landowners, implementing fire prevention measures, conducting controlled burns, and promoting education and awareness about wildfire risks to safeguard private lands and neighboring communities.
Sierra Pacific Industries	Sierra Pacific Industries (SPI) is a private timberland company with a significant focus on forest management practices, including fire management. Its scope involves implementing forest stewardship measures, such as fuel reduction, prescribed burns, and sustainable logging practices, to minimize wildfire risks and maintain the health and resilience of its timberlands while balancing ecological conservation and timber production goals.
Nature Conservancies	Nature conservancies in California often engage in conservation efforts that include fire management practices. Their scope involves utilizing controlled burns, ecological restoration, and collaborative partnerships to maintain healthy fire-adapted ecosystems, promote biodiversity, and mitigate wildfire risks while preserving and protecting natural habitats and landscapes.
Entrepreneurs and Larger Companies	Businesses in California engaged in fire management often focus on developing innovative technologies, services, or solutions to address wildfire prevention, mitigation, or recovery. Their scope involves leveraging business innovation, such as creating firefighting equipment, fire-resistant materials, or specialized services, to enhance fire preparedness, response capabilities, and community resilience in the face of wildfires.
Climate Mitigation / Adaptation Organizations	Climate mitigation and adaptation organizations in California work to address the root causes of climate change and its impact on wildfires. Their scope involves advocating for policies, conducting research, and implementing strategies that mitigate greenhouse gas emissions, promote resilient landscapes, and enhance community preparedness to reduce the risk and impact of wildfires exacerbated by changing climatic conditions.
National Wildfire Coordinating Group	The National Wildfire Coordinating Group (NWCG) facilitates interagency coordination and standardization of wildfire management practices nationally. In California, it helps coordinate and disseminate standardized wildfire response protocols, training, and resources among federal, state, tribal, and local agencies to ensure a cohesive and effective approach to wildfire management across diverse landscapes and jurisdictions.
Carbon Developers	Carbon developers in California often focus on carbon offset projects and initiatives that involve forest management and carbon sequestration. Their scope involves implementing forest restoration, reforestation, or carbon offset projects that may indirectly contribute to fire management efforts by restoring healthy ecosystems and reducing the risk of severe wildfires through improved forest health and resilience.

Appendix 1, cont: estimated influence and interest levels by agency - indicators of which organizations to include when moving toward field trials in any particular application.

- **Influence** indicates a stakeholder's relative power over and within a project. A stakeholder with high influence would control key decisions within the project and have strong ability to facilitate implementation of project tasks and cause others to take action.
- **Importance** indicates the degree to which the project cannot be considered successful if needs, expectations, and issues are not addressed.

Stakeholder	Estimated Influence	Estimated Importance
CA Wildfire and Forest Resilience Task Force (State)	High	High
US Forest Service (Fed)	High	High
US Department of Agriculture (Fed)	High	Medium
CA Department of Forestry and Fire Protection (CalFire) (State)	High	High
CA Natural Resources Agency (State)	High	High
EPA (Fed)	High	High
California Air Resources Board (State)	Medium	Medium
CA Department of Toxic Substances Control (State)	Medium	High
Office of Planning and Research (State)	Medium	Low
CA Department of Insurance (State)	Medium	Low
CA Public Utilities Commission (State)	Medium	Low
CA Energy Commission (State)	Low	Low
CA Department of Water Resources (State)	Medium	Low
CA Division of Mines and Geology (State)	Low	Low
FireWise Communities	Low	Low
Tribal Organizations	Medium	High
Private Landowner Associations	Medium	High
Sierra Pacific Industries	High	Medium
Nature Conservancies	Medium	Medium
Entrepreneurs and Larger Companies	Low	Medium
Climate Mitigation / Adaptation Organizations	Medium	Low
National Wildfire Coordinating Group	High	Medium
Carbon Developers	Medium	Low

Appendix 1, cont: estimated influence and interest levels by agency - indicators of which organizations to include when moving toward field trials in any particular application.

Potential Alignment

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. CA Wildfire and Forest Resilience TA	-	o	o	o	o	o	o	o	o	o	x	x	o	o	o	o	x	x	o	o	o	o	
2. US Forest Service	o	-	o	o	o	o	o	o	o				o	o	o	o	x	x	o	x			
3. US Department of Agriculture	o	o	-	o	o	o	o	o	o						o	o	o		o				o
4. CalFire	o	o	o	-	o	o	o	o	o	o	o	o	o			o	o	o					o
5. CA Natural Resources Agency	o	o	o	o	-	o	o	o	o				o	o		o	x	x		x			
6. EPA	o	o	o	o	o	-	o	o	o				o	o		o	x	x		x			x
7. California Air Resources Board	o	o	o	o	o	o	-	o	o	o			o	o						x			
8. CA Department of Toxic Substances	o	o	o	o	o	o	o	-	o	o			o	o						x			
9. Office of Planning and Research	o	o	o	o	o	o	o	o	-	o	o	o	o	o	o	o	o	o	o		o	o	o
10. CA Department of Insurance	o			o			o	o	o	-	o	o					o						
11. CA Public Utilities Commission	x			o					o	o	-	o			x	x			x		x	x	x
12. CA Energy Commission	x			o					o	o	o	-											
13. CA Department of Water Resources	o	o		o	o	o	o	o	o				-	o	o	o			o				
14. CA Division of Mines and Geology	o	o			o	o	o	o	o				o	-									
15. FireWise Communities	o	o	o						o		x		o		-	o	o	x	o			o	
16. Tribal Organizations	o	o	o	o	o	o			o		x		o		o	-	x	x		x			x
17. Private Landowner Associations	x	x	o	o	x	x			o	o					o	x	-	x		x			
18. Sierra Pacific Industries	x	x		o	x	x			o						x	x	x	-	x		x	x	
19. Nature Conservancies	o	o	o						o		x		o		o			x	-		o	o	
20. Entrepreneurs and Companies	o	x			x	x	x	x								x	x			-			
21. Climate Organizations	o								o		x							x	o		-	o	o
22. National Wildfire Coordinating Group	o								o		x				o			x	o		o	-	
23. Carbon Developers			o	o		x			o		x					x					o		-

APPENDIX 2

Summary Table of Consulted Experts and Individuals + Organizations Engagement in Focused Forums

Attendee	Company	Role and Technical Expertise	#1	#2	#3	#4
Adam AJ Schlenger	Lab to Land, Decisioning Model Analyst	scientific innovation decision analyst, oceanographer, carbon removal specialist and climate entrepreneur		X	X	X
Adam Joseph	The Nature Conservancy	leverages economics and finance to accelerate California conservation				X
Adina Abeles	Chan Zuckerberg Initiative	researcher, scientist; biotechnology and regulatory policy for native tree restoration			X	
Alec Apodaca	Amah Mutsun Land Trust	environmental archaeologist specializing in ecological research on Indigenous stewardship practices, Amah Mutsun Land Trust			X	
Andy Newhouse	New York College of Environmental Design and Forestry	researcher, scientist; biotechnology and regulatory policy for native tree restoration		X		
Angela Mele	Illustrator & Interpretive Planner	scientific and species illustrator, interpretive planner			X	X
Anncy Caroline Thresher	Stanford University	bioethicist focused on synthetic biology, invasive species, and emerging environmental technologies			X	X
Anthony DiMeglio	Tidal Grow AgriScience	expert in biotech risk characterization, nature-positive benefit assessment, and chitosan for agricultural biotech	X	X	X	X
Avery Hill	Stanford	Global change ecologist, mapping the future of California's forests in a warmer, higher-carbon future	X			
Beatrijs Kuijpers	Aspen Institute	convener and aggregator of cross-sector insights across energy, environment, and communications	X			
Beth Shapiro	University of California, Santa Cruz	evolutionary molecular biologist, ancient DNA analyst, MacArthur Genius and HHMI Investigator	X	X	X	X
Bethany Kolody	Innovative Genomics Institute	marine biologist turned soil-GHG emission researcher, studying complex microbial ecosystems through metagenomics				X
Bianca DeSanctis	University of California, Santa Cruz	mathematician with a focus on ancient environmental DNA, population genetics, molecular evolution, UCSC Genome Institute			X	
Brad Ringeisen	Innovative Genomics Institute	live-cell printing pioneer, innovating at the intersection of physical, biological + genetic sciences	X			
Bridget Baumgartner	Molecular Biologist, Previously Revive & Restore	molecular and quantitative biologist focused on de-extinction and climate applications of biotech			X	X

Brock Wooldridge	UCSC postdoc	evolutionary biologist studying intertidal biodiversity through DNA barcoding, UCSC Ecology,Behavior and Evolution			X	
Chad Gallinat	Conservation X Labs	research scientist now catalyzing climate technologies - rapid prototyping facilities, design competitions, and innovation prizes				X
Chad Mitcham	US Fish and Wildlife	biologist, spearheaded first-of-its-kind adult translocation of Ohlone tiger beetles in Santa Cruz County, US Fish and Wildlife			X	
Charles Lester	Ocean and Coastal Policy Center	coastal management leader with expertise in sea level rise, coastal resilience, law and policy, Ocean & Coastal Policy Center			X	
Courtney Creamer	US Geological Survey	research soil scientist; microorganisms, carbon and nitrogen in soils, US Geological Survey		X		X
Dan Gluesenkamp	CA Biodiversity Institute	community-scale habitat conservation ecologist, biodiversity conservation leader via eDNA data, CA Biodiversity Institute			X	
Dan Porter	The Nature Conservancy	forest program director; leading, managing, and serving California forest strategy	X	X		
Dan Sanchez	Carbon Direct	fire expert and carbon-climate systems thinker with expertise in bioenergy, carbon capture, renewable fuels, and biomass				X
Don Croll	University of California, Santa Cruz	marine ecologist, complex systems-scale conservation modeling, Island Conservation founder, UCSC Ecology + Evolutionary Biology			X	
Ed Smith	The Nature Conservancy	regional ecologist; increase the quality and scale of ecological restoration of forests in the Sierra Nevada		X		
Eli Ilano	United States Forest Service, Tahoe National Forest	National Forest lead; expert in the governance, ecology and community impact of wildfire, also: a biomimicry aficionado	X	X		
Elliot Weiss	Lab to Land Fellow	microbial extremophile and genetic researcher investigating the impact of fire on California soil microbiomes	X	X		
Emily Vitas	Lab to Land Institute	operations guru for all things Lab to Land Institute	X	X	X	X
Eric Palkovacs	University of California, Santa Cruz	coastal and freshwater ecologist, specializing in eco-evolutionary dynamics and climate resilience			X	X
Evelyn Arce-Erickson	Indigenous Resilience Consulting	passionate advocate for Indigenous self-determination, grassroots facilitator, and philanthropic strategist	X			
Federica Di Palma	Genome British Columbia	biotechnologist with global experience (and impact) across conservation, governance and boundary-pushing science				X
Hari Balasubramanian	Eco Advisors	global climate impact strategy expert moving substantial resources in service of complex systems challenges	X			
Jason Delborne	North Carolina State University	experienced leader at the intersection of hard and social sciences in service of bioethics and emerging biotech	X			

Jen Quick Cleveland	University of California, Santa Cruz	molecular ecologist, rNA specialist, and protein chemist with an interest in sequencing an entire ecosystem				X
John Carlos Garza	NOAA	molecular ecology and genetic analyst, salmon guru, UCSC, Institute of Marine Sciences			X	
Jonathan Hicken	Seymour Center	science education and public impact leader, mobilizing climate action for coastal habitats, Seymour Marine Discovery Center			X	
Julie Shapiro	Keystone Policy Center	forger of shared solutions to complex problems for people and planet through facilitation and partnership generation	X			
Keolu Fox	University of California, San Diego	genome scientist focused on evolutionary genetics and indigenizing biomedical research	X			
Kevin Webb	Superorganism	climate vulnerability and biodiversity loss expert, venture capitalist for biodiversity, angel investor & advisor			X	
Kyle Jacobsen	United States Forest Service, Tahoe National Forest	fire chief and forest manager for the Tahoe National Forest		X		
Leah Duran	Chan Zuckerberg Initiative	skilled communicator of complex science to broad audiences to drive action and impact, storyteller, former park ranger	X			
Luis Marquez	Ginkgo Bioworks	plant-microbe Interactions, cell programming, molecular ecology	X			
Maria Astolfi	Lab to Land Fellow	bioengineer, natural products entrepreneur, and leader in building watershed scale resilience of indigenous lands	X	X		X
Marion Wittmann	Gordon and Betty Moore Foundation	philanthropist and technical expert in reducing the threat of severe wildfire and enabling beneficial fire				X
Mark Zimring	The Nature Conservancy	ecological economist, conservation strategist, grinding out the hard yards to turn good conservation ideas into action	X		X	
Mary Louise Gifford	Innovative Genomics Institute, Climate Consultant	carbon markets and climate expert; strategy, product and technologies development		X		
Maya Elson	University of California, Santa Cruz	regenerative mycologist and ecologist examining regenerative designs for fungal and microbial soil communities		X		
Melinda Adams	Haskell Indian Nations University, Environmental Science Dept	enviro scientist rooted in land stewardship lessons of Indigenous culture across plants, soil, carbon, nutrient and water cycles				X
Michael Falkowski	NASA	terrestrial ecologist solving ecosystem-scale scientific challenges through geospatial planning, remote sensing	X			
Michael Grone	CA State Parks (former Tribal Liaison)	historical ecologist, archeologist, and traditional ecological knowledge of coastal resources, CA State Parks			X	
Nathan Walworth	Vesta	microbiome scientist, ocean carbon removal entrepreneur, innovator and cultural forecasting specialist			X	X
Ñawi K. Flores	Kinray Hub	pioneering Indigenous-led R&D for symbiotic solutions across advanced sciences, traditional knowledge, and climate realities				X

Nazish Jeffery	Federation of American Scientists	bioeconomy specialist, biosecurity, science policy and communication expert, Federation of American Scientists			X	
Nitin Vaish	Ginkgo Bioworks	strategist focused on sustainable, low carbon production of innovative biotechnologies at scale		X		
Paige Gardner	UCSC PhD student	biologist, mapping fish populations under climate pressures, UCSC Ecology + Evolutionary Biology			X	
Paul Reginato	Homeworld Collective	bioengineer and atmospheric carbon removal specialist, building community for applied climate biotechnology		X		X
Rachel Meyer	University of California, Santa Cruz	advancing understanding of biodiversity, from drinks to ethnobotany, genomics to community science and webtools - and fire				X
Raviv Turner (MRV)	Nature Tech Collective	nature-based solutions accelerator, monitoring-reporting-and-verification specialist, global climate market strategist				X
Rolando Perez	Lab to Land Fellow	bioengineer, fungi researcher, and poet philosopher of biotechnology, ethics and resilience	X	X		X
Sallie Calhoun	Paicines Ranch	rancher, investor, philanthropist rebuilding healthy agricultural soils to sequester carbon and mitigate climate change	X			X
Sifang Chen	Carbon180	national policy strategist, enabling fit-for-purpose, technically-informed, climate-critical biotech, nanotech and CDR governance				X
Stewart Wilson	CalPoly	soil scientist, phosphorous biogeochemist, using machine learning to understand where soils and soil processes exits on earth				x
Teal Brown Zimring	Lab to Land Institute	political economist, network builder, climate finance and conservation strategy expert, Lab to Land executive director	X	X	X	X
Tim LaSalle	CSU Chico	regenerative agriculture systems expert, specialist in soil, carbon, food security and enabling resilience in degrading landscapes				X
Tom Quigley	Superorganism	venture capitalist for biodiversity, angel investor & advisor		X		
Topher Wilkins	Lab to Land Institute	community-builder, global impact convener, facilitator, Lab to Land community and partnerships lead	X	X	X	X

Ecological Threat Prioritization Survey Respondents

In order to evaluate the relative importance and degree of vulnerability of ecosystem services at risk and therefore focus feasible biotechnology research and solutions on those threatened ecosystem services, we conducted a survey of the following expert ecologists.

Eric LoPresti	University of South Carolina
Sasha Wright	California State University
Jade d'Alpoim Guedes	University of Washington
Elsa Cleland	University of California San Diego
Carolyn Kurle	University of California San Diego
Natalie Posdaljian	Scripps Institution of Oceanography
Donald Strong	University of California Davis
Jay Stachowicz	University of California Davis
Nick Barber	San Diego State University
Sarah Kimball	University of California Irvine
Eric LoPresti	University of South Carolina
Sasha Wright	California State University
Jade d'Alpoim Guedes	University of Washington
Elsa Cleland	University of California San Diego
Carolyn Kurle	University of California San Diego
Natalie Posdaljian	Scripps Institution of Oceanography
Donald Strong	University of California Davis
Jay Stachowicz	University of California Davis
Nick Barber	San Diego State University
Sarah Kimball	University of California Irvine
Kurt Anderson	University of California Riverside
Ryan Gasbarro	UC Santa Cruz; NOAA
Eric Wood	California State University Los Angeles
Yiwen Chiu	Cal Poly San Luis Obispo
Paul Edelman	Santa Monica Mountains Conservancy
Tim Miller	University of California Santa Cruz
Emilio Laca	University of California Davis
Joshua Schimel	University of California Santa Barbara
Rich Ambrose	University of California Los Angeles
Kailen Mooney	University of California Irvine
Jayson Smith	Cal Poly Pomona
Richard Cobb	Cal Poly San Luis Obispo
John Durand	University of California Davis
Robert Fisher	U.S. Geological Survey
Renske Kirchholtes	University of California Santa Cruz
Jamie Kneitel	California State University, Sacramento
John Eadie	University of California Davis
Christopher Surfleet	Cal Poly San Luis Obispo

REFERENCES.