PNAS
nexus

1

2 **Main Manuscript for**

3 Reimagine Fire Science for the Anthropocene

4

5 Jacquelyn K. Shuman[1], Jennifer K. Balch[2], Rebecca T. Barnes[3], Philip E. Higuera[4],
6 Christopher I. Roos[5], Dylan W. Schwilk[6], E. Natasha Stavros[2], Tirtha Banerjee[7], Megan
7 M. Bela[8,9], Jacob Bendix[10], Sandro Bertolino[11], Solomon Bililign[12], Kevin D. Bladon[13],
8 Paulo Brando[14], Robert E. Breidenthal[15], Brian Buma[16], Donna Calhoun[17], Leila M. V.
9 Carvalho[18], Megan E. Cattau[19], Kaelin M. Cawley[20], Sudeep Chandra[21], Melissa L.
10 Chipman[22], Jeanette Cobian-Iñiguez[23], Erin Conlisk[24], Jonathan D. Coop[25], Alison
11 Cullen[26], Kimberley T. Davis[4], Archana Dayalu[27], Fernando De Sales[28], Megan
12 Dolman[19], Lisa M. Ellsworth[29], Scott Franklin[30], Christopher H. Guiterman[8,31], Matthew
13 Hamilton[32], Erin J. Hanan[33], Winslow D. Hansen[34], Stijn Hantson[35], Brian J. Harvey[36],
14 Andrés Holz[37], Tao Huang[19], Matthew D. Hurteau[38], Nayani T. Ilangakoon[2], Megan
15 Jennings[39], Charles Jones[18], Anna Klimaszewski-Patterson[40], Leda N. Kobziar[41], John
16 Kominoski[42], Branko Kosovic[43], Meg A. Krawchuk[44], Paul Laris[45], Jackson Leonard[46], S.
17 Marcela Loria-Salazar[47], Melissa Lucash[48], Hussam Mahmoud[49], Ellis Margolis[50], Toby
18 Maxwell[51], Jessica L. McCarty[52], David B. McWethy[53], Rachel S. Meyer[54], Jessica R.
19 Miesel[55], W. Keith Moser[46], R. Chelsea Nagy[2], Dev Niyogi[56], Hannah M. Palmer[57], Adam
20 Pellegrini[58], Benjamin Poulter[59], Kevin Robertson[60], Adrian V. Rocha[61], Mojtaba
21 Sadegh[62], Fernanda Santos[63], Facundo Scordo[64,65], Joseph O. Sexton[66], A. Surjalal
22 Sharma[67], Alistair M. S. Smith[68,69], Amber J. Soja[70,71], Christopher Still[44], Tyson
23 Swetnam[72], Alexandra D. Syphard[73], Morgan W. Tingley[74], Ali Tohidi[75], Anna T.
24 Trugman[18], Merritt Turetsky[76], J. Morgan Varner[60], Yuhang Wang[77], Thea Whitman[78],
25 Stephanie Yelenik[79], Xuan Zhang[57]

26

27 [1]Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder,
28 CO, USA

29 [2]Earth Lab, CIRES, University of Colorado Boulder, Boulder, CO, USA

30 [3]Environmental Studies Program, Colorado College, Colorado Springs, CO, USA

31 [4]Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT,
32 USA

33 [5]Department of Anthropology, Southern Methodist University, Dallas, TX, USA

34 [6]Department of Biological Sciences, Texas Tech University, Lubbock, TX, USA

35 [7]University of California, Irvine, CA, USA

[8]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado at Boulder, Boulder, CO, USA

[9]NOAA Chemical Sciences Laboratory, Boulder, CO, USA

[10]Department of Geography and the Environment, Syracuse University, Syracuse, NY, USA

[11]Department of Life Sciences and Systems Biology, University of Turin, Torino, Italy

[12]Department of Physics, North Carolina A&T State University, Greensboro, NC, USA

[13]Department of Forest Engineering, Resources, and Management, Oregon State University, Corvallis, OR, USA

[14]Earth System Science, University of California Irvine, Irvine, CA USA

[15]Department of Aeronautics & Astronautics, University of Washington, Seattle, WA, USA

[16]Integrative Biology, University of Colorado Denver, Denver, CO, USA

[17]Department of Mathematics, Boise State University, Boise, ID, USA

[18]Department of Geography, University of California Santa Barbara, Santa Barbara, CA, USA

[19]Human-Environment Systems, Boise State University, Boise, ID, USA

[20]National Ecological Observatory Network, Battelle, Boulder, CO, USA

[21]Global Water Center, University of Nevada, Reno, NV, USA

[22]Department of Earth and Environmental Sciences, Syracuse University, Syracuse, NY, USA

[23]Department of Mechanical Engineering, University of California Merced, Merced, CA, USA

[24]Point Blue Conservation Science, Petaluma, CA, USA

[25]Clark School of Environment and Sustainability, Western Colorado University, Gunnison, CO, USA

[26]Evans School of Public Policy and Governance, University of Washington, Seattle, WA, USA

[27]Atmospheric and Environmental Research, Lexington, MA, USA

[28]Department of Geography, San Diego State University, San Diego, CA, USA

[29]Department of Fisheries, Wildlife, & Conservation Sciences, Oregon State University, Corvallis, OR, USA

[30]School of Biological Sciences, University of Northern Colorado, Greeley, CO, USA

[31]NOAA's National Centers for Environmental Information (NCEI), Boulder, CO, USA

[32]School of Environment and Natural Resources, The Ohio State University, Columbus, OH, USA

[33]Department of Natural Resources and Environmental Science, University of Nevada, Reno, NV, USA

[34]Cary Institute of Ecosystem Studies, Millbrook, NY, USA

[35]Faculty of Natural Sciences, Universidad del Rosario, Bogotá, Colombia

[36]School of Environmental and Forest Sciences, University of Washington, Seattle, WA, USA

[37]Department of Geography, Portland State University, Portland, OR, USA

[38]Department of Biology, University of New Mexico, Albuquerque, NM, USA

[39]Institute for Ecological Monitoring & Management, San Diego State University, San Diego, CA, USA

[40]Department of Geography, California State University Sacramento, Sacramento, CA, USA

[41]College of Natural Resources, University of Idaho, Coeur d'Alene, ID, USA

[42]Institute of Environment & Department of Biological Sciences, Florida International University, Miami, FL, USA

[43]Weather Systems & Assessment Program, National Center for Atmospheric Research, Boulder, CO, USA

[44]Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR, USA

[45]Department of Geography, California State University Long Beach, Long Beach, CA, USA

[46]Rocky Mountain Research Station, U.S.D.A. Forest Service, Flagstaff, AZ, USA

[47]School of Meteorology, University of Oklahoma, Norman, OK, USA

[48]Department of Geography, University of Oregon, Eugene, OR, USA

[49]Department of Civil & Environmental Engineering, Colorado State University, Fort Collins, CO, USA

[50]U.S. Geological Survey, Fort Collins Science Center, New Mexico Landscapes Field Station, Los Alamos, NM, USA

[51]Department of Biological Sciences, Boise State University, Boise, ID, USA

[52]Department of Geography and Geospatial Analysis Center, Miami University, Oxford, OH, USA

[53]Department of Earth Sciences, Montana State University, Bozeman, MT, USA

[54]Department of Ecology & Evolutionary Biology, University of California Santa Cruz, Santa Cruz, CA, USA

[55]Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, MI, USA

[56]Jackson School of Geosciences, and Cockrell School of Engineering, University of Texas at Austin, Austin, TX, USA

[57]Department of Life & Environmental Sciences, University of California Merced, Merced, CA, USA

[58]Department of Plant Sciences, University of Cambridge, Cambridge, UK

[59]NASA Goddard Space Flight Center, Greenbelt, MD, USA

102   [60]Tall Timbers Research Station and Land Conservancy, Tallahassee, FL, USA

103   [61]Department of Biological Sciences, University of Notre Dame, Notre Dame, IN, USA

104   [62]Department of Civil Engineering, Boise State University, Boise, ID, USA

105   [63]Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

106   [64]Global Water Center and the Department of Biology, University of Nevada, Reno, NV, USA

107   [65]Instituto Argentino de Oceanografía (IADO-CONICET-UNS), Bahía Blanca, Argentina

108   [66]terraPulse, Inc., North Potomac, MD, USA

109   [67]Department of Astronomy, University of Maryland, College Park, MD, USA

110   [68]Department of Earth and Spatial Sciences, College of Science, University of Idaho, Moscow, ID,
111   USA

112   [69]Department of Forest, Rangeland, and Fire Science, College of Natural Resources, University
113   of Idaho, Moscow, ID, USA

114   [70]NASA Langley Research Center, NASA, Langley, VA, USA

115   [71]National Institute of Aerospace, NASA, Langley, VA, USA

116   [72]Data Science Institute, University of Arizona, Tucson, AZ, USA

117   [73]Conservation Biology Institute, La Mesa, CA, USA

118   [74]Ecology and Evolutionary Biology, University of California Los Angeles, Los Angeles, CA, USA

119   [75]Department of Mechanical Engineering, San Jose State University, San Jose, CA, USA

120   [76]Institute of Arctic & Alpine Research, University of Colorado Boulder, Boulder, CO, USA

121   [77]School of Earth & Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA

122   [78]Department of Soil Science, University of Wisconsin-Madison, Madison, WI, USA

123   [79]Rocky Mountain Research Station, U.S.D.A. Forest Service, Reno, NV, USA

124

125   *Jacquelyn K. Shuman, National Center for Atmospheric Research, Climate and Global Dynamics
126   Laboratory, P.O. Box 3000, Boulder, CO 80305, USA

127   **Email:** jkshuman@ucar.edu

128   **Author Contributions:**

129   All Authors - J.K.S., J.K.B., R.T.B, P.E.H, C.I.R, D.W.S, E.N.S., T.B., M.M.B., J.B., S.B., S.B.,
130   K.D.B, P.B., R.E.B, B.B, D.C., L.M.V.C., M.E.C., K.M.C., S.C., M.L.C., J.C.I., E.C., J.D.C., A.C.,
131   K.T.D., A.D., F.D., M.D, L.M.E., S.F., C.H.G., M.H., E.J.H, W.D.H., S.H., B.J.H., A.H., T.H.,
132   M.D.H, N.T.I., M.J., C.J., A.K.P., L.N.K., J.K., B.K., M.A.K., P.L., J.L., S.M.L.S., M.L., H.M., E.M.,
133   T.M., J.L.M., D.B.M, R.S.M., J.R.M, W.K.M., R.C.N., D.N., H.M.P., A.P., B.P., K.R., A.V.R., M.S.,
134   F.S., F.S., J.O.S., A.S.S., A.M.S.S., A.J.S., C.S., T.S., A.D.S., M.W.T., A.T., A.T.T., M.T., J.M.V.,
135   Y.W., T.W., S.Y., X.Z. designed and performed research; and J.K.S, J.K.B., R.T.B, P.E.H, C.I.R,
136   D.W.S, E.N.S. wrote the paper.

137 **Competing Interest Statement:** The authors declare no competing interest.

138 **Classification:** Biological, Health, and Medical Sciences/Environmental Sciences, Physical
139 Sciences and Engineering/Sustainability Science

140 **Keywords:** wildfire, climate change, resilience, wildland-urban interface, social-ecological
141 systems

142

143 **Abstract**
144 Fire is an integral component of ecosystems globally and a tool that humans have harnessed for
145 millennia. Altered fire regimes are a fundamental cause and consequence of global change,
146 impacting people and the biophysical systems on which they depend. As part of the newly
147 emerging Anthropocene, marked by human-caused climate change and radical changes to
148 ecosystems, fire danger is increasing, and fires are having increasingly devastating impacts on
149 human health, infrastructure, and ecosystem services. Increasing fire danger is a vexing problem
150 that requires deep transdisciplinary, trans-sector, and inclusive partnerships to address. Here, we
151 outline barriers and opportunities in the next generation of fire science and provide guidance for
152 investment in future research. We synthesize insights needed to better address the long-standing
153 challenges of innovation across disciplines to (i) promote coordinated research efforts; (ii)
154 embrace different ways of knowing and knowledge generation; (iii) promote exploration of
155 fundamental science; (iv) capitalize on the "firehose" of data for societal benefit; and (v) integrate
156 human and natural systems into models across multiple scales. Fire science is thus at a critical
157 transitional moment. We need to shift from observation and modeled representations of varying
158 components of climate, people, vegetation, and fire to more integrative and predictive approaches
159 that support pathways towards mitigating and adapting to our increasingly flammable world,
160 including the utilization of fire for human safety and benefit. Only through overcoming institutional
161 silos and accessing knowledge across diverse communities can we effectively undertake
162 research that improves outcomes in our more fiery future.

163 **Significance Statement**

164 Fires can be both useful to and supportive of human values, safe communities and ecosystems,
165 and threatening to lives and livelihoods. Climate change, fire suppression, and living closer to the
166 wildland-urban interface have helped create a global wildfire crisis. There is an urgent, ethical
167 need to live more sustainably with fire. Applying existing scientific knowledge to support
168 communities in addressing the wildfire crisis remains challenging. Fire has historically been
169 studied from distinct disciplines, as an ecological process, a human hazard, or an engineering
170 challenge. In isolation, connections among human and non-human aspects of fire are lost. We
171 describe five ways to re-envision fire science and stimulate discovery that help communities
172 better navigate our fiery future.

173

174 **Main Text**
175
176 **Introduction**
177

178 Fire is a long-standing natural disturbance and a fundamental component of ecosystems globally
179 (1). Fire is also an integral part of human existence (2), used by people to manage landscapes for
180 millennia (3). As such, fire - or broadly biomass burning - can take on many forms: fires managed
181 for human benefit or ecosystem health include prescribed or cultural burning, and response
182 management beyond suppression; fires viewed as an immediate threat to human values are

183 typically suppressed, and under increasingly extreme conditions have an increased chance of
184 escaping suppression efforts. Fires can be ignited intentionally (e.g., prescribed or cultural
185 burning and arson) or unintentionally (e.g., accidental human-caused or lightning-caused). They
186 can happen in the wildlands and into human developed areas as in the wildland-urban interface
187 (WUI). In the Anthropocene[1], the current era characterized by the profound influence of human
188 impacts on planetary processes and the global environment (4), ***fires from lightning and***
189 ***unplanned human-related ignitions (including arson; henceforth referenced as wildfires)***
190 result in increasingly negative impacts on economic (e.g. loss of structures and communities),
191 public health (e.g. loss of life, air pollution, water and soil contamination), and ecological aspects
192 of society (e.g. shifts in vegetation, carbon storage) (5).

193 Recent decades have seen a substantial increase globally in the length of fire seasons (6), the
194 time of year when conditions are conducive to sustain fire spread, increased area burned in many
195 regions, and projected increases in human exposure and sensitivity to fire disasters (7–11). Fire
196 seasons are occurring months earlier in Arctic and boreal regions (12). In the western United
197 States, the area burned in the 21st century has nearly doubled compared to the late 20th century,
198 enabled by warmer and drier conditions from anthropogenic climate change, resulting in dry,
199 flammable vegetation (13). Fire activity in the 21st century is increasingly exceeding the range of
200 historical variability characterizing boreal (14) and Rocky Mountain subalpine (15) forest
201 ecosystems for millennia. Unprecedented fires in the Pantanal tropical wetland in South America
202 (16) and ongoing peatland fires across tropical Asia (17) exemplify the global scope of recent fire
203 extremes.

204 Shifts in wildfire patterns ***can*** come with increasingly negative human and ecological impacts.
205 Globally, dangerous smoke levels are more common as a result of wildfires (9, 10, 18, 19). The
206 2019-2020 Australian wildfire season produced fires that were larger, more intense, and more
207 numerous than in the historical record (20), injecting the largest amount of smoke into the
208 stratosphere observed in the satellite era (21, 22) and impacting water supplies for millions of
209 residents (23). While extreme fire events capture public attention and forest fire emissions
210 continue to rise (24, 25), the ongoing decline of burned-area across some fire-dependent
211 ecosystems might have equally large social and environmental impacts. Global burned area has
212 decreased by approximately 25% over the last two decades, with the strongest decreases
213 observed across fire-dependent tropical savanna ecosystems and attributed to human
214 interactions (26). Decreases across these systems are important, as maintaining diverse wildfire
215 patterns can be essential for biodiversity or achieving conservation goals (27).

216 Humans are fundamental drivers of changing wildfire activity via climate change, fire suppression,
217 land development, and population growth (26, 28–30). Human-driven climate change is
218 aggravating fire danger across western North America (13, 31, 32), Europe (33, 34), and
219 Australia (35). Exacerbated by this increasing fire danger from heavy fuel loads and greater
220 flammability from drought and tree mortality, human-caused ignitions increased wildfire
221 occurrence and extended fire seasons within parts of the US (28), and it is these human-caused
222 wildfires that are most destructive to homes and property (36). Concurrent with these challenges
223 is a growing recognition that Indigenous peoples have been living with fire as an essential Earth-
224 system process (30). Although some Indigenous societies have lived in relatively low-density
225 communities, others have lived at scales analogous to the modern wildland-urban interface for
226 centuries, making Indigenous fire lessons relevant for the sustainability of post-industrial
227 communities as well (e.g. 37).

228 As wildfire danger increases, we are only beginning to understand longer-term post-fire impacts.
229 These include regeneration failure of vegetation (38, 39), changes to biodiversity through
230 interactions with climate change, land use and biotic invasions (27), landslides and debris flows
231 (40), contaminated water and soil (23, 41), and exposure to hazardous air quality for days to
232 weeks in regions that can extend thousands of kilometers from smoke sources (9, 10, 19, 42).
233 Increasing wildfire activity and associated negative impacts are expected to continue over the
234 21st century, as greenhouse gas emissions continue to rise (7, 43, 44).

[1] The Anthropocene currently has no formal status in the Divisions of Geologic Time.
https://pubs.usgs.gov/fs/2018/3054/fs20183054.pdf

235 The rapid pace of changing fire activity globally is a significant challenge to the scientific
236 community, in both understanding and communicating change. Even the metrics we use to
237 quantify "fire" come up short in many instances. For example, total area burned and ecological
238 fire severity are useful for characterizing some key dimensions of fire, but often do not capture
239 negative human impacts. For example, the 2021 Marshall Fire in Colorado, U.S.A., was less than
240 2,500 hectares, but was more destructive, in terms of structures lost, than the two largest wildfires
241 in recorded Colorado history, each of which burned approximately 80,000 hectares. The 2018
242 Mati Fire in Greece burned only 1,276 hectares, but destroyed or damaged 3,000 homes and was
243 the second-deadliest weather-related disaster in Greece (11). While evidence suggests
244 increasing aridity will lead to more burning (7, 32, 43, 45), the 2021 Marshall Fire and 2018 Mati
245 Fire remind us that fire area burned is a poor indicator of the negative impacts of wildfires on the
246 built environment.

247 Given the shifts in wildfire activity and its increasingly devastating impacts, the need to fund
248 research and adopt policy to address fire-related challenges continues to grow. These challenges
249 may be best addressed with coordinated proactive and collective governance through
250 engagement of scientists, managers, policy-makers and citizens (23). A recent United Nations'
251 report recognized extreme wildfires as a globally relevant crisis, highlighting the scope of this
252 challenge (46). To address this crisis we need to recast how we study fire as an inherently
253 transdisciplinary, convergent research domain to find solutions that cross academic, managerial,
254 and social boundaries. As society urgently looks for strategies to mitigate the impacts of wildfires,
255 the scientific community must deliver a coherent understanding of the diverse causes, impacts,
256 management paths and likely future of fire on Earth that considers the integrated relationships
257 between humans and fire. Humans are not only affected by fire, but are also fundamental to its
258 behavior and impact through our changes to the biosphere and our values, behaviors, and
259 conceptions of risk.

260 The challenge of understanding the integrated role of humans and fire during the Anthropocene is
261 an opportunity to catalyze the next generation of scientists and scientific discovery. It requires
262 funding that develops collaborative, transdisciplinary science, dissolves disciplinary boundaries
263 and aligns research goals across traditional academic fields and ways of knowing. This
264 represents an opportunity to build scientific practices that are respectful and inclusive of all, by
265 creating spaces to share and co-produce knowledge between and among all stakeholders. Such
266 practice demands multi-scale data collection and analysis to develop models that test our
267 understanding, support safer communities, and provide long-term projections. By reinventing the
268 training of scientists to reflect this transdisciplinary, multi-stakeholder, data-driven approach, we
269 can help revolutionize community practices and provide information needed by communities to be
270 able to better live with fire - in all its forms - in our increasingly flammable world.

271 Here we identify five key challenges as a call to action to advance the study of fire as a
272 fundamental aspect of life on Earth (Figure 1).

273   1. Integrate across disciplines by promoting coordination among physical, biological, and
274   social sciences
275   2. Embrace different ways of knowing and knowledge generation to identify resilience
276   pathways
277   3. Use fire as a lens to address fundamental science questions
278   4. Capitalize on the "firehose" of data to support community values
279   5. Develop coupled models that include human dimensions to better anticipate future fire

280 These challenges are a synthesis of discussions of a group of mainly U.S.A. based researchers
281 at the National Science Foundation's Wildfire in the Biosphere workshop. The challenges of fire
282 science extend beyond national borders, and our hope is that funding agencies, land stewards,
283 and the larger fire science research community will join to address them. Within each call-to-
284 action challenge we describe the nature of the challenge, address the social impacts, identify
285 fundamental scientific advances necessary, and propose pathways to consider across
286 communities as we address our place in a more fiery future (Supplementary Table 1). Acting on
287 these challenges will assist in better addressing the immediate impacts of fire, as well as post-fire
288 impacts (e.g., landslides, vegetation shifts). The focus on immediate needs is not meant to
289 undermine the importance of longer-term impacts of fires, which in many ways are less
290 understood, rather to highlight their urgency.

291 **Discussion**
292
293 1: Challenge: Integrate across disciplines by promoting coordination among physical, biological,
294 and social sciences
295
296 *Wildfire is a biophysical and social phenomenon, and thus its causes and societal impacts cannot*
297 *be understood through any single disciplinary lens.*

298 While studied for over a century, wildland fire science often remains siloed within disciplines such
299 as forestry, ecology, anthropology, economics, engineering, atmospheric chemistry, physics,
300 geosciences, and risk management. Within each silo, scientists often exclusively focus on fire
301 from a specific perspective – fires as a human hazard, fire as a management tool, or fire as an
302 ecological process. Collectively we have deep knowledge about specific pieces of fire science;
303 however, to move fire science forward and answer fundamental questions about drivers and
304 impacts of fire, we must break out of traditional silos (e.g., institutional type, research focus,
305 academic vs management) (47) to a more holistic and integrated approach across social (48),
306 physical, and biological sciences, and including Traditional Ecological Knowledge (49) (See
307 Challenge 2).

308 Fire affects every part of the Earth system: the atmosphere, biosphere, hydrosphere, and
309 lithosphere and plays a critical role in local to global water, carbon, nutrient, and climatic cycles
310 by mediating the transfer of mass and energy at potentially large scales and in discrete pulses.
311 Ecosystems and fire regimes are changing; we need to be prepared to anticipate tipping points
312 and abrupt transitions to novel or alternative states. To fully understand the causes and
313 consequences of shifting fire regimes we must accept fire as a process with feedbacks between
314 social and ecological systems while increasing respect among diverse communities (e.g., 50).
315 Rethinking collaborations across disciplines provides opportunities to determine shared values
316 and goals (51) as well as new modes of practice that dismantle inequitable and exclusionary
317 aspects of our disciplines (52). Team dynamics are particularly important in multi-disciplinary
318 collaborations given the varied experiences, expertise and discipline-specific language used by
319 team members. In many cases these differences, in addition to the historical and systematic
320 inequities within STEM (Science, Technology, Engineering and Math) fields (e.g., 53, 54) have
321 kept disciplines siloed and some groups excluded (55).

322 We need to build upon the adaptive, integrated knowledge and "use-inspired" approaches, such
323 as those put forth by Kyker-Snowman et al. (56) and Wall et al. (57), by including empiricists,
324 modelers, practitioners and domain experts from broad disciplines where they are involved at
325 every stage of data collection, idea development, and model integration. In this approach, the
326 two-way exchange of ideas is emphasized in order to effectively incorporate domain expertise
327 and knowledge into models of systems that can not only improve understanding, but eventually
328 move towards forecasting capability (See Challenge 5).

329

330   2: Challenge: Embrace different ways of knowing and knowledge generation to identify resilience
331   pathways

332

333   *Fire is an intrinsic part of what makes humans human, such that all humans from diverse groups*
334   *and perspectives can provide valuable insights; thus co-produced knowledge is a prerequisite to*
335   *innovation in fire science.*

336   Given the urgent need to reduce wildfire disaster losses and to promote pathways to live
337   sustainably with fire, it is critical to integrate knowledge from across disciplinary, organization, and
338   community boundaries (58). Knowledge co-production offers a model that identifies and produces
339   science needed to drive change (59) through iterative, sustained engagement with key
340   stakeholders (60). Specifically, development of mitigation tools and strategies enables social-
341   ecological systems to transform from a resistance mindset to a resilience mindset (61).

342   There exist millennia of knowledge by Indigenous peoples of Tribal Nations that hold Traditional
343   Ecological Knowledge (TEK) of ancient burning practices (62–66) used to maintain healthy
344   ecosystems. Indigenous and non-Indigenous place-based societies, such as traditional fire
345   practitioners in Europe and elsewhere, have used fire to safeguard communities, promote desired
346   resources and support cultural lifeways for centuries to millennia (37, 49, 67–72). Working
347   together, scientists from diverse cultural perspectives can co-define resilience across ecocultural
348   landscapes (73), using this knowledge to identify perspectives of resilience to wildfire (72, 74).
349   Our fire science community needs to work with diverse communities to determine what is
350   valuable, generating needed information on risk scenarios and potential resilience pathways in
351   the face of a changing climate, while upholding data principles that respect Tribal sovereignty and
352   intellectual property (75).

353   We must accept fire as a social-ecological phenomenon that operates across multiple scales in
354   space and time: fire acutely affects ecosystems, humans, and the biosphere; fire is a selective
355   pressure and driver of ecological change; and humans, including various management practices,
356   influence fire behavior and impacts. We need to understand where vulnerable communities are
357   before wildfires occur, to build better, create defensible spaces around homes, reduce unintended
358   human ignitions (e.g, downed power lines), and promote Indigenous management strategies and
359   prescribed burning practices where they could mitigate disaster risk (37). Returning fire to
360   landscapes and developing a culture of fire tailored to specific settings is increasingly seen as the
361   most effective path forward. *We repeatedly converged on the need for "sustainable" strategies for*
362   *human communities to coexist with fire and smoke to become more aligned with TEK. Our*
363   *authorship group, however, reflective of STEM disciplines more broadly, consists of non-*
364   *Indigenous scientists. This situation emphasizes the need to prioritize collaboration with*
365   *Indigenous scientists and community partners in developing ways to adapt to fire in a changing*
366   *world.*

367   It is critical to recognize the human role in using fire in the environment, and bring that into our
368   understanding of adapting management for a more firey world. In turn, this can inform
369   development of coupled models (see Challenge 5) representing fire as a human-biophysical
370   phenomenon and can be used for management. To do so, we need to understand different value
371   systems and develop metrics through co-production, thus collectively defining what success looks
372   like for all stakeholders. This perspective provides scientific support for adaptive management
373   and policy in the face of continuing human-caused change, including climate change. The resist-
374   accept-direct (RAD) framework is explicitly designed to guide management through ecological
375   transformations (76), a scenario increasingly likely with unprecedented climate change and
376   enabled by fire. Because fire can catalyze social and ecological transformations, the RAD
377   framework will be particularly useful for coming decades. Applying decision frameworks such as
378   RAD requires incorporating human values, perceptions, and dynamism into fire management,
379   within and beyond natural sciences (51, 77). Thus the process itself offers potential for
380   transdisciplinary innovation and inclusion of different ways of knowing (e.g. TEK) by requiring

381   interdisciplinary engagement, including paleo scientists, ecologists, traditional knowledge holders,
382   cultural anthropologists, archeologists, remote sensing experts, modelers, policy scientists, and
383   community and government partners.

384   In addition to working across disciplines we need to be aware of extant systems of oppression
385   inherent in Western science(78). The lack of diversity among knowledge contributors in co-
386   produced science and among scientists themselves fundamentally limits innovation, applicability,
387   as well as being fundamentally unjust (79). Furthermore, as fire is a global ecosystem process,
388   the research community should reflect a similar breadth in perspectives (80). However, fire
389   science, not unlike many STEM fields, has problems with representation across all axes of
390   identity, including gender, race, ethnicity, LGBTQA+, and disability (e.g. 81). For example, the
391   majority of our authorship group work at U.S. institutions, likely limiting the scope of our
392   discussions. To change course, we need to interrogate our own practices and limit opportunities
393   for bias. Providing clarity and transparency about and throughout decision-making processes
394   (grants, job postings, publications), training reviewers about bias, requiring the use of rubrics for
395   all evaluations, and anonymizing application materials whenever possible, are all effective
396   strategies to reduce gender and racial bias (82). Given the importance of representation, as a
397   community we need to elevate a diverse group of role models (83), e.g., highlighting notable
398   accomplishments of women-identifying fire scientists (84). To embrace diverse knowledge
399   requires explicit consideration of equity in stakeholder participation and fire science recruitment
400   and training from underrepresented backgrounds.
401
402   3. Challenge: Use fire as a lens to address fundamental science questions
403
404   *We should use fire to answer fundamental scientific questions within and across physical,*
405   *biological, and social sciences.*

406   Fire is a ubiquitous and pervasive phenomenon, historically studied and tested in natural
407   philosophy and scientific disciplines (85). It is also an ancient phenomenon with strong impacts
408   on the Earth system and society across scales. Thus, fire is an excellent subject for asking basic
409   questions in physical, biological, and social sciences. Here, we present three fundamental
410   science areas that use fire to understand change: a) ecology and evolutionary biology; b) the
411   evolution of *Homo sapiens;* and c) social dynamics.

412   Fire is a catalyst for advances in ecology and evolutionary biology, providing a lens to examine
413   how life organizes across scales and how organismal, biochemical, and physiological traits and
414   fire-related strategies evolve. Consequently, fire ecology provides a framework for predicting
415   effects of dramatic environmental changes on ecosystem function and biodiversity across spatial
416   and temporal scales (27, 86), especially where fire may have previously not been present or has
417   been absent for extended periods (e.g., 87). Research is needed that targets the synergy of
418   theoretical, experimental, and modeling approaches exploring the fundamental evolutionary
419   processes of how organisms and communities function in dynamic and diverse fire environments.
420   Fire allows researchers to investigate the fundamental and relative roles of traits and strategies
421   across plant, animal, and microbial communities (27), and evaluate the influence of smoke on the
422   function of airborne microbial communities (88), photosynthesis (89), and aquatic systems (90). A
423   focus on fire has advanced evolutionary theory through the understanding of the evolution of
424   plant traits and subsequent influence on the fire regime and selective environment, i.e.,
425   feedbacks (91). Fire-vegetation feedbacks may have driven the diversification and spread of
426   flowering plants in the Cretaceous era (92, 93). This hypothesis builds upon processes observed
427   at shorter time scales (e.g., the grass-fire cycle, 94) and suggests flowering plants fueled fire that
428   opened space in gymnosperm-dominated forests. This functional diversity can be parameterized
429   into land surface models (see Challenge 5) by using phylogenetic lineage-based functional types
430   to characterize vegetation, and could enhance the ecological realism of these models (95).
431   Critically needed is an understanding of the reciprocal effects of fire and organismal life history
432   characteristics and functional traits that characterize Earth's fire regimes.

433   Fire provides an important lens through which we interpret major processes in human evolution.
434   For example, the pyrophilic primate hypothesis (96) leverages observations from primatology (97)
435   and functional generalization from other fire-forager species (98) to suggest that fire was critical
436   for the evolution of larger-brained and big-bodied *Homo erectus* in sub-saharan Africa by 1.9
437   million years ago. These populations relied upon fire-created environments and may have
438   expanded burned areas from natural fire starts, all without the ability to start fires on their own.
439   Fire-starting became a staple technology around 400,000 years ago (99), after which human
440   ancestors could use fire in fundamentally new ways, including to further change their own
441   selective environment (100). For example, at least some Neandertal (*Homo sapiens*
442   *neandertalensis*) groups in Europe used fire to intentionally change their local environment more
443   than 100,000 years ago (101), and Middle Stone Age people (*Homo sapiens sapiens*) in east
444   Africa may have done the same shortly thereafter (3).

445   Fire illuminates social dynamics and can be a lens through which we examine fundamental
446   issues in human societies, and even the dynamics of gendered knowledge (102). Specifically, fire
447   questions convenient assumptions about population density and human-environmental impacts.
448   For example, small populations of Maori hunter-gatherers irreversibly transformed non-fire-
449   adapted South Island New Zealand plant communities when they arrived in the 13th century CE
450   (103, 104), whereas large populations of Native American farmers at densities comparable to the
451   modern wildland-urban interface subtly changed patch size, burn area, and fire-climate relations
452   in fire adapted pine forests over the past millennium (37). Similarly, in an ethnographic context
453   much Aboriginal burning is done by women (105) and male uses of fire tend to have different
454   purposes (106) with potential implications for varied social and environmental pressures on
455   gendered fire uses, goals, and outcomes.

456   Answering fundamental fire science questions about evolutionary biology and the dynamics of
457   human societies could help illuminate the role of humans in cross-scale pyrogeography. This is
458   especially important in the Anthropocene as species, communities, and ecosystems arising from
459   millennial-scale evolutionary processes respond to new disturbance regimes and novel
460   ecosystem responses (107). Moreover, with increasing extreme fire behavior in many regions
461   (16, 17, 35, 108), human societies must learn to live more sustainably with fire in the modern
462   context (109). Fire is a catalyst for exploring fundamental questions and highlights the need for
463   interagency fire-specific funding programs to support basic science. The direct benefits to society
464   of fire research are well acknowledged, but fire scientists are not organized as a broad
465   community to argue for coordinated efforts to support basic science. Current fire-focused funding
466   sources are usually limited to narrowly applied projects, while funders of basic science treat fire
467   as a niche area. The result is duplicated efforts and competition for limited funds instead of
468   coordination across an integrated fire science community.

469
470   4. Challenge: Capitalize on the "firehose" of data to support community values
471
472   *We need funding to harness the data revolution and aid our understanding of fire.*

473   The volume, type, and use of data now available to study fire in the biosphere is greater than ever
474   before - a metaphorical "firehose" delivering vast amounts of information. Multidisciplinary science
475   campaigns to study fire behavior and emissions are data intensive and essential for improving
476   applications from local, regional to global scales (e.g. ABoVE - 110, MOYA - 111, FASMEE - 112,
477   FIREX-AQ - 113, MOYA/ZWAMPS - 114, WE-CAN - 115). Observation networks supported by
478   the U.S. National Science Foundation (e.g., NEON, National Ecological Observatory Network,
479   116) and the Smithsonian sponsored ForestGEO plots (117, 118) are uniquely valuable for the
480   duration and intensity of data collection. Additionally, there are dozens of public satellites, and
481   even more private ones, orbiting the planet collecting remote-sensing data related to pre-, active,
482   and post-fire conditions and effects, thereby facilitating geospatial analysis from local, to regional
483   and global scales (119, 120). Terabases of genome-level molecular data on organisms spanning

484   from microbes to plants and animals are readily generated (121). Finally, laboratory, field, and
485   incident data exist like never before, where in the past there was limited availability.

486   While these data exist, there are challenges with the spatial and temporal frequency and
487   coverage and duration of observations. Airborne flight campaigns cover a limited domain in space
488   and time, while geostationary satellites provide high temporal resolution with relatively coarse
489   spatial resolution and polar orbiting satellites provide higher spatial resolution, but lower temporal
490   resolution. These tradeoffs in resolution and coverage lead to different data sources providing
491   conflicting estimates of burned area (122, 123). We need investment in laboratory and field
492   infrastructure for studying fire across a range of scales and scenarios (124) and continued work
493   comparing and accounting for biases across existing data streams. We must develop
494   infrastructure and support personnel to collect real-time observation data on prescribed or cultural
495   fires (125) and wildfires in both wildlands and the wildland-urban interface across scales: from the
496   scale of flames (i.e., centimeters and seconds) to airshed (kilometers and hours), to fire regimes
497   (regions and decades).

498   Furthermore, many measures of fire processes and impacts are inferred from static datasets
499   (126), while fires and their effects are inherently dynamic; collecting observations that capture
500   these dynamics, such as the response of wind during a fire event, would greatly reduce
501   uncertainties in forecasting the impacts of fire on social-ecological systems. For fast-paced, local
502   processes like fire behavior and the movement of water and smoke, we need more high
503   frequency observations from laboratory and field-based studies, such as the role of flame-
504   generated buoyancy in fire spread (127), to update empirical relationships, some established by
505   decades-old research and still used in models (128, 129). For centennial- to multi-millennial
506   processes covering regions and continents, we need paleoclimate and paleoecological data sets
507   that cover the variation in fire regimes (e.g., low severity vs. high severity) across ecoregions
508   (130, 131).

509   We need technologies that collect data relevant for better understanding fire impacts on
510   ecosystems and humans. New technology (e.g., ground-, air-, and space-borne lidars, radars,
511   [hyperspectral] spectrometers, and [multispectral] radiometers) would enable measurements to
512   help characterize surface and atmospheric structure and chemistry and better understand human
513   land cover and land use in conjunction with fire impacts on air and water quality, ecosystems, and
514   energy balance. We must use molecular techniques to capture the direct and indirect effects of
515   soil heating on soil organic matter composition (132), belowground biological communities (133,
516   134), organism physiology (135), and ecosystem function processes (136). Finally, laboratory
517   work can help better understand the mechanisms of heat transfer (137, 138), firebrand ember
518   generation, behavior and transport (139, 140), atmospheric emissions (141) and transformation of
519   fire plumes (115).

520   One challenge is that these data are not well integrated for studying fire disturbance, as many
521   were not specifically designed to examine the causes or effects of fire within an integrated social-
522   ecological construct. For example, the use of diverse sets of multi-scale (tree, patch, local and
523   regional landscape) and multi-proxy records (pollen and charcoal, tree-ring fire scars, tree cohort
524   analysis, inventories, photographic imagery, surveys, and simulation modeling) can be used to
525   determine structure, tree-species composition and fire regimes (72, 142) and departures from
526   historical ranges of variability (15, 143). However, this type of integrated historical data across a
527   spatiotemporal continuum is not readily accessible to fire scientists, policymakers and
528   communities. Current capabilities of remote sensing measurements of vegetation properties (144)
529   are also not easily ingested as relevant information for more traditional fire models (145). Finally,
530   there is limited access to global datasets of research-quality event-based data (24, 146–149),
531   which is necessary to advance the understanding of human and biophysical processes of fire.

532   Many of these data are housed in disciplinary databases, such as the International Multiproxy
533   Paleofire Database (150), which can be challenging for non-specialists to access and use. We
534   need to compile and merge these diverse data across spatial (m^2 to Earth System) and temporal

535 (milli-seconds to millennia) scales to support integration across disciplines, research groups, and
536 agencies. Previous work provides an extensible framework for co-aligned airborne and field
537 sampling to support ecological, microbiological, biogeochemical and hydrological studies (112,
538 151). This work can be used to inform integration and coordination of data collection across
539 platforms (field and remotely sensed), scales (flame to airshed), and systems (atmosphere,
540 vegetation, soil, geophysical), to establish a network that will produce long-term, open-access,
541 and multi-disciplinary datasets related to fire science. This effort requires a reevaluation of how
542 we collect data, ensuring we do so in ways that address key societal needs (e.g., aiding in human
543 adaptability and maintenance of biodiversity). It highlights the need to coordinate across
544 laboratory, field and model-based research in designing future campaigns to develop, not only a
545 common platform, but also a common language and coordinated data management across
546 disciplines. Standardized data collection (e.g., observables, units, etc.) and protocols for quality
547 control, archiving and curation will be essential to merge existing datasets (90) and create new
548 ones.

549 In support of increased utility, we need to establish and use common metadata standards and a
550 community of practice for open algorithms and code, informed by the FAIR data principles making
551 data and code **F**indable on the web, digitally **A**ccessible, **I**nteroperable among different computing
552 systems, and thus **R**eusable for later analyses (152) and data literacy communities such as
553 PyOpenSci (https://www.pyopensci.org/) and ROpenSci (https://ropensci.org/). Implementation of
554 FAIR principles are complemented by the CARE (**C**ollective Benefit, **A**uthority to Control,
555 **R**esponsibility, and **E**thics) principles that protect Indigenous sovereignty and intellectual property
556 (75). This requires not only building coordination among federal agencies, but also with state,
557 local and Tribal governments and institutions. Such a community of practice, exemplary of ICON
558 (**I**ntegrated, **C**ollaborative, **O**pen, **N**etworked) science principles and practices (153), would
559 facilitate more frequent collaborations across disciplines and lead to convergent research and
560 data-intensive scientific discovery.

561 By compiling and merging diverse datasets, we can remove barriers to searching, discovering,
562 and accessing information across disciplines, thereby accelerating scientific discovery to
563 understand drivers and impacts of fire, helping support the development of more fire-resilient
564 communities. There is considerable potential to harness this data revolution and explore cross-
565 disciplinary research in the form of biomimicry adapted from long-term parallels from flora, fauna,
566 and Indigenous peoples' responses to fire (154), management planning with Potential
567 Operational Delineations (PODs; 155), and digital twins (156) that use coupled models including
568 human dimensions (see Challenge 5) to adapt and test historical parallels and potential solutions
569 for human communities and broader social-ecological systems.

570
571 5: Challenge: Develop coupled models that include human dimensions to better anticipate future
572 fire

573
574 *To better anticipate future fire activity and its impacts on and feedback with social-ecological*
575 *systems, we must develop coupled models that integrate human- and non-human dimensions.*

576 We need modeling frameworks that better represent fire in a social-ecological system, and that
577 can be applied across multiple spatial and temporal scales spanning wildland-rural-urban
578 gradients (8, 11, 20). Such frameworks should capture differences between managed and
579 unmanaged fire as they relate to: preceding conditions, ignition sources (28), fire behavior and
580 effects on ecosystems, humans, and the biosphere. Making this distinction between managed
581 and unmanaged fire in modeling is essential to characterizing changes in the natural system due
582 to the influence from human behavior (26). Fire has been a primary human tool in ecosystem
583 management (30), and thus unraveling the variability in human-fire interactions over space and
584 time (see Challenges 2 and 3) is necessary for understanding fire in the biosphere (26, 30, 69).
585 There are multiple types of models that can benefit from better accounting for human interactions.

586   First, an improved forecasting system is needed to project both managed (e.g., prescribed burn
587   and wildfire response) and unmanaged (i.e., wildfire) fire spread and smoke behavior, transport
588   and transformation (112). This can aid society's strategic and managed response to fire in terms
589   of community resilience (47, 74). Models of fire behavior and effects span spatial and temporal
590   scales, but fundamental to each is the consideration of fuels, vegetation, and emissions. We must
591   work to capture fuel heterogeneity, including the physiological dynamics that influence vegetation
592   fuel loading (157), fuel moisture (158, 159), and the flammability of live and dead vegetation (160,
593   161). Fuel moisture and its variation in space and time have the capacity to alter fire behavior
594   (162) and ecosystem vulnerability to wildfire (163). Currently, most models do not capture both
595   these types of fuels *and* plant physiological dynamics, despite both influencing fire behavior,
596   effects and subsequently land surface recovery. Several wildfire propagation models exist
597   ranging from empirical to process-based (127, 164), but they either entirely focus on wildlands
598   (112, 164) or pertain to limited aspects to wildfire behavior in communities focusing on
599   interactions among a group of structures (165) and not on the heterogeneous landscapes of the
600   wildland-urban interface (166, 167). We are making significant advances in capturing the impacts
601   of fire on winds during an event (164) as well as on local weather conditions (168, 169), which
602   both have the capacity to alter fire behavior and path. Advances in analytical approaches are
603   making it possible to model community vulnerability (170) and risk (171) from a fire propagation
604   perspective while accounting for the interaction between structures (172). However, to date, we
605   do not have consensus on a model to assess the survivability of individual structures from wildfire
606   events, as available urban fire spread models are not designed for these communities and
607   underestimate the fire spread rate in most cases (172). Developing such models is vital for
608   determining how to manage wildfire risk at the community level.

609   Second, land surface models, which simulate the terrestrial energy, water and carbon cycle) often
610   represent fire occurrence and impacts, but omit key aspects or are parameterized in a simple
611   manner (173). As such, there is a need to develop fire models within land surface models that
612   integrate fire behavior and effects representative of the social-ecological environment within
613   which humans interact with fires and subsequently influence impacts to terrestrial energy, water,
614   and carbon cycles. The current generation of fire-enabled land surface models demonstrate that
615   a lot of uncertainty is due to how the human impact on fires is currently represented, and
616   exemplifies the need for a better representation of human dimensions within global fire models
617   (174–177). Relationships between people and fire are driven by interactions between the social
618   environment in which humans act (e.g. livelihood system, land tenure, land use), the physical
619   environment (e.g., background fire regime, landscape patterns, land management legacies) and
620   the policy sphere. The current generation of fire-enabled land surface models are not able to
621   represent fire in this social-ecological environment, and thus struggle to represent both historical
622   changes in global fire occurrence (26), as well as how these changes have impacted ecosystems
623   and society with sufficient regional variability in the timing and type of human impacts on fires
624   (174, 175). Additionally, current land surface models do not represent mixed fuel types between
625   natural vegetation, managed land, and the built-environment, which influence fire spread,
626   characteristics and impact directly. Land surface models rarely represent the effects of fire on
627   organic matter (i.e., pyrogenic organic matter production (178), or the non-linear effects of
628   repeated burning on soil carbon stocks (179). As this likely plays an important role in the net
629   carbon balance of wildfires (178), these omissions may represent oversights in estimates of the
630   impact of fires on carbon stocks (180). While land surface models often include simplified post-
631   fire vegetation dynamics for seed dispersal and tree seedling establishment, competition during
632   succession, formation of large woody debris, and decomposition (e.g., 157, 181), they exclude
633   the influence humans have on these processes through land management.

634   Third, fire-enabled Earth system models, which seek to simulate the dynamic interactions and
635   feedbacks between the atmosphere, oceans, cryosphere, lithosphere and land surface (as such
636   incorporate land surface models), use a simplistic representation of fire simulating aggregate
637   burned area rather than the spread and perimeters of individual fires (182). This is a challenge for
638   projecting the broad scale impacts of fire on ecosystem resilience and functioning, because the
639   temporal and spatial patterns of fire that vary as a function of managed versus unmanaged fire,

640 underpin whether and how ecosystems recover (183, 184). This further affects smoke emission
641 speciation, formation and behavior of greenhouse gases, aerosols, and secondary pollutants that
642 affect the climate system (185, 186) through the absorption and scattering of solar radiation and
643 land surface albedo changes. Our limited understanding is due in part to challenges related to
644 representing this complexity and the resulting processes and impacts within and across
645 interacting model grid cells..

646 There is a need for the infrastructure to implement and nest models across multiple scales,
647 linking from fine to coarse temporal and spatial scales and including a two-way coupling to allow
648 interaction between models. This would, for example, allow Earth system models to better
649 capture changing vegetation and fuels through time, as modeled in land surface models; this in
650 turn would help modelers capture finer-scale dynamics such as interactions between fire and
651 weather and human interactions with individual fire events (e.g., suppression efforts). Reducing
652 uncertainties across scales provides an opportunity to use data-assimilation to benchmark
653 against multiple types of data at sites, for various scales, fires (prescribed/cultural and wild), and
654 under variable conditions (see Challenge 4). Advanced analytics in machine learning and artificial
655 intelligence can help ease computational complexity (187–189) in such an integrated framework.

656 Nested, coupled modeling frameworks that integrate across physical, biological, and social
657 systems will not only enhance our understanding of the connections, interactions and feedbacks
658 among fire, humans, and the Earth system, but also enable adaptation and resilience planning if
659 we create metrics to gauge the response of social-ecological systems to fire (e.g., 126, 190).
660 These metrics would include fire impacts on ecosystem services, human health, ecosystem
661 health, and sustainable financing through policies on fire suppression, air and water quality, and
662 infrastructure stability. Recent progress in understanding the characteristics of western United
663 States community archetypes, their associated adaptation pathways, and the properties of fire-
664 adapted communities (191, 192) should be explored across a diverse set of communities and
665 used to inform such metrics.

666 Metrics for risk and resilience would need to be incorporated in these nested, coupled models
667 that include human dimensions so that projections before, during, and after a fire could allow for
668 informed decision making. Risk includes not only the hazard, or potential hazard, of fire, but the
669 exposure (directly by flame or indirectly from smoke) and vulnerability, as susceptibility, to be
670 negatively impacted by the hazard; all of which are different for managed versus unmanaged fire
671 (20, 108, 143). Using models to quantify risk could, for example, guide planned management
672 shifts from fire suppression to increased use of prescribed burning as an essential component for
673 managing natural resources (143, 193, 194), but is currently challenging to implement due to
674 smoke effects (195). Next-generation, integrated human-fire models are necessary to help
675 managers both locally, those who use prescribed fire near communities (125, 196), and regionally
676 or nationally, those who report emissions. While such a comprehensive framework would address
677 the specific needs of different stakeholders and policy makers, it would also be accessible and
678 broadly comprehensible to the general public (e.g., fire paths forecast), similar to existing national
679 warning systems for hurricanes and tornadoes. A focus on community resilience to wildfires
680 expands the definition of risk beyond human impact to consider ecological and biological risk
681 more holistically, as well as their role in a coupled social-ecological system. Integrating human
682 behavior and decision dynamics into a nested modeling framework would allow for another
683 dimension of feedback and interactions. Thus, integration of data and processes across scales
684 within a nested, coupled modeling framework that incorporates human dimensions creates
685 opportunities to both improve understanding of the dynamics that shape fire-prone systems and
686 to better prepare society for a more resilient future with increased fire danger.

687
688 **Conclusion**

689 *Now in the emerging era of the Anthropocene, where climate change and decoupling of historical*
690 *land management have collided, society needs large-scale investment in the next generation of*

691   *fire science to help us live more sustainably in our increasingly flammable world.* Fire is a
692   complex phenomenon that has profound effects on all elements of the biosphere and impacts
693   human activities on a range of spatial and temporal scales. *We need a proactive fire research*
694   *agenda.* Fire science has been reactive in that it responds to agency opportunities and conducts
695   research in response to past fires. It is essential that we transition from this reactive stance to
696   proactively thinking about tomorrow's needs by acknowledging and anticipating future fire activity.
697   *This next generation of fire science will require significant new investment for a center that*
698   *synthesizes across disciplines (Challenge 1), is diverse and inclusive (Challenge 2), innovative*
699   *(Challenge 3), and data-driven (Challenge 4), while integrating coupled models that consider*
700   *human dimensions and values (Challenge 5) (Figure 1, Supplementary Table 1).*

701   One cause of current fragmentation within the U.S.A is the narrow focus of major funding
702   sources. Funding currently targets short term goals, on small, single-Principal Investigator-led
703   research, usually aimed at one aspect of fire science; it should target a holistic reimagination of
704   our relationship with fire entirely, across academic, managerial, and social boundaries. This will
705   create a broader and deeper understanding of the multifaceted nature of fire, with less focus on
706   case studies and more focus on case integration. International projects funded by the European
707   Commission have implemented a multi- and interdisciplinary approach, but can still be improved.
708   Support for applied research will be most effective by aiming at both short- and long-term
709   applications and solutions. There are active and prominent discussions on the need to fund fire
710   science across government, local and Indigenous entities that are all vested in understanding fire.
711   These investments will be critical to advancing our ability to generate new insights into how we
712   live more sustainably with fire. Fire will continue to have enormous societal and ecological
713   impacts, and accelerate positive feedbacks with climate change over the coming decades.
714   Understanding, mitigating, and managing those impacts will require addressing the presented five
715   challenges to inform how we serve environmental and social justice by sustainably living and
716   interacting with fire in our natural world.

717

Data Sharing
718

720   All data is included in the manuscript and/or supporting information.
721

733   **References**
734

735   1. K. K. McLauchlan, *et al.*, Fire as a fundamental ecological process: Research advances and
736   frontiers. *J. Ecol.* **108**, 2047–2069 (2020).

737   2. M. J. Medler, Speculations about the Effects of Fire and Lava Flows on Human Evolution.
738   *Fire Ecol.* **7**, 13–23 (2011).

739   3. J. C. Thompson, *et al.*, Early human impacts and ecosystem reorganization in southern-
740   central Africa. *Sci. Adv.* **7**, eabf9776 (2021).

741   4. P. J. Crutzen, Geology of mankind. *Nature* **415**, 23–23 (2002).

742   5. D. M. J. S. Bowman, *et al.*, Vegetation fires in the Anthropocene. *Nat. Rev. Earth Environ.*
743   (2020) https:/doi.org/10.1038/s43017-020-0085-3.

744   6. W. M. Jolly, *et al.*, Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat*
745   *Commun* **6**, 7537 (2015).

746   7. D. M. J. S. Bowman, *et al.*, Human exposure and sensitivity to globally extreme wildfire
747   events. *Nat. Ecol. Evol.* **1**, 0058 (2017).

748   8. V. C. Radeloff, *et al.*, Rapid growth of the US wildland-urban interface raises wildfire risk.
749   *Proc. Natl. Acad. Sci.* **115**, 3314–3319 (2018).

750   9. L. M. David, *et al.*, Could the exception become the rule? "Uncontrollable" air pollution events
751   in the U.S. due to wildland fires. *Environ. Res. Lett.* (2021) https:/doi.org/10.1088/1748-
752   9326/abe1f3.

753   10. S. Augusto, *et al.*, Population exposure to particulate-matter and related mortality due to the
754   Portuguese wildfires in October 2017 driven by storm Ophelia. *Environ. Int.* **144**, 106056
755   (2020).

756   11. A. Ganteaume, R. Barbero, M. Jappiot, E. Maillé, Understanding future changes to fires in
757   southern Europe and their impacts on the wildland-urban interface. *J. Saf. Sci. Resil.* **2**, 20–
758   29 (2021).

759   12. J. L. McCarty, *et al.*, Reviews and syntheses: Arctic fire regimes and emissions in the 21st
760   century. *Biogeosciences* **18**, 5053–5083 (2021).

761   13. Y. Zhuang, R. Fu, B. D. Santer, R. E. Dickinson, A. Hall, Quantifying contributions of natural
762   variability and anthropogenic forcings on increased fire weather risk over the western United
763   States. *Proc. Natl. Acad. Sci.* **118** (2021).

764   14. R. Kelly, *et al.*, Recent burning of boreal forests exceeds fire regime limits of the past 10,000
765   years. *Proc. Natl. Acad. Sci.* **110**, 13055–13060 (2013).

766   15. P. E. Higuera, B. N. Shuman, K. D. Wolf, Rocky Mountain subalpine forests now burning
767   more than any time in recent millennia. *Proc. Natl. Acad. Sci.* **118**, e2103135118 (2021).

768   16. R. Libonati, C. C. DaCamara, L. F. Peres, L. A. Sander de Carvalho, L. C. Garcia, Rescue
769   Brazil's burning Pantanal wetlands. *Nature* **588**, 217–219 (2020).

770   17. S. E. Page, A. Hooijer, In the line of fire: the peatlands of Southeast Asia. *Philos. Trans. R.*
771   *Soc. B Biol. Sci.* **371**, 20150176 (2016).

772   18. D. A. Kalashnikov, J. L. Schnell, J. T. Abatzoglou, D. L. Swain, D. Singh, Increasing co-
773   occurrence of fine particulate matter and ground-level ozone extremes in the western United
774   States. *Sci. Adv.* **8**, eabi9386 (2022).

775   19. W. J. Requia, H. Amini, R. Mukherjee, D. R. Gold, J. D. Schwartz, Health impacts of wildfire-
776   related air pollution in Brazil: a nationwide study of more than 2 million hospital admissions
777   between 2008 and 2018. *Nat. Commun.* **12**, 6555 (2021).

778   20. R. H. Nolan, *et al.*, What Do the Australian Black Summer Fires Signify for the Global Fire
779   Crisis? *Fire* **4**, 97 (2021).

780   21. E. Hirsch, I. Koren, Record-breaking aerosol levels explained by smoke injection into the
781   stratosphere. *Science* **371**, 1269–1274 (2021).

782   22. P. Yu, *et al.*, Persistent Stratospheric Warming Due to 2019–2020 Australian Wildfire Smoke.
783   *Geophys. Res. Lett.* **48**, e2021GL092609 (2021).

784   23. F.-N. Robinne, *et al.*, Scientists' warning on extreme wildfire risks to water supply. *Hydrol.*

785   *Process.* **35**, e14086 (2021).

786 24. D. van Wees, *et al.*, Global biomass burning fuel consumption and emissions at 500-m
787   spatial resolution based on the Global Fire Emissions Database (GFED). *Geosci. Model Dev.*
788   *Discuss.*, 1–46 (2022).

789 25. B. Zheng, *et al.*, Increasing forest fire emissions despite the decline in global burned area.
790   *Sci. Adv.* **7**, eabh2646 (2021).

791 26. N. Andela, *et al.*, A human-driven decline in global burned area. *Science* **356**, 1356–1362
792   (2017).

793 27. L. T. Kelly, *et al.*, Fire and biodiversity in the Anthropocene. *Science* **370**, eabb0355 (2020).

794 28. J. K. Balch, *et al.*, Human-started wildfires expand the fire niche across the United States.
795   *Proc. Natl. Acad. Sci.* **114**, 2946–2951 (2017).

796 29. Poulter Benjamin, Freeborn Patrick H., Jolly W. Matt, Varner J. Morgan, COVID-19
797   lockdowns drive decline in active fires in southeastern United States. *Proc. Natl. Acad. Sci.*
798   **118**, e2105666118 (2021).

799 30. D. M. J. S. Bowman, *et al.*, The human dimension of fire regimes on Earth. *J. Biogeogr.* **38**,
800   2223–2236 (2011).

801 31. M. C. Kirchmeier-Young, N. P. Gillett, F. W. Zwiers, A. J. Cannon, F. S. Anslow, Attribution of
802   the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earths Future*
803   **7**, 2–10 (2019).

804 32. J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across
805   western US forests. *Proc. Natl. Acad. Sci.* **113**, 11770–11775 (2016).

806 33. R. Barbero, J. T. Abatzoglou, F. Pimont, J. Ruffault, T. Curt, Attributing Increases in Fire
807   Weather to Anthropogenic Climate Change Over France. *Front. Earth Sci.* **8** (2020).

808 34. M. Turco, *et al.*, Climate drivers of the 2017 devastating fires in Portugal. *Sci. Rep.* **9**, 13886
809   (2019).

810 35. N. J. Abram, *et al.*, Connections of climate change and variability to large and extreme forest
811   fires in southeast Australia. *Commun. Earth Environ.* **2**, 1–17 (2021).

812 36. N. Mietkiewicz, *et al.*, In the Line of Fire: Consequences of Human-Ignited Wildfires to
813   Homes in the U.S. (1992–2015). *Fire* **3** (2020).

814 37. C. I. Roos, *et al.*, Native American fire management at an ancient wildland–urban interface in
815   the Southwest United States. *Proc. Natl. Acad. Sci.* **118**, e2018733118 (2021).

816 38. J. D. Coop, *et al.*, Wildfire-Driven Forest Conversion in Western North American Landscapes.
817   *BioScience* **70**, 659–673 (2020).

818 39. W. Rammer, *et al.*, Widespread regeneration failure in forests of Greater Yellowstone under
819   scenarios of future climate and fire. *Glob. Change Biol.* **27**, 4339–4351 (2021).

820 40. M. A. Thomas, *et al.*, Postwildfire Soil-Hydraulic Recovery and the Persistence of Debris
821   Flow Hazards. *J. Geophys. Res. Earth Surf.* **126**, e2021JF006091 (2021).

822 41. I. Campos, N. Abrantes, Forest fires as drivers of contamination of polycyclic aromatic
823   hydrocarbons to the terrestrial and aquatic ecosystems. *Curr. Opin. Environ. Sci. Health* **24**,
824   100293 (2021).

825 42. M. Burke, *et al.*, The changing risk and burden of wildfire in the United States. *Proc. Natl.*
826   *Acad. Sci.* **118**, e2011048118 (2021).

827   43. J. T. Abatzoglou, *et al.*, Projected increases in western US forest fire despite growing fuel
828   constraints. *Commun. Earth Environ.* **2** (2021).

829   44. D. Touma, S. Stevenson, F. Lehner, S. Coats, Human-driven greenhouse gas and aerosol
830   emissions cause distinct regional impacts on extreme fire weather. *Nat. Commun.* **12**, 212
831   (2021).

832   45. M. Turco, *et al.*, On the key role of droughts in the dynamics of summer fires in
833   Mediterranean Europe. *Sci. Rep.* **7**, 81 (2017).

834   46. United Nations Environment Programme, "Spreading like Wildfire – The Rising Threat of
835   Extraordinary Landscape Fires" (2022).

836   47. A. M. S. Smith, *et al.*, The Science of Firescapes: Achieving Fire-Resilient Communities.
837   *BioScience* **66**, 130–146 (2016).

838   48. E. Kuligowski, Burning down the silos: integrating new perspectives from the social sciences
839   into human behavior in fire research. *Fire Mater.* **41**, 389–411 (2017).

840   49. F. K. Lake, *et al.*, Returning Fire to the Land: Celebrating Traditional Knowledge and Fire. *J.*
841   *For.* **115**, 343–353 (2017).

842   50. A. P. Fischer, *et al.*, Wildfire risk as a socioecological pathology. *Front. Ecol. Environ.* **14**,
843   276–284 (2016).

844   51. P. E. Higuera, *et al.*, Integrating subjective and objective dimensions of resilience in fire-
845   prone landscapes. *BioScience* **69**, 379–388 (2019).

846   52. V. B. Chaudhary, A. A. Berhe, Ten simple rules for building an antiracist lab. *PLOS Comput.*
847   *Biol.* **16**, e1008210 (2020).

848   53. R. E. Bernard, E. H. G. Cooperdock, No progress on diversity in 40 years. *Nat. Geosci.* **11**,
849   292–295 (2018).

850   54. E. Marín-Spiotta, *et al.*, Hostile climates are barriers to diversifying the geosciences in
851   *Advances in Geosciences*, (Copernicus GmbH, 2020), pp. 117–127.

852   55. A. Mattheis, L. Nava, M. Beltran, E. West, Theory-Practice Divides and the Persistent
853   Challenges of Embedding Tools for Social Justice in a STEM Urban Teacher Residency
854   Program. *Urban Educ.*, 0042085920963623 (2020).

855   56. E. Kyker-Snowman, *et al.*, Increasing the spatial and temporal impact of ecological research:
856   A roadmap for integrating a novel terrestrial process into an Earth system model. *Glob.*
857   *Change Biol.* **28**, 665–684 (2022).

858   57. T. U. Wall, E. McNie, G. M. Garfin, Use-inspired science: making science usable by and
859   useful to decision makers. *Front. Ecol. Environ.* **15**, 551–559 (2017).

860   58. L. Peek, J. Tobin, R. M. Adams, H. Wu, M. C. Mathews, A Framework for Convergence
861   Research in the Hazards and Disaster Field: The Natural Hazards Engineering Research
862   Infrastructure CONVERGE Facility. *Front. Built Environ.* **6** (2020).

863   59. A. V. Norström, *et al.*, Principles for knowledge co-production in sustainability research. *Nat.*
864   *Sustain.* **3**, 182–190 (2020).

865   60. A. Bamzai-Dodson, A. E. Cravens, A. A. Wade, R. A. McPherson, Engaging with
866   Stakeholders to Produce Actionable Science: A Framework and Guidance. *Weather Clim.*
867   *Soc.* **13**, 1027–1041 (2021).

868   61. C. Béné, L. Doyen, From Resistance to Transformation: A Generic Metric of Resilience
869   Through Viability. *Earths Future* **6**, 979–996 (2018).

870   62. R. W. Kimmerer, F. K. Lake, The Role of Indigenous Burning in Land Management. *J. For.*
871   **99**, 36–41 (2001).

872   63. T. Marks-Block, W. Tripp, Facilitating Prescribed Fire in Northern California through
873   Indigenous Governance and Interagency Partnerships. *Fire* **4**, 37 (2021).

874   64. J. Mistry, B. A. Bilbao, A. Berardi, Community owned solutions for fire management in
875   tropical ecosystems: case studies from Indigenous communities of South America. *Philos.*
876   *Trans. R. Soc. B Biol. Sci.* **371**, 20150174 (2016).

877   65. B. Bilbao, J. Mistry, A. Millán, A. Berardi, Sharing Multiple Perspectives on Burning: Towards
878   a Participatory and Intercultural Fire Management Policy in Venezuela, Brazil, and Guyana.
879   *Fire* **2**, 39 (2019).

880   66. P. Laris, S. Caillault, S. Dadashi, A. Jo, The Human Ecology and Geography of Burning in an
881   Unstable Savanna Environment. *J. Ethnobiol.* **35**, 111–139 (2015).

882   67. M. R. Huffman, The Many Elements of Traditional Fire Knowledge: Synthesis, Classification,
883   and Aids to Cross-cultural Problem Solving in Fire-dependent Systems Around the World.
884   *Ecol. Soc.* **18**, 1–36 (2013).

885   68. D. Yibarbuk, *et al.*, Fire ecology and Aboriginal land management in central Arnhem Land,
886   northern Australia: a tradition of ecosystem management. *J. Biogeogr.* **28**, 325–343 (2001).

887   69. C. I. Roos, *et al.*, Living on a flammable planet: interdisciplinary, cross-scalar and varied
888   cultural lessons, prospects and challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **371**, 20150469
889   (2016).

890   70. M. R. Coughlan, Farmers, flames, and forests: Historical ecology of pastoral fire use and
891   landscape change in the French Western Pyrenees, 1830–2011. *For. Ecol. Manag.* **312**, 55–
892   66 (2014).

893   71. F. Seijo, R. Gray, Pre-Industrial Anthropogenic Fire Regimes in Transition: The Case of
894   Spain and its Implications for Fire Governance in Mediterranean Type Biomes. *Hum. Ecol.*
895   *Rev.* **19**, 58–69 (2012).

896   72. Knight Clarke A., *et al.*, Land management explains major trends in forest structure and
897   composition over the last millennium in California's Klamath Mountains. *Proc. Natl. Acad. Sci.*
898   **119**, e2116264119 (2022).

899   73. K. Copes-Gerbitz, S. Hagerman, L. Daniels, Situating Indigenous knowledge for resilience in
900   fire-dependent social-ecological systems. *Ecol. Soc.* **26** (2021).

901   74. D. B. McWethy, *et al.*, Rethinking Resilience to Wildfire. *Nat. Sustain.* **2**, 797–804 (2019).

902   75. S. R. Carroll, *et al.*, The CARE Principles for Indigenous Data Governance. *Data Sci. J.* **19**,
903   43 (2020).

904   76. G. W. Schuurman, *et al.*, Navigating Ecological Transformation: Resist–Accept–Direct as a
905   Path to a New Resource Management Paradigm. *BioScience* (2021)
906   https:/doi.org/10.1093/biosci/biab067 (December 20, 2021).

907   77. S. D. Crausbay, *et al.*, A Science Agenda to Inform Natural Resource Management
908   Decisions in an Era of Ecological Transformation. *BioScience* **72**, 71–90 (2022).

909   78. A. A. Berhe, *et al.*, Scientists from historically excluded groups face a hostile obstacle course.
910   *Nat. Geosci.* **15**, 2–4 (2022).

911   79. R. Haacker, M. Burt, M. Vara, Moving Beyond the Business Case for Diversity. *Eos* (2022)
912   (March 29, 2022).

913 80. K. L. Riley, T. Steelman, D. R. P. Salicrup, S. Brown, On the need for inclusivity and diversity
914   in the wildland fire professions. In: Hood, S.M.; Drury, S.; Steelman, T.; Steffens, R. [eds]
915   *Proc. Fire Contin.-Prep. Future Wildland Fire*; 2018 May 21-24; Missoula, MT. Proc. RMRS-
916   P-78. Fort Collins CO: US Dep. Agric. For. Serv. Rocky Mt. Res. Stn. P 2-7 (2020).

917 81. C. Macinnis-Ng, X. Zhao, Addressing Gender Inequities in Forest Science and Research.
918   *Forests* **13**, 400 (2022).

919 82. B. Schneider, M. A. Holmes, "Science behind Bias" in *Addressing Gender Bias in Science &*
920   *Technology*, ACS Symposium Series., (American Chemical Society, 2020), pp. 51–71.

921 83. H. Etzkowitz, C. Kemelgor, M. Neuschatz, B. Uzzi, J. Alonzo, The Paradox of Critical Mass
922   for Women in Science. *Science* **266**, 51–54 (1994).

923 84. A. M. S. Smith, *et al.*, Recognizing Women Leaders in Fire Science. *Fire* **1**, 30 (2018).

924 85. S. J. Pyne, Fire in the mind: changing understandings of fire in Western civilization. *Philos.*
925   *Trans. R. Soc. B Biol. Sci.* **371**, 20150166 (2016).

926 86. J. G. Pausas, J. E. Keeley, D. W. Schwilk, Flammability as an ecological and evolutionary
927   driver. *J. Ecol.* **105**, 289–297 (2017).

928 87. J. R. P. Worth, *et al.*, Fire is a major driver of patterns of genetic diversity in two co-occurring
929   Tasmanian palaeoendemic conifers. *J. Biogeogr.* **44**, 1254–1267 (2017).

930 88. L. N. Kobziar, *et al.*, Wildland fire smoke alters the composition, diversity, and potential
931   atmospheric function of microbial life in the aerobiome. *ISME Commun.* **2**, 1–9 (2022).

932 89. K. S. Hemes, J. Verfaillie, D. D. Baldocchi, Wildfire-Smoke Aerosols Lead to Increased Light
933   Use Efficiency Among Agricultural and Restored Wetland Land Uses in California's Central
934   Valley. *J. Geophys. Res. Biogeosciences* **125**, e2019JG005380 (2020).

935 90. F.-N. Robinne, D. W. Hallema, K. D. Bladon, J. M. Buttle, Wildfire impacts on hydrologic
936   ecosystem services in North American high-latitude forests: A scoping review. *J. Hydrol.* **581**,
937   124360 (2020).

938 91. K. Laland, B. Matthews, M. W. Feldman, An introduction to niche construction theory. *Evol.*
939   *Ecol.* **30**, 191–202 (2016).

940 92. W. J. Bond, A. C. Scott, Fire and the spread of flowering plants in the Cretaceous. *New*
941   *Phytol.* **188**, 1137–1150 (2010).

942 93. W. J. Bond, J. J. Midgley, Fire and the Angiosperm Revolutions. *Int. J. Plant Sci.* **173**, 569–
943   583 (2012).

944 94. C. M. D'Antonio, P. M. Vitousek, Biological invasions by exotic grasses, the grass/fire cycle,
945   and global change. *Annu. Rev. Ecol. Syst.* **23**, 63–87 (1992).

946 95. D. M. Griffith, *et al.*, Lineage-based functional types: characterising functional diversity to
947   enhance the representation of ecological behaviour in Land Surface Models. *New Phytol.*
948   **228**, 15–23 (2020).

949 96. C. H. Parker, E. R. Keefe, N. M. Herzog, J. F. O'connell, K. Hawkes, The pyrophilic primate
950   hypothesis. *Evol. Anthropol. Issues News Rev.* **25**, 54–63 (2016).

951 97. J. D. Pruetz, N. M. Herzog, Savanna Chimpanzees at Fongoli, Senegal, Navigate a Fire
952   Landscape. *Curr. Anthropol.* **58**, S337–S350 (2017).

953 98. M. Bonta, *et al.*, Intentional Fire-Spreading by "Firehawk" Raptors in Northern Australia. *J.*
954   *Ethnobiol.* **37**, 700–718 (2017).

955 99. K. MacDonald, F. Scherjon, E. van Veen, K. Vaesen, W. Roebroeks, Middle Pleistocene fire

956   use: The first signal of widespread cultural diffusion in human evolution. *Proc. Natl. Acad.*
957   *Sci.* **118**, e2101108118 (2021).

958   100.   K. N. Laland, M. J. O'Brien, Niche Construction Theory and Archaeology. *J. Archaeol.*
959   *Method Theory* **17**, 303–322 (2010).

960   101.   W. Roebroeks, *et al.*, Landscape modification by Last Interglacial Neanderthals. *Sci. Adv.*
961   **7**, eabj5567.

962   102.   C. Eriksen, *Gender and wildfire: landscapes of uncertainty* (Routledge, 2014).

963   103.   D. B. McWethy, *et al.*, Rapid landscape transformation in South Island, New Zealand,
964   following initial Polynesian settlement. *Proc. Natl. Acad. Sci.* **107**, 21343–21348 (2010).

965   104.   G. L. Perry, J. M. Wilmshurst, M. S. McGlone, D. B. McWethy, C. Whitlock, Explaining
966   fire driven landscape transformation during the Initial Burning Period of New Zealand's
967   prehistory. *Glob. Change Biol.* **18**, 1609–1621 (2012).

968   105.   R. Bliege Bird, D. W. Bird, B. F. Codding, C. H. Parker, J. H. Jones, The "fire stick
969   farming" hypothesis: Australian Aboriginal foraging strategies, biodiversity, and
970   anthropogenic fire mosaics. *Proc. Natl. Acad. Sci.* **105**, 14796–14801 (2008).

971   106.   D. M. J. S. Bowman, *et al.*, Pyrodiversity is the coupling of biodiversity and fire regimes in
972   food webs. *Philos. Trans. R. Soc. B Biol. Sci.* **371**, 20150169 (2016).

973   107.   J. G. Pausas, J. E. Keeley, Abrupt Climate-Independent Fire Regime Changes.
974   *Ecosystems* **17**, 1109–1120 (2014).

975   108.   V. Iglesias, J. K. Balch, W. R. Travis, US fires became larger, more frequent, and more
976   widespread in the 2000s. *Sci. Adv.* **8** (2022).

977   109.   M. A. Moritz, *et al.*, Learning to coexist with wildfire. *Nature* **515**, 58–66 (2014).

978   110.   C. E. Miller, *et al.*, An overview of ABoVE airborne campaign data acquisitions and
979   science opportunities. *Environ. Res. Lett.* **14**, 080201 (2019).

980   111.   P. A. Barker, *et al.*, Airborne measurements of fire emission factors for African biomass
981   burning sampled during the MOYA campaign. *Atmospheric Chem. Phys.* **20**, 15443–15459
982   (2020).

983   112.   Y. Liu, *et al.*, Fire behaviour and smoke modelling: model improvement and
984   measurement needs for next-generation smoke research and forecasting systems. *Int. J.*
985   *Wildland Fire* **28**, 570–588 (2019).

986   113.   M. S. Johnson, K. Strawbridge, K. E. Knowland, C. Keller, M. Travis, Long-range
987   transport of Siberian biomass burning emissions to North America during FIREX-AQ. *Atmos.*
988   *Environ.* **252**, 118241 (2021).

989   114.   MOYA/ZWAMPS Team, *et al.*, Isotopic signatures of methane emissions from tropical
990   fires, agriculture and wetlands: the MOYA and ZWAMPS flights. *Philos. Trans. R. Soc. Math.*
991   *Phys. Eng. Sci.* **380**, 20210112 (2022).

992   115.   B. B. Palm, *et al.*, Quantification of organic aerosol and brown carbon evolution in fresh
993   wildfire plumes. *Proc. Natl. Acad. Sci.* **117**, 29469–29477 (2020).

994   116.   R. C. Nagy, *et al.*, Harnessing the NEON data revolution to advance open environmental
995   science with a diverse and data-capable community. *Ecosphere* **12**, e03833 (2021).

996   117.   K. J. Anderson-Teixeira, *et al.*, CTFS-ForestGEO: a worldwide network monitoring forests
997   in an era of global change. *Glob. Change Biol.* **21**, 528–549 (2015).

998   118.   J. A. Lutz, A. J. Larson, M. E. Swanson, Advancing fire science with large forest plots and

999   a long-term multidisciplinary approach. *Fire* **1**, 5 (2018).

1000   119.   N. Gorelick, *et al.*, Google Earth Engine: Planetary-scale geospatial analysis for
1001   everyone. *Remote Sens. Environ.* **202**, 18–27 (2017).

1002   120.   M. J. Wooster, *et al.*, Satellite remote sensing of active fires: History and current status,
1003   applications and future requirements. *Remote Sens. Environ.* **267**, 112694 (2021).

1004   121.   J. K. Jansson, E. S. Baker, A multi-omic future for microbiome studies. *Nat. Microbiol.* **1**,
1005   1–3 (2016).

1006   122.   D. L. A. Gaveau, A. Descals, M. A. Salim, D. Sheil, S. Sloan, Refined burned-area
1007   mapping protocol using Sentinel-2 data increases estimate of 2019 Indonesian burning.
1008   *Earth Syst. Sci. Data* **13**, 5353–5368 (2021).

1009   123.   R. Ramo, *et al.*, African burned area and fire carbon emissions are strongly impacted by
1010   small fires undetected by coarse resolution satellite data. *Proc. Natl. Acad. Sci.* **118**,
1011   e2011160118 (2021).

1012   124.   A. M. S. Smith, *et al.*, Towards a new paradigm in fire severity research using dose–
1013   response experiments. *Int. J. Wildland Fire* **25**, 158–166 (2016).

1014   125.   C. B. Clements, *et al.*, Fire weather conditions and fire–atmosphere interactions observed
1015   during low-intensity prescribed fires – RxCADRE 2012. *Int. J. Wildland Fire* **25**, 90–101
1016   (2015).

1017   126.   T. Yabe, P. S. C. Rao, S. V. Ukkusuri, S. L. Cutter, Toward data-driven, dynamical
1018   complex systems approaches to disaster resilience. *Proc. Natl. Acad. Sci.* **119**, e2111997119
1019   (2022).

1020   127.   M. A. Finney, *et al.*, Role of buoyant flame dynamics in wildfire spread. *Proc. Natl. Acad.*
1021   *Sci.* **112**, 9833–9838 (2015).

1022   128.   C. E. Van Wagner, Conditions for the start and spread of crown fire. *Can. J. For. Res.* **7**,
1023   23–34 (1977).

1024   129.   R. C. Rothermel, "A mathematical model for predicting fire spread in wildland fuels"
1025   (USDA Forest Service, Intermountain Forest and Range Experiment Station, 1972).

1026   130.   G. M. Davies, A. Gray, G. Rein, C. J. Legg, Peat consumption and carbon loss due to
1027   smouldering wildfire in a temperate peatland. *For. Ecol. Manag.* **308**, 169–177 (2013).

1028   131.   J. Cobian-Iñiguez, *et al.*, Wind Effects on Smoldering Behavior of Simulated Wildland
1029   Fuels. *Combust. Sci. Technol.* **0**, 1–18 (2022).

1030   132.   J. R. Miesel, W. C. Hockaday, R. K. Kolka, P. A. Townsend, Soil organic matter
1031   composition and quality across fire severity gradients in coniferous and deciduous forests of
1032   the southern boreal region. *J. Geophys. Res. Biogeosciences* **120**, 1124–1141 (2015).

1033   133.   T. Whitman, *et al.*, Soil bacterial and fungal response to wildfires in the Canadian boreal
1034   forest across a burn severity gradient. *Soil Biol. Biochem.* **138**, 107571 (2019).

1035   134.   D. Revillini, *et al.*, Microbiome-mediated response to pulse fire disturbance outweighs the
1036   effects of fire legacy on plant performance. *New Phytol.* **233**, 2071–2082 (2022).

1037   135.   J. M. Varner, *et al.*, Tree crown injury from wildland fires: causes, measurement and
1038   ecological and physiological consequences. *New Phytol.* **231**, 1676–1685 (2021).

1039   136.   A. F. A. Pellegrini, *et al.*, Decadal changes in fire frequencies shift tree communities and
1040   functional traits. *Nat. Ecol. Evol.* **5**, 504–512 (2021).

1041   137.   D. Frankman, *et al.*, Measurements of convective and radiative heating in wildland fires.

1042   *Int. J. Wildland Fire* **22**, 157–167 (2012).

138.   A. Aminfar, *et al.*, Using Background-Oriented Schlieren to Visualize Convection in a Propagating Wildland Fire. *Combust. Sci. Technol.* **192**, 2259–2279 (2020).

139.   S. L. Manzello, *et al.*, Firebrand generation from burning vegetation1. *Int. J. Wildland Fire* **16**, 458–462 (2007).

140.   A. Tohidi, N. B. Kaye, Comprehensive wind tunnel experiments of lofting and downwind transport of non-combusting rod-like model firebrands during firebrand shower scenarios. *Fire Saf. J.* **90**, 95–111 (2017).

141.   K. Sekimoto, *et al.*, High- and low-temperature pyrolysis profiles describe volatile organic compound emissions from western US wildfire fuels. *Atmospheric Chem. Phys.* **18**, 9263–9281 (2018).

142.   R. K. Hagmann, *et al.*, Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecol. Appl.* **31**, e02431 (2021).

143.   P. F. Hessburg, S. J. Prichard, R. K. Hagmann, N. A. Povak, F. K. Lake, Wildfire and climate change adaptation of western North American forests: a case for intentional management. *Ecol. Appl.* **31**, e02432 (2021).

144.   E. N. Stavros, *et al.*, ISS observations offer insights into plant function. *Nat. Ecol. Evol.* **1**, 1–5 (2017).

145.   E. N. Stavros, *et al.*, Use of imaging spectroscopy and LIDAR to characterize fuels for fire behavior prediction. *Remote Sens. Appl. Soc. Environ.* **11**, 41–50 (2018).

146.   N. Andela, *et al.*, The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth Syst. Sci. Data* **11**, 529–552 (2019).

147.   J. K. Balch, *et al.*, FIRED (Fire Events Delineation): An Open, Flexible Algorithm and Database of US Fire Events Derived from the MODIS Burned Area Product (2001–2019). *Remote Sens.* **12**, 3498 (2020).

148.   L. A. St. Denis, N. P. Mietkiewicz, K. C. Short, M. Buckland, J. K. Balch, All-hazards dataset mined from the US National Incident Management System 1999–2014. *Sci. Data* **7**, 64 (2020).

149.   J. San-Miguel-Ayanz, *et al.*, Comprehensive monitoring of wildfires in Europe: the European forest fire information system (EFFIS) in J. Tiefenbacher [Ed.], *Approaches to Managing Disaster – Assessing Hazards, Emergencies and Disaster Impacts*, IntechOpen (2012)

150.   W. Gross, C. Morrill, E. Wahl, New advances at NOAA's World Data Service for Paleoclimatology – Promoting the FAIR principles. *Past Glob. Change Mag.* **26**, 58–58 (2018).

151.   K. D. Chadwick, *et al.*, Integrating airborne remote sensing and field campaigns for ecology and Earth system science. *Methods Ecol. Evol.* **11**, 1492–1508 (2020).

152.   M. D. Wilkinson, *et al.*, The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* **3**, 160018 (2016).

153.   A. E. Goldman, S. R. Emani, L. C. Pérez-Angel, J. A. Rodríguez-Ramos, J. C. Stegen, Integrated, Coordinated, Open, and Networked (ICON) Science to Advance the Geosciences: Introduction and Synthesis of a Special Collection of Commentary Articles. *Earth Space Sci.* **9**, e2021EA002099 (2022).

154.   A. M. S. Smith, C. A. Kolden, D. M. J. S. Bowman, Biomimicry can help humans to

1086   coexist sustainably with fire. *Nat. Ecol. Evol.* **2**, 1827–1829 (2018).

1087   155.   S. M. Greiner, *et al.*, Pre-season fire management planning: the use of Potential
1088   Operational Delineations to prepare for wildland fire events. *Int. J. Wildland Fire* **30**, 170–178
1089   (2020).

1090   156.   P. Bauer, B. Stevens, W. Hazeleger, A digital twin of Earth for the green transition. *Nat.*
1091   *Clim. Change* **11**, 80–83 (2021).

1092   157.   E. J. Hanan, M. C. Kennedy, J. Ren, M. C. Johnson, A. M. S. Smith, Missing Climate
1093   Feedbacks in Fire Models: Limitations and Uncertainties in Fuel Loadings and the Role of
1094   Decomposition in Fine Fuel Accumulation. *J. Adv. Model. Earth Syst.* **14**, e2021MS002818
1095   (2022).

1096   158.   A. F. Talhelm, A. M. S. Smith, Litter moisture adsorption is tied to tissue structure,
1097   chemistry, and energy concentration. *Ecosphere* **9**, e02198 (2018).

1098   159.   R. H. Nolan, J. Hedo, C. Arteaga, T. Sugai, V. Resco de Dios, Physiological drought
1099   responses improve predictions of live fuel moisture dynamics in a Mediterranean forest.
1100   *Agric. For. Meteorol.* **263**, 417–427 (2018).

1101   160.   R. H. Nolan, *et al.*, Linking Forest Flammability and Plant Vulnerability to Drought.
1102   *Forests* **11**, 779 (2020).

1103   161.   W. Ma, *et al.*, Assessing climate change impacts on live fuel moisture and wildfire risk
1104   using a hydrodynamic vegetation model. *Biogeosciences* **18**, 4005–4020 (2021).

1105   162.   W. M. Jolly, D. M. Johnson, Pyro-Ecophysiology: Shifting the Paradigm of Live Wildland
1106   Fuel Research. *Fire* **1**, 8 (2018).

1107   163.   K. Rao, A. P. Williams, N. S. Diffenbaugh, M. Yebra, A. G. Konings, Plant-water
1108   sensitivity regulates wildfire vulnerability. *Nat. Ecol. Evol.* **6**, 332–339 (2022).

1109   164.   J. L. Coen, W. Schroeder, Coupled weather-fire modeling: from research to operational
1110   forecasting. *Fire Manag. Today* **75**, 39–45 (2017).

1111   165.   K. McGrattan, *et al.*, Computational fluid dynamics modelling of fire. *Int. J. Comput. Fluid*
1112   *Dyn.* **26**, 349–361 (2012).

1113   166.   W. E. Mell, S. L. Manzello, A. Maranghides, D. Butry, R. G. Rehm, The wildland - urban
1114   interface fire problem - current approaches and research needs. *Int. J. Wildland Fire* **19**, 238
1115   (2010).

1116   167.   E. Ronchi, S. M. V. Gwynne, G. Rein, P. Intini, R. Wadhwani, An open multi-physics
1117   framework for modelling wildland-urban interface fire evacuations. *Saf. Sci.* **118**, 868–880
1118   (2019).

1119   168.   G. A. Grell, S. R. Freitas, A scale and aerosol aware stochastic convective
1120   parameterization for weather and air quality modeling. *Atmospheric Chem. Phys.* **14**, 5233–
1121   5250 (2014).

1122   169.   G. Grell, S. R. Freitas, M. Stuefer, J. Fast, Inclusion of biomass burning in WRF-Chem:
1123   impact of wildfires on weather forecasts. *Atmospheric Chem. Phys.* **11**, 5289–5303 (2011).

1124   170.   H. Mahmoud, A. Chulahwat, Unraveling the Complexity of Wildland Urban Interface
1125   Fires. *Sci. Rep.* **8**, 9315 (2018).

1126   171.   H. Mahmoud, A. Chulahwat, Assessing wildland–urban interface fire risk. *R. Soc. Open*
1127   *Sci.* **7**, 201183 (2020).

1128   172.   N. Masoudvaziri, *et al.*, Streamlined wildland-urban interface fire tracing (SWUIFT):

1129   Modeling wildfire spread in communities. *Environ. Model. Softw.* **143**, 105097 (2021).

1130   173.   S. Hantson, *et al.*, The status and challenge of global fire modelling. *Biogeosciences* **13**,
1131   3359–3375 (2016).

1132   174.   L. Teckentrup, *et al.*, "Sensitivity of simulated historical burned area to environmental
1133   andanthropogenic controls: A comparison of seven fire models" (Biogeochemistry: Land,
1134   2019) https:/doi.org/10.5194/bg-2019-42 (March 12, 2022).

1135   175.   S. Venevsky, Y. Le Page, J. M. C. Pereira, C. Wu, Analysis fire patterns and drivers with
1136   a global SEVER-FIRE v1.0 model incorporated into dynamic global vegetation model and
1137   satellite and on-ground observations. *Geosci. Model Dev.* **12**, 89–110 (2019).

1138   176.   M. Forkel, *et al.*, A data-driven approach to identify controls on global fire activity from
1139   satellite and climate observations (SOFIA V1). *Geosci. Model Dev.* **10**, 4443–4476 (2017).

1140   177.   E. Chuvieco, *et al.*, Human and climate drivers of global biomass burning variability. *Sci.*
1141   *Total Environ.* **779**, 146361 (2021).

1142   178.   M. W. Jones, C. Santín, G. R. van der Werf, S. H. Doerr, Global fire emissions buffered
1143   by the production of pyrogenic carbon. *Nat. Geosci.* **12**, 742–747 (2019).

1144   179.   A. F. A. Pellegrini, *et al.*, Fire frequency drives decadal changes in soil carbon and
1145   nitrogen and ecosystem productivity. *Nature* **553**, 194–198 (2018).

1146   180.   G. Lasslop, *et al.*, Global ecosystems and fire: Multi-model assessment of fire-induced
1147   tree-cover and carbon storage reduction. *Glob. Change Biol.* **26**, 5027–5041 (2020).

1148   181.   J. E. Stenzel, *et al.*, Fixing a snag in carbon emissions estimates from wildfires. *Glob.*
1149   *Change Biol.* **25**, 3985–3994 (2019).

1150   182.   S. Hantson, *et al.*, Quantitative assessment of fire and vegetation properties in
1151   simulations with fire-enabled vegetation models from the Fire Model Intercomparison Project.
1152   *Geosci. Model Dev.* **13**, 3299–3318 (2020).

1153   183.   W. D. Hansen, D. Abendroth, W. Rammer, R. Seidl, M. G. Turner, Can wildland fire
1154   management alter 21st-century subalpine fire and forests in Grand Teton National Park,
1155   Wyoming, USA? *Ecol. Appl.* **30**, e02030 (2020).

1156   184.   M. G. Turner, *et al.*, The magnitude, direction, and tempo of forest change in Greater
1157   Yellowstone in a warmer world with more fire. *Ecol. Monogr.* **92**, e01485 (2022).

1158   185.   J. T. Fasullo, *et al.*, Coupled Climate Responses to Recent Australian Wildfire and
1159   COVID-19 Emissions Anomalies Estimated in CESM2. *Geophys. Res. Lett.* **48**,
1160   e2021GL093841 (2021).

1161   186.   Y. Zou, *et al.*, Using CESM-RESFire to understand climate–fire–ecosystem interactions
1162   and the implications for decadal climate variability. *Atmospheric Chem. Phys.* **20**, 995–1020
1163   (2020).

1164   187.   Q. Zhu, *et al.*, Building a machine learning surrogate model for wildfire activities within a
1165   global Earth system model. *Geosci. Model Dev.* **15**, 1899–1911 (2022).

1166   188.   Y. Song, Y. Wang, Global Wildfire Outlook Forecast with Neural Networks. *Remote Sens.*
1167   **12**, 2246 (2020).

1168   189.   T. C. McCandless, B. Kosovic, W. Petzke, Enhancing wildfire spread modelling by
1169   building a gridded fuel moisture content product with machine learning. *Mach. Learn. Sci.*
1170   *Technol.* **1**, 035010 (2020).

1171   190.   M. Altaweel, A. Virapongse, D. Griffith, L. Alessa, A. Kliskey, A typology for complex

1172   social-ecological systems in mountain communities. *Sustain. Sci. Pract. Policy* **11**, 1–13
1173   (2015).

1174   191.   T. B. Paveglio, From Checkers to Chess: Using Social Science Lessons to Advance
1175   Wildfire Adaptation Processes. *J. For.* **119**, 618–639 (2021).

1176   192.   M. Carroll, T. Paveglio, Using community archetypes to better understand differential
1177   community adaptation to wildfire risk. *Philos. Trans. R. Soc. B Biol. Sci.* **371**, 20150344
1178   (2016).

1179   193.   K. C. Ryan, E. E. Knapp, J. M. Varner, Prescribed fire in North American forests and
1180   woodlands: history, current practice, and challenges. *Front. Ecol. Environ.* **11**, e15–e24
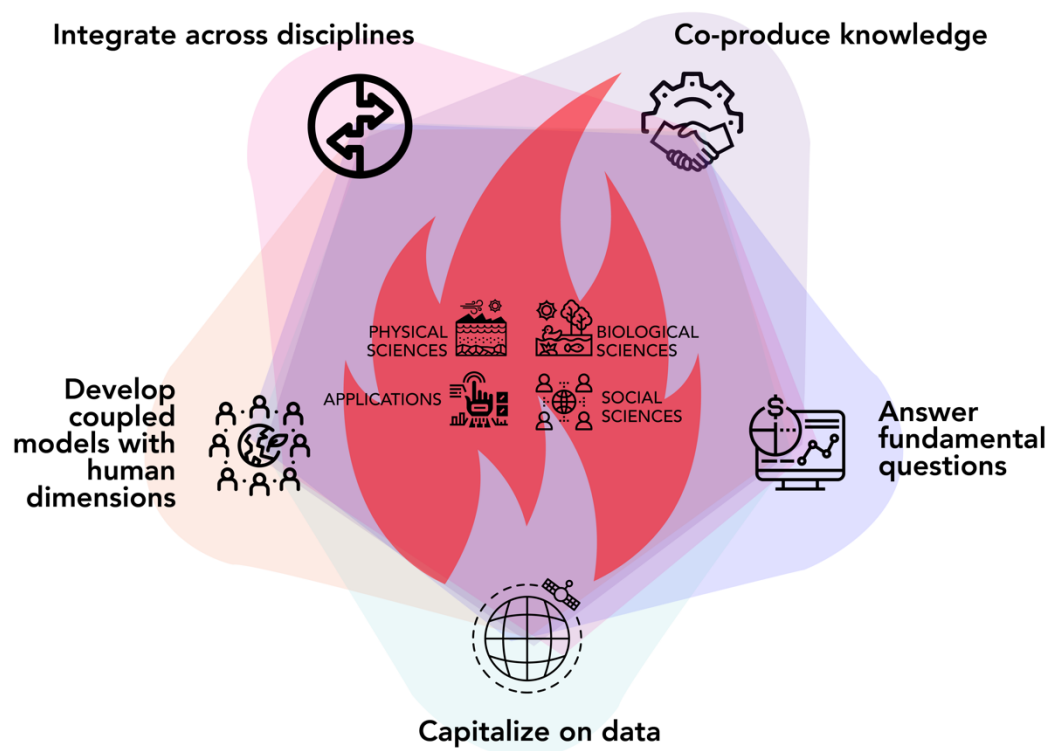1181   (2013).

1182   194.   M. E. Hunter, M. D. Robles, Tamm review: The effects of prescribed fire on wildfire
1183   regimes and impacts: A framework for comparison. *For. Ecol. Manag.* **475**, 118435 (2020).

1184   195.   C. A. Schultz, *et al.*, Policy barriers and opportunities for prescribed fire application in the
1185   western United States. *Int. J. Wildland Fire* **28**, 874–884 (2019).

1186   196.   J. K. Hiers, *et al.*, Prescribed fire science: the case for a refined research agenda. *Fire*
1187   *Ecol.* **16**, 11 (2020).

1188
1189
1190

1191
1192 **Figure**

Integrate across disciplines

Co-produce knowledge

Develop coupled models with human dimensions

PHYSICAL SCIENCES

BIOLOGICAL SCIENCES

APPLICATIONS

SOCIAL SCIENCES

Answer fundamental questions

Capitalize on data

1193

1194 **Figure 1.** We need a proactive fire research agenda to support human values and create safe
1195 communities as impacts from lightning and unplanned human-caused wildfires increase in the
1196 Anthropocene. Such an agenda will span multiple disciplines and translate understanding to
1197 application while answering fundamental science questions, incorporating diverse and inclusive
1198 partnerships for knowledge co-production, capitalizing on the wealth of new and existing data,
1199 and developing models that integrate human dimensions and values.

1200