**Supplemental Information**

For Future of Fire Consortium. 2020. Fire as a fundamental ecological process: research advances and frontiers. *Journal of Ecology*.

Data available:

McLauchlan, Kendra et al. (2020), Fire as a fundamental ecological process: research advances and frontiers, Dryad, Dataset, <https://doi.org/10.5061/dryad.2280gb5nm>

Four Tables

Description of survey methods

Two Boxes

Two Figures

Supplemental Literature Cited

**Supplemental Table 1. Summary of contrasting approaches for assessing fire severity based on remote sensing or field measurements.**

Here, substrate metrics refer to fire impacts on the organic and/or mineral horizons of soil although some substrate metrics also address impacts to woody debris.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Assessment metric** | **Ecosystem stratum** | **Data type** | **Considerations** | **Selected references** |
| Remote sensing1 | | | | |
| Differenced normalized burn ratio (dNBR) | Vegetation | Continuous | Absolute difference change detection  Correlated to pre-fire vegetation chlorophyll content | Key and Benson (2005)  Miller et al. (2009) |
| Relativized dNBR (RdNBR) | Vegetation | Continuous | Removes biasing effect of pre-fire vegetation that exists for dNBR  More suitable than dNBR for areas of heterogenous vegetation type and/or cover | Miller and Thode (2007)  Miller et al. (2009) |
| Geospatial data provided from the Monitoring Trends in Burn Severity (MTBS) program\* | Vegetation | Continuous or Categorical | Outputs include continuous NBR, dNBR, and RdNBR layers derived from delayed-assessment1 Landsat imagery, thresholded into severity classes based on analyst interpretation | Eidenshink et al. (2007) |
| Burned Area Reflectance Classification (BARC) | Vegetation | Categorical (4- or 256-class) | Derived from preliminary dNBR  Used by Burned Area Emergency Response (BAER) teams to produce soil burn severity maps that guide post-fire rehabilitation2 | USDA (2018) |
| Field measurement | | | | |
| Composite Burn Index (CBI) | Vegetation and substrate | Categorical | Visually estimated relative change across multiple vertical strata  Correlated to Landsat NIR and red or SWIR bands  Composite of severity metrics and ecosystem responses | Ashcroft et al. (2009)  Chuvieco et al. (2006) |
| Vegetation burn severity: trees | Vegetation | Continuous | Measurements of, e.g., bole char height, height of tree-crown scorch and crown torch (foliage consumption by flames), percent of tree-crown scorched and torched, tree mortality | Agee (1993) |
| Vegetation burn severity: understory vegetation | Vegetation | Categorical | Visual indicators given separately for forests, shrublands & grasslands | Ryan and Noste (1985), Neary et al. (2008), NPS (2003) |
| Vegetation burn severity: shrubs | Vegetation | Continuous | Based on diameters of smallest remaining twigs in shrublands | (Moreno and Oechel, 1989) |
| Substrate severity | Substrate | Categorical | Visual indicators given separately for forests, shrublands & grasslands | Ryan and Noste (1985), Neary et al. (2008), NPS (2003) |
| Soil Post-Fire Index (SPFI) | Substrate | Categorical | Based on loss of surface organic cover and change to mineral soil color  Index derived from literature review | Jain et al. (2012) |
| Soil burn severity (SBS) | Substrate | Categorical | Assessed by USA federal or state BAER teams based on initial dNBR3 maps; used to correct severity categories to prioritize areas for post-fire rehabilitation | (Parsons et al., 2010) |

1 Remote sensing metrics are derived primarily from Landsat satellite imagery, for which 1984 is the earliest available data, and primarily detect fire impacts on the upper strata of vegetation, whereas the ability to detect changes on lower strata depends on ecosystem structure and composition (Eidenshink et al., 2007; Miller and Quayle, 2015). Preliminary assessment products such as BARC detect change between pre-fire imagery and imagery obtained during or soon after fire, compared to delayed-assessment products such as MTBS maps which rely primarily on pre- and post-fire imagery separated by approximately one calendar year.

2 For large wildfires occurring on lands managed by the USDA Forest Service and US Department of Interior

3 Preliminary maps are usually (but not always) based on dNBR values (Keeley, 2009)

**Supplemental Table 2. List and brief description of selected fire models.**

See (Reinhardt et al., 2001) and (Reinhardt and Dickinson, 2010) for additional model descriptions.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model Name** | **Spatial coverage** | **Temporal Scale** | **Vegetation Type** | **Reference** |
| CLM-Li fire module | Global | half-hourly | "Big-leaf" type | (Li et al., 2013) |
| CTEM fire module | Global | daily | "Big-leaf" type | (Melton and Arora, 2016) |
| JULES-INFERNO | Global | half-hourly | "Big-leaf" type | (Mangeon et al., 2016) |
| JSBACH-SPITFIRE | Global | daily | "Big-leaf" type with height | (Hantson et al., 2015; Lasslop et al., 2014) |
| ORCHIDEE-SPITFIRE | Global | daily | "Big-leaf" type with height | (Yue et al., 2014) |
| LPJ-SPITFIRE | Global | daily | "Big-leaf" type with height | (Thonicke et al., 2010) |
| LPJ-LMFIRE | Global | daily | "Big-leaf" type with multiple height classes | (Pfeiffer et al., 2013) |
| FATES-SPITFIRE | Global/Regional | daily | Size-structured cohorts with inter- and intraspecific competition | (Lawrence et al., 2019) |
| LANDIS-II | Landscape | daily | Age-structured species cohorts with inter- and intra-specific competition | (Scheller et al., 2019; Sturtevant et al., 2009) |
| LANDCLIM | Landscape | daily | Size-structured cohorts with inter- and intraspecific competition | (Schumacher et al., 2004; Schumacher et al., 2006) |
| UVAFME | Forest Stand/Regional | daily | Size-structured trees with inter- and intraspecific competition | (Foster et al., 2019; Shuman et al., 2017) |
| FOFEM 6.4 | Point | minutes | Stylized fuel models and canopy characteristics | (Lutes, 2017) |
| CONSUME | Point | minutes | Stylized fuel models and canopy characteristics | (Prichard et al., 2005) |
| CAWFE | Site/Fire Event | seconds to a day | Stylized fuel models and canopy characteristics | (Coen et al., 2013) |
| FIRETEC | Site/Fire Event (meter resolution) | sub-seconds | 3D representation of individual plants and fuels | (Linn et al., 2002) |
| WFDS | Sub-meter to Fire/event | sub-seconds to seconds | 3-D representation of fuels, vegetation, and structures | (Mell et al., 2007) |
| BehavePlus | Point | none (time independent) | Stylized fuel models and canopy characteristics | (Andrews, 2014) |
| FlamMap | Landscape | none (time independent) | Stylized fuel models and canopy characteristics | (Finney, 2006) |
| FARSITE | Landscape | none (time independent) | Stylized fuel models and canopy characteristics | (Finney, 1998) |
| LANDIS PRO | Landscape | annual | Age-structured species cohorts with inter- and intraspecific competition | (Wang et al., 2014) |
| FATE, FATELAND | Patch, landscape | annual | Age-structured species cohorts with inter- and intraspecific competition | (Moore and Noble, 1990; Pausas and Lloret, 2007) |
| Fire-BGC | Landscape | daily | Size-structured trees with inter- and intraspecific competition | (Keane et al., 2011) |
| WRF-Fire | Landscape | seconds-a day | Stylized fuel models and canopy characteristics | (Coen et al., 2013) |
| iLand | Landscape | daily | Size-structured trees with inter- and intraspecific competition | (Seidl, 2012) |

**Description of Future of Fire community survey methods**

The five steering committee members of the Future of Fire Consortium prepared an 8-question survey designed to assess the current state of fire ecology research and to identify priorities in fire ecology (Supplemental Box 1). A description of the survey and a link to the survey were distributed in an email sent on October 4, 2017 (Supplemental Box 2) to relevant science communities including the Ecolog-listserv (~19,000 subscribers) and the Association for Fire Ecology-listserv (~1700 subscribers). We received 66 responses by the deadline of October 13, 2017. We then conducted bottom-up coding to collate the 176 responses to the survey question “What are the biggest unmet scientific challenges currently in fire research? Rank the top 3-5.” A bottom-up coding approach allows for themes to be extracted from text while avoiding biases that can be introduced by setting pre-determined categories (Glaser, 1999). The bottom-up coding process led to the identification of ten themes that repeatedly appeared in the text of responses (Supplemental Table 3). NVivo 12 Plus software was used to assess the capability of the ten themes to represent the survey responses and to better refine replicable code. The steering committee members then reorganized and grouped the ideas in the ten themes into six categories that could be substantively developed at the workshop (Supplemental Table 4).

Those six categories were distributed to the 44 Future of Fire workshop participants, and during the workshop participants chose to contribute primarily to one of the six categories. The content of each of the six categories was further developed through Future of Fire Consortium members answering a set of prompts in a group setting focused on one of the six categories. The prompts were phrased as three questions: (1) Discuss three to five advances in this area of fire ecology in the past five years, (2) Identify three to five exciting questions/challenges/frontier topics in this area, and (3) Begin to identify research needs to advance this area (technical, conceptual, locations, spatiotemporal scales, etc.). Most of the text of the manuscript originated at the workshop through the process of group members discussing and answering these questions together.

Because the survey question was open-ended, and contained a request to rank (i.e. prioritize) scientific areas, we could explore the importance that respondents placed on each of the six categories, later developed in the Future of Fire manuscript. All but one of the six categories was ranked as the most important fire ecology research priority by over 10% of respondents (Supplemental Figure 1). Because we had specified that respondents identify 3-5 categories, most respondents only listed 3 research priority areas, and only 6 participants named 5 research areas (Supplemental Figure 2).

We understand that there is a large amount of unanalyzed data associated with this survey, particularly for the categorical questions, the structure of the survey, and potential crosswalk analyses. However, we are reporting the qualitative analyses we conducted for the purpose of this manuscript that yielded robust results.

**Supplemental Box 1. Future of Fire Community Survey**

We encourage all members of the fire ecology community to fill out the survey, whether or not you will attend the Future of Fire workshop, November 2017. Your input here is valued and will be used to frame questions at the workshop and direct future scientific priorities in fire ecology.

The goal of the Future of Fire workshop is to advance understanding of fire as an Earth system process, an ecological process, and an important agent of global change. Specific goals are to (1) identify the key questions and priorities for fire science research, especially regarding fire and ecological processes from populations to ecosystem levels; (2) establish fire science as a central research area within basic science to better complement the applied aspects of fire ecology; and (3) find and promote areas of synergy among previously separate areas of fire science based within ecology but interacting with other disciplines.

**With which scientific discipline do you primarily identify? \***

*Check all that apply.*

|  |  |
| --- | --- |
| Microbial ecology | Biogeochemistry (nutrients) |
| Soil processes | Fire as an evolutionary process |
| Population ecology | Fire management |
| Vegetation dynamics | Fire biogeography |
| Community ecology | Fire modeling |
| Ecosystem processes | Fire remote sensing |
| Fire emissions | Other: |
| Biogeochemistry (carbon) |  |

**What timescales do you usually study? \***

*Check all that apply.*

|  |  |
| --- | --- |
| Less than a day | Decades |
| Days to weeks | Centuries |
| Months | Millennia |
| Years (annual) | Other: |

**What spatial scales do you usually study? \***

*Check all that apply.*

|  |  |
| --- | --- |
| Plot | Continent |
| Landscape | Global |
| Region | Other: |
| Subcontinent |  |



**What tools do you use in your work? \***

*Check all that apply.*

|  |  |
| --- | --- |
| Experiments | Lab work |
| Models | Climate data |
| Observations | Meta-analysis |
| Remote sensing | Other: |

**What do we know in your scientific area today that we did not know five years ago? \***

**What are the biggest unmet scientific challenges currently in fire research? Rank the top 3-5. \***

**What are the most significant barriers, apart from funding, to meeting the scientific challenge(s) outlined above? \***

**What are the most critical geographic locations or biomes to study for advancement of fire ecology? \***

**Supplemental Box 2. Text of email sent to Ecolog listserv and Association for Fire Ecology listserv on October 4, 2017.**

Hello,

As a member of the fire ecology research community, we value your input on a new effort to identify current scientific priorities in fire ecology. These will be developed at the upcoming Future of Fire workshop in Colorado, Nov. 6 and 7. Whether or not you are attending the workshop, there is so much activity around this topic and we want to make sure that is captured and that \*your\* science is represented.

To that end, we are conducting an online survey prior to the workshop. The link is here:

<https://goo.gl/forms/aG4iankG6f1Ph08W2>

We will be accepting responses until 5 pm Central time next **Friday, 13 October**.

Anyone who identifies as a fire researcher is welcome to participate, so please forward/share/tweet with relevant communities.

Thank you again for your interest in this effort, and your willingness to take a few minutes to help identify fire ecology research priorities.  
  
very best,

Kendra McLauchlan  
   
on behalf of the steering committee:  
   
Brendan Rogers (Woods Hole Research Center)  
  
Jen Schweitzer (University of Tennessee)

Alan Tepley (Smithsonian Institute)  
  
Tom Veblen (University of Colorado)

**Supplemental Table 3. The codebook for ten themes produced by manually coding responses to a survey question.**

Each name is also called a “node” in NVivo.

| Name | Description |
| --- | --- |
| A1 Fire-associated risks to humanity | Study of the risk to life, health, infrastructure and property, ways of life (farming, landuse, etc) and associated costs due to fire; study of human coexistence with fire (including management and fire fighting); political discussions about fire; different ways of viewing fire as a hazard |
| A2 Changes in fire regimes | Study of the changes in fire regimes and determining causation for and effects of variation in fire regimes |
| A3 Post-fire effects | Study of post-fire data, management, and ecosystem restoration and recovery |
| A4 Species, vegetation and soil | Study of interactions between fire and species, vegetation and soil such as feedbacks, shifting assemblages and mortality |
| A5 Fire properties | Study of fire characteristics such as severity, repeat burning, ability to spread, fire physics; relating fire behaviors to ecosystem processes; study of fire resilience |
| A6 Fire fuels | Study of fire and fuel management; study of non-vegetation fuels; understanding the role of fuels in specific biomes as well as in the larger ecological picture |
| A7 Fire behavior drivers | Study of the drivers of fire behavior on global and ecosystem-specific scales; study of the interactions between fire drivers and how changes in drivers affect an ecosystem and subsequent fire; distinguishing between natural and human drivers |
| A8 Fire-related models and technology | Advancement of fire understanding through existing models; the improvement of models and different fire-related technologies |
| A9 Climate change and fire | Study of how fire will evolve in a warming world including the development of concepts to describe the changes; the study of separate and combined interactions between climate and fire regimes, fire fuels and human activity |
| Aa10 Fire history and broad-scale fire ecology | Study of over-arching ecological themes or general fire interactions such as fire-atmosphere/fire-climate/fire-landscape relationships; study of historical and long-term fire characterization and implications; the different ways of communicating with the public about fire |

**Supplemental Table 4. The codebook for six categories produced by reducing and reorganizing the content in the ten themes.**

Each name is also called a “node” in NVivo. Note that the first theme “Risks to humanity” was eliminated from further development because to do so would require significant input from social scientists and managers, who were underrepresented at the Future of Fire workshop.

| Name | Description |
| --- | --- |
| Meta 1- Fire regimes | Study of over-arching ecological themes and global fire interactions (ie fire-atmosphere/fire-climate/fire-landscape relationships); study of historical and long-term fire characterization and implications; the different ways of communicating with the public about fire |
| Aa10 Fire history and broad-scale fire ecology | Study of over-arching ecological themes or general fire interactions such as fire-atmosphere/fire-climate/fire-landscape relationships; study of historical and long-term fire characterization and implications; the different ways of communicating with the public about fire |
| Division- A2 Changes in fire regimes- Fire regimes | Study of how fire activity has changed over time; study of the implications of changing fire regimes on a global scale. This is the portion of Theme 2: Changes in fire regimes that was regrouped into Category 1: Fire regimes |
| Meta 2- Drivers of changing fire regimes | Study of the interactions between fire drivers, and how changes in drivers affect an ecosystem and subsequent fire; study of how fire will evolve in a warming world and the seasonal implications; study of separate and combined interactions between climate and fire regimes, fire fuels and human activity |
| A7 Fire behavior drivers | Study of the drivers of fire behavior on global and ecosystem-specific scales; study of the interactions between fire drivers and how changes in drivers affect an ecosystem and subsequent fire; distinguishing between natural and human drivers |
| A9 Climate change and fire | Study of how fire will evolve in a warming world including the development of concepts to describe the changes; the study of separate and combined interactions between climate and fire regimes, fire fuels and human activity |
| Division- A1 Fire-associated risks to humanity- Drivers of changing fire regimes | Study of human-fire interactions with an emphasis on how humans change fire. The portion of Theme 1: Fire associated risks to humanity that was regrouped into Category 2: Drivers of changing fire regimes |
| Division- A2 Changes in fire regimes- Drivers of changing fire regimes | Study of seasonal implications of changing fire regimes; study of the variation in fire regimes. The portion of Theme 2: Changes in fire regimes that was regrouped into Category 2: Drivers of changing fire regimes |
| Meta 3- Aboveground | Study of interactions between fire and species and vegetation such as feedbacks, mortality, and shifting assemblages and shift causation |
| Division- A4 Species, vegetation, and soil- Aboveground | Study of the interactions between fire and species and vegetation. The portion of Theme 4: Species, vegetation and soil that was regrouped into Category 3: Aboveground |
| Division- A5 Fire properties- Aboveground | Study of ecology and evolution in response to fire. The portion of Theme 5: Fire properties that was regrouped into Category 3: Aboveground |
| Meta 4- Belowground | Study of post-fire data, management, and ecosystem restoration and recovery; study of interactions between fire and soil organic matter, belowground biota, and soil carbon and nutrient stocks |
| A3 Post-fire effects | Study of post-fire data, management, and ecosystem restoration and recovery |
| Division- A4 Species, vegetation, and soil- Belowground | Study of the interactions between fire and soil, belowground processes, duff, carbon pools and belowground mortality. The portion of Theme 4: Species, vegetation and soil that was regrouped into Category 4: Belowground |
| Division- A5 Fire properties- Belowground | Study of fire effects on biogeochemistry and how they are connected to fire resilience. The portion of Theme 5: Fire properties that was regrouped into Category 4: Belowground |
| Meta 5- Fire behavior | Study of fire characteristics such as severity, repeat burning, ability to spread, fire physics; relating fire behaviors to ecosystem processes; study of fire resilience and the effects of fuel management; understanding the role of fuels |
| A6 Fire fuels | Study of fire and fuel management; study of non-vegetation fuels; understanding the role of fuels in specific biomes as well as in the larger ecological picture |
| Division- A5 Fire properties- Fire behavior | Study of fire characteristics such as severity, repeat burning, ability to spread, fire physics; relating fire behaviors to ecosystem processes.The portion of Theme 5: Fire properties that was regrouped into Category 5: Fire behavior |
| Meta 6- Models | Advancement of fire understanding through existing models; the improvement of models and different fire-related technologies |
| A8 Fire-related models and technology | Advancement of fire understanding through existing models; the improvement of models and different fire-related technologies |

**Supplemental Figure 1. The percentage of responses containing content corresponding to one of the six categories, ranked by priority.**

**Supplemental Figure 2. The number of responses containing content corresponding to one of the six categories, ranked by priority.**

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