Shared Arctic Variables:
A Perspective-Driven Approach to Wildfire Management in the Arctic Region

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Introduction

Observing and data systems have been widely recognized as critical infrastructures to support decision-making and understanding across sectors in the Arctic and globally yet, from the standpoint of conventional observing systems, the Arctic region can be considered poorly observed (Starkweather et al., 2021). To address this shortcoming, the Sustaining Arctic Observing Networks (SAON) Roadmap for Arctic Observing and Data Systems (ROADS) initiative was designed to create a systematic planning mechanism to develop and/or link Earth Observation (EO) system requirements and implementation strategies within the Arctic region. Part of this initiative involves supporting the concept of Shared Arctic Variables (SAVs), which are defined as "...measurable phenomena or processes that are important enough to multiple communities and/or sectors to make it worth the work to coordinate their acquisition across the Arctic observing community" (Starkweather et al., 2021). The SAON ROADS initiative has various organizations collaborating and supporting the SAV process. Specifically, Arctic PASSION has collaborated and produced documentation for the SAON initiative by supporting the various existing and planned expert panels throughout the conceptualization phase to completion of the project(s). To learn more about the formation of EP's and general supporting documentation, the SAON ROADS AP has a suite of documents that elaborate on those processes.

The concept of the wildfire theme as an SAV, uses expert panels to build upon previous harmonization attempts by providing explicit consideration to Indigenous inclusion, ensuring local communities play an integral role in the development of a holistic solution to changing wildfire regimes in the Arctic region. More specifically, observations and data systems that warrant a level of effort associated with this initiative should serve multiple sectors and data user groups while also addressing priorities at the intersection of Arctic community-identified needs, regionally identified cross-sectoral needs and those of global observing programs (Bradley et al., 2023). SAVs are responsive to the information needs of Arctic Indigenous Peoples, drawing on their capacity to co-design and co-manage observing efforts and, given the geographic setting and diverse range of rightsholders represented, the Arctic region is well-positioned to highlight the need for an internationally coordinated Arctic observing system (Bradley et al., 2023). Currently, there are three themes being actively pursued by experts under the SAV framework: wildfires, living on frozen ground (or permafrost), and sea ice. The World Data Systems International Technology Office (WDS-ITO) supports the work of SAON ROADS by contributing to the literature review and documentation processes under the SAV wildfire theme.

Purpose Statement & Audience

The WDS-ITO is proud to support the SAON ROADS initiative by conducting a literature review to highlight a subset of variables that are of importance to Arctic rightsholders in the context of wildfires on local, regional, and global scales and can be linked to existing observing assets. In particular, the purpose of this document is to aid the participants of two expert panels (EPs) in their deliberations on the theme of wildfires under the SAV framework. This will be done by synthesizing a selected set of EO assets, identifying how collected variables can be used to influence our understanding of wildfire events, and recognizing key rightsholders involved in the collection of data. This document will also draw comparisons between various essential variables frameworks and a sample of observing networks/assets. The EPs are in the early stages of explicitly defining Shared Arctic Variables that relate to proposed themes, meaning that this document may act as a ‘starting point’ for expert panelists in the future.

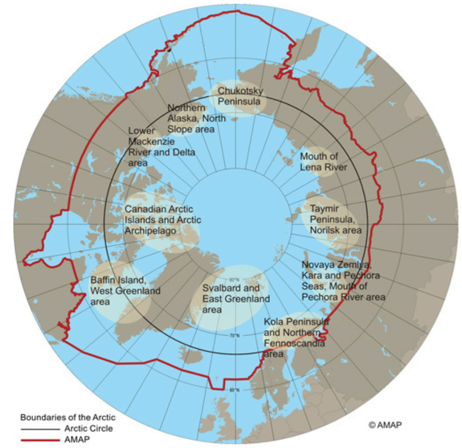

Figure 1. This image depicts the geographical boundaries used for this document, which is modeled after the coverage area used by the Arctic Monitoring and Assessment Programme (AMAP, 2023)

Research Boundaries

For the purpose of this document, the ‘Arctic region’ has been modeled after the Arctic Monitoring and Assessment Programs (AMAP) geographical coverage map (figure 1). More specifically, this document focuses on a single line of latitude (roughly 50 degrees North) and all lines of longitude (0-180 degrees) that pass through it. This coverage includes the High Arctic to sub-Arctic regions of Canada, the Kingdom of Denmark (Greenland and the Faroe Islands), Finland, Iceland, Norway, the Russian Federation, Sweden and the United States (Alaska), including associated marine areas. In addition to a wide range of international interest, there is also a diverse range of cultural perspectives that intertwine within the Arctic region.

Methodology

This document highlights intersections between the concepts of SAVs, various essential variable frameworks already in practice, and how these tools can be applied to the management of wildfire events in the Arctic region. A public access Zotero library and group have been created to capture the documents reviewed during this process, with keywords mentioned by respective authors highlighted as tags. Additionally, an observation asset and variable tracking spreadsheet has been attached in the Appendix section for reference. In an effort to identify variables known to influence forest fire behavior, this document begins by conducting a literature review to answer the following:

- ➔ What high-level variables are known to influence forest fire behavior?
- ➔ Are there observing assets in the Arctic region that actively monitor and track these driving variables?
- ➔ How can these variables be integrated into existing earth observing systems?
- ➔ What barriers stand in the way of achieving this goal?

Literature Review: Identifying Variables Known to Influence Forest Fire Behavior

Wildfire Theme Background

Before answering our first research question, it is important to point out that the term 'wildfire' itself has different meanings depending on the circumstances and region in which it occurs. The journal article "The Dilemma of Wildfire Definition: What it Reveals and What it Implies" (2020), captures just how dynamic this term is. In fact, several terms are used to describe vegetation fires in areas outside of the urban environment around the world (Bento-Gonçalves et al., 2012). In Canada, a *wildfire* refers to "any unplanned or unwanted natural or human-caused fire, as contrasted with a prescribed burn" and the term *forest fire* is described as "any wildfire or prescribed fire that is burning in forested areas, grass, or alpine/tundra vegetation" (CIFFC, 2013). The latter is also used by the European Commission of Joint Research Centre Institute for Environment and Sustainability, along with many European countries, in their annual reports (Camia et al., 2009). In the United States, *wildland fire* has been defined as "any non-structure fire that occurs in wildland and includes wildfire, wildland fire use, and prescribed fire" (National Wildfire Coordinating Group, 2012). The use of multiple terms to simply describe wildfires not only acknowledges its relevance to different research, political and operational domains, but also reveals a lack of a common understanding surrounding the "nature" of wildfires; resulting in distinct representations or misrepresentations of the same phenomenon, making it inherently difficult to establish a sustainable wildfire management policy (Pausas & Keeley, 2019b). Shifting our focus to the circumstances in which wildfires occurs, global distribution (Archibald et al., 2013; Doerr & Santín, 2016; Krawchuk et al., 2009; Moritz et al., 2014, International Union of Forest Research Organizations, 2018) reflects the coincidence of three basic requirements: (1) fuel able to burn and sustain combustion allowing a fire to spread, (2) the environmental conditions that promote combustion and (3), a source of ignition, initiating the combustion process (Krawchuk et al., 2009). All of this is to say that one of the initial steps in addressing the theme of wildfire through a SAV process should be to emphasize the acceptance of common terminology, requiring enough detail and collaboration to ensure that all parties reach common ground (i.e., a starting point). It is our assertion that active engagement, open dialogue, and collaboration with a wide variety of groups interested in a common theme (i.e wildfire) are the critical building blocks required to create a holistic solution to an interdisciplinary problem - especially when considering dynamic issues on multiple scales (i.e., local, regional global; fundamental to the success of the SAV framework). The challenge posed for the EPs moving forward is to remain conscious and respectful of multiple perspectives when discussing similar concepts or approaches, while also maintaining a broad focus on the theme of wildfire and associated impacts. The precision and aptitude applied by the EPs when establishing definitions can influence: (1) the effectiveness of adopted solutions to actually address and solve a problem, (2) the societal relationships with fire, (3) the perceived nature of the problem, (4) the policy making process, (5) the range of policy solutions to be considered and (6), the governance level that bears the responsibility (Fifer & Orr, 2013; Morss, 2005; Pescaroli & Alexander, 2015).

Wildfires have unique and dynamic relationships with many of Earth's ecosystems that have undoubtedly shaped their evolution (Pausas & Keeley, 2019a); wildfires are also considered one of the most dangerous natural disasters to human societies (Doerr & Santín, 2016). The occurrence of fire is fundamental to the preservation of many life cycles and maintaining natural diversity in many ecosystems (Pausas & Keeley, 2019b). However, a millennia of intensive agricultural and silvicultural activity, the use of (or lack of) fire as a land management tool, added pressures by human activities and effective fire suppression across Europe and North America, have resulted in unique and complex patterns of land-covers and fire occurrence with little resemblance to a natural fire regime (Doerr & Santín, 2016). There are also a myriad of tools available that can assess the impact of climate variability and change of wildfire events, which include: fire danger rating systems, remote sensing, dynamic global landscape and vegetation models, integrated fire vegetation models, empirical models and fire behavior models (Herawati et al., 2015). Many countries collect and share information across North America and Europe relating to wildfire events, but a lack of harmonized information has hindered its evaluation, analysis, and the development of a common approach to wildfire management (San-Miguel-Ayanz et al., 2013). Variables that can be considered essential or shared by a diverse range of rightsholders in the context of wildfires are entirely dependent on their relationship with these events, making them subjective in nature. One of the most comprehensive efforts to harmonize data in Europe is the European Forest Information System, which is a joint collaboration between various European countries and the European Commision (San-Miguel-Ayanz et al., 2012). This is a large repository of information on individual wildfires in Europe with 43 contributing countries providing a common set of data, including time of occurrence, location, size, and cause of a fire (San-Miguel-Ayanz et al., 2013). Firelinks was also established as an open, EU-spanning network for researchers, practitioners, policymakers, and other rightsholders involved in wildfire research and land management in 2018, bridging the gap between diverse experiences (Fernandez-Anez et al., 2021). Although there appears to be a decline in the total global area burned by wildfires from 1996 and 2015 (Andela et al., 2017; Doerr & Santín, 2016), the frequency and intensity of boreal wildfires in Russia, Alaska, Canada, and others have drastically increased over the 20th and early 21st century (Forkel et al., 2019; Ponomarev et al., 2016; Soja et al., 2007; Turetsky et al., 2011). The spatiotemporal distribution of forest fires in Siberia also reveals a growing concern surrounding future surface warming in high-northern latitudes (García-Lázaro et al., 2018; Ponomarev et al., 2016). Global and regional model outputs further predict an increase in the extent and severity of boreal wildfires due to climate change (Boulanger et al., 2014; Chapin III et al., 2000; Flannigan et al., 2013). However, focusing on a single outcome or ecological function, such as global area burned for example, may marginalize other important functions such as wildlife habitat or ecosystem health. This calls for the collective engagement of siloed rightsholders, with traditionally narrow or specific relationships with wildfires, for the purpose of creating a holistic solution to an interdisciplinary problem. Openly entering interdisciplinary conversations through the use of dialogue and collaborative workshops is a critical step in establishing a social consensus on how to effectively respond to changing wildfire regimes. The Arctic region, an area that is experiencing more frequent and severe wildfire events in the wake of a changing climate, requires local, regional, and global coordination to actively create an interdisciplinary approach to wildfire management.

The section below is an introduction to the second basic requirement for wildfires to occur, and sheds light on our first research question by unpacking known, high-level environmental variables influencing these events. For the purpose of this document, the term *wildfire* is used in reference to any unplanned or uncontrolled fire originating or spreading within vegetated areas of the Arctic region. This is not intended to be an explicit definition, and can certainly be addressed and rephrased by the EPs to suit the needs of the SAV process. However, in the essence of finding common ground, this definition can be used as a shared starting point by all panelist members.

High-Level Variables Influencing Wildfire Behaviour

Wildfire regimes are inherently dynamic and constantly changing in response to a wide array of environmental conditions that can influence their occurrence, rate of spread, and other associated impacts (i.e., intensity of burn). Understanding the context in which this process occurs becomes critically important, as the weight carried by any *one* variable is entirely dependent on the perspective of the end-user. This is a strong illustration of how the SAV concept can be used and applied to the management of wildfires within the Arctic region; acting as a knowledge sharing opportunity and a mechanism to bridge the gap between traditionally siloed agencies with either narrow or specific relationships with wildfires. For the purpose of providing SAV panelist members under the wildfire theme with a sample of these conditions, we turn our focus to four trackable variables associated with weather conditions that can be easily applied to a suite of calculations and used to interpret the available moisture content within fuels (vegetation). It is also important to make the distinction between climate and weather, as the former refers to long-range weather conditions while the latter is attributed to short-term changes in the atmosphere (Tedim & Leone, 2020). Further research will be needed to address how climatic conditions may influence wildfires and further fit into the ideologies of the SAV framework. Using meteorological information from weather stations (observation networks/assets), these variables are used to create various indices measuring daily fire danger, i.e., the risk of fire occurrence, the expected rate of spread and fire intensity (Steinfeld et al., 2022). Fire management agencies around the globe have commonly relied upon fire weather indices as a mechanism to assess and predict weather conditions most conducive to fire (Steinfeld et al., 2022).

Our sample of variables associated with weather include:

1. Wind speed and direction
2. Relative humidity (RH)
3. Surface temperature
4. 24-hour precipitation

Fire danger also has a unique relationship with soil and vegetation dryness (fuel moisture, see Thornthwaite, 1948; Nesterov, 1949; Käse, 1969), which in turn is directly related to temperature, precipitation and humidity. Wind speed is a contributing factor that influences the rate of fire spread (Reinhard et al., 2005; Potter and Potter, 2012). In effect, this means that fire danger is at its highest under hot, dry, and windy weather conditions and predicting available moisture content in vegetation structures, or fuels, can be considered critical to understanding the regional wildfire environment. Although developed for use in Canadian pine forests, the Canadian Forest Fire Weather Index System (CFFWIS) is generally accepted as the most widely referenced fire weather index globally, both in practice and in research (Steinfeld et al., 2022). The CFFWIS is used to predict fire danger in several European countries, including the European Forest Fire Information System (EFFIS); classifying data on wind, relative humidity, temperature, and precipitation as critical fire weather observations to assess available moisture content in vegetation structures (Steinfeld et al., 2022). Similarly, the US National Fire Rating Danger System (NFDRS version 2016) operates within many of the same, or similar, guidelines as the CFFWIS. Below is a crosswalk between FWI weather inputs, fuel moisture codes, and fire behavior indices with their NFDRS counterparts, developed by the National Wildfire Coordinating Group (NWCG), and it displays a sample of variables that are important to national governments.

Table 1: This table provides a crosswalk between the FWI system weather inputs, fuel moisture codes, and fire behavior indices with their closest NFDRS counterparts (NWCG, 2012).

FWI System	Elements	NFDRS 2016
Daily Observations Required (4) (at Solar Noon) Temperature Relative Humidity Windspeed Rainfall **Hourly Observations for GFMC** Add Solar Radiation	**Weather Observations**	**Hourly Observations Required (120)** Temperature Relative Humidity Windspeed Rainfall Solar Radiation
	Intermediate Weather Outputs	Max/Min Temperature Max/Min Relative Humidity Precipitation Duration Daylength Vapor Pressure Deficit (VPD) Growing Season Index (GSI)
Fine Fuel Moisture Code (FFMC) – (5-16hr Timelag) Grass Fuel Moisture Code (GFMC) – (not part of Daily FWI)	**Fine Fuel Moisture**	1 hr Fuel Moisture 10 hr Fuel Moisture
Duff Moisture Code (DMC) – (15 day or 360 hour Timelag)	**Intermediate Fuel Moisture**	100 hr Fuel Moisture Live Herbaceous Fuel Moisture (LHM)
Drought Code (DC) (53 day or 1272 hour Timelag)	**Drought Indicators**	1000 hr Fuel Moisture Live Woody Fuel Moisture (LWM) Keetch-Byrum Drought Index (KBDI)
Initial Spread Index (ISI) Buildup Index (BUI) Fire Weather Index (FWI)	**Fire Behavior Outputs**	Ignition Component (IC) Spread Component (SC) Energy Release Component (ERC) Burning Index (BI)

Essential Variables

The importance of the essential variables frameworks reflect in the uptake and impact of the following EV groups, since their creation further initiatives, by allowing specific domain communities to define their own set of useful EVs to address any gaps from the current framework (Lehmann, A., et al, 2023). The GEO community has been making progress on a further 11 subset groups to add to the EV framework.

As we have seen, fire management agencies around the globe have routinely relied upon weather observations to predict fire behavior. This section addresses our second research question by focusing on existing observation assets and established networks in the Arctic region to determine if our high-level variables are currently tracked and/or publicly accessible. Table 2 is an accumulation of variables already collected by three pre-established programs operating within similar domains. The variables mentioned above, i.e., temperature, precipitation, wind (velocity and direction), and RH, are currently collected by various organizations contributing to the Essential Climate Variable (ECV), Essential Biodiversity Variables (EBVs), and Essential Ocean Variables (EOV) frameworks. Overlapping focus by various organizations reasserts that the CFFWIS and NFDRS can be considered strong starting points in the context of wildfires under the SAV framework. Grouping these variables together creates a myriad of fire weather indices, can be used to improve local preparedness plans, and represent an opportunity for collaboration through monitoring initiatives and community workshops. These linkages provide insight into how certain high-level weather variables, currently tracked under existing frameworks, can be used and integrated into the SAV process under the wildfire theme - further reducing the likelihood of duplicated efforts.

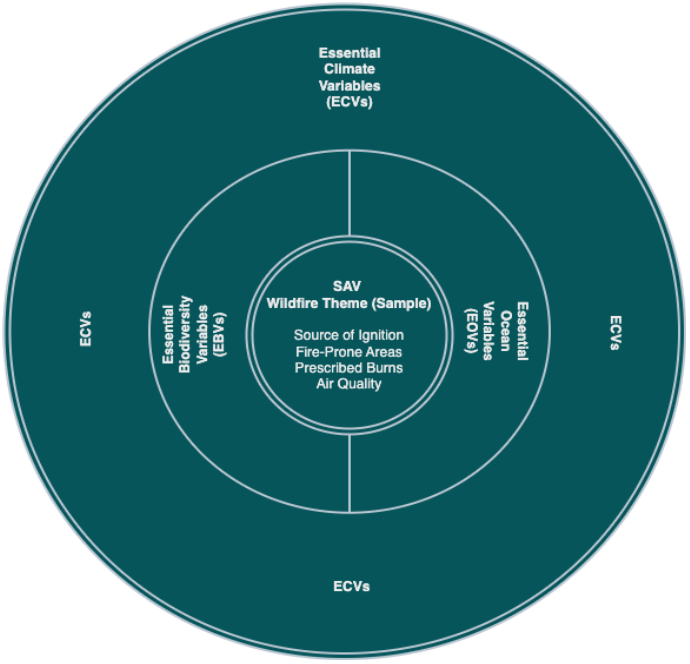

Figure 2: This is a depiction used to show the interconnections between various essential variable frameworks, the SAV concept and wildfire theme. Our sample of variables associated with proposed SAVs are represented within the center circle. The EBVs, EOVs and ECVs frameworks have already been tasked with identifying changes in a myriad of environmental variables, some of which play an integral role in shaping local wildfire dynamics. The diagram intends to depict how all Essential Variables contribute to the larger climate ecosystem in a positive feedback loop.

Essential Climate Variables (ECV)

The Global Climate Observing System (GCOS) was established in 1992 for the purpose of coordinating and ensuring the availability and accessibility to climate information for all potential end-users (Houghton et al., 2012; World Meteorological Organization (WMO) et al., 2010). In an effort to characterize the state of our global climate system and to aid monitoring and planning of mitigation and adaptation measures, GCOS was tasked with identifying which observations were to be addressed by a series of satellite missions and other Earth observing networks (Espinosa et al., 2020). This data supports the daily collection and monitoring of 54 key variables from our atmosphere, oceans and terrestrial systems (Espinosa et al., 2020), which subsequently supports climate science initiatives, policy frameworks, and various climate services (Giuliani et al., 2017). These observations are now called ECVs (Bojinski et al., 2014), and can be further described as geophysical records of systematic observations that track climate variability and change, as well as associated impacts, across three domains (Bojinski et al., 2014). 30 of the 54 ECVs heavily rely on satellite-based observations, often complemented by in-situ measurements (CEOS and ESA, 2015). Given the wide scope of the ECV framework, these processes ultimately require international collaboration between coordination networks, space agencies, and research institutions or programs spanning a myriad of data management systems. Specifically worth noting is that 'Fire' and other directly related fire terms are included in the ECV list (see table below).

Essential Ocean Variables (EOV)

The ocean is monitored by a wide variety of observing platforms, some of which are organized in observing networks (i.e. Argo, OceanGlider, The Global Sea Level Observing System or GLOSS etc.). This research has been instrumental in enhancing forecasts of the physical and chemical states of our oceans. Currently, most of these platforms or networks record physical data (i.e., salinity, temperature, etc.). Using complementary measures of temperature, height, roughness, and color, it is now possible to continually assess the state of the global ocean surface from space (Muller-Karger et al., 2018). EOVs present the opportunity to broaden data inputs such as temperature, precipitation, wind (velocity), and humidity collected on land (i.e., ECV framework), and may also be useful in assessing changes in water quality and other characteristics as they relate to wildfires in the Arctic region in real-time.

Essential Biological Variables (EBV)

In an effort to optimize various biodiversity monitoring initiatives, and inspired by ECVs, the Group on Earth Observations Biodiversity Observation Network (GEO BON) developed the concept of EBVs to serve as the foundation for a globally coordinated monitoring program. The aim of the EBV framework was to initially identify a minimum set of variables that can be used to capture changes in global biodiversity, and can be further described as state variables that stand between primary observations and high level indicators (i.e., the Living Plant Index). EBVs represent essential aspects of biodiversity (from ecosystem functioning to species population) and can be incorporated with other EBVs or additional types of data, such as data on drivers and pressures, to deliver high-level indicators (Pereira et al., 2013; GEO BON, 2015a). Six EBV classes, with twenty-one specific EBV names have now been established; many of which have the potential to either directly or indirectly influence the effects of wildfire events.

Table 2: The table below compiles the 3 major essential variable frameworks into one spot.Each column is broken down by identified sub-categories. Throughout the entire table the terms highlighted in red are known to affect forest fire behaviors and further displays the complicated feedback loops and interconnectedness of the essential variable framework(s).

Essential Biodiversity Variables	**Essential Ocean Variables**	**Essential Climate Variables**
Genetic composition	**Physics**	**Atmosphere**
Genetic diversity (richness and heterozygosity) Genetic differentiation (number of genetic units and genetic distance) Effective population size Inbreeding	Sea state Ocean surface stress Sea ice Sea surface height Sea surface temperature Subsurface temperature Surface currents Subsurface currents Sea surface salinity Subsurface salinity	Precipitation Pressure (surface) Surface radiation budget Surface Wind Speed and direction Temperature (near surface) Water vapour (surface) Earth Radiation Budget Lightning Temperature (upper-air)

	Ocean surface heat flux Ocean bottom pressure	Water vapour (upper air) Cloud properties Wind speed and direction (upper-air) Aerosols properties Carbon Dioxide, Methane and other Greenhouse gases Ozone Precursors (supporting the Aerosol and Ozone ECVs)
Species populations	**Biochemistry**	**Land**
Species distributions Species abundances	Oxygen Nutrients Inorganic carbon Transient tracers Particulate matter Nitrous oxide Stable carbon isotopes Dissolved organic carbon	River Discharge Groundwater Lakes Soil Moisture Snow Glacier Ice sheet and Ice shelves Permafrost Albedo Landcover Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) Leaf Area Index (LAI) Above-ground biomass Soil Carbon Land Surface Temperature Fire Evaporation from land Anthropogenic Greenhouse Gas Fluxes Anthropogenic Water Use
Species traits	**Biology and Ecosystems**	**Ocean**
Morphology Physiology Phenology Movement Reproduction	Phytoplankton biomass and diversity Zooplankton biomass and diversity Fish abundance and distribution Marine turtles, birds, mammals abundance and distribution Hard coral cover and composition Seagrass cover and composition Macroalgal canopy cover and composition Mangrove cover and composition	Ocean Surface Heat Flux Sea Ice Sea Level Sea State Sea Surface Salinity Sea Surface Temperature Subsurface Currents Subsurface Salinity Subsurface Temperature Surface Currents Surface Stress Inorganic Carbon

	Microbe biomass and diversity Invertebrate abundance and distribution	Nitrous Oxide Nutrients Ocean Colour Oxygen Transient Tracers Marine Habitat Properties Plankton
Community composition	**Cross-disciplinary (including human impact)**	
Community abundance Taxonomic/phylogenetic diversity Trait diversity Interaction diversity	Ocean sound Ocean colour Marine debris	
Ecosystem functioning		
Primary productivity Ecosystem phenology Ecosystem disturbances/dynamics		
Ecosystem structure		
Live cover fraction Ecosystem distribution Ecosystem vertical profile Management history		

Societal Benefits

The Institute for Defence Analyses (IDA) Science and Technology Policy Institute (STPI) facilitated an international effort and the result was the development of a notional assessment framework in the form of a value tree. This value tree consists of thematic domain areas or societal benefit areas (SBAs), sub-areas under each SBA, and domain-specific objectives that rely on EOs to deliver societal benefits (IDA Science and Technology Policy Institute and Sustaining Arctic Observing Networks, 2017). This framework was designed to serve as the foundation for future national or international efforts to assess the contribution of Earth observations to the delivery of societal benefit in the Arctic, and represents an international benchmark that could be used or adapted by interested organizations or nations to assess their own reliance on Earth-observing systems to achieve key objectives in the Arctic (IDA Science and Technology Policy Institute and Sustaining Arctic Observing Networks. 2017). Identifying EO assets that collect fire-specific variables using the SAV framework is a critical step to not only understanding the end-user benefits of various rightsholders, but also the added benefit of reducing the likelihood of overlap or duplication of efforts by highlighting common interests between rightsholders. Analyzing this framework in the context of wildfires as a SAV theme presents an opportunity for the EPs to determine the societal benefits derived by multiple stakeholders in the Arctic region. A specific way that the STPI has worked to bridge the gap between observation networks and societal benefits is through a value tree analysis (Strahlendorff, M., et al , 2019). First produced in 2019, this group has worked to further expand upon the first iteration of the value-tree , as a well flushed out, connected tree combined with the framework gives a robust picture of the entire ecosystem.

Data Systems

The balance between scientific representation of data and/or information may not always be usable in a real-world setting, but is critical for understanding Arctic systems. The article "Toward an Integrated Arctic Observing Network" (2006) highlights that, unfortunately, long-term records for key arctic variables are incomplete and there are measurement gaps in all domains. There are currently various data systems that incorporate observation networks and their assets in the Arctic. Observation assets include sites, transects, observatories, projects, and networks or systems. These data systems range from interactive map interfaces that display metadata on available assets spatially, to static data search portals. Relating to wildfire the WGClimate has put together an inventory of climate data records from space agency sponsored initiatives and existing data products related to fire monitoring can be found. Furthermore, a specific challenge to the Polar observation network community is that there is no current standard that is widely adopted for describing observation assets. For example, the Polar Observation Asset Working Group (POA WG) is currently working to establish an observation network registry that acts as a catalog of all existing observation networks and their assets in a single user interface; the main challenge this group is encountering is the lack of metadata standardization and adoption within the observation network community. With the help of the Arctic Portal team, the POA WG has a pilot interface Registry of Polar Observing Networks (RoPON) that will be used to help bridge gaps in the observation networks framework. Alternatively, data search portals are currently the most flushed out data systems available for the arctic region and conform to international linked open data standards, various metadata standards, and in turn enhance dataset discoverability (Payne & Verhey, 2022). An ongoing challenge for both of these systems is interoperability, machine readability, and consistent implementation. This section will highlight examples of observation network assets and how existing controlled vocabularies can aid SAV integration into existing data portals.

Observation Networks

As part of this synthesis document, the authors have put together a sample of established available observation networks and assets, and the available variables that are recorded within them. Since there is no central registry other than the new pilot from POA WG (Pilot announced July 2023), the onus for network discovery is on the end user, and is quite labour intensive. Stakeholders and arctic inhabitants are constantly being affected by the changing climate and may not necessarily have access to the same data tools that are more well-known globally. Knowing where information is held and what data is available is a large barrier to many. In the arctic this is coupled with varying access to reliable internet connections and hardware. Data systems for Observation Networks such as Polar Tep viewer, Hotspot Satellite Observation - NASA, Global Wildfire Information system (GWIS) and the GAWSIS portal, work to incorporate various sources of global observation assets into a single interface, displayed on a map. These portals allow for filtering by location, station, variables, projects, and more. Globally, other major networks that focus on wildfire monitoring such as the global wildfire information systems, such as services from Copernicus, that share lightning detection from satellites.

- Wildfire Data System(s) Note: There are existing data systems specifically for wildfire monitoring but operated on a more regional scale. For example: Canadian Fire Maps; although they are typically more data products than services, as it shows the mapped datasets for public consumption; compared to offering available assets with access to the recorded data

A relatively new data system currently under development for the wildfire community is INFRA. INFRA is described as incorporating data from observation networks, integrated into a central system and transformed into ingestible information for the end-user. The most important aspect of this data system is to ensure the product is benefiting the end user, in this case, arctic Indigenous rights holders. If done holistically, the end user should be able to go to the original portal and retrieve information/data about SAV variables, and be able to utilize the outputs.

Linking Variables to Data Systems

The pathways mentioned above are just the 'tip of the iceberg' for data system dissemination. SAV application and usability can assist in producing data products that suit the needs of end-users, and the following can act as an example of integration into existing data systems. The WDS-ITO created an SAV spreadsheet, which was intended to be a starting point for how variables can be incorporated in larger data systems, and have interoperability enhanced through existing Linked Open Data networks through the use of controlled vocabularies and other discovery pathways. For our purposes, there was no tooling used, rather our dedicated research associate collected networks named in literature, POA WG lists, and conference presentations, and investigated each individually. Although, since the launch of the aforementioned RoPON, the registry is the authoritative source for available observation assets in the Arctic region.

Within data portals and networks, there is an opportunity for linking controlled vocabularies to enhance interoperability. Linked open data is structured data which is interlinked with other data so it becomes more useful through semantic queries. In practice, this can be implemented through providing permanent identifiers embedded with identified keywords in the metadata; in turn this can enhance discoverability, and the community would be able to build infrastructure to compile information automatically.

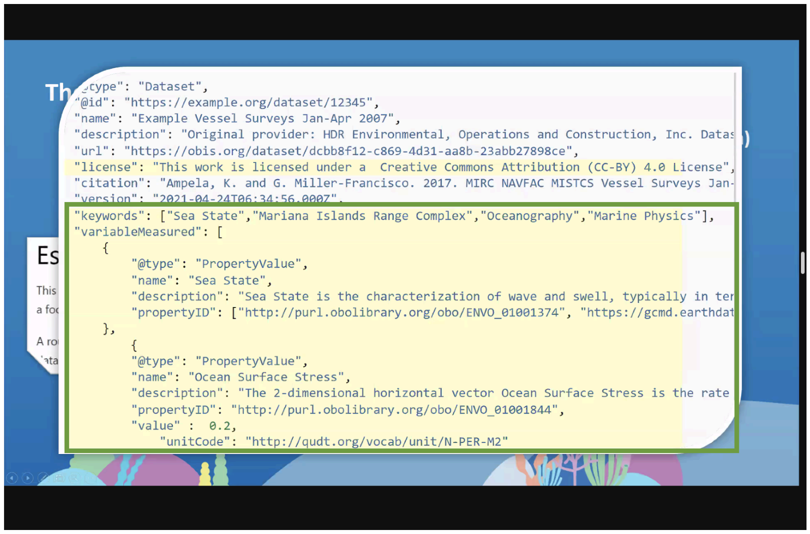

Figure 3: This figure is a screenshot of controlled vocabularies being incorporated with keywords and embedded in available metadata records which enhances interoperability. Within the green square is an example of oceanographic keywords linked with their permanent identifiers (in this case a link to the ontology). Keywords highlighted under 'variableMeasured' are "Sea State" linked to OBO and GCMD ontologies and "Ocean Surface Stress" linked to OBO foundry. Screenshot was from Pier Luigi Buttigieg, 24 Jan 2023, ESIP Winter Meeting -- Earth and Space Science Knowledge Commons: From vision to implementation Session.

As it is our understanding that the SAV process is not creating data systems, but rather, utilizing existing systems, it is our recommendation to incorporate controlled vocabularies alongside each selected variable. This can be coupled with specific recommendations and implementation strategies to better integrate and link systems of relevance. This would benefit interoperability initiatives as observation asset data systems are developed and would avoid having to incorporate it as an afterthought. In practice, this would look like identifying an existing controlled vocabulary definition with a permanent identifier from an established ontology that data systems can implement in their metadata schemas as outlined in Figure 3 above. This would enhance interoperability and establish an agreed upon definition for identified variables, as definitions vary depending on the term and ontology used. For example, wildland fire and wildfire may be used interchangeably in conversation but may have different definitions depending on region, subject domain, and application. This has been investigated by the ESIP Semantic Harmonization cluster in relation to sea-ice terms. Where roughly 340 sea ice-terms were harmonized between just the Semantic Web for Earth and Environment Technology (SWEET) ontology and The Environment Ontology (ENVO), the process for this harmonization work took roughly 5 years and found differences for the exact same term but inconsistencies with the actual outlined term definitions. The recently completed "Harmonizing GCW Cryosphere Vocabularies with ENVO and SWEET: Towards a General Model for Semantic Harmonization" (Duerr et al., 2023), outlines the process for semantic harmonization and links to the sea-ice harmonization mapping project. By incorporating and completing the decision making process during the SAV process, this will ensure interoperability long-term, and reduce the risk of ambiguities.

Table 3: Example of identified variable accompanied by an existing established ontology/vocabulary with a permanent identifier. Note: This table is used for example purposes and not intended to be the final recommendation of any variable/ ontology preferences.

Variable	Ontology	Permanent Identifier
Temperature	The Environment Ontology (ENVO)	http://purl.obolibrary.org/obo/PATO_0000146
Relative Humidity	Global Change Master Directory (GCMD)	https://gcmd.earthdata.nasa.gov/KeywordViewer/scheme/sciencekeywords/a249c68f-8249-4285-aad2-020b3c5aefc3
Surface Wind	National Snow and Ice Data Center (NSIDC)	https://nsidc.org/learn/cryosphere-glossary/surface-wind

Through linking a controlled ontology and permanent identifier to a SAV variable, it aids the end-user when searching both in data portals and observation networks. When the variable identifier is incorporated in the metadata of either an observation asset and/or the project level metadata keyword, it allows for harvesting infrastructure to consolidate its results and give back the exact information the user is looking for, again reducing ambiguities and increasing data discoverability. The WDS-ITO has collected and consolidated a set of commonly used ontologies labeled "Polar Vocabulary Tracking" in the polar community through surveying the larger polar research data management community and utilizing the resources of the ADC/SCADM/IASC - Semantic and Vocabulary Working group. It is worth noting that the ENVO Ontology has the online capabilities to create a 'subset' directory -- for example, if there is an agreed upon set of wildfire or other variable groups, the ENVO ontology is able to have the group categories and readily accessible for interested parties in a separate group, increasing interoperability. It should be noted that these ontologies are lacking representation from Indigenous stakeholders. It is currently being investigated on how to make the resource list of ontologies itself machine readable, but in the meantime, this list can be a good starting point for SAV variable applicable definitions.

Semantics Discussion

The worldwide distribution of wildfires (Archibald et al., 2013; Doerr & Santín, 2016; Krawchuk et al., 2009; Moritz et al., 2014; Robinne et al., 2019) depicts three basic requirements: (1) fuel able to burn, sustain combustion, allowing fire to spread continuously; (2) environmental conditions that facilitate the process of combustion; and (3) a source of ignition to initiate the process (Krawchuk et al., 2009). The term wildfire is used in this document to describe any uncontrolled or unplanned fire in a vegetated area. With this said, the myriad of terms used to describe this phenomenon reflects the need and relevance of wildfire as an SAV theme, given the range of research, political, and operational domains interests. It also reveals a common issue: the lack of a common understanding surrounding the 'nature' of wildfires (i.e., its own identity); resulting in varying representations of data, misunderstandings of the same phenomenon, ultimately making it inherently difficult to establish an interdisciplinary wildfire management policy (Pausas & Keeley, 2019b). A clear indication of this is that the term ‘wildfire’ itself holds a plethora of meanings based on varying characteristics of the event, location of burn, or the perspective of an individual witnessing the event. Terms such as bushfire, forest fire, landscape fire, vegetation fire, wildland fire, grass fire, wildland urban interface fire, rural fire, and peat fire are all used to describe the same phenomenon depending on the vegetation burned or the context in which they occur (Tedim & Leone, 2020). Wildfires are classified as a natural hazard by global data sets (i.e., National Aeronautics and Space Administration, the United Nations Office for Disaster Risk Reduction, political entities (i.e., European Union), governments (Bolan et al., 2017), as well as scientists (Bishop et al., 1998; S. M. McCaffrey, 2004; Moritz et al., 2014; Tarolli & Cavalli, 2013). To name a few interpretations, wildfires are categorized as a semi-natural hazard (Cavan & McMorrow, 2009; Gazzard et al., 2016), climate sensitive hazard (Bedel et al., 2013; Emrich & Cutter, 2011), natural disturbance (Bond & Keeley, 2005; Elliott et al., 2011; Ponomarev et al., 2015; Roberts, 2004), disturbance (White & Picket, 1985), aggression (Shea, 1940) and ecological or socio-ecological disturbance (Coughlan, 2013; S. McCaffrey et al., 2015). Each country also possesses its own national rules and regulations in relation to reporting wildfire events, making direct comparisons and analyses fairly difficult (Fernandez-Anez et al., 2021). Detailed and accurate comparisons between countries is complicated by: (1) quality concerns of fire-cause investigations; (2) the heterogeneity of national classifications, causes of fire categories, classification criteria, and level of detail; (3) length of time national databases have been in practice; and (4) a restrictive European Wildland fire classification scheme (Tedim et al., 2015).

Conclusion

The broad relationships between wildfires and land-use dynamics, landscape conservation, atmospheric emissions, vegetation structure and diversity, among other focus areas, make this a notable field of research for a wide range of professionals. The growing interest to facilitate the use of multiple data sources by respective rightsholders in the Arctic, as well as the expanding use of remote sensing data by wildfire management agencies, researchers, and local community members explains the increase in peer-reviewed journals, books, and technical conferences available today on this topic. This plethora of research represents both a strength and weakness in the ROADS process as it relates to the wildfire theme; due to a lack of a consistent or harmonized approach to reporting resulting in multiple representations of the same or similar phenomenon. From a data management perspective, multiple representations are further muffled by a lack of common terminology or guidelines resulting in information gaps, or incomplete datasets. However, we have found that remote sensing data as it relates to the available moisture content on fuels , i.e., wind speed and direction, RH, surface temperature and 24-hour precipitation, are widely accessible and currently tracked by various essential climate frameworks. The connections between these high-level variables, remote sensing data, and operational indices has expanded in recent years, largely due to improvements in EO systems and a stronger understanding of the relationship between remotely sensed data and variables known to influence wildfires.

Where do we go from here in defining variables under the theme of wildfire using the SAV framework? The concept of SAVs as they relate to the theme of wildfires has a strong foundation with many data sources, lessons learned, and international working groups asking many of the same questions. The challenge posed for the EPs moving forward is to remain conscious and respectful of multiple perspectives when discussing similar concepts or approaches. Each individual has a slightly different relationship with fire, making it critical to understand the context and circumstances in which it occurs. If discussing ignition sources, a shared concern could be the occurrence of lightning as well as the potential for human-caused wildfires; representing an opportunity for community collaboration, as well as the establishment of 'best practices' for local inhabitants. It is also an opportunity for Indigenous fire stewardship to provide the foundation for prescribed burning activities to take place, especially given that many of the lessons learned have been neglected in practice (i.e., relentless fire suppression v. allowing an area to burn). Focusing on global air quality, food security (drinking water) and the impact of wildfires, the cascading effects of fire in permafrost zones of the Arctic could also be viewed as a shared priority that fits well under the SAV Framework, wildfire theme, and overlaps with initiatives already underway (i.e., EP on permafrost).

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Appendices & Links

- [Zotero library]
- [Zotero Group]

Synthesis Document Experience: Note from RA

During the process of preparing two expert panels (EPs) on the theme of wildfire as a Shared Arctic Variable (SAV), I was given the opportunity to broaden my understanding of an extremely dynamic environmental process (wildfire regimes). I cannot express the gratitude I have for the WDS-ITO and SAON ROADs team for allowing me to build upon the concept of SAVs and the wildfire theme. I started by creating an open-source public access Zotero library that captures a wide variety of research and interest on the theme of wildfires in the Arctic region, which then fostered a synthesis document and excel spreadsheet on available Earth observing assets in collaboration with multiple working groups. This experience has been one of the most enlightening and rewarding opportunities of my professional career. I have been encouraged to highlight some of the challenges faced during this process, which include: (1) the lack of a consistent approach to wildfire reporting and common terminology by each country in the Arctic region, (2) the overall absence of Indigenous engagement and disregard for traditional knowledge in modern wildfire management practices, and (3) the dynamic nature of fire itself prompts many responses on how to effectively manage wildfire events in practice, leading to multiple interpretations of the same phenomenon. Inconsistent approaches to reporting and a murky relationship between terms has resulted in critical information gaps in data; the focus on wildfire suppression and absence of Indigenous Fire Stewardship in modern wildfire practices highlights the need for a shared understanding; and the importance of context when discussing wildfire themes is highly relevant. For example, prescribed burning activities require certain conditions to occur without inadvertently causing more harm than good (i.e., wind conditions, timing of year, high-intensity burns vs. low-intensity burns etc.).

The one message I can share from my experience throughout this process is that active engagement, open dialogue, and collaboration with a wide variety of groups interested in a common theme are the critical building blocks to creating a holistic solution to an interdisciplinary problem - especially when considering multiple scales (i.e., local, regional, global). The challenge I pose for the EPs moving forward is to remain conscious and respectful of multiple perspectives when discussing similar concepts or approaches, while also maintaining a broad focus on the theme of wildfire and associated impacts. The lessons learned during your deliberations will set a benchmark for wildfire management best practices in the Arctic region - a necessary endeavor in the wake of a changing climate with global implications. From my perspective, collaboratives are designed to establish a social consensus that then provides a meaningful path forward for all participants. However, in the context of wildfires, focusing on a single outcome such as fuel loading or suppression may marginalize the importance of other critical functions, such as wildlife habitat or ecosystem services. Developing a truly holistic approach to wildfire management requires a commitment, by all parties who are experts in their own right, to recognize the importance of active listening and respectful engagement between groups. It is my opinion that this is fundamental to the success of SAVs in general in addressing extremely dynamic challenges.

I wanted to take this opportunity to wish goodluck to the wildfire EPs and those working towards similar goals in associated SAV themes (living on frozen ground or permafrost, and sea ice), and will close this post by sharing a brief story that I believe captures the importance and true meaning of SAV work within the theme of wildfire:

‘During my time with the Ministry of Natural Resources and Forestry (MNRF) as a Type I Fire Ranger from 2013-2018, I was dispatched to Kasabonika Lake First Nation in Northern Ontario to respond to a wildfire. We were asked to provide an update to the local community to address any public safety concerns regarding the incident. The phrase ”no values are threatened at this time” was used by a member of my crew to describe the current fire behavior, as well as the likelihood of the fire reaching any local infrastructure. However, this comment did not necessarily capture other considerations (i.e. trap lines, unmarked cabins, culturally sensitive areas etc.) which were indeed at risk and critically important to the community. With the help of community members, we were able to identify, locate, and respond to additional areas at risk. This experience illustrates the importance of open dialogue, active engagement, and respectful listening between groups during an emergency.’