



# Seasonality of biological and physical systems as indicators of climatic variation and change

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## Abstract

Evidence-based responses to climate change by society require operational and sustained information including biophysical indicator systems that provide up-to-date measures of trends and patterns against historical baselines. Two key components linking anthropogenic climate change to impacts on socio-ecological systems are the periodic inter- and intra-annual variations in physical climate systems (seasonality) and in plant and animal life cycles (phenology). We describe a set of national indicators that reflect sub-seasonal to seasonal drivers and responses of terrestrial physical and biological systems to climate change and variability at the national scale. Proposed indicators and metrics include seasonality of surface climate conditions (e.g., frost and freeze dates and durations), seasonality of freeze/thaw in freshwater systems (e.g., timing of stream runoff and durations of lake/river ice), seasonality in ecosystem disturbances (e.g., wildfire season timing and duration), seasonality in vegetated land surfaces (e.g., green-up and brown-down of landscapes), and seasonality of organismal life-history stages (e.g., timings of bird migration). Recommended indicators have strong linkages to variable and changing climates, include abiotic and biotic responses and feedback mechanisms, and are sufficiently simple to facilitate communication to broad audiences and stakeholders interested in understanding and adapting to climate change.

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## 1 Introduction

Understanding existing and predicted impacts of climate change on managed and natural ecological systems is critical for supporting policy and resource management decisions. In the United States (U.S.), synthesizing global change effects on key U.S. systems and sectors and describing the current and future (25 to 100 year) trends are required at least once every 4 years by the U.S. Global Change Research Act (Section 106). This requirement is met through periodic production of the U.S. National Climate Assessment (NCA) under the auspices of the U.S. Global Change Research Program (e.g., Melillo et al. 2014; Reidmiller et al. 2018). To improve efficiency and to better track and understand trends over time, Buizer et al. (2013) described the development of a “sustained assessment” process for the NCA. As part of the sustained assessment process, the 3rd NCA Advisory Committee (Kenney et al. 2014) recommended the development of an integrated set of “physical, natural, and societal indicators that communicate and inform decisions about key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness.” The indicator framework and an initial set of indicators were described in Kenney et al. (2014), and the process for selection and production of indicators was detailed in Kenney et al. (2016). Kenney et al. (2018) outline recommendations for expanding this system, of which periodic inter- and intra-annual variations in physical climate systems (i.e., seasonality) and in plant and recurring animal life cycles (i.e., phenology) are an integral part.

Spatial and temporal changes in seasonal physical and biological phenomena serve as robust indicators of environmental variation and climate change for natural and managed earth system processes (IPCC 2014). Intra- and interannual variations in the timing of life-cycle events, abundance, or distribution of organisms are often coupled to seasonal variations in physical drivers such as accumulated temperature, precipitation, or day length (Parmesan 2007). Trends in seasonal biological and physical processes, either alone or in combination, have been linked to changes in the timing and nature of aeroallergens (Weber 2012), outbreaks of disease (Lafferty 2009; Sapkota et al. 2019) and forest pests (Liebhold 2012), invasions of nonnative organisms (Wolkovich and Cleland 2010), onset and duration of wildfire (Westerling 2016), the abundance and distribution of organisms (Cleland et al. 2012), patterns of human recreation (Fisichelli et al. 2015), changes in agricultural yield (Seifert and Lobell 2015), and changes in ecosystem processes such as carbon and nutrient cycling (Richardson et al. 2013).

To date, there is no single system of seasonal biological and physical indicators for the nation. Existing indicator systems tend to focus on biological (e.g., Pereira et al. 2013) or physical variables (e.g., Bojinski et al. 2014) or are not comprehensive or sustained (EPA 2016). In addition, although seasonal variations in biological and physical parameters are familiar concepts, we have limited understanding of their patterns, drivers, interactions, and feedback effects, particularly at the regional to national scales and the decadal time frames associated with long-term changes in climate. This shortcoming arises because monitoring of plant and animals that is standardized, routine, long-term, and continental-scale has been rare—with the exception of birds—preventing comprehensive studies of the link between climate and ecological variability in time and space (Zuckerberg et al. 2020). Additional research would improve our integrative understanding of individual, interactive, and feedback

effects of physical and biological drivers, particularly within the context of climate change (Pau et al. 2011; Richardson et al. 2013).

The development of an integrated system of physical and biological indicators driven by seasonal variation and change could inform appropriate responses to climate change and could help answer remaining grand challenge questions in natural and managed systems, such as

1. how do spatial and temporal variations in physical and biological conditions—past, present, and future—affect the abundance, movement, distribution, genetics, and interactions of organisms within their environment?
2. what is the nature and intensity of interactive and feedback effects between coupled biological and physical systems, and how do these interact with the socio-ecological systems that people live in, and
3. how are seasonal to sub-seasonal variations in biological, physical, and socio-ecological systems best understood within the longer-term context of global environmental variation and change?

The purpose of this paper is to summarize the recommendations of a technical team convened by the USGCRP Indicator Work Group (Kenney et al. 2014) to identify, prioritize, and recommend phenological and seasonality indicators for consideration as part of the “sustained assessment” process of the USGCRP NCA (Buizer et al. 2013; Kenney et al. 2016, 2018). The goal of the phenology and seasonality technical team was to identify and describe a potential set of biological (i.e., phenological) and physical (i.e., seasonal) indicators that (1) reflect sub-seasonal to seasonal drivers and responses to climate variability and change at national scales and (2) provide information about the sustainability of national socio-ecological systems. Proposed indicators have strong linkages to variable and changing climates; integrate both abiotic and biotic drivers, responses, and feedback mechanisms; and are simple enough to facilitate communication to broad audiences and stakeholders interested in understanding and adapting to increasingly variable and changing climates.

## 2 Methods

The USGCRP Indicator Work Group provided process and decision criteria for prioritization and selection of indicators to all technical teams charged with identifying and prioritizing potential indicators (Kenney et al. 2014). Process requirements included the development of a conceptual representation of key phenomena, and decision criteria required that indicators were scientifically defensible, did not require abundant additional research, and could inform decision-making while contributing to a sustained activity within the National Climate Assessment (Kenney et al. 2016, 2018; USGCRP 2015). Additional criteria used to prioritize potential indicators included consideration of whether the indicator (1) had been scientifically vetted; (2) was operational and sustainable; (3) was important to societal benefit in areas such as biodiversity, agriculture, and human health; and (4) had a relationship to climate variation that can be communicated to a broad audience.

The phenology and seasonality technical team included 10 experts drawn from academia and federal agencies. The team met weekly between February and May 2013, during which we developed a conceptual framework for seasonal and

phenological indicators, identified a potential list of indicators, evaluated and prioritized the indicators on the list against standardized criteria, and then described a final set of proposed indicators. Because of time constraints, we did not consider potential ocean (e.g., marine, coastal, estuarine) indicators.

Identification of potential indicators was guided by a conceptual model of seasonal physical and biological processes within a global context (see Fig. 1 in the Online Resource). The model illustrates how processes may operate individually or interactively as drivers or stressors on the goods and services provided by ecosystems and how, in turn, spatial and temporal changes in ecosystem properties or processes may feed back onto drivers or stressors.

Because of the nested nature of potential biological or physical indicators, the fact that multiple metrics could be used to represent each indicator and the presence of potentially competing representations for each metric, we (the technical team) developed a hierarchical system to identify (1) potential suites of related indicators and (2) metrics for measuring the status of each indicator through time and space. This system creates broad categories, or *suites*, of indicators that reflect biogeochemical status or processes (e.g., surface climate, hydroclimatology, temporal patterns in the vegetated land surface, organismal phenology). In turn, *metrics* describe potential measures or variables that reflect the status of the indicator. This nested approach is consistent with Kenney et al. (2016), is complementary to the approach adopted by EPA (2016), and resulted in a set of 8 recommended indicators (Table 1).

### 3 Proposed seasonal physical and biological indicators

We developed a hierarchical system that included types of indicators (e.g., Surface Climate Seasonality), one or more named indicators within each type (e.g., Seasonal Climate Indicators), and potential metrics that could be used to describe each indicator (e.g., Date of Last Spring Frost) (cf. Table 1). The following sections contain short narrative descriptions for each indicator, potential metrics, and their data sources and a brief description of how the indicator meets the decision criteria described above.

#### 3.1 Surface Climate Seasonality—Seasonal Climate Indicators

Seasonal Climate Indicators describe seasonal patterns in climatological conditions and are often calculated from daily meteorological records (e.g., minimum and maximum temperatures, precipitation amount). Such indicators are derived from daily temperature and precipitation data from the Global Historical Climatology Network (GHCN-Daily; Menne et al. 2012) to identify changes in the timing of important seasonal climate events and are expressed as “day of year” or “days per year.” Many indicators that exist are simple to calculate and easy to communicate, such as onset, end, and duration of the frost-free season (using thresholds such as hard freeze at  $-2$  °C or freeze at  $0$  °C); number of days each year below freezing; number of hot days above a given percentile; and days each year that exceed some threshold of minimum or maximum temperature, depending on the application (cf. Table 1). These indicators are valuable for tracking and communicating conditions particularly relevant to agriculture and natural ecological systems (e.g., Kukul and Irmak 2018).

Data underlying seasonal climate indicators can be derived from station-based historical datasets such as those curated by the Global Historical Climatology Network (GHCN; Menne et al. 2012). The methods can also be applied to contemporary or forecasted data (e.g., from numerical weather forecasts), so they can be updated and delivered in real time or as short-term (or eventually longer-lead) forecasts. Because the indicators are well established and relatively straightforward and have strong ties to societal activities (e.g., agricultural planting or harvest dates), they should be relatively easy to communicate to a broad set of nonscientist stakeholders (such as resource managers, agriculturalists, and the public).

### 3.2 Surface Climate Seasonality—Potential Growing Season

At landscape scales, beyond the distribution of individual weather stations, the Potential Growing Season can be estimated using satellite-based, microwave remote sensing that determines the state of the land surface, whether frozen ( $<0\text{ }^{\circ}\text{C}$ ) or nonfrozen ( $>0\text{ }^{\circ}\text{C}$ ). The onset, end, and duration of the nonfrozen season defines the period of potential biological activity and the

**Table 1** Seasonal physical and biological indicators include suite (or type), name, potential metrics, and data sources

Indicator suite	Indicator name	Metrics	Data source
Surface Climate Seasonality	Seasonal Climate Indicators (SCI)	Last spring frost/freeze; first fall frost/freeze; frost/freeze-free season, number of frost/freeze days; exceedance dates for percentiles of cumulative annual heating or precipitation; heat stress (start, end, duration)	Ground-based meteorological data
	Potential Growing Season	Frozen and nonfrozen seasons (start, end, duration); primary spring thaw and fall freeze timing; frost days (timing, frequency, duration)	Satellite microwave remote sensing
	Extended Spring Indices	Timing of spring onset (first leaf, first bloom)	Ground-based meteorological data; ground-based organismal data
Seasonality of Snow and Ice	Snowmelt Runoff (timing of snowmelt pulse in snowfed streams)	Winter/spring center of volume	Ground-based stream gage observation networks
	Freshwater (Lake and River) Ice Seasonality	Freeze date; ice break-up date; ice-free duration	Ground-based observational (ice-in/ice out) data
Land Surface Phenology	Vegetation Growing Season	Timing of remotely sensed vegetation index transitions (start, peak, end, duration)	Satellite-based spectral reflectance data
Ecosystem Disturbance Seasonality	Wildfire Season	Flammable season timing and duration (start, peak, end, duration)	Ground-based meteorological data
Organismal Phenology	Species Migration and Seasonal Distribution	Bird wintering range: latitude of bird center of abundance	Ground-based observational data

availability of soil moisture, which, in turn, defines the growing season and heightened biological and hydrological activity (Table 1). The nonfrozen season can indicate earlier and longer growing seasons as well as the relaxation of freezing temperature limitations on ecosystem processes.

The National Aeronautics and Space Administration (NASA) maintains a multidecade, daily-scale Freeze/Thaw Earth System Data Record (FT-ESDR) of freeze and thaw conditions that is among the longest (> 35 years) global satellite environmental data records (Kim et al. 2017). The FT-ESDR domain encompasses all land areas where frozen temperatures can constrain ecosystem (i.e., biological and hydrological) processes. Satellite microwave measurements are particularly sensitive to freeze-thaw transitions, can be obtained independent of clouds or light conditions, and enable repeated local to global assessment of conditions suitable for basic and applied climate research (Kim et al. 2012).

This indicator should be readily understandable by the general public and the resource management community, given strong applications to agriculture (such as frost risk, cropping, and growth suitability guidelines), forests and rangelands (such as ecosystem health and productivity), transportation (such as accessibility or potential for icy conditions), and human health (such as temporal risk of certain vector-borne diseases).

### 3.3 Surface Climate Seasonality—Extended Spring Indices

The Extended Spring Indices (SI-x) are modified heat-sum accumulation models with empirical thresholds linked to recurrent seasonal life-cycle events of cultivated and native plants. The models were developed by Schwartz et al. (2006) and are derived from multidecadal relationships between meteorological conditions (particularly minimum and maximum daily temperature data) and in situ observations of transition dates for events such as leaf-out and flowering of cloned (genetically identical) plant species. These data are now curated by the USA National Phenology Network (USA-NPN). A strength of the models is that they can be determined for any daily meteorological or gridded climatological dataset, which enables extrapolation beyond the relatively limited number of stations with long-term, ground-based phenological observations (Ault et al. 2015). The USA-NPN offers historical, real-time, and short-term forecasts of the Extended Spring Indices for the conterminous U.S. and Alaska (Crimmins et al. 2017).

The SI-x metrics of First Leaf and First Bloom (cf. Table 1) are correlated with phenological transition of other native and cultivated plant species and have been linked to local- to landscape-scale ecosystem processes such as snow-water equivalent, carbon uptake period, and potential for wildfire (Martinuzzi et al. 2019), as well as continental-scale synoptic climatology (Mehdipoor et al. 2019). The Spring Indices are described here as an indicator of the onset of biological activity in spring, which resonates with stakeholders including the public. Spatiotemporal variation in spring onset has implications for ecosystem processes (such as streamflow, potential for fire, establishment of invasive species), recreation (skiing, hunting, and fishing), and agriculture (pollination services, managing weeds and insect pests) (Enquist et al. 2014). The SI-x maps offered by the USA-NPN are widely used by the news media, decision-makers, and natural resource managers for applications ranging from anticipating the start to the allergy season to anticipating damage to crops from late-season frosts (Ault et al. 2013).

### 3.4 Seasonality of Snow and Ice—Snowmelt Runoff

This indicator, based on daily stream discharge measurements, indicates the timing of snowmelt runoff from watersheds (Dudley et al. 2017). Winter/spring center of volume is defined as

the date when half of the streamflow between January 1 and June 30 passed a particular gage (EPA 2016) (Table 1). Snowmelt pulses are typically defined using daily stream discharge measurements from gages in snowmelt-dominated basins that are minimally affected by reservoir regulation, water diversions, and land-use changes. Streamflow data are managed by and are freely and publicly available from the USGS.

Runoff from spring snowmelt can contribute up to 75% of annual runoff for basins dominated by snowmelt in the western U.S. (McCabe and Clark 2005). The timing and magnitude of snowmelt is important in flood protection. Mountain runoff is captured in reservoirs in late spring and early- to mid-summer and then redistributed widely to sustain agriculture and urban centers throughout the growing season. Compared with western states, earlier snowmelt and associated higher spring flow may have a smaller impact on water supplies in the eastern U.S.; in these states, rainfall and streamflow vary less over the year. Altered patterns in snowmelt and streamflow could lead to more frequent or severe winter ice jams and associated floods as well as mismatches in the timing of peak springtime flow and migration of anadromous fish such as spring-spawning Atlantic salmon.

### 3.5 Seasonality of Snow and Ice—Freshwater (Lake and River) Ice Seasonality

Freeze date (ice-on) is the earliest date a body of water body is observed to be completely ice-covered; breakup date (ice-off) is the latest date of ice breakup preceding open water (Table 1). Annual duration of ice cover is defined as the number of days that a water body is completely covered with ice. A multidecadal record of freeze and ice breakup dates is managed by the National Snow & Ice Data Center (NSIDC) with support from the National Oceanic and Atmospheric Administration (NOAA) for rivers and lakes across the Northern Hemisphere. Other regional datasets, such as for the Great Lakes region (e.g., Mason et al. 2016) or for major rivers in Alaska (e.g., Sagarin and Micheli 2001; Bieniek et al. 2011), provide region-specific inference but did not meet the criteria for a national indicator established for this study.

Lake and river ice are a significant part of the hydrological cycle, and current trends reflect the shrinkage of the Earth's cryosphere, a widely recognized effect of ongoing climate change (Magnuson et al. 2000). Timing of freeze and ice breakup in rivers and lakes is thus an important seasonal indicator and appears in other indicator systems (e.g., EPA 2016). The presence of freshwater ice affects the risk of flooding. Floods can be difficult to predict and can occur abruptly, posing significant risk to biodiversity, humans, property, and infrastructure. Projections of future climates indicate possible delays in fall and winter freeze-up and shifts towards earlier spring ice breakup with increasing temperature and changes in snow cover.

### 3.6 Land Surface Phenology—Vegetation Growing Season

Land surface phenology (LSP) examines the timing and intensity of biological responses in the vegetated land surface across broad geographical scales, with the data usually coming from spaceborne sensors. Satellite data are processed into a set of metrics such as time of green-up, peak greenness, or brown-down and are typically expressed in day of year (Table 1).

The data underlying LSP are obtained from earth-observing satellites with (near-)daily observation cycles, primarily the moderate resolution imaging spectroradiometer (MODIS)

acquired since mid-2000, and from the advanced very high resolution radiometer (AVHRR) acquired since 1989 (or 1981 at lower spatial resolution). MODIS data used to generate LSP metrics are managed by NASA and distributed by the Land Processes Distributed Active Archive Center (LPDAAC). AVHRR data are managed and distributed by both USGS and NOAA. Both MODIS and AVHRR data are freely available, broadly vetted, and well documented. NOAA's operational replacement for the AVHRR is the Visible Infrared Imaging Radiometer Suite (VIIRS), and it also produces data from which LSP metrics can be generated (Zhang et al. 2018) and maintain continuity of LSP observations (Moon et al. 2019).

The spectral data collected by these sensors are processed into vegetation indices (VIs), which provide an indication of the absorption of photosynthetically active radiation primarily by live green vegetation. Data are generally composited into coarser (8–16 day) time series to reduce atmospheric contamination effects, mostly by clouds. By constructing a VI time series, the seasonal pattern of the greenness of the land surface can be represented. There are several widely used algorithms for identifying LSP metrics from VI time series. Each approach has its own strengths and weaknesses, supporting peer-reviewed publications and active use within the scientific community.

### 3.7 Ecosystem Disturbance Seasonality—Wildfire Season

Wildfire seasonality is complementary to other identified wildfire risk indicators (e.g., frequency, extent, and severity) (EPA 2016). Research shows that there is a strong relationship between climate and fire in the western U.S., specifically between warming, timing of spring onset, and increased fire activity (Westerling 2016), as well as annual area burned (Abatzoglou and Williams 2016).

Our proposed Flammable Season Timing and Duration (FSTD) Indicator refers to day of onset, peak, end, and duration (number of days) of the fire season (Table 1). FSTD is estimated from daily surface meteorological observations (e.g., temperature, humidity, precipitation, and solar radiation) and can be expressed as an absolute value and/or an anomaly from an historical benchmark period (cf. Jolly et al. 2015; Hobbins et al. 2016). Sources and algorithms for the baseline data inputs are well established in the literature and are widely accessible. Alternative indicators, albeit with shorter time-series, include direct observations of fire activity or extent (e.g., Eidenshink et al. 2007).

Daily meteorological observations also serve to estimate fuel dryness and fire intensity, the Energy Release Component (ERC), which is an output of the National Fire Danger Rating System (NFDRS). The NFDRS, generated from fuel characteristics and daily weather, uses a rating system that is understood and respected by the public: Low, Moderate, High, Very High, and Extreme. These metrics reflect an area's immediate fire protection need; they are widely used by fire managers to determine restrictions relative to public access and activities associated with wildfire ignitions.

### 3.8 Organismal Phenology—Species Migration and Seasonal Distribution

Changing climate conditions affect the timing of organismal behavior, phenology, and species distributions (Cohen et al. 2018; Lipton et al. 2018). Although the U.S. has a long tradition of sustained phenological observations of organisms at individual sites—particularly in terrestrial systems—there are few instances where the same species or phenological phase (e.g., migration, reproduction, flowering or fruiting) for a given species has been observed systematically



across its full or even partial range (Wolkovich et al. 2012), particularly within aquatic or marine systems (but see Poloczanska et al. 2013 and Pinsky et al. 2013). In contrast, relatively long-term and broadly distributed phenological and distributional data on avian species are available and can be placed in the context of changing climates, so we selected as an indicator the geographic position of bird wintering ranges. This indicator, also established by the EPA (EPA 2016), utilizes data from annual Christmas Bird Counts that are managed by the National Audubon Society. The Bird Wintering Ranges Indicator addresses shifts in the latitude and the distance to the coast of winter ranges of North American birds over the past half-century (Table 1). Data are collected by citizen scientists, working in partnership with professional researchers, who identify and count common bird species each year in roughly 2000 locations through North America. Data collectors follow rigorous protocols consistently across time and space.

Bird distributions in North America have increased in latitude since 1960, and this shift is attributed to climate change (McDonald et al. 2012). Birds are a strong indicator of changing environmental conditions because they are adapted to specific habitats, food sources, and temperature ranges. The timing of seasonal life cycle events in birds such as migration is driven by temperature, sun angle, and other conditions. As such, shifts in spatial and temporal patterns of bird behavior can indicate changes in seasonal meteorological conditions or changes in the availability of suitable food and habitat. This indicator could be further enhanced through the addition of arrival and departure dates, perhaps derived from other national bird monitoring datasets, or by integrating information on changes in availability of resources (e.g., insects, nectar, nesting habitat) at endpoints or along the migratory pathway.

## 4 Discussion

### 4.1 Linking phenology and seasonality with climate variability and change

Physical and biological indicators of seasonality form an integrated system of drivers and responses that operate across scales to control physical, ecological, and societal processes in response to climate change and variation. The linkage of climate variability and change with indicators of seasonality should facilitate understanding of relationships among physical drivers (e.g., Surface Climate Indicators) and biological responses (e.g., Vegetation Growing Season), as well as feedbacks among these variables (Fig. 1 in Online Supplemental Material). For example, rapid heat accumulation in late winter and early spring may shift activity of vegetation to earlier in the season, with attendant impacts on fuel moisture and an earlier onset to the fire season (Westerling 2016), with an intensification of drought impacts or shifts in seasonal temperature regimes negatively affecting regional agricultural production (Ault et al. 2013).

### 4.2 Empowering stakeholders with intuitive indicators

Because the timing of seasonal physical and biological events influences many aspects of everyday life, engaging the public in paying attention to the timing of these events can benefit science and society. First, scientists and nonscientists alike can contribute to documenting shifts in rain and snowfall; ice break-up; leaf-out, flowering, and leaf color change; and

migration and insect hatch through citizen science programs using rigorous observation protocols (e.g., Reges et al. 2016; Rosemartin et al. 2014). Second, changes in the timing of weather and biological events may require social and economic adaptation to cope with the changes (Lawler 2009). Examples of adaptive strategies include farmers adjusting annual planting or harvesting dates or types of crops (Seifert and Lobell 2015), ski resorts deciding whether to invest in artificial snowmakers (Paquin et al. 2016), and families shifting the timing of vacations to national parks (Buckley and Foushee 2012; Fisichelli et al. 2015). Third, the physical and biological indicators described here have the potential to complement human health information maintained elsewhere, supporting an increased understanding of trends and seasonal changes in phenomena that are directly tied to human health. Indicators such as the timing of spring onset, frost days, and heat stress metrics are indicative of disease and health risks including periods of activity for disease vectors (Brand and Keeling 2017) and aeroallergens (Zhang et al. 2015; Ziska et al. 2011), incidence of asthma and allergic disease (Sapkota et al. 2020), and temperature extremes (Keatinge 2003). Finally, seasonal timing is relatively straightforward to observe and document and can serve as an entry point into a deeper understanding of seasonal cycles, how they are changing, and the consequences of these changes.

### 4.3 Operationalizing indicators

Implementing a more comprehensive set of phenological indicators for the nation has been recommended to the USGCRP as part of a sustained assessment process (Kenney et al. 2014). A pilot indicator system with 16 indicators to date was released by the USGCRP and included as part of the 4th NCA (USGCRP 2018, <https://www.globalchange.gov/browse/indicators>). Two of the indicators recommended herein—frost-free season and start of spring—are included in the USGCRP indicator system. Though this is a useful start, we recommend implementing a fuller representation of phenological indicators and endorse the approach recommended by Kenney et al. (2018) of building out a few indicators as part of the NCA reports, with the expertise of the authors, and then maintaining them in future reports.

### 4.4 Research needs and potential applications

Conspicuously missing from our set of recommended indicators are phenological observations of many plant and animal species from terrestrial and aquatic—let alone—marine systems. Ad-hoc, single-site phenological records for plants (e.g., Cook et al. 2008; Crimmins et al. 2010) and animals (e.g., Pinsky et al. 2013; Staudinger et al. 2019) have been analyzed for secular trends—sometimes in support of international and national climate assessments (e.g., EPA 2016)—but these records met few of the defined criteria for national indicators in this study. The recent U.S. National Climate Assessment (Lipton et al. 2018) outlines observed effects of climate change on biodiversity across organizational scales, including individuals (e.g., genetics, behavior, morphology, and physiology), populations (e.g., phenology or migration), and species (e.g., shifts in seasonal distributions or ranges) in variety of ecological systems that indicate increasing scientific understanding of organismal response to physical climate drivers such as shifting seasonality. The broad synthesis in Lipton et al. (2018) could form the basis for additional organismal indicators of phenology.

Interestingly, experimental manipulations may be insufficient to determine phenological sensitivities (Wolkovich et al. 2012). Similarly, spatial data may be an insufficient substitute

for temporal data in support of phenological modeling (Jochner et al. 2013). This suggests that broadly distributed observations of organismal phenology, collected using standardized definitions and protocols, will be critical to understanding relationships between organisms and changing environmental and climatic conditions. The USA National Phenology Network, established in 2007, is charged with collecting and organizing historical and contemporary phenological datasets that can eventually help fill the observational data gap at the national scale (Schwartz et al. 2012). Similarly, the development of a marine biodiversity observation network would fill the need for a systematic and long-term program to evaluate ocean biodiversity and to support resource management and conservation (Duffy et al. 2013; Muller-Karger et al. 2018).

Our recommended national indicators of physical and biological seasonality can provide strategic guidance for the growth and development of national monitoring activities that could leverage on, or expand and strengthen, the indicator system (e.g., Jones et al. 2010; Kenney et al. 2018). A nationally standardized suite of indicators could also be integrated with international indicator systems that describe patterns and trends for climate (Bojinski et al. 2014), biodiversity (Pereira et al. 2013), ocean processes (Miloslavich et al. 2018), or ecosystem services (Mononen et al. 2016). These would not only enable integrated assessments of societal benefit areas nationally and internationally but could also contribute more broadly to international activities such as the Group on Earth Observations System of Systems or the Intergovernmental Platform on Biodiversity and Ecosystem Services. An integrated indicator system can also serve as an outlet for distributed multiscale, multiplatform national observing systems (Jones et al. 2010). Advances in cyberinfrastructure and data management which enable the development of “big data” for natural ecosystems should greatly facilitate the interoperability and eventual integration of data to support dynamic national indicators systems (Hampton et al. 2013).

We considered possible applications of indicators to natural resource management and decision- and policy-making when evaluating potential indicators (Enquist et al. 2014). While most national-scale indicators are insufficiently resolved to support local decisions, seasonality indicators for runoff, freezing, and fire and organismal phenology can be evaluated at a scale that is relevant to local decisions on management of water, agriculture, and forests. However, a sustainable national system of indicators useful to human society will require development, refinement, and delivery of indicators useful for local management (i.e., local-scale planning, assessment, evaluation, and policy-making) (Jackson et al. 2016).

The value of an indicator system that can provide forecasts or predictions of potential future conditions (i.e., leading indicators), with spatiotemporal control, would be paramount. For example, short-term meteorological forecasts, which predict conditions on the order of days, are vital to decision-making by a variety of stakeholders. The ability to integrate both meteorological and biophysical data, enabled in part by recent advances in cyberinfrastructure, are driving the development of a new field of ecological forecasting (Dietze et al. 2018). However, many critical planning and management decisions—from reservoir and agricultural operations to detection and control of invasive organisms to controlling wildfire to planning harvest seasons and outdoor recreation—need information weeks to months in advance. A recent focus on improved sub-seasonal to seasonal forecasts (S2S), i.e., forecasts made weeks to months in advance, could support decision-making, increase economic vitality, and protect the environment (National Academies of Science 2016). The development of a sustained, national, scalable, and extensible system of indicators as recommended here could readily leverage S2S forecasts, enabling the development and delivery of societally useful information

and knowledge to a variety of stakeholders interested in understanding, anticipating, detecting, attributing, and mitigating or adapting to the impacts of climate variability and change.

## 4.5 Conclusions

We identified the importance of both physical and biological processes that form an integrated system of drivers and responses operating across scales in a multi-stressor context to control physical, ecological, and societal processes in response to climate change and variation. This particular approach creates a strong, though not exclusive, linkage between climate change and various metrics that should facilitate understanding of relationships among physical drivers and seasonal and phenological responses, as well as feedbacks among these variables. Further, this approach should facilitate the communication of these relationships to broad audiences and provides an opportunity to engage stakeholders in the process of developing, refining, and delivering indicators. The implementation and communication of seasonality indicators that are particularly obvious to people where they live can support and empower stakeholders and the public to formulate and implement adaptive responses to climate change.

An Integrated, quantitative, national-scale indicators are crucial for tracking and understanding tracking the timing of seasonal events in physical and biological systems in an era of rapidly changing climate conditions. Here, we present a suite of such indicators. These indicators enable tracking conditions, anticipating vulnerabilities, and facilitating intervention or adaptation and can be measured, evaluated, and forecasted on time scales ranging from days to centuries, all of which have their places in management and stakeholder engagement (White et al. 2017; Dietze et al. 2018; Bradford et al. 2020; Crimmins et al. 2020).

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