

Popular summary:

Phenology focuses on the timing of biological events such as flower opening or bird migration. This paper discusses some of the challenges in predicting and assessing phenological responses. The paper also reviews some of the advances being made in phenological research, including 1) satellite phenology products, 2) ground-based instrumentation, and 3) cyber-infrastructure. Finally, the paper described how these advances are helping diverse research and application areas, including the assessment of climate change on phenology as well as how phenological research can help land management decisions.

1 Learning the rhythm of the seasons in the face of global 2 change: phenological research in the 21st Century

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4 Jeffrey T. Morisette¹, Andrew D. Richardson², Alan K. Knapp³, Jeremy I. Fisher⁴, Eric A.
5 Graham⁵, John Abatzoglou⁶, Bruce E. Wilson⁷, David D. Breshears⁸, Geoffrey M.
6 Henebry⁹, Jonathan M. Hanes¹⁰ and Liang Liang¹¹.

7
8 ¹ NASA Goddard Space Flight Center, Greenbelt MD 20770. Jeff.morisette@nasa.gov,
9 301-614-5498.

10 ² University of New Hampshire, Complex Systems Research Center, Durham NH 03824.
11 andrew.richardson@unh.edu 603-868-7654.

12 ³ Department of Biology, Colorado State University, Ft. Collins, CO 80523.
13 aknapp@colostate.edu, 970-491-7010.

14 ⁴ Synapse Energy Economics Inc., 22 Pearl Street, Cambridge, MA 02139.
15 jfisher@synapse-energy.com, 617-661-3248 x245

16 ⁵ Center for Embedded Networked Sensing, UCLA 3563 Boelter Hall Los Angeles, CA
17 90095-1596. egraham@cens.ucla.edu, 310-206-2476

18 ⁶ Division, of Atmospheric Science, Western Regional Climate Center, Desert Research
19 Institute, Reno, NV 89512. John.Abatzoglou@dri.edu, 775-674-7064

20 ⁷ Environmental Sciences Division, Oak Ridge National Laboratory, Box 2008 MS-6407,
21 Oak Ridge, TN 37831-6407. wilsonbe@ornl.gov, (865) 574-6651.

22 ⁸ School of Natural Resources, Institute for the Study of Planet Earth, and Department of
23 Ecology and Evolutionary Biology, University of Arizona, Tucson, AZ 85742.

24 daveb@email.arizona.edu

25 ⁹ South Dakota State University, Brookings, SD 57007, Geoffrey.Henebry@sdstate.edu

26 ¹⁰ Department of Geography, University of Wisconsin-Milwaukee, Milwaukee, WI
27 53201-0413, jmhanes@uwm.edu, (773) 407-0083

28 ¹¹ Department of Geography, University of Wisconsin Milwaukee, Milwaukee, WI
29 53211, lliang@uwm.edu, (414)229-2436

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Abstract

Phenology is the study of recurring life-cycle events, of which classic examples include flowering by plants as well as animal migration. Phenological responses are increasingly relevant for addressing applied environmental issues. Yet, challenges remain with respect to spanning scales of observation, integrating observations across taxa, and modeling phenological sequences to enable ecological forecasts in light of future climate change. Recent advances that are helping to address these challenges include refined landscape-scale phenology estimates from satellite data, advanced instrument-based approaches for field measurements, and new cyber-infrastructure for archiving and distribution of products. These advances are aiding in diverse areas including modeling land-surface exchange, evaluating climate-phenology relationships, and aiding land management decisions.

In a nutshell

- Phenology focuses on the timing of biological events such as flower opening or bird migration.
- Predicting and assessing phenological responses can be challenging due to issues associated with spatial scale, differences across taxa, and forecasting in time.
- Satellite products, ground-based instrumentation, and cyber-infrastructure are all advancing phenological research.
- These advances are helping diverse research and application areas including assessing impacts of climate change and aiding land management decisions.

Panel 1. Author contribution for this article
JTM, ADR, AKK, JIF, EG, and JA co-conceived and co-developed the idea for the manuscript. All authors helped edit each draft. JTM refined the content and scope, led sections 1 and 5, provided figure 2, compiled all drafts, prepared the final version of the manuscript, and facilitated the gathering of contributions. ADR co-led section 4.1, contributed to section 3, provided figure 3, and led the development of figure 1. AKK co-led section 4.2. JIF led section 4.3. EG co-led section 3. JA co-led section 4.1 and 4.2. BEW co-led section 3. DDB co-refined the intellectual content and scope and helped connect the various contributions. GMH co-developed sections 2 and 3 and made significant contributions to figure 1. JMH and LL co-developed section 2.

1. Introduction

“In June as many as a dozen species may burst their buds on a single day. No man can heed all of these anniversaries; no man can ignore all of them.”

Aldo Leopold, *A Sand County Almanac*

The Leopold quote above only partially captures the profound complexity and ubiquity of seasonal biological events. Yet it is the ever-present and ever-changing cyclical nature of all living things, and their interactions with each other and the abiotic environment, that make phenology such a complex, intricate, and challenging field. Fortunately, this growing field is starting to address this complexity, and new advances are helping the ecological community address some key research and practical issues.

Phenology is the study of recurring life-cycle events that are initiated and driven by environmental factors. Examples of such events in plants, which are the primary focus of this article, include the onset of growth and photosynthesis in the spring and the senescence and abscission of deciduous vegetation in the fall. Since there is an interaction between plants' life-cycle events and temperature and precipitation (Menzel et al. 2005; Kathuroju et al. 2007), phenological studies integrate climate-biosphere relationships and can be used to document and evaluate the effects of climate change at both the individual species and aggregate levels (Schwartz et al. 2006; Cleland et al. 2007). Furthermore, observing and documenting changes in the phenologies of various species support efforts to reconstruct past climates and make predictions about biological responses to future climate scenarios (Chaine et al. 2004; Cook et al. 2005). Multiple and intricate links between plant phenology and variations in weather (short-term, days to weeks) and climate (long term, years to centuries) can also feed back to the atmosphere and climate system, as well as influence ecological interactions at multiple scales (individual to community to ecosystem) and trophic (producers to consumers) levels (Figure 1).

In this paper we first present some of the challenges for research in the field of phenology. We continue by describing some recent advances in phenological research. Finally, we describe how the knowledge gained from these advances can address some challenges and advance our understanding of phenological events and their connection to climate and management issues.

2. Cross-cutting challenges for phenological research

Phenological responses are increasingly relevant for addressing applied environmental issues, yet some key challenges require additional attention if phenological responses are to be used to effectively link climate drivers and land management:

1. Reconciling scales of observation
2. Integrating observations across taxa; and
3. Modeling phenological sequences to enable forecasting.

These challenges are considered cross-cutting issues because they can relate to research on any of the phenological topics shown in Figure 1. The first two issues have received

1 some attention in the literature while the third is expected to be an active area of future
2 research.

3
4 Phenological observations cover a wide **range of scales** (Table 1), and hence challenges
5 remain in relating observations from the scale of an individual leaf up to observations that
6 span landscapes. Monitoring of plants and animals has traditionally been conducted at
7 the ground level (Schwartz, 2003). Records of plant phenology have varying extents and
8 spans but are generally restricted to particular species at discrete locations (Caprio, 1966).
9 In the last 25 years, monitoring of the vegetated land surface by space-borne sensors has
10 introduced multiple new scales of observation, which now extend from ecosystems to
11 regions and continents (Reed et al., 1994; Zhang et al., 2003). Land surface phenology
12 can provide a synoptic view of vegetation dynamics (Moulin et al., 1997; de Beurs and
13 Henebry, 2004). Recent work on bioclimatic models track meteorological drivers to
14 simulate regional scale phenological responses to climatic variations (de Beurs and
15 Henebry 2005; Jolly et al. 2005; Schwartz et al., 2006; Zhang et al., 2007). Increasing
16 spatial extent often implies consideration of more than one species. For both remote and
17 proximate sensors, comprehending how discrete life events of multiple species will
18 impact various measurements remains an active area of research (Chuine et al., 2000;
19 Schwartz et al., 2002; Graham et al., 2006; Richardson et al., 2007).

20
21 **Integrating observations across taxa** requires a cooperative and cross-disciplinary
22 effort to synthesize extant phenological data from diverse sources; such synthesis across
23 taxa poses an analogous challenge to the previously discussed issues of spatial scale.
24 These must be brought together under a common conceptual framework of plant, insect,
25 and animal phenologies from terrestrial and aquatic environments across diverse biomes
26 (Schwartz, 2003; Cleland et al., 2007, Parmesan, 2007). Phenological studies are now
27 tackling some of the more complex and challenging issues associated with systems of
28 mixed dominance of woody and herbaceous plants (e.g., Harris et al. 2003), which pose
29 particular challenges in tracking the cause of phenological response, most notably after
30 major disturbance events (Rich et al. 2008).

31
32 **Forecasting** of phenological sequences is currently a key challenge if observations are to
33 be used to improve land management. Recent advances hold the promise of providing
34 much needed feedback to numerical weather prediction and biogeochemical models
35 (White and Nemani 2006; Kathuroju et al., 2007). Further efforts are needed to establish
36 sufficient understanding of phenological processes, based on present and past data, to
37 allow extrapolation into the future.

38 **3. Recent advances in phenological research**

39 There has been steady and continued improvements in satellite sensors and related data
40 processing algorithms, imaging tools used as *in-situ* sensors, and expanded connectivity
41 through the Internet. These have created three major advances that can contribute to
42 improved applications in phenology, especially with respect to the cross-cutting
43 challenges presented above:

- 44 1. Refined landscape-scale phenology estimates from satellite data

- 1 2. Novel, affordable and convenient instrument-based approaches to field
- 2 measurements and
- 3 3. Cyber-infrastructure to coordinate archiving and distribution of data products.

4
5 **Land surface phenology** is defined as the seasonal pattern of variation in the properties
6 of vegetated land surfaces on the regional or global scale and is typically characterized
7 using satellite remote sensing products (Friedl, et al., 2006). While the observed patterns
8 are related to biological phenomena, land surface phenology is distinct from traditional
9 definitions of vegetation phenology, which refer to specific life cycle events such as
10 budbreak, flowering, or leaf senescence and are based on *in-situ* observations of
11 individual plants or species. Land surface phenology provides aggregate information at
12 moderate (250-m) to coarse (25-km) spatial resolution; which relates to the timing of
13 vegetation growth, senescence, and dormancy and associated surface phenomena at
14 seasonal and inter-annual scales (Friedl, et al., 2006). An example land surface phenology
15 product, length of the 2005 growing season, is shown in Figure 2; where broad gradients
16 related to latitude, elevation, and vegetation type can be discerned.

17
18 Currently, data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS)
19 are being used to produce a global phenology product at 1km spatial resolution (Zhang et
20 al. 2003). New efforts are underway to use MODIS data to produce a 250m-spatial
21 resolution phenology product for North America (Figure 2, MODIS for NACP, the North
22 American Carbon Program: no date). Moving from 1km to 250m represents a 16-fold
23 increase in resolution. This will help show more local patterns related to microclimate,
24 species composition, disturbance and land use. Also, research is being directed to
25 consider phenology across a range of scales (Fisher and Mustard, 2007). Finally, public-
26 domain software is now available to extract phenology metrics from satellite time-series
27 data (Jönsson and Eklundh, 2004), thus allowing researchers to more easily conduct their
28 own specific land surface phenology analysis.

29
30 Modeling efforts to characterize land surface phenology have generally relied on simple
31 functions of meteorological drivers such as accumulated growing degree-days (de Beurs
32 and Henebry, 2005), minimum temperature, photoperiod, vapor pressure deficit (Jolly et
33 al. 2005), and minimum relative humidity (Brown and de Beurs, accepted). Forecasting
34 land surface phenology with these approaches has been explored (White and Nemani
35 2006) but models are not yet adequate for long-term prognostication.

36
37 **Advanced field monitoring devices** that can provide phenological information are
38 becoming less expensive, easier to use, and smaller in size, even as they have expanded
39 in capacity. With newly-developed radiometric sensors and digital imagers, phenological
40 monitoring can now move from a labor-intensive pursuit to a state approaching
41 automation. These methods have been described as "near" remote sensing (Richardson et
42 al., 2007). Indeed, imaging with digital cameras (capable of detecting red, green, blue, .
43 and, in some cases, near-infrared, channels) is now commonplace and examples of their
44 use in agriculture and ecology is growing (Goddijn and White 2006). Timing and
45 duration of flowering has been measured with imagers (Adamsen et al., 2000). Large-
46 scale networks of battery-operated wireless imagers have now become technologically

1 feasible for use in tight areas that are hard to observe without disturbing the environment
2 being monitored (Rahimi et al. 2006). For example, Ko et al. (2007) used imaging
3 hardware placed in avian nest boxes to automatically detect bird presence and count eggs
4 over the nesting cycle. Automated discovery of phenological events using imagery has
5 recently been successful through a combination of low-level, robust image analysis with
6 more complex machine learning algorithms. Examples include automatically identifying
7 and counting individual flowers from images captured in a 5000 m² field with a pan-tilt-
8 zoom camera and calculating of leaf areas of Rhododendron in a temperate forest using a
9 camera on a mobile platform (Figure 3, Graham, unpublished data).

10
11 Recent studies have combined automatic imaging, simple color analysis, and
12 sophisticated CO₂ measurements to quantify carbon cycles at a range of scales (from
13 patches of moss, Graham et al. 2006, to large stands of deciduous trees, Richardson et al.
14 2007). Figure 4 shows images from a networked digital webcam at the Bartlett
15 AmeriFlux site in the White Mountain National Forest of New Hampshire. The color
16 channel information extracted from these images is used to quantitatively track seasonal
17 changes in phenology of the maple-beech-birch canopy, and these have been related to
18 tower-based measurements of surface-atmosphere exchanges (via eddy covariance
19 methods, Richardson et al., 2007). The image sequence shows early spring, prior to leaf
20 out; late spring, when the canopy is nearly fully developed; and early autumn, at the peak
21 of fall color.

22
23 Features such as remote pan, tilt, and zoom of fixed-position cameras, as well as motion
24 detection and automatic image acquisition and web posting, offer opportunities for
25 researchers not only to obtain scientifically valuable data but also to engage the public
26 through outreach and educational activities. The list of potential applications will
27 undoubtedly grow as sensor technologies become even more applicable, accessible, and
28 affordable.

29
30 **Cyber-infrastructure** plays a critical role in the collection, management, and
31 dissemination of information in modern research efforts, particularly as these efforts
32 involve: multiple research entities, data collected across a range of spatial and temporal
33 scales, and study complex systems (Atkins et al., 2003). With the recent development of a
34 United States National Phenology Network (USA-NPN, no date: Betancourt et al. 2007),
35 the cyber-infrastructure challenge of coordinating numerous data streams, collected
36 across a range of spatial and temporal scales, becomes paramount. This network must be
37 able to take data from at least three different types of providers: (1) research and
38 monitoring networks (e.g. Ameriflux, the USA National Science Foundation's Long
39 Term Ecological Research sites, Monarch Watch, Hummingbird Monitoring Network,
40 the Global Learning and Observations to Benefit the Environment Program, etc.), (2)
41 professionals in agricultural and land management activities, and (3) citizen scientists
42 from a wide variety of backgrounds and interests. Indeed, a flagship USA-NPN effort,
43 "Project Budburst" (2007), is highly successful in using the Internet and a consistent set
44 of protocols to create a large network of citizen scientists interested in contributing to a
45 phenological database. Studies of citizen science networks (Cooper et al. 2007) outline
46 such issues as integration of citizen science data with other sources, concerns about

1 quality of data, and incentives for researchers. Nevertheless, data from citizen sources as
2 well as other research and monitoring networks must feed into a broad set of end users,
3 including researchers, land managers, and policy decision makers. A key cyber-
4 infrastructure challenge for the USA-NPN, as well as the broader phenology community,
5 is how these multi-scale observations can be integrated into a cohesive data framework
6 that will provide access to a broad and dense network of raw observations of defined
7 quality, as well as synthesized higher-order products derived from these observations.

8
9 A number of recent cyber-infrastructure developments will help the phenological
10 community achieve these goals. There are now common tools for managing ecological
11 data and metadata (Michner, 2006). In addition, the work in astronomy to develop virtual
12 observatories is beginning to migrate into earth science and there is much progress being
13 made in combining data from multiple places into virtual observatories (McGuinness et
14 al., in press). As a result, there is growing pressure from sponsoring agencies on the
15 various earth observing networks to work together to enhance data sharing to meet
16 societal needs (e.g. Adang, 2006).

17 **4. Research and practical implications**

18 How do these recent advances address the cross-cutting challenges listed above to
19 address key environmental challenges of concern? Here, we provide examples in the
20 areas of climate research and land management.

21 ***4.1 Interactions between changing phenologies and climate change***

22 In the context of global climate change the “phenology – climate connection” presents a
23 challenge to ecologists and climatologists alike. The challenge of scale is particularly
24 critical here since phenological observations are typically done at the plant level, while
25 climate-change research has focused on much larger scales. It is crucial for the
26 ecological community to better quantify phenological responses to climatic drivers.
27 Likewise, it is crucial for the climate community to better quantify the influence of
28 phenology on climate (e.g., through surface-atmosphere exchanges). Ample evidence
29 exists that 20th century climate change has altered phenologies (Schwartz et al, 2006;).
30 And land surface phenology can be coupled with assimilated meteorological information
31 to explore relationships across large areas (Zhang et al., 2007). Given the increasing rate
32 of climate change projected in the 21st century, there is a pressing need to establish the
33 spatial and temporal phenological response to climate change. Improving our
34 understanding, across all taxa and scales, of intra- and inter-species phenological
35 sensitivity to climate change will help ecologists identify vulnerable ecosystems and
36 potential ecological asynchronies (e.g., Williams et al., 2007).

37
38 Questions remain unanswered as to how the multivariate influence of meteorological
39 conditions (e.g., temperature, precipitation, solar radiation) drives phenology. In
40 addressing these questions, it is important to disaggregate phenological response to
41 climate change from that associated with climate variability. For example, it is critical to
42 understand the influence of extreme events (e.g., heat waves, hard freezes, drought) and
43 dominant modes of climate variability (e.g., El Niño-Southern Oscillation, Northern

1 Annular Mode) on phenological events, as well as the “memory” of flora and fauna to
2 antecedent conditions.
3
4 While the causal link between climate and phenology is conceptually straightforward,
5 less appreciated is the potential influence of phenology on climate (Alessandri et al.,
6 2007). Changes in the surface energy balance, induced by phenology, act to modify local
7 surface temperatures, humidity, and regional circulation regimes. Given the potentially
8 important role of phenology on local climate through physical feedback processes, it is
9 essential to include phenological changes as part of the land-surface atmosphere
10 interaction in the next generation of regional climate models. Similarly, accounting for
11 phenology in hydrologic models may further improve the representation of coupling
12 between the land-surface and atmosphere to improve local and regional analysis.
13
14 Feedbacks between vegetation and the lower atmosphere occur across a range of
15 timescales, from minutes (e.g., transpiration) to centuries (e.g., species distribution,
16 Pielke et al., 1998; see also Figure 1). Seasonal changes in the phenology of deciduous
17 canopies, especially spring green-up and autumn senescence, can alter both physical
18 (surface energy balance and surface roughness) and biogeochemical (nutrient uptake and
19 release; photosynthesis and carbon sequestration) properties of the land surface. Together
20 these have consequences for the structure of the planetary boundary layer, ambient
21 surface temperature and humidity, cloud physics and precipitation patterns, soil thermal
22 properties, and levels of atmospheric CO₂ (e.g., Schwartz 1992).
23
24 In order to best resolve the intricate details that govern both present day and future
25 climate processes, climate models must account for bidirectional feedbacks between the
26 biosphere and the atmosphere (Pitman 2003). This requires the implementation of
27 coupled dynamic global vegetation – climate models (Kucharik et al., 2006). Phenology
28 schemes currently implemented in state-of-the-art land surface schemes; e.g. Integrated
29 Biosphere Simulator (IBIS), Simple Biosphere Model, version 2 (SiB2), Community
30 Land Model (CLM), are inadequate to resolve the complexities of surface-atmosphere
31 exchanges associated with phenology. Either phenology is prescribed or driven in the
32 models. When prescribed, phenology is not responsive to environmental drivers. When
33 driven by the model, phenology predictions tend to be biased because the models use a
34 limited number of plant functional types and overly simple representations of ecosystem
35 processes (Kucharik et al., 2006).
36
37 The advances in phenological research can improve our understanding of the climate-
38 phenology connection. Improvement and standardization of land surface phenology
39 products can facilitate the climate modeling community’s use of such data. Coincident
40 field monitoring of both phenological and meteorological observations will help inform
41 the coupling between the two. Finally, advances in sensors and cyber-infrastructure can
42 ensure that a full suite of both phenological *and* climatic measurements can be collected
43 in an integrated and consistent fashion across a wide range of sites. These measurements,
44 together with improved land surface phenology products and assimilated meteorological
45 data are the required components to improve our understanding of the phenology-climate
46 change connection and sensitivities at local to regional scales.

1 **4.2 Land use and management**

2 Many ecosystem processes, from which we derive economic benefit, depend on climatic
3 patterns and follow seasonal cycles (Figure 1). The ability to predict both seasonal and
4 inter-annual variation in the phenology of a range of ecosystems has significant
5 management implications for grazing, forestry and agriculture, pest management, disease
6 vectors and allergens, energy consumption, water availability and conservation, and
7 tourism and hunting, amongst others applications. In each of these disciplines, improved
8 understanding and forecasting of phenologies may be able to improve management
9 techniques and, in some cases, also reduce the risk of undesirable outcomes (e.g., disease
10 outbreaks, crop failure, or forest fires). For example, grass protein content falls rapidly
11 through early summer as the grasses mature and senesce. By timing grazing to
12 phenology, forage quality can be maintained longer prior to senescence (Ganskopp et al.,
13 2007) and managers can selectively graze to optimize returns and sustainability. In terms
14 of public health, better phenological forecasting would be relevant for improved
15 prophylactic treatment of asthma and allergies. Early work, correlating climate with
16 pollen production (e.g. Subiza et al., 1992) found that near-term pollen abundances could
17 be predicted with reasonable accuracy. Finally, Chuine and Belmonte (2004) used
18 species-specific temperature-driven phenological models to predict pollen abundance for
19 13 highly allergenic species in France and Spain with moderate success. This is bound to
20 be an active area of future research.

21
22 For land management, the predominant challenge is related to prediction. Managers need
23 to know how today's management decisions will impact tomorrow's ecosystem
24 processes. But issues of scale and taxa are also relevant. For most land management
25 scenarios, the management unit includes many individual plants or animals. Thus
26 individual observations must be scaled up to the management unit. Also, interactions
27 between ecosystem processes implies that management of one domain will effect others.
28 So, understanding phenological response across taxa can be important.

29
30 New work in land surface phenology (Fisher and Mustard, 2007, MODIS for NACP (no
31 date) provides satellite-derived phenology data at a higher spatial resolution. While land
32 managers are likely to be more familiar with measurements collected at a local scale
33 (individual plant or animal), when these measurements are coupled with higher-
34 resolution landscape phenology data there may be new insights on how local activities
35 relate to the larger management area. Also, a better link between climate and phenology
36 can help connect existing climate forecasts to phenological forecasts. By having
37 predictions of both future climate and future phenology, land managers will have added
38 insight about the ecosystem services relevant to them.

39 **5. Conclusion**

40 As long as there are living organisms on our planet, we can expect to see seasonal
41 patterns in life cycle events. Understanding these events define the scope of phenological
42 research. The better we understand these cycles, the better we will understand the world
43 around us. This understanding can help us adapt to climate change and better manage our
44 natural resources.

45

1 Remote sensing of land surface phenology will continue to be refined and coupled with
2 more traditional ground observations. Retrospective studies will extend phenology
3 records further back in time. Field sensors will become more affordable and accessible,
4 thereby allowing a full suite of measurements to be collected across globally distributed
5 science, management, and citizen scientist networks. Cyber-infrastructure will enable
6 these data to be synthesized and utilized by increasingly advanced spatial-temporal
7 analysis and modeling activities, perhaps in a manner analogous to the way in which real-
8 time meteorological observations are fed into numerical models to provide continually
9 updated weather forecasts for distribution to a wide range of end users.

10
11 Promoting an awareness of the synergy and connectedness of these activities will help the
12 research and management communities make the most of the new information. The USA-
13 NPN will promote such awareness (Betancourt et al., 2007). The USA-NPN has been
14 established to help coordinate phenological research in the United States and connect that
15 research with the international community. Given the advances and issues presented
16 here, it is certainly a timely idea now blooming with possibilities.

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26 article.

1 **7. References**

- 2 Adang T. 2006. Global Earth Observation System of Systems (GEOSS): Initial Actions
3 to Enhance Data Sharing to Meet Societal Needs. Eos Trans AGU 87(36) Jt. Assem.
4 Suppl., Abstract IN52A-05.
- 5 Adamsen FJ, Coffelt TA, Nelson JM, Barnes EM, and Rice RC. 2000. Method for Using
6 Image from a Color Digital Camera to Estimate Flower Number. Crop Science 40:704-
7 709.
- 8 Alessandri A, Gualdi S, Polcher J, and Navarra A., 2007: Effects of Land Surface-
9 Vegetation on the Boreal Summer Surface Climate of a GCM. *J. Climate*, **20**, 255–278.
- 10 Atkins DE, Drogemaler KK, Feldman SI, Garcia-Molina H, Klein ML, Messerschmitt
11 DG, Ostriker JP and Wright MH. 2003. Revolutionizing Science and Engineering
12 through Cyberinfrastructure. USA National Science Foundation.
13 <http://www.nsf.gov/od/oci/reports/atkins.pdf>. Viewed 7 Dec 2007.
- 14 Brown M and de Beur KM. Evaluation of multi-sensor semi-arid crop season parameters
15 based on NDVI and rainfall. Remote Sensing of Environment. In press.
- 16 Betancourt JL, Schwartz MD, Brashears DD, Brewer CA, Frazier G, Gross JE; Mazer
17 SJ, Reed BC, and Wilson BE. 2007. Evolving Plans for the USA National Phenology
18 Network. Eos Trans. AGU 88(19) 211.
- 19 Caprio JM. 1966. Pattern of Plant Development in the Western United States (Bulletin
20 607). Bozeman, MT: Montana State University.
- 21 Chuine I, Cambon G, and Comtois P. 2000. Scaling phenology from the local to the
22 regional level: advances from species-specific phenological models. Global Change
23 Biology 6 943-952.
- 24 Chuine I and Belmonte J. 2004. Improving prophylaxis for pollen allergies: Predicting
25 the time course of the pollen load of the atmosphere of major allergenic plants in France
26 and Spain. Grana. 43:1–17.
- 27 Chuine I, Yiou P, Viovy N, Seguin B, Daux V and Le Roy Ladurie E. 2004. Grape
28 ripening as a past climate indicator. Nature 432: 289.
- 29 Cleland EE, Chuine I, Menzel A, Mooney HA, and Schwartz MD. 2007. Shifting plant
30 phenology in response to global change. Trends in Ecology & Evolution 22 357-365.
- 31 Cook B, Smith TM, and Mann ME. 2005. The North Atlantic Oscillation and regional
32 phenology prediction over Europe. Global Change Biology 11: 919-926.
- 33 Cooper CB, Dickinson J., Phillips T, and Bonney R.. 2007. Citizen science as a tool for
34 conservation in residential ecosystems. Ecology and Society 12(2): 11. [online] URL:
35 <http://www.ecologyandsociety.org/vol12/iss2/art11/>
- 36 de Beurs KM and Henebry GM. 2004. Land surface phenology climatic variation and
37 institutional change: Analyzing agricultural land cover change in Kazakhstan. Remote
38 Sensing of Environment 89 497-509.

- 1 de Beurs KM and Henebry GM. 2005. Land surface phenology and temperature variation
2 in the International Geosphere Biosphere Program high-latitude transects. *Global Change*
3 *Biology* 11 779-790.
- 4 Fisher JI and Mustard JF. 2007. Cross-scalar satellite phenology from ground Landsat
5 and MODIS data. *Remote Sensing of Environment* 109 261-273.
- 6 Friedl M, Henebry GM, Reed B., Huete A, White M, Morisette JT, Nemani R, Zhang
7 XY, and Myneni R. 2006. Land Surface Phenology NASA white paper.
8 <http://lcluc.umd.edu/Documents/land-esdr.asp>. Viewed 7 Dec 2007.
- 9 Ganskopp D, Aguilera L, and Vavra M. 2007. Livestock Forage Conditioning Among Six
10 Northern Great Basin Grasses. *Rangeland Ecology & Management*. 60 1:71-78.
- 11 Goddijn LM and White M. 2006. Using a digital camera for water quality measurements
12 in Galway Bay. *Estuarine Coastal and Shelf Science* 66:429-436.
- 13 Graham EA, Hamilton MP, Mishler BD et al. 2006. Use of a networked digital camera to
14 estimate net CO₂ uptake of a desiccation tolerant moss. *International Journal of Plant*
15 *Sciences* 167:751-758.
- 16 Harris AT, Asner GP, and Miller ME. 2003. Changes in vegetation structure after long-
17 term grazing in pinyon-juniper ecosystems: integrating imaging spectroscopy and field
18 studies. *Ecosystems* 6: 368-383.
- 19 Jolly WM, Nemani R, and Running SW. 2005. A generalized bioclimatic index to predict
20 foliar phenology in response to climate. *Global Change Biology* 11 619-632.
- 21 Jönsson P. and Eklundh L.. 2004. TIMESAT-a program for analyzing time-series of
22 satellite sensor data. *Computers & Geosciences* 30: 833-845.
- 23 Kathuroju N, White MA, Symanzik J, Schwartz MD, Powell JA and Nemani RR. 2007.
24 On the use of the advanced very high resolution radiometer for development of
25 prognostic land surface phenology models. *Ecological Modeling* 201:144-156.
- 26 Ko T, Charbiwala ZM, Ahmadian S et al. 2007. Exploring tradeoffs in accuracy energy
27 and latency of Scale invariant feature transform in wireless camera networks. First
28 ACM/IEEE international conference on distributed smart cameras (icdsc-07) September
29 25-28, Vienna, Austria.
- 30 Kucharik CJ, Barford CC, El Maayar M, Wofsy SC, Monson RK, and Baldocchi DD.
31 2006. A multiyear evaluation of a Dynamic Global Vegetation Model at three AmeriFlux
32 forest sites: Vegetation structure phenology soil temperature and CO₂ and H₂O vapor
33 exchange. *Ecological Modeling* 196: 1-31.
- 34 McGuinness D, Fox P, Cinquini L, West P, Garcia J, Benedict JL, and Middleton D. The
35 Virtual Solar-Terrestrial Observatory: A Deployed Semantic Web Application Case
36 Study for Scientific Research. *Proceedings of Innov. Applic. Artif. Intell.*, In press.
- 37 Meier U. 2001. Growth stages of mono- and dicotyledonous plants. German Federal
38 Biological Research Centre for Agriculture and Forestry, BBCH-Monograph, Blackwell
39 Science, Berlin.

- 1 Menzel A, Estrella N, and Testka A. 2005. Temperature response rates from long-term
2 phenological records. *Climate Research* 30: 21-28.
- 3 Michner WK. 2006. Meta-Information Concepts for Ecological Data Management.
4 *Ecological Informatics* 1(1)3-7.
- 5 Miller-Rushing AJ, Primack RB, Primack D, and Mukunda S. 2006. Photographs and
6 herbarium specimens as tools to document phenological changes in response to global
7 warming. *American Journal of Botany* 93 1667-1674.
- 8 MODIS for NACP. (nd) accweb.nascom.nasa.gov. Viewed 7 Dec 2007.
- 9 Moulin S, Kergoat L, Viovy N, and Dedieu G. 1997. Global-scale assessment of
10 vegetation phenology using NOAA/AVHRR satellite measurements. *Journal of Climate*
11 10 1154-1170.
- 12 Parmesan C. 2007. Influences of species latitudes and methodologies on estimates of
13 phenological response to global warming. *Global Change Biology* 13 1860-187.
- 14 Pielke RA, Avissar R, Raupach M, Dolman AJ, Zeng X, and Denning AS. 1998.
15 Interactions between the atmosphere and terrestrial ecosystems: influence on weather and
16 climate. *Global Change Biol.* 4: 461-475.
- 17 Pitman AJ. 2003. The evolution of and revolution in land surface schemes designed for
18 climate models. *Int. J. Climatol.* 23: 479-510.
- 19 Project Budburst. 2007. Project Budburst: A National Phenology Network Field
20 Campaign for Citizen Scientists. www.budburst.org. Viewed 14 March 2008.
- 21 Rahimi MS Ahmadian S Zats D et al. 2006. Magic of Numbers in Networks of Wireless
22 Image Sensors. Workshop on Distributed Smart Cameras (DSC), October 31, 2006
23 Boulder, CO, US.
- 24 Reed BC, Brown JF, Vanderzee D, Loveland TR, Merchant JW, and Ohlen D.O. 1994.
25 Measuring Phenological Variability from Satellite Imagery. *Journal of Vegetation*
26 *Science* 5 703-714.
- 27 Rich PM, Breshears DD, and White AB. 2008. Phenology of Mixed Woody-Herbaceous
28 Ecosystems Following Extreme Events: Net and Differential Responses. *Ecology*. In
29 press.
- 30 Richardson AD, Jenkins JP, Braswell BH et al. 2007. Use of digital webcam images to
31 track spring green-up in a deciduous broadleaf forest. *Oecologia* 152 (2): 323-334.
- 32 Schwartz MD. 1992. Phenology and springtime surface-layer change. *Monthly Weather*
33 *Rev.* 120: 2570-2578.
- 34 Schwartz M. D. Reed B. and White M. A. 2002. Assessing satellite-derived start-of-
35 season (SOS) measures in the conterminous USA. *International Journal of Climatology*
36 22 1793-1805.
- 37 Schwartz MD. 2003. *Phenology: an Integrative Environmental Science* Kluwer
38 Academic Publishing Dordrecht The Netherlands.
- 39 Schwartz MD, Ahas R, and Aasa A. 2006. Onset of spring starting earlier across the
40 Northern Hemisphere. *Global Change Biology* 12: 343-351.

- 1 Subiza J, Masiello JM, Subiza JL, Jerez M, Hinojosa M, and Subiza E. 1992. Prediction
2 of annual variations in atmospheric concentrations of grass pollen. A method based on
3 meteorological factors and grain crop estimates. *Clinical & Experimental Allergy*. 22
4 5:540-546.
- 5 USA-NPN. (nd). United States National Phenology Network. www.usanpn.org. Viewed
6 14 March 2008
- 7 White MA and Nemani RR. 2006. Real-time monitoring and short-term forecasting of
8 land surface phenology. *Remote Sensing of Environment* 104:43-49.
- 9 Williams JW, Jackson ST, and Kutzbach JE. 2007. Projected distributions of novel and
10 disappearing climates by 2100 AD *PNAS* 104: 5738 - 5742.
- 11 Zhang XY, Friedl MA, Schaaf CB, Strahler AH, Hodges JCF, Gao F, Reed BC and
12 Huete A. 2003. Monitoring vegetation phenology using MODIS. *Remote Sensing of*
13 *Environment* 84 471-475.
- 14 Zhang XY, Tarpley D. and Sullivan JT. 2007. Diverse responses of vegetation to a
15 warming climate. *Geophysical Research Letters* 34:L19405.

| Spatial Scale | Data Sources | Examples | Metrics | Advantages | Limitations |
|---|--|---|--|--|---|
| Plot ($< 10 \text{ km}^2$) | Observational networks; historical documents; non-conventional records; controlled experiments | European Phenology Network (EPN), century long; Kyoto cherry blossom records, millennium long (Schwartz, 2003); Arboretum fixed date photographing (Miller-Rushing et al., 2006). | Mainly dates (in day of year) of critical life cycle events; BBCH scale* for economical plants in Germany. | In-situ accuracy; long time span; regional extent. (Varying with different datasets) | Discrete point data separated from local ecological context; limited geographic extent. |
| Landscape (Visually distinct patches of vegetated land; $10 - 10^2 \text{ km}^2$) | Intensive research sites | Ameriflux flux tower sites (Kuchark et al., 2006). | Customized continuous life cycle protocol with fine details | Improved in-situ accuracy with pixel sized landscape representativeness. | Labor intensive; short temporal coverage (2006-present). |
| Regional ($10^2 - 10^5 \text{ km}^2$) | Bioclimatic Modeling; | Spring Indices (SI), based on cloned species (Schwartz et al., 2006). | SI First Leaf and SI First Bloom | Standardized response, regional coverage | Limited to temperate land regions with weather data coverage; model inadequacy. |
| Continental to Global ($> 10^5 \text{ km}^2$) | Spaceborne Sensors; Data Assimilation Systems | Vegetation indices from AVHRR (since 1982, Moulin et al., 1997); MODIS (since 2000, Zhang et al., 2003). | Start of season (SOS), end of season (EOS), and growing season length; peak VI position in thermal time | Integrated land surface signals; regional to global coverage. | Sensitive to method; multiple sources of noise: clouds, sensor calibration and artifacts; trade-off between spatial and temporal resolutions. |

*Biologische Bundesanstalt, Bundessortenamt and CHemical industry (Meier,2001)

Table 1: Phenological Monitoring Across Scales

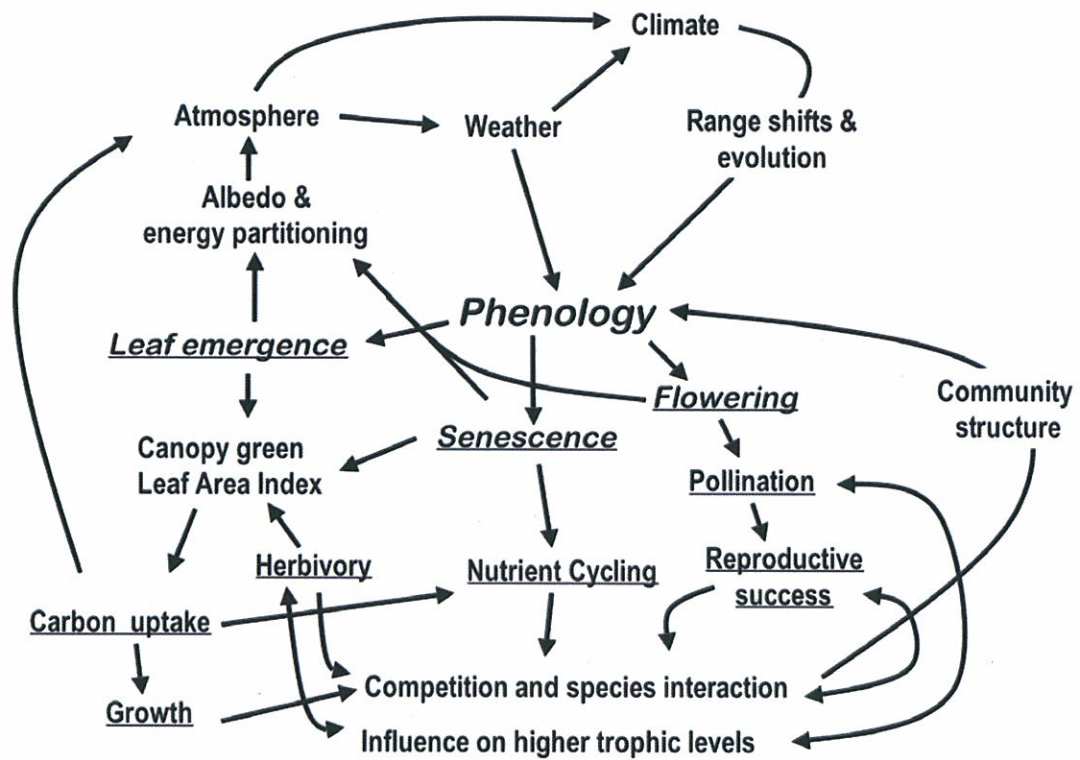


Figure 1: Conceptual model showing some of the ways in which plant phenology in temperate climates is intricately linked to variation in weather (short-term, days to weeks) and climate (long term, years to centuries), feeds back to the atmosphere and climate system, and influences ecological interactions at multiple scales (individual to community to ecosystem) and trophic (producers to consumers) levels. Underline denotes ecosystem services from which management or economic benefits are derived.

Length of Growing Season for 2005

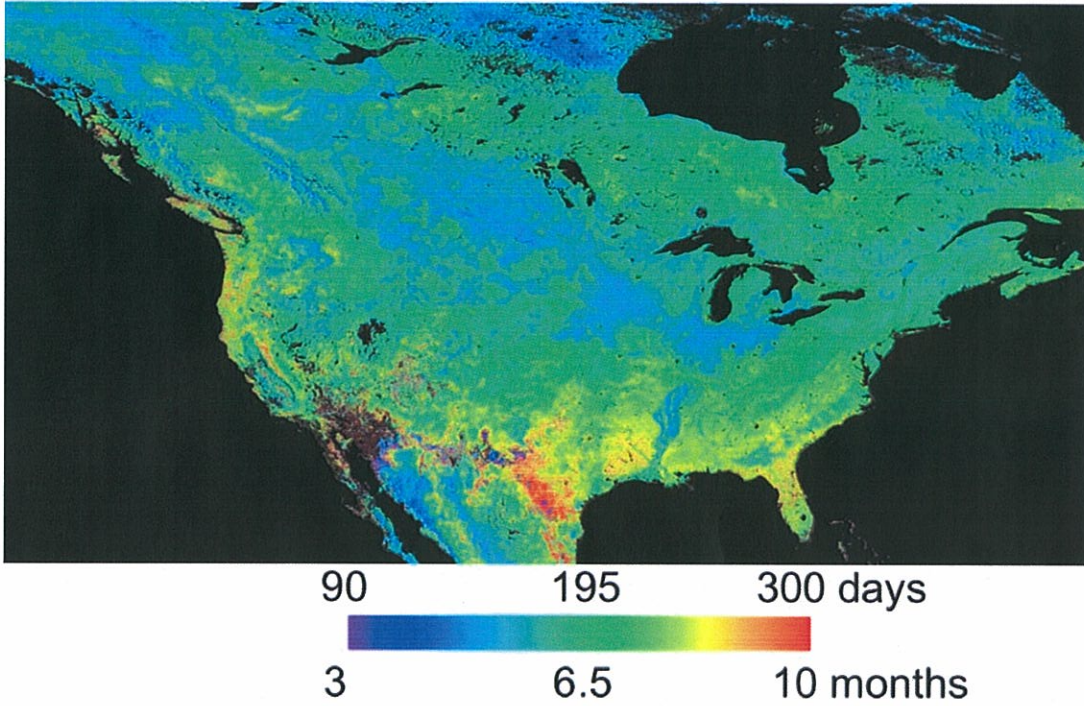


Figure 2: Example phenology product derived from 250m time series data from NASA's Moderate Resolution Image Spectroradiometer (MODIS for NACP, no date).

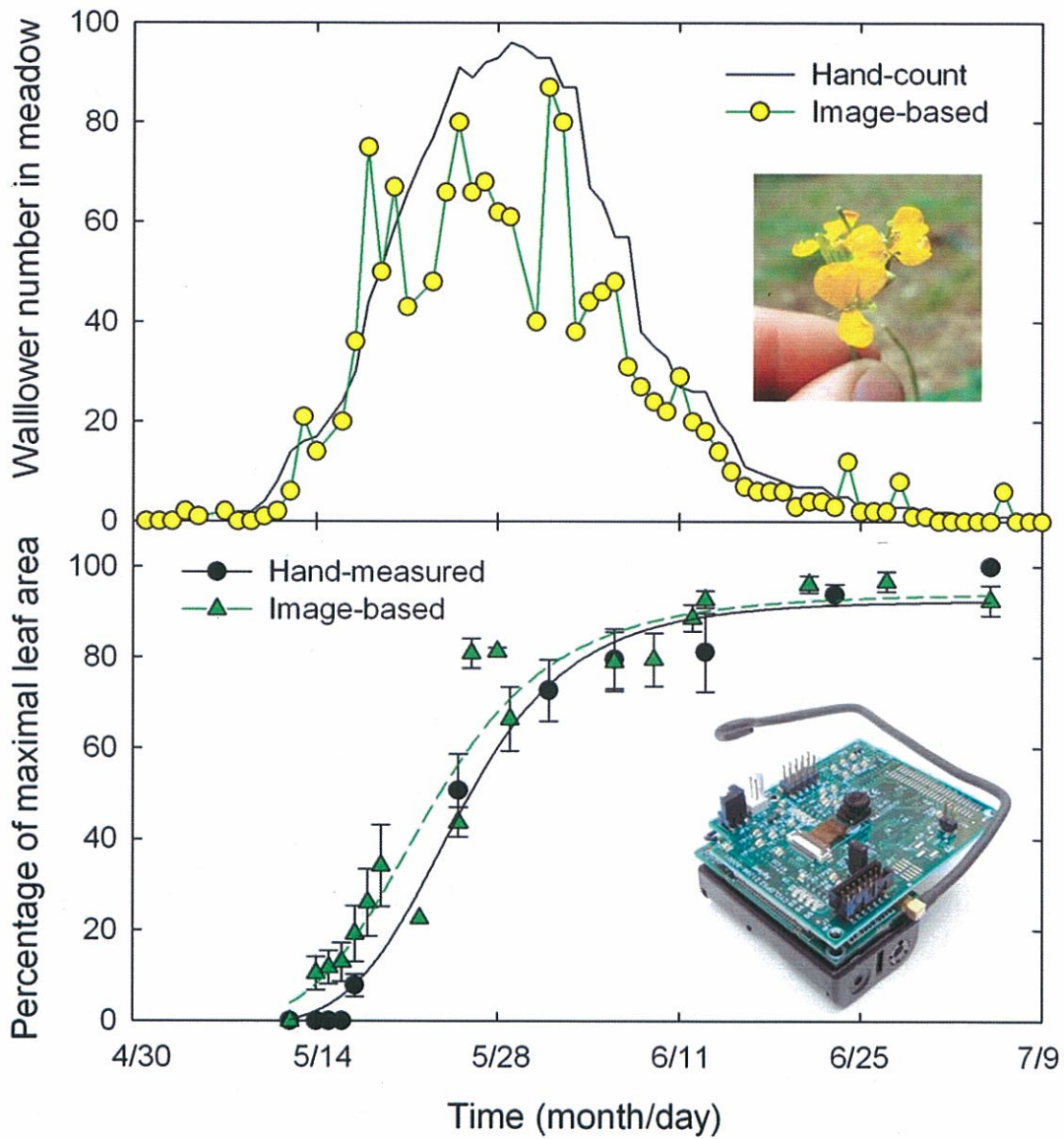


Figure 3: Example of automatically identifying and counting individual flowers from images captured in a 5000 m² field with a pan-tilt-zoom camera (top panel) and calculating of leaf areas of Rhododendron in a temperate forest using a camera on a mobile platform (bottom panel). Inset is an example of a small, wireless, battery-powered camera that can be networked for automated image retrieval (<http://research.cens.ucla.edu/>).

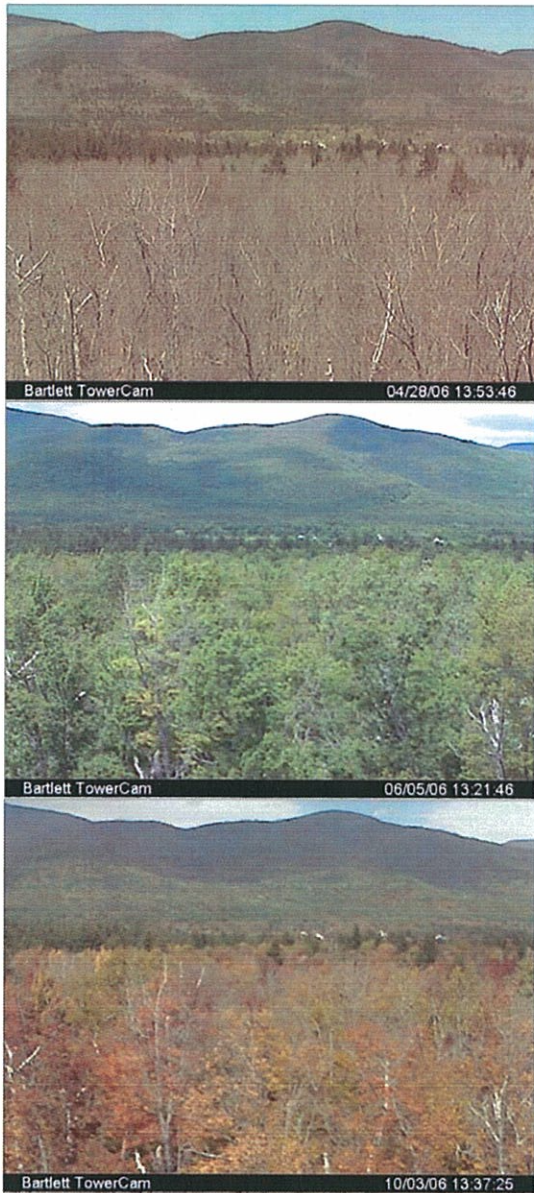


Figure 4: Webcam images from a field site in the White Mountain National Forest: a: early spring, b: late spring, and c: early autumn.