Using phenocams to monitor our changing Earth: toward a global phenocam network

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Rapid changes to the biosphere are altering ecological processes worldwide. Developing informed policies for mitigating the impacts of environmental change requires an exponential increase in the quantity, diversity, and resolution of field-collected data, which, in turn, necessitates greater reliance on innovative technologies to monitor ecological processes across local to global scales. Automated digital time-lapse cameras – "phenocams" – can monitor vegetation status and environmental changes over long periods of time. Phenocams are ideal for documenting changes in phenology, snow cover, fire frequency, and other disturbance events. However, effective monitoring of global environmental change with phenocams requires adoption of data standards. New continental-scale ecological research networks, such as the US National Ecological Observatory Network (NEON) and the European Union's Integrated Carbon Observation System (ICOS), can serve as templates for developing rigorous data standards and extending the utility of phenocam data through standardized ground-truthing. Open-source tools for analysis, visualization, and collaboration will make phenocam data more widely usable.

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Understanding and adapting to global environmental change is one of the major challenges of the 21st century. Among the most visible outcomes of alterations in environmental properties and processes are shifts in phenology (the seasonal activity of plants and animals). Climate-driven changes in plant phenology, for instance, can have ecosystem-wide impacts, ranging from altered carbon budgets and productivity (Ciais *et al*. 2013) to effects on pollinators (Bellard *et al*. 2012) and crop yields (Lobell *et al*. 2011). However, quantifying such changes over large areas at appropriate timescales is challenging, even with satellite remote-sensing products.

In a nutshell:

- Automated digital time-lapse cameras (phenocams) are powerful tools for recording and understanding ecological responses to global environmental change
- Documenting such changes in the environment is critical for informed decision making and to reduce or counteract negative outcomes
- Advances in digital imaging, computing, and networking technologies provide new opportunities for phenological monitoring, and the availability of low-cost, easy-to-use camera hardware brings the goal of developing a global environmental monitoring network within reach of most researchers
- Standardization of practices and metadata recording will improve the utility of phenocams and facilitate their integration with other monitoring methods

Repeat photography has been used to detect and document changing landscapes since the earliest days of photography. Collections of photographs acquired from fixed locations have largely framed our understanding of global change processes, including desertification, glacial retreat, and alterations in land cover and land use (Webb 2010). Until recently, ground-based collection of time-series image data over long periods was expensive and technically challenging, but advancements in imaging and communication technologies are enabling continuous, widespread monitoring of the environment.

As high-quality, low-cost digital cameras have become more widely available, interest in applying these tools to ecological studies has expanded. "Near-surface remote sensing" utilizes data from automated ground-based sensors to augment conventional remote-sensing data, and to help bridge the gap between satellite monitoring and traditional on-the-ground observations. "Phenocams" – digital cameras configured to capture time-lapses – can provide a permanent, continuous visual record of the environment over years or even decades. The term "PhenoCam" was first coined to describe a collaborative, regional-scale camera

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network in the northeastern US that was used to track seasonal changes in the phenology of forested ecosystems (Richardson *et al.* 2009; phenocam.sr.unh.edu), but "phenocam" now refers more generally to any digital camera used for time-lapse or repeat photography to study phenological and other environmental changes. Information captured by phenocams can provide essential baseline data for tracking such changes, as well as for monitoring conservation and restoration efforts. Phenocams are ideal for documenting alterations in plant phenology, animal migrations, and biotic and abiotic disturbance events. They can also be calibrated to estimate carbon, water, and nutrient fluxes, and many other processes relating to global change (Richardson *et al.* 2007, 2013a; Ahrends *et al.* 2009; Morisette *et al.* 2009; White *et al.* 2009).

Phenocam use typically falls into two categories: (1) long-term monitoring (years to decades) and (2) short-term field campaigns (days to months). In the former case, the emphasis is generally on choosing robust, automated camera hardware and maintaining a continuous image record of a consistent field of view (FOV) for as long as possible. In the latter case, the research question often dictates what camera hardware is to be used (eg specialized cameras filtered for specific wavebands; WebTable 1). Here, we focus primarily on phenocams used for long-term monitoring, as this type of data is generally more suitable for cross-scale comparison and standardization.

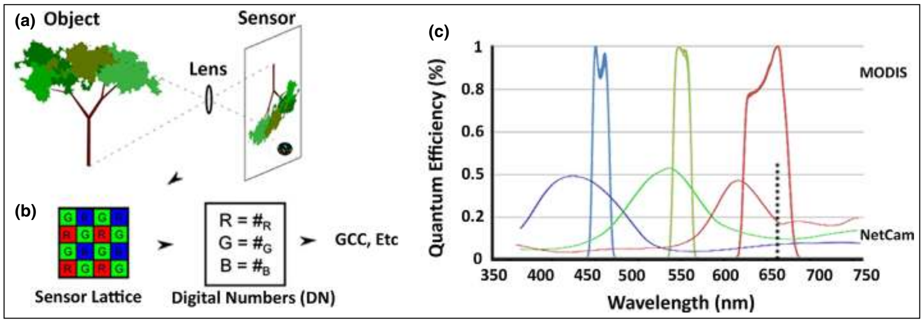

Figure 1. *(a and b) How camera sensors work. (a) In a typical imaging system, a lens concentrates light onto a digital chip organized in a lattice structure sensitive to one or more spectral bands (b). Light hitting each "pixel" on the sensor is recorded as a numeric value quantifying the intensity of the sensor's electrical response to light at that wavelength. Sensor precision and the conversion step, whereby measured responses are given a particular color value, are crucial for how accurately these values quantify biological processes. Most cameras are sensitive only to visible light wavelengths (~350–750 μm; [c]) recorded as red, green, and blue (RGB) values resulting in a digital photo. Most non-professional cameras record JPEG image format. JPEG images are compressed to reduce file size but in doing so reduce image accuracy. Some cameras can also save "raw" format images that contain a minimally processed dump of the sensor data, preserving maximum available sensor information. Consequently, raw images are a preferred format, but have much larger file sizes than JPEGs and can be difficult to work with, because they require camera-specific metadata to be opened. (c) Typical spectral response for various imaging sensors. Internet protocol (IP) and digital single-lens reflex (DSLR) cameras typically record overlapping bands of RGB wavelengths (shorter lines). Most cameras have a "cut-filter" (dotted line) over the imaging sensor that omits light in the near-infrared (nIR) beyond about 650 nm. Some "night-vision" (nIR) capable IP-cameras permit programmatic removal of the cut-filter, enabling capture of an image with moderate sensitivity in the nIR (see Petach* et al. *2014). Spectral responses of moderate resolution imaging spectroradiometer (MODIS) satellite camera bands 3, 4, 1 (tall lines) are shown for comparison. MODIS sensors are highly sensitive to specific wavelengths and have no channel overlap, thus enabling them to record spectrally independent information and avoid or target specific atmospheric features. Figure created by JG, TBB, DM, and J McCorkel (NASA); MODIS data were obtained from www.mcst.gsfc.nasa.gov/calibration/parameters; StarDot data were obtained from www.stardot.com.*

Phenocam science and technology

Automated image analysis techniques can be used to extract quantitative color (red, green, blue [RGB]; Figure 1), and, with some cameras, near-infrared data (Figure 1c). Information derived from these data provides metrics for vegetation status (eg green chromatic coordinate [GCC]; Figure 2; Gillespie *et al.* 1987; Sonnentag *et al.* 2012) and a modified normalized difference vegetation index (NDVI; Figure 1c; Nijland *et al.* 2014; Petach *et al.* 2014). Long-term deployment of phenocams is most useful for monitoring vegetation types that show strong color variation driven by biological response to local climate (Figure 2; Sonnentag *et al.* 2012) or disturbance events, such as defoliation by herbivores (Nagler *et al.* 2014). Tracking color changes over time enables identification of the timing and development of discrete "phenophases", including leaf-expansion, canopy development, senescence, and flowering (Figure 2; Inoue *et al.* 2014). Daily imagery from upward-facing cameras has also been used to track seasonal variation in leaf area index (LAI; leaf area per unit ground area) using gap-fraction theory (Ryu *et al.* 2012).

Phenocam-derived data can be combined with data obtained from other co-located sensors (eg micrometeorology, surface–atmosphere fluxes) and manually recorded phenological data to characterize the relationship between environmental drivers and phenological responses (Figure 2; Toomey *et al.* 2015; Wingate *et al.* 2015). Phenocams can depict how seasonal plant cycles influence ecosystem carbon budgets,

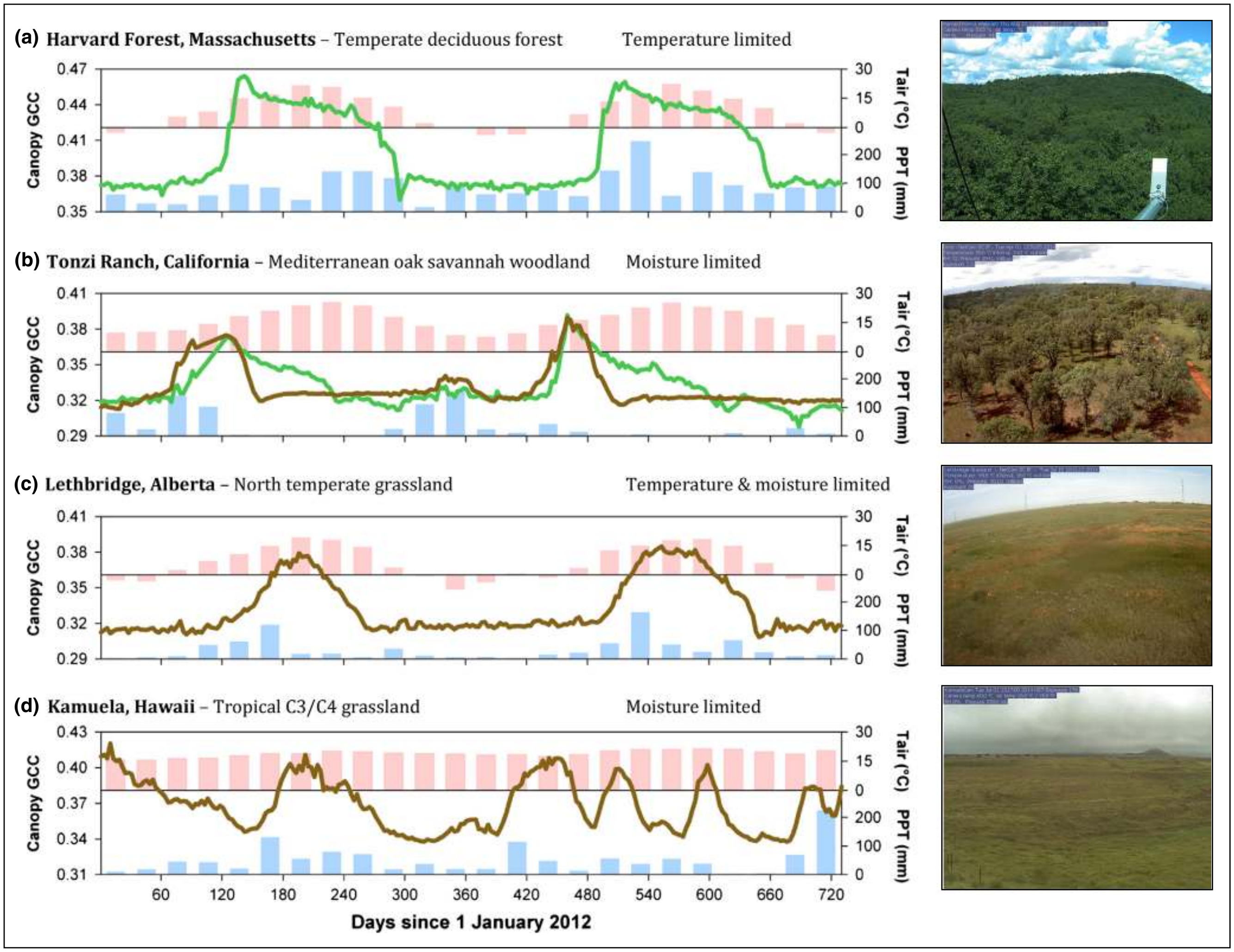

Figure 2. *Vegetation canopy greenness, as quantified by green chromatic coordinate (GCC) using PhenoCam imagery, in relation to seasonal patterns of monthly precipitation (blue bars) and air temperature (red bars). Lines correspond to GCC for trees (green) and grasses (brown) in camera field of view (FOV). (a) Harvard Forest, Massachusetts: interannual variation in greenness is largely limited to phase shifts at the start and end of the active period; there are also differences among species in both phase and seasonal amplitude; (b) Tonzi Ranch, California: substantial interannual variation in the duration and timing of the active period, as well as phenological differences between grass (earlier "green-up") and trees (stay green longer); (c) Lethbridge, Alberta, Canada: duration of active period is largely driven by water availability, with strong temperature limitation during the cold winter months; (d) Kamuela, Hawaii (Day 196): frequency, duration, and timing of green-up events varies from year to year depending on precipitation. All sample images were taken at noon on 1 Jul 2014 (Day of Year 183).*

show how these cycles scale from organisms to landscapes (Hufkens *et al.* 2012), and estimate gross primary productivity in some vegetation types (Toomey *et al.* 2015). They can also measure changes in the fractional cover of green vegetation, flowering phenology in annual or perennial plants (Crimmins and Crimmins 2008), snow cover (Julitta *et al.* 2014), and grassland phenology (Inoue *et al.* 2015). There has been less focus on the detection of phenological events in non-deciduous biomes, such as temperate or tropical evergreen forests, although seasonal changes in the apparent greenness of evergreen canopies has been related to changes in photosynthetic activity (Toomey *et al.* 2015). Within-canopy intra- and inter-specific variation can also be quantified from phenocams, but relatively little research has been undertaken in this area.

■ Phenocam hardware

Hardware selection and existing standards

Given that consumer-grade cameras are not designed for scientific imaging, it is important to understand the strengths and limitations of the information they produce (Sonnentag *et al.* 2012). Moreover, the value of derived data is dependent on multiple factors beyond sensor quality and resolution.

An assortment of new camera models are released each year, and novel imaging hardware and computing platforms emerge regularly; consequently, many different types of phenocams are now in use globally. A major challenge for practitioners within the phenocam community, therefore, is how to create long-term, consistent datasets when the core sensor technology (ie digital imaging hardware) is continuously changing and improving. In addition, there is a considerable amount of variability in camera reliability, cost, image quality, and technical complexity (WebTable 1). Two large-scale networks – the Phenological Eyes Network (PEN; Nasahara and Nagai 2015; pen.agbi.tsukuba.ac.jp) and the PhenoCam network (Richardson *et al.* 2007; phenocam.sr.unh.edu) – have developed protocols that are available for adoption by other researchers. The PhenoCam network employs above-canopy, tower-mounted, StarDot-brand, 5-megapixel "internet protocol" (IP) cameras (WebTable 1) that are angled downward toward the region of interest (Richardson *et al.* 2013b). These cameras also capture near-infrared imagery to measure NDVI (Petach *et al.* 2014). PEN uses both upward- and downward-facing, Nikon-brand cameras with 180° fisheye lenses (Nasahara and Nagai 2015). The Terrestrial Ecosystem Research Network (TERN) in Australia is transitioning from using a mix of "game-cams" and IP cameras to using IP cameras and raspberry-Pi based systems (WebTable 1). "gamecams" (WebTable 1) and IP cameras. The US National Ecological Observatory Network (NEON) and the European Union's Integrated Carbon Observation System (ICOS) are following the lead of PhenoCam and are installing IP cameras.

Due to the rapid advances in camera and camera-related technologies, there is no "best" hardware for a given application. New phenocam users must therefore decide between adopting more established but older technologies, relying on newer but less proven technologies, or developing custom solutions (WebTable 1; WebPanel 1). Newer cameras may cost less or provide higher-resolution data, but these data may not be congruent with data from larger research networks or published data acquired with more common cameras.

Camera and image format choice

Camera hardware and image format have considerable impacts on image quality (Macfarlane *et al.* 2014). Consequently, metrics that quantify a *specific* environmental state, such as LAI, are more affected by camera and image format than are *relative* phenological metrics, such as GCC-derived phenophase transition dates (Sonnentag *et al.* 2012). For all phenocam data it is very important to maintain the same camera FOV because the unit of measurement with a phenocam is the section of landscape imaged. Changes in the FOV complicate automated processing and reduce long-term data continuity, particularly in heterogeneous environments where phenology of vegetation types may be of more interest than an averaged value from the entire FOV (see WebPanel 1 for additional technical considerations).

■ Building a global phenocam network

Adoption of data standards and open-access data is crucial

As the use of phenocams becomes more commonplace, formal metadata standards and best practices should be adopted to facilitate wider collaboration between data creators and to increase data usability. Although there are major hurdles for developing a global phenocam network, the success of bottom-up collaborative networks like FLUXNET (www.fluxnet.ornl.gov) provides reason for optimism. FLUXNET is a "network of networks" that uses eddy covariance techniques to measure surface–atmosphere exchanges of carbon, water, and heat. FLUXNET has promoted community standards and protocols, and encouraged data sharing and collaboration, thus enabling the aggregation of data from hundreds of individually managed FLUXNET sites globally into publicly available standardized datasets.

However, FLUXNET data are largely derived from research-grade and well-characterized standard hardware, and integrating data from the diverse range of phenocams in use globally requires resolution of issues not yet addressed by FLUXNET. In general, discrete occurrence data, such as phenophase transition dates, are interoperable between camera types because such measures are derived from relative scales (eg GCC) rather than from quantitative measures (eg LAI). Further research will need to focus on (1) what measurements relating to phenological indicators can be reliably compared among various cameras; (2) what procedures and software tools can be used (eg low-cost camera calibration panels, automated calibration software) to improve interoperability between images from different camera hardware and image datasets; and (3) what methods are best for classifying and categorizing large image datasets to facilitate discovery and use by the community.

Both PhenoCam and PEN serve as examples of the kind of bottom-up, collaborative programs that are possible with current technology. Although relying on different protocols and hardware, these networks have successfully conducted automated, multi-year phenocam programs, and are providing critical data for studying phenological patterns across wide geographic domains and biome types.

Expanding phenocam networks and reconciling scales of observation

Automated camera networks, co-located with additional instrumentation (eg micrometeorology, surface–atmosphere fluxes), assist scaling across data products – from individual organisms to communities to landscapes. This provides opportunities for comparing phenocam datasets as well as integration with both observer-based records and satellite and airborne collected data. New continental-scale monitoring networks that have broader mandates for environmental monitoring, such as NEON (Keller *et al.* 2008), ICOS, and TERN, are incorporating phenocams into their instrument platforms and working to develop phenocam coordination networks within the regions being monitored. Phenocam datasets at well-developed research sites add considerable value to the extensive monitoring data from these networks (eg Wingate *et al.* 2015). The huge quantities of data being generated by these research networks necessitate the development of standards for organizing and delivering extremely large datasets from diverse sensor types demanding varied levels of post-processing. Most of these data are available through open-data frameworks that include explicit licensing terms and metadata standards to promote reuse and data sharing by stakeholders. Although this type of data standardization and public data availability has become common in some research disciplines (eg remote sensing, astronomy), such methods are largely new to the field ecology community; however, image data from PhenoCam, NEON, TERN, and ICOS are, or will soon be, made publicly available.

Installation of phenocams by continental-scale monitoring networks is also helping to formalize phenocam metadata and data standards. Many metadata standards exist for describing data (eg Ecological Markup Language, Audubon core). What specific standard is chosen is less important than ensuring that (1) the standard is well-documented and published online and (2) all camera records meet minimum metadata requirements, such as those established by existing camera networks (WebTable 2). Standardizing hardware, camera settings, and image-naming protocols among sites facilitates both the integration of existing and future phenology networks and scaling from local to regional to global coverage. New phenocam users should contact the relevant phenocam network in their area to register their camera and share data.

The long-term goal of an integrated global phenocam network would be the creation of a well-curated database listing all available phenocams and related datasets with robust metadata on image provenance, availability, data quality, and tracking of post-processing and validation steps (WebPanel 2). Such a database would enable users to register a digital object identifier (DOI) or persistent internet link to the data and analysis code used for a particular publication, and for the development of software packages that can directly access and analyze all available phenocam data.

Connecting phenocams and citizen science

Phenological studies can be expanded by integrating phenocam data with data collected by citizen scientists who volunteer for phenology projects such as USA National Phenology Network's (USA-NPN's) Nature's Notebook and NEON's Project BudBurst. Engaging citizen scientists in collection and analysis of phenological data fills an essential scientific need and provides an opportunity to engage non-scientists in the scientific process. Additional synergies arise when sampling techniques can be standardized between projects; for example, NEON's observer-based phenological assessments will use survey protocols developed by the USA-NPN to facilitate integration between these two data sources (Denny *et al.* 2014).

Researchers in other scientific fields, such as astronomy (www.zooniverse.org), have successfully engaged volunteers online to process and analyze millions of images (Raddick *et al.* 2013). Ecological research programs are adopting similar initiatives (eg Hill *et al.* 2012), and should further explore this approach for user recruitment and incentivizing public participation (Newman *et al.* 2012). A new collaboration between PhenoCam, NEON's Project BudBurst, and Zooniverse called Season Spotter (www.seasonspotter.org) is integrating crowdsourcing with traditional automated image analysis to maximize the amount of phenological information that can be extracted from camera images.

Expanding coverage

Major challenges must still be overcome before effective phenocam coverage at the global scale can be achieved (Figure 3). At present, PEN, PhenoCam, TERN and ICOS have web portals. PhenoCam, TERN (www. phenocam. org.au) and ICOS (http://european-webcam-network.net/) provide publicly accessible data online. Cameras are used at many research sites globally, but most images are not indexed within any central database, making data discovery and re-use difficult. Coverage also remains poor across large regions of the globe, including South America, Africa, and much of Asia (Figure 3).

To expand spatial coverage, exploration is also warranted into potential data products available from the many thousands of public web cameras (webcams) worldwide. The Archive of Many Outdoor Scenes (AMOS; www.amos.cse.wustl.edu), for example, is a global collection of long-term time-lapse imagery from nearly 30 000 public webcams (Jacobs *et al.* 2009). Images from thousands of traffic cameras are also available online (Morris *et al.* 2013). Although non-research cameras often have lower-image quality and may lack important metadata (such as location), public webcam data represent a vast but largely untapped resource for phenological monitoring (Jacobs *et al.* 2009; Graham *et al.* 2010). For analyzing such varied data types, automated classification and filtering tools are essential. One possible solution would be the development of a multi-tiered organizational struc-

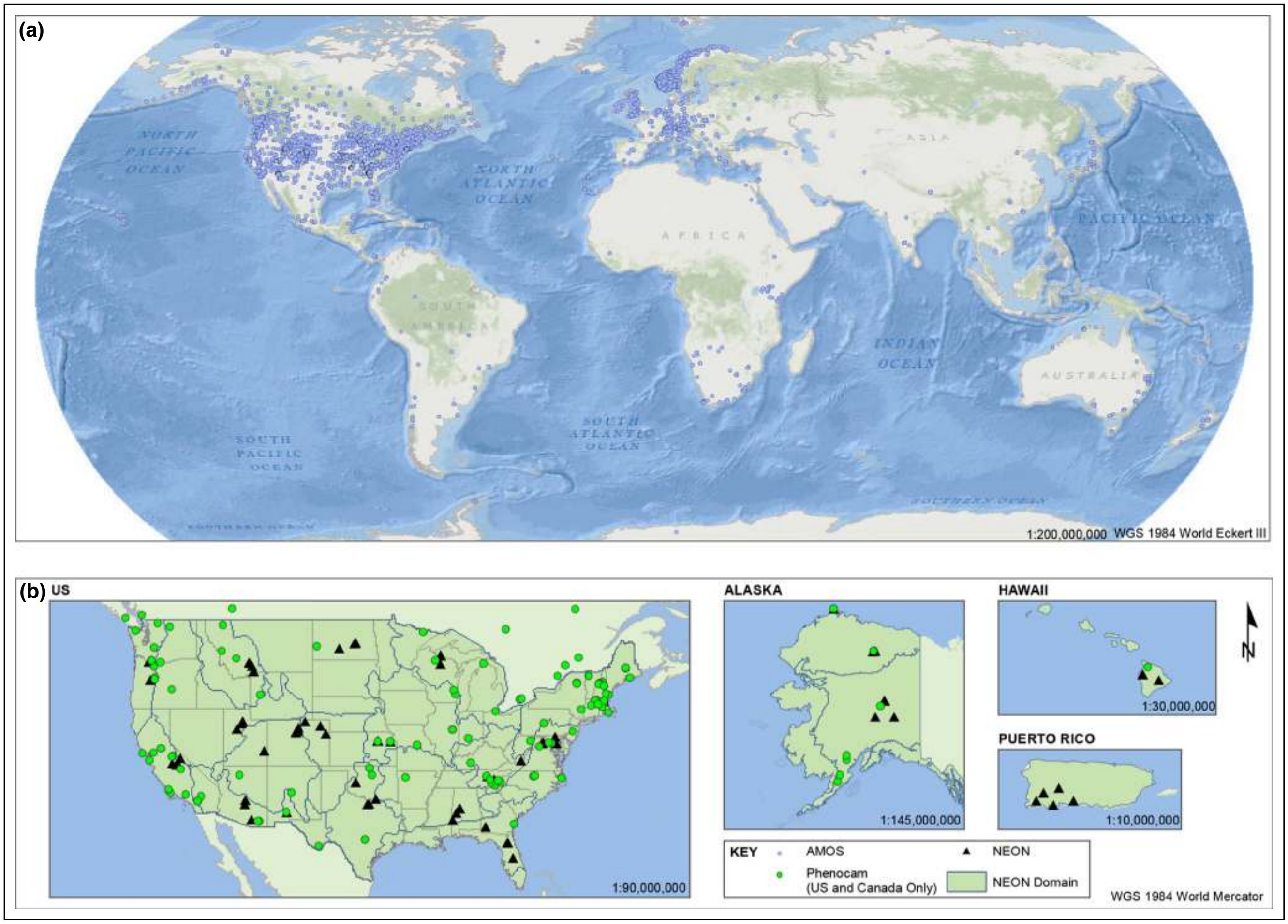

Figure 3. *(a) Map of PhenoCam network camera coverage compared to known webcams globally, as indexed by the AMOS project (www.amos.cse.wustl.edu). AMOS is a long-term collection of time-lapse imagery from publicly accessible, outdoor webcams around the world, including PhenoCam network sites. Despite the nearly 30 000 cameras in AMOS, extensive gaps still exist in the Southern Hemisphere and Asia. Although less than 1% of cameras archived by AMOS follow the PhenoCam network protocols, AMOS cameras still represent an invaluable data source. A classification system is needed for categorizing, ingesting, and integrating thousands of automated near-surface phenology observations collected with a range of protocols and hardware (WebPanel 2). (b) PhenoCam network cameras (US sites). All images from these cameras are being archived and are publicly accessible. Figure created by MWD, MSC, and M Slater (NEON Inc). Map courtesy of M Slater (NEON Inc). Data contributed by R Pless and N Jacobs (AMOS), NEON, and PhenoCam.*

ture for webcam data, based on metadata quality (WebPanel 2); such a structure would allow available camera data to be cataloged prior to analysis, and would permit users to quickly filter images and data products by automated quality metrics or available metadata.

Next-generation monitoring

An array of new technologies are becoming available that will greatly expand the quantity and utility of phenocam data. We discuss several below.

Pan–tilt–zoom and gigapixel imaging

Pan–tilt–zoom (PTZ) camera systems can move a camera to multiple preset "views" (Granados *et al.* 2013), thus enabling monitoring of much larger spatial areas. Some PTZ cameras can be programmed to capture overlapping images that can be stitched together with software to form multi-billion-pixel ("gigapixel") resolution panoramas (Figure 4; Brown *et al.* 2012). Gigapixel imaging is an emerging technology that holds great promise because such images have sufficient resolution for monitoring thousands of individual plants over hundreds to thousands of hectares (Figure 4). For repeat photography and non-time-series panoramas, commercial hardware such as the GigaPan (www.gigapan.org) enables regular cameras to capture images at thousands of times the resolution of a normal camera image (Nourbakhsh and Sargent 2010). Automated, weatherproof systems for capturing time-lapse gigapixel images have been developed (Brown *et al.* 2012) but

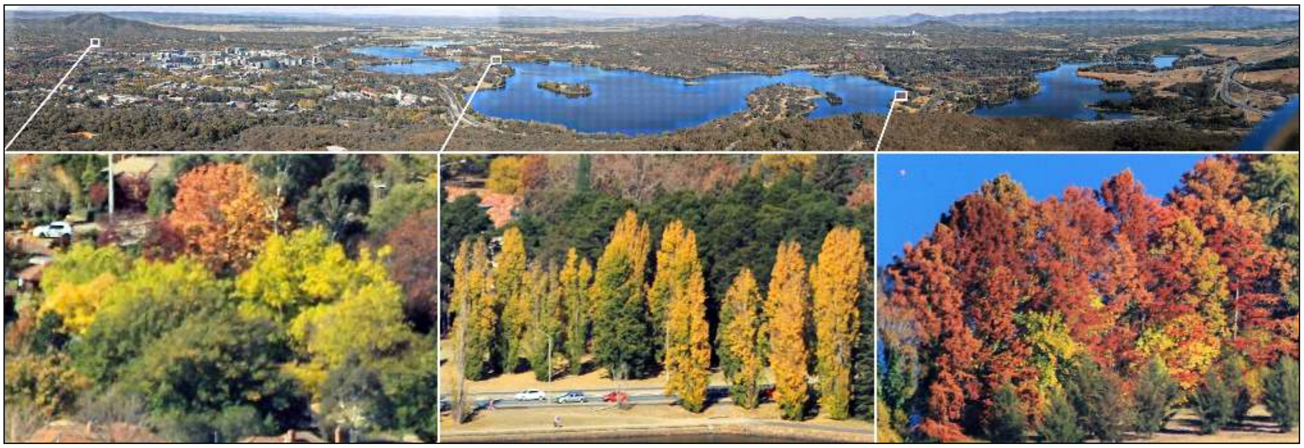

Figure 4. *Example of a 13.2-billion-pixel-resolution "gigapixel" panorama showing fall phenology in non-native deciduous trees in Canberra, Australia (full image: www.gigapan.com/gigapans/136045). Panorama generated from 2400 18MP images taken with a GigaPan-Epic-pro robotic camera head, Canon 60D camera, and Sigma DG 150–500-mm lens (image stitched with GigaPan FX Pro). Distance from camera to subset images (left to right): ~4.5 km, ~3.3 km, and ~1.7 km. Area in image with sufficient resolution for identifying phenophases from individual trees is approximately 3000 ha. See www.gigavision.org for examples of gigapixel time-lapse.*

are not yet in wide use due to their technical complexity and the challenges of data management and analysis.

Unmanned aerial vehicles

Unmanned aerial vehicle (UAV) technology is developing rapidly and will play a major role in future ecological monitoring (Koh and Wich 2012; Anderson and Gaston 2013). Off-the-shelf UAVs that cost less than US$2000 can now generate high-spatial-resolution digital imagery and map layers as well as centimeter-resolution, three-dimensional (3D) "point clouds" of vegetation and topography using a phone "app" to control the UAV and desktop or internet-based software to process the images (eg www.pix4D.com, www.dronemapper.com). Restrictive regulatory frameworks in most countries and limited tools for biological analysis of UAV-derived data are primary challenges to UAV-based monitoring.

Mesh sensor networks

Wireless-mesh sensor networks that are used to measure soil properties, micro-meteorological parameters (temperature/relative humidity), and photosynthetically active radiation can quantify environmental drivers of phenology at considerably better spatial resolutions than traditional weather stations (Burgess *et al.* 2010; Rankine *et al.* 2014). Precision microclimate data can be coupled with phenocam-derived datasets and low-cost full-genome sequencing of thousands of individuals to allow better modeling of climate–phenology relationships and identification of traits for species adaptability to climate change (Whitham *et al.* 2006).

Smart devices and social networks

Mobile technologies and social networking are also generating huge collections of images, many of them public. Consider that while the AMOS archive has collected 7.3 million images in total (2006–2014), an estimated 1.8 billion images are now uploaded to social media *daily* (Meeker 2014). Images from mobile devices usually contain metadata, including location, camera compass direction, and sensor type, facilitating calculation of the specific geospatial location being sampled by each photo. Extracting biological information from such images can be challenging, but automated processing algorithms can select only images and scenes that meet specific criteria. Algorithms now exist to correct lighting variation and other artifacts across huge datasets of time-series images. For example, Martin-Brualla *et al.* (2015) mined 86 million public, geolocated, online photos and automatically created time-lapses from any location with more than 300 images; over 10 000 time-lapse series, were constructed in this way, including one showing the retreat of the Briksdalsbreen Glacier in Norway in 3D that was reconstructed from 9400 images over a 10-year time span. This software was largely automated and ran unsupervised. Integrating repeat photography tools into phone camera apps (eg www.projectrephoto.com) combined with, for example, onsite signage encouraging visitors to contribute images (eg www.picturepost.unh.edu) could help build these datasets (West *et al.* 2013).

Image processing

In addition to hardware advances, the potential of advanced computer algorithms and computational pipelines using large internet-based "cloud" computer systems has barely been tapped for phenocam data. Such "cloud" computing (ie on the internet rather than on local hardware) allows users to scale their computational requirements, on-demand, from a few to thousands of processors at relatively low cost. Cloud-based processing solutions make production of high-resolution panoramic and 3D datasets widely accessible and produce better-standardized data products. Development of long-term collaborations with researchers in the field of computer vision is recommended for such projects. Cloud computation also enables wider use of automated and semi-automated software pipelines for analyzing and mining large image datasets (eg Martin-Brualla *et al.* 2015). Publication of datasets and analysis code linked to persistent DOIs is becoming the norm in many scientific fields (eg Fisch *et al.* 2015; Filippa *et al.* nd), and the tools to accomplish this are being developed for NEON, TERN, and ICOS data. DOIs and persistent uniform resource locators (URLs) coupled with published interoperable data standards promote collaborative analysis and re-analysis of phenocam and related sensor data.

■ Summary and recommendations

A global phenocam network would facilitate wide-scale collaborative research across biomes and climate zones, with the potential to measure global change impacts on plant phenology, productivity, and function over timescales ranging from seasons to decades.

For a global phenocam network to reach its full potential, we recommend the following: (1) create and adhere to metadata and image-naming standards for all camera-based data sources (WebPanel 2); (2) register all publicly available phenocams in a global database, with existing datasets made publicly available wherever possible; (3) establish new national- and continental-scale camera networks (with data-hosting infrastructure), to serve as clearinghouses for data sharing and to improve phenocam coverage in underrepresented ecosystems and regions (Figure 3); (4) co-locate new cameras at existing long-term research sites; (5) create mechanisms and standards (similar to those for satellite data products) for releasing phenocam images and derived-data products, along with co-located sensor data for ecosystem modeling efforts; (6) create mechanisms for provisioning phenocam datasets with global identifiers (DOIs, persistent URLs, etc); (7) create software and scripts to facilitate easier management and analysis of large time-series image archives (eg Filippa *et al.* nd) and rapid integration of new datasets into the network; (8) design new software tools for image alignment and standardization across camera types; (9) build web portals with "web-services" that allow direct access to phenocam data products via common programming tools, such as R, Matlab, and Python; (10) adopt existing data standards and robust data management practices for new phenocam deployments to enable the creation of visualization, collaboration, and analysis tools that can work with any public dataset; (11) promote strong collaborations between phenocam projects globally and with local citizen-science phenology projects; and (12) explore non-conventional camera data sources, such as AMOS (Figure 3) and online repositories of georeferenced images (eg traffic cameras, social media), as well as setting up collaborations with specialists in computer vision technologies.

■ Conclusions

Understanding the ecological impacts of global environmental change depends on integrating complementary monitoring approaches. High temporal and spatial resolution phenological datasets are an essential tool for understanding cross-scale ecosystem processes, and imagery from phenocams can be used to obtain information about phenological changes across a wide range of ecosystem types. Among other end-uses, these data are important for creating models to forecast shifts in phenology under different climate-change scenarios. Continued technological advances provide further opportunities for image-based, real-time monitoring of natural systems. However, critical issues related to standardization, metadata, data sharing, and re-use will need to be addressed as phenocam technology continues to grow and evolve. A coordinated global phenocam network that promotes standardization and data sharing, and facilitates the discovery and re-use of archived image data, would greatly enhance global change research capacity.

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