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Capturing change: the duality of time-lapse imagery to acquire data and depict ecological dynamics

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ABSTRACT. We investigate the scientific and communicative value of time-lapse imagery by exploring applications for data collection and visualization. Time-lapse imagery has a myriad of possible applications to study and depict ecosystems and can operate at unique temporal and spatial scales to bridge the gap between large-scale satellite imagery projects and observational field research. Time-lapse data sequences, linking time-lapse imagery with data visualization, have the ability to make data come alive for a wider audience by connecting abstract numbers to images that root data in time and place. Utilizing imagery from the Platte Basin Timelapse Project, water inundation and vegetation phenology metrics are quantified via image analysis and then paired with passive monitoring data, including streamflow and water chemistry. Dynamic and interactive time-lapse data sequences elucidate the visible and invisible ecological dynamics of a significantly altered yet internationally important river system in central Nebraska.

Key Words: *data visualization; passive monitoring; river ecology; time-lapse imagery*

INTRODUCTION

Interconnected change among societal, economic, and environmental systems, such as technology advancement, land and water use changes, and declining biodiversity, has heightened the importance of understanding natural systems and interconnected social-ecological dynamics. Increased demand for water, food, and other natural resources for human use has significantly modified most natural systems and consequently challenged the Earth's capacity to sustain human life as well as robust biodiversity (Millennium Ecosystem Assessment 2005, Chapin et al. 2010, Ceballos et al. 2015). By damming river systems, reducing hydrologic connectivity by draining wetlands, converting prairies for agriculture, and developing urban centers, human activity continues to have pervasive impacts on ecosystems (Foley et al. 2005). Effective conservation and the future availability of natural resources relies on understanding natural systems, scientific understanding to measure biotic and abiotic responses to anthropogenic impacts, and understanding within society to build support for science-driven management and policy and to foster sustainability (Jordan et al. 2009). We examine dual utilizations of time-lapse imagery as a tool to collect data and as a communicative medium integrating images and data visualization to depict ecological change through time.

Photography has helped progress our knowledge base of natural systems and humanity, and played a significant role in defining various archetypes that construct our understanding of social-ecological paradigms, such as conservation, scientific inquiry, and capitalism (Trachtenberg 1989, DeLuca and Demo 2000, Banks and Zeitlin 2015). Over the last century, a symbiotic affiliation has developed between society, ecology, and photography. The ethnographic work of Bateson and Mead (1942) used cameras as recording devices to study Balinese social organization, interactions, agricultural practices, and industrialization, among many other human dynamics (Bateson and Mead 1942). Their pivotal work formed the basis of visual anthropology and laid the foundation for the use of images in research on human behavior and society (Jacknis 1988). Collier and Collier (1986) further advanced this field, expanding upon the camera as a recording device for societal and natural inquiry (Collier and Collier 1986). Because ecology and photography are historically and innately founded in observation (Sagarin and Pauchard 2010), photography has aided in our understanding of natural phenomena, processes and ecosystems, dating back to the late 1800s when astronomers captured the first solar eclipse with the daguerreotype (Hayden 2008), to today, where imagery is used to monitor environmental changes (Brown et al. 2016). Simultaneously, images have proven to be a valuable tool and powerful voice for conserving the natural world, exemplified by the work of Ansel Adams, Carleton Watkins, and William Henry Jackson (Hales 1988, DeLuca and Demo 2000, Ward 2008).

The advancement of digital technology has improved data acquisition and observational efficiency, information exchange, and connectivity among social-ecological systems, redefining how individuals interact with, infer meaning from, and collect information about the natural world (Sagarin and Pauchard 2010, Boehnert 2012). Time-lapse imagery has evolved as a multifunctional technique for visual documentation and quantitative investigation, aiding both scientific inquiry and science communication. It is widely used to document trend, condition (Bradley et al. 2010), and to quantitatively assess ecosystem changes across a wide range of systems including glacial fluctuations (Byers 2007), grassland processes (Migliavacca et al. 2011), and forest phenology (Zhao et al. 2012, Richardson et al. 2009, Sonnentag et al. 2012). In aquatic systems, time-lapse technology was used to measure the growth of Staghorn coral (Barnes and Crossland 1980), whereas Bellwood et al. (2006) discovered through the use of time-lapse video that a particular batfish species plays a significant role in coral reef recovery (Bellwood et al. 2006). Concurrently, time-lapse photography is an increasingly used technique in documentaries,

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television segments, or interactive media. For example, Disneynatures' © movie *Wings of Life* (Candler et al. 2013) and BBC's © *Planet Earth* (Fothergill et al. 2007) used time-lapse to illustrate biological processes, such as butterflies emerging from their chrysalis and plant growth stages. At a larger spatial and temporal scale, James Balog's *Chasing Ice* documents retreating glaciers in the Arctic and illustrates a global issue that's challenging to observe, i.e., the effects of a changing climate (Chasing Ice 2013).

Many of the environmental challenges facing society are not entirely visible or are difficult to convey, and thus, can add to societal misunderstanding or unfamiliarity (Hansen and Machin 2013). By coupling time-lapse imagery with data visualizations, we create time-lapse data sequences that contextualize visible changes alongside concrete information that may be difficult to see with the human eye or comprehend via the data alone. The objective of this study was to explore the monitoring and communication potential of digital time-lapse imagery to enhance the understanding of natural systems and social-ecological dynamics. We collaborated with the Platte Basin Timelapse project (PBT), a multimedia endeavor to foster awareness and build community through visualizing a watershed in motion (http://www.plattebasintimelapse.org). As of January 2017, PBT has collected more than half a million images. Imagery from the PBT archive was used for analysis and linked with data visualizations to create time-lapse data sequences illustrating a socially and ecologically significant river system in the Great Plains.

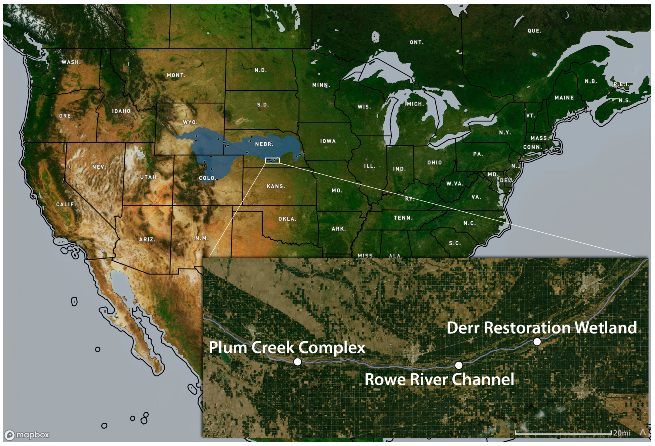
METHODS

Study area

The Platte River Basin is an economically important, internationally critical ecosystem and a key example of a stressed and human-dominated watershed (National Resource Council 2004). As one of the most significant riverine systems in the Great Plains (Williams 1978), the Platte River provides many societal benefits, such as hydroelectric power, irrigation, and recreational opportunities to communities throughout Nebraska and its tributaries in Wyoming and Colorado (Fig. 1). The central Platte River Basin, NE is an ecologically critical region, providing habitat for wildlife, including numerous endangered species, such as Whooping Cranes (*Grus americana*), Interior Least Terns (*Sterna antillarum*), and Piping Plovers (*Charadrius melodus*) and a key migratory corridor for thousands of Sandhill Cranes (*Antigone canadensis*) and waterfowl. Water-provisioning infrastructure, such as dams and diversions, engineered for industrial, agricultural, and domestic use has removed or retimed 70% of the Platte's natural flow regime, directly and indirectly altering the structural, biological, and ecological characteristics of the watershed (Williams 1978, Aiken 1999, Strange 1999, Brei et al. 2008). Reduced flood pulses and stream flow have limited the natural structuring process of sediment scouring, encouraged the encroachment of vegetation, and had an impact on wildlife habitat (Eschner 1981, Johnson 1994). The recent modified flow regimes have prompted legal litigation and recovery plans to manage land and restore adequate stream flows, resulting in contention among various public, industry, and governmental entities.

The study region is a section of the central Platte River Basin extending from Lexington, Nebraska, USA, eastward to Grand Island, in south central Nebraska. Data was collected from three research sites within the central Platte River Basin: Plum Creek Complex (PCC), Rowe River Channel (RRC), and Derr Restoration Wetland (DRW; Fig. 1). The PCC (40° 40′ 50.29″ N, 99° 33′ 12.08″ W) near the town of Overton, Nebraska, is the furthest west location, situated on the south channel of the Platte River. The RRC study site (40° 40′ 3″ N, 98° 53′ 32.64″ W), near Gibbon, Nebraska, is maintained by the National Audubon Society and adjacent to the Platte River's south channel. The third research location, DRW (40° 44′ 27.67″ N, 98° 34′ 22″ W), near Wood River, Nebraska, consists of a restored wetland slough owned and managed by the Nature Conservancy.

Fig. 1. Map of study locations Plum Creek Complex (PCC), Rowe River Channel (RRC), and Derr Restoration Wetland (DRW), in the central Platte River Basin of Nebraska, USA.



Time-lapse camera systems

High resolution digital camera stations (Fig. 2) were installed at each site by the Platte Basin Timelapse project. Each camera station is comprised of a Nikon D300 DSLR camera with a 12.3 megapixel crop sensor (DX) and Nikkor 18-70mm 1:3.5-4.5 lens. A TRLcam intervalometer (http://www.TRLcam.com) controls the interval settings and the timing is adjusted by a GPS module to account for differing daily sunrise and sunset times. The intervalometer was generally set to capture one red-green-blue (RGB) color channel image every hour beginning at sunrise and ending at sunset, although it occasionally was set to capture specific phenomena at other intervals (i.e., 15 minutes). The equipment is contained within weatherproof housing constructed from ultra-violet stabilized polycarbonate plastic made by Serpac with modifications of optical glass, an aluminum lens hood, and a ball mount to secure the camera to a mounting pole approximately 2.5 meters above ground. The systems are powered by a 30-watt solar panel and stored in a lithium ion battery. Camera operation is verified daily by cellular technology that sends an image via email to confirm acquisition. The images are automatically uploaded to PBT's 1.5 terabyte image library and accessible through Phocalstream, software technology developed by the Jeffrey S. Raikes School for Computer Science and Management at the University of Nebraska-Lincoln.

Fig. 2. Examples of two time-lapse camera installations. On the left, a close up of the intervalometer, camera, and capacitors and on the right, an installation with solar panel and additional monitoring equipment overlooking the Platte River, Nebraska. As part of the Platte Basin Timelapse Project (www.plattebasintimelapse.org), over 40 of these camera systems were installed throughout the Platte River watershed in Colorado, Wyoming, and Nebraska.

Image-analysis: vegetation dynamics and water inundation

We utilized time-lapse cameras to quantitatively assess the temporal characteristics of vegetation at all sites and water inundation at one site, DRW. At each location, three images a day were selected between the hours of 10:00 and 14:00 for standardization of sun position and shadow. The selected images were then vetted for obstructions or weather variations within the frame of view. If possible, additional images without interferences were selected to complete the sequence of three images a day per site.

To assess vegetation phenology, particularly green-up and senescence, imagery was batch analyzed by selecting a region of interest (ROI) within each image. The ROI was a standardized selection at each site that encompassed predominately vegetation. The average digital number for each red-green-blue (RGB) color channel within the ROI was used to calculate the green chromatic coordinate (Gcc) vegetation index. Green chromatic coordinate is robust to variations in weather and light illumination (Sonnentag 2012) and has been used to characterize phenophase and variations in vegetation (Richardson et al. 2009, Zhao et al. 2012).

$G_{CC}= DN_G/ DN_R+DN_G+DN_B$ (Equation 1; Woebbecke et al. 1995)

In addition to vegetation phenology, imagery captured at DRW, a ground-water fed slough, was assessed for hydrological changes by quantifying water inundation through image classification because the site does not have a stream gauge, and thus, changes in hydrology were previously unmeasured. Time-lapse images were batch analyzed in Image J (Rasband 1998, Schneider et al. 2012), a Java-based image analysis program created by the National Institute of Health, using a custom script modified from a health sciences microscopy technique (Hadi et al. 2011, Schneider et al. 2012, Hakonen et al. 2014). The RGB images were transformed to the cylindrical hue-saturation-value (HSV, also called HSB; brightness) color space for more accurate color statistics (Chang et al. 2010). Hue is the spectral property of a specific color, saturation is the intensity perception of a color, and value denotes the perception of brightness of a color. The hue slice of the HSV stack was cropped to a region of interest (ROI), which encompassed the most wetland area and cropped out the sky and remaining terrestrial landscape to reduce errors associated with variations between images. The ROI was converted to a binary (black and white) image where pixel values were denoted as 1 or 0. The level of thresholding was determined by an automatic function that divided the image into background (0) and objects (1) by producing a test threshold and calculating the average of pixels above and below the test threshold. Area statistics were calculated using the area fraction function with an overlaying mask. An accuracy check was completed by visually comparing the original image to the produced mask.

Climatic/environmental variables

Stream gauge data were available for RRC and PCC, and thus, streamflow measurements were obtained for the river channel study sites from corresponding United States Geologic Survey (USGS) streamflow-gaging stations: RRC from station ID 06770200 near Kearney, Nebraska (40° 41′ 08″ N, 99° 26′ 20″ W NAD27) and PCC from site ID 06768025 near Overton, Nebraska (40° 40′ 44″ N, 99° 29′ 21″ NAD83).

Time-lapse data sequences

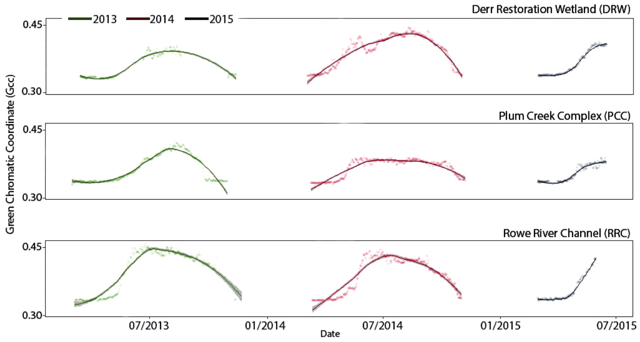
To visualize system changes over time, time-lapse imagery was coupled with data graphics to create time-lapse data sequences. We explored multiple techniques and software to accommodate various platforms, media, and frameworks. Static examples were developed for avenues with one-dimensional platforms or constrained format requirements, such as posters, paper publications, and informational brochures. Static time-lapse data sequences also acted as an architectural frame and a prototype for interactive examples. Graphics were created using R (R Development Core Team 2008) statistical analysis software and Adobe Creative Suite, including Illustrator, After Effects, and Photoshop (Adobe Systems Incorporated 2012). The time and location of time-series data points were matched with the time-stamp and site of corresponding imagery. Digitally interactive examples were constructed using HTML, CSS, and JavaScript with D3 as the primary graphing library.

RESULTS

Proximal sensing

By employing time-lapse camera systems as proximal sensors, we documented environmental changes within a riverine system. Image analysis of RGB color channels allowed us to analyze quantitative and qualitative time-series data. Modeling Gcc over time revealed distinct trends and seasonal characteristics of vegetation phenology within the riparian zones of the river and wetland (Fig. 3). However, there were observed differences in phenological change between sites and years. In 2013, the initial green-up phenophase began later at PCC and DRW compared to 2014 and 2015. Contrastingly, all years were relatively similar at RRC. Changes in vegetation from management activity were also evident within the data. At DRW, a drastic decline in greenness, followed by an immediate increase, was observed during June 2014, an effect of haying/cutting associated with land management.

Fig. 3. Vegetation phenology showing the results of the green chromatic coordinate vegetation index at Derr Restoration Wetland, Plum Creek Complex, and Rowe River Channel for 2013, 2014, and the spring of 2015.



Metrics of water inundation at DRW were evaluated by comparing the original imagery to the produced masks. Overall, the results show promise as an employable and accurate method, however accuracy varied among years. In 2013, a total of 308 images were batch analyzed to classify water inundation. Of these, 69 of the corresponding masks were deemed inaccurate and discarded for an error rate of 0.22. In 2014, 635 images were analyzed and 61 were discarded for an error rate of 0.09. In 2015, a total of 281 images were analyzed and of those, 2 were discarded, resulting in a < 0.01 error rate. We suggest a decrease in error rate from 2013 to 2015 may have resulted from greater stabilization within the time-lapse camera systems because the structures and technology advanced over time. By visually comparing the hydrographs at RRC and PCC with water inundation measurements at DRW, we observed general similarities of temporal fluctuations and patterns throughout seasons and with regard to weather events. A slight delay was evident at DRW compared to the river channel sites; a reasonable observation given the more extensive system of streamflow and subirrigation for water to reach the wetland (Fig. 4).

Time-lapse data sequences

The integration of time-lapse imagery and data visualization elucidated a range of visible, subtle, and invisible changes, ecological phenomena, and evidence of an altered system; the scale at which pattern and process take place, vegetation dynamics including the encroachment of woody and invasive vegetation, and river hydrogeochemistry. Constructed examples demonstrate multifaceted applications and framing of time-lapse data sequences to convey and explore natural systems.

Water chemistry fluctuations

http://www.ebrinbuck.com/OXY.html

Often, the association between visible landscape changes and water quality fluctuations are indistinguishable and not observable to the human eye alone. By merging images with data graphics, we can see relationships and trends among visible and invisible occurrences, offering insight into complex natural systems and elucidating broader concepts (Fig. 5). In Figure 5, the top graph illustrates changes in dissolved oxygen at hourly intervals from March to September 2013. A difference in concentration is evident between spring (March/April) and late summer (July/August), largely attributed to interrelated factors linked to seasonality. The decreasing trend in dissolved oxygen is commonly a factor of temperature; as water temperature increases, the solubility of gas decreases, and thus, dissolved oxygen concentrations decline. The diel variation, illustrated by the graph as moderate oscillations in March and more drastic oscillations in July, is demonstrative of ecological dynamics associated with seasonal activity, most predominately primary productivity. Photosynthesis, the underlying biological process, is conceptually represented as the greening up of vegetation seen in the time-lapse images. The more drastic oscillations observed in July and August are suggestive of aquatic photosynthetic activity generating dissolved oxygen during the day. Because vegetation relies on the sun for energy, photosynthesis ceases at night, and thus the dissolved oxygen levels decrease.

The time-lapse data sequence in Figure 5 presents a framework encompassing a holistic systems perspective to illuminate the interconnectedness of a stressed watershed; intertwined dynamics varying in time, frequency, association, and visibility. For example, seasonality is consistent and can be observed by the human eye, but is easily overlooked because of the slow rate of transitional occurrence. Time-lapse imagery's capacity to compress time elucidates this subtle phenomenon. Paired with data visualizations, the association among abiotic and biotic changes can be observed concurrently with seasonality; temperature, vegetation phenology, and variations in water chemistry. Moreover, Figure 5 alludes to the concept of a connected system by depicting the increase in contaminants in relation to the increase in streamflow. This visual illustration frames a narrative to discern the interconnected dynamics of terrestrial-aquatic systems, land-use impacts, drainage through a watershed, and the implications of human-use activities on water quality and natural systems.

Engineered hydrology

http://www.ebrinbuck.com/hydropower.html

Dams and diversions, engineered for human-use activities, have significantly altered the timing, duration, and quantity of the historic streamflow of the central Platte River Basin over the last century (Aiken 1999, Strange 1999), thus having an impact on the habitat of endangered and threatened species and resulting in litigation and regulatory agreements. Located downstream from a hydropower plant, the Platte River, at study location PCC, experiences pulses in streamflow from hydrocycling (Fig. 6). In accordance with regulatory agreements, the power authority is required to meet instream flow and environmental requirements for the section of river where PCC is located. This includes the cycling of surface water from March 18 to April 30 to decrease nightly influxes of river stage. The engineered flow regime of the Platte River at PCC oscillates approximately every four days from March 18 to April 30, and approximately 24 hours in the beginning of March and May. The hydrograph of a location upstream of the control infrastructure is presented in Figure 6 to illustrate the dichotomy and contrast between sites and the resulting drastic variation in streamflow from human engineering. The time-lapse data sequence offers contextual meaning with vivid visual changes, and in an interactive framework, evokes a

Fig. 4. Hydrograph of streamflow at Rowe River Channel (RRC) and water inundation data at Derr Restoration Wetland (DRW). Streamflow data at RRC was acquired from U.S. Geological Survey stream gauge data, whereas water inundation at DRW is data resulting from image analysis of time-lapse imagery.

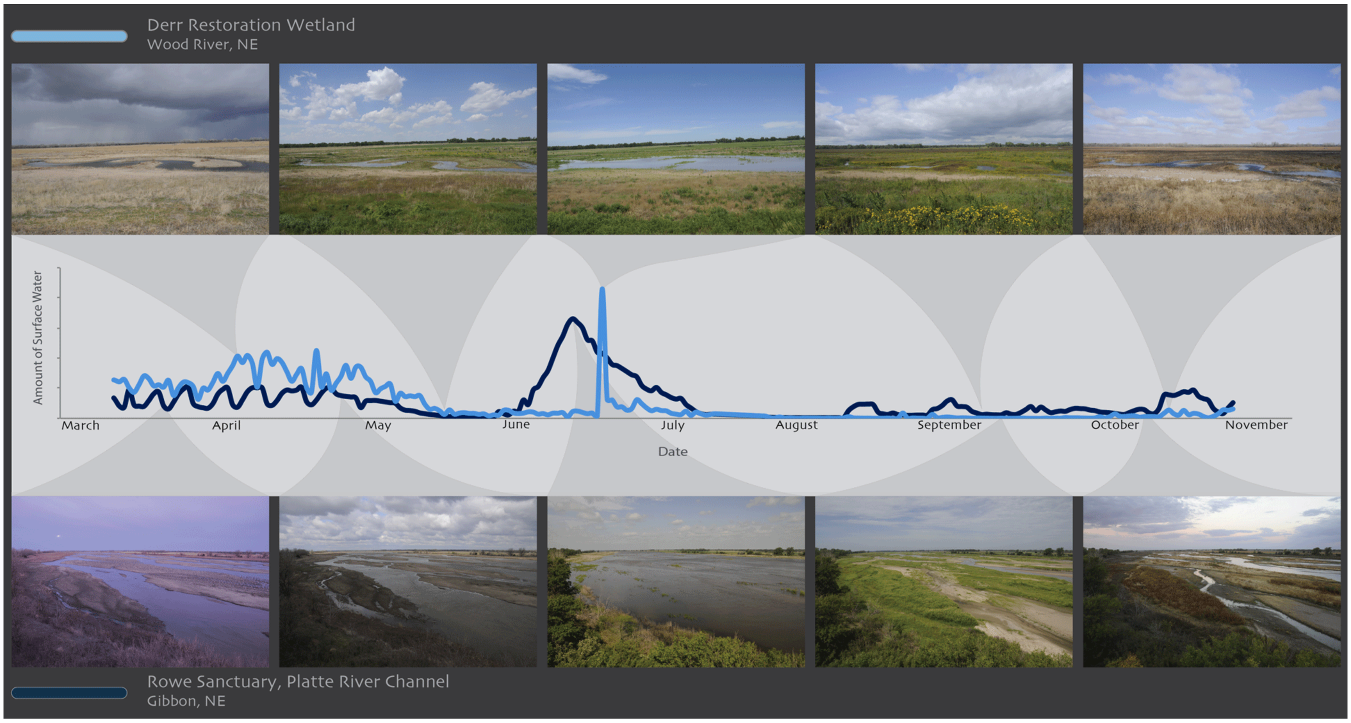


Fig. 5. Static time-lapse data sequence illustrating dissolved oxygen (mg/L) and nitrate (mg/L) measurements at Rowe River Channel in 2013.

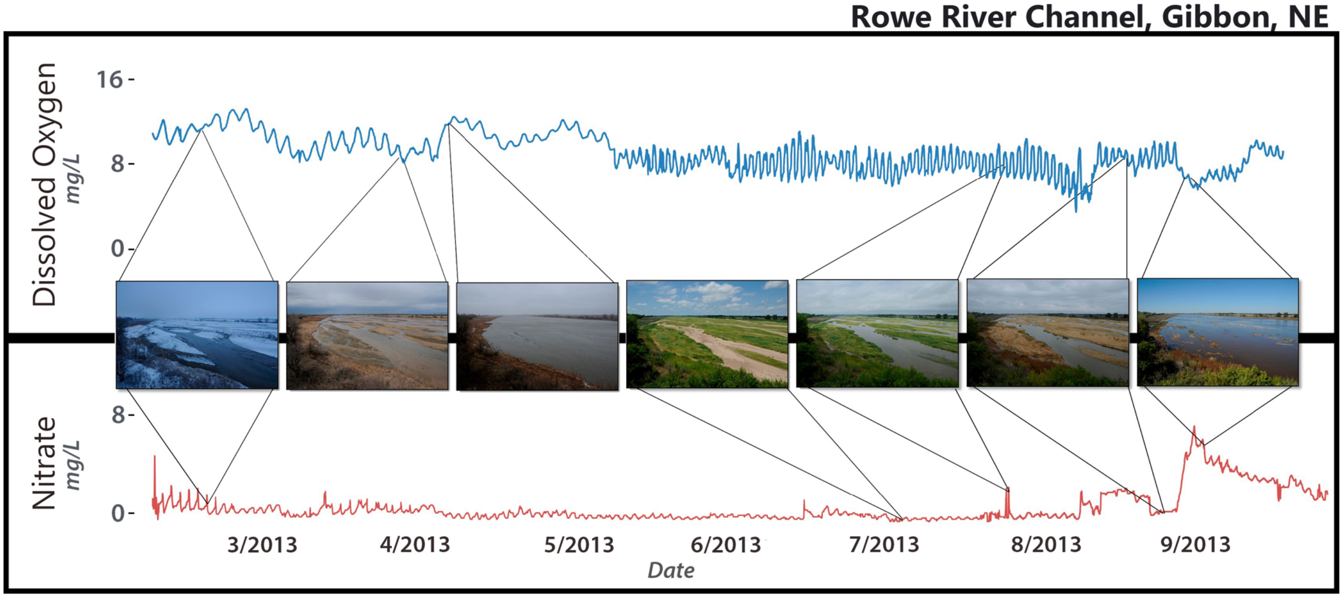
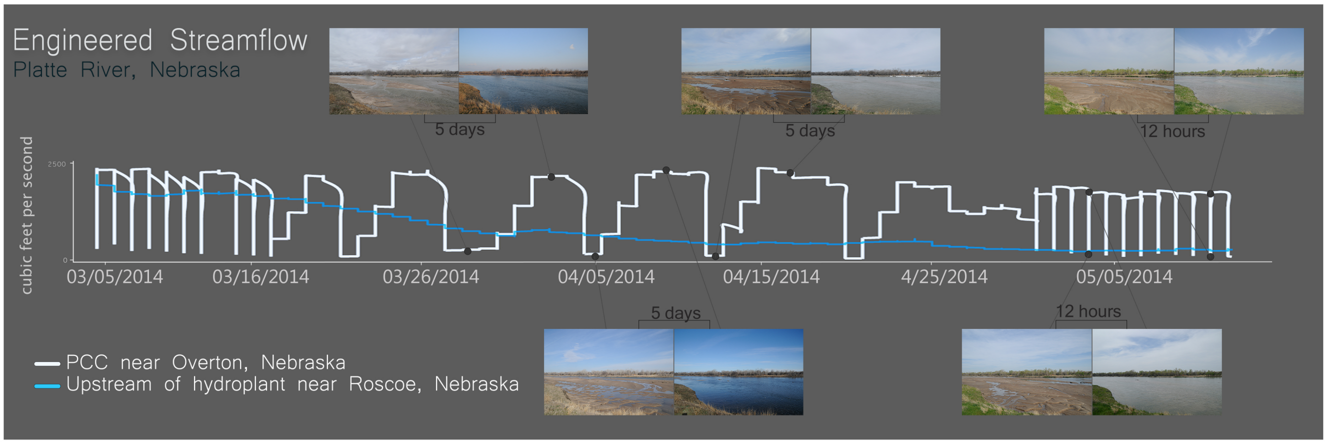


Fig. 6. Static time-lapse data sequence illustrating the hydrograph during the spring of 2014 at Plum Creek Complex (light blue), a site located downstream from a hydropower plant on the Platte River in Nebraska. The hydrograph of a site located upstream, without controlled water releases, is included for comparison (dark blue).



stark disparity in river discharge within short intervals of time. A narrative framework is suggested, alluding to the controversy among federal agencies, environmental groups, industry, and individuals within a water-stressed landscape, exemplifying the complex dynamics of coupled social and ecological systems.

River morphology

As a ground-based passive monitoring technique, time-lapse imagery acquires synoptic field data, including fluvial morphology, as illustrated in Figure 7. Image analysis can assess flow, sediment transport, erosion, and additional topographic data (Chandler et al. 2002). The Platte River is a dynamic and braided prairie river system, and thus, requires a versatile method for data collection. This is evident in Figure 7 because the variability in streamflow and the changing physical characteristics of the riverbank are documented by time-lapse imagery. The capacity to observe hydrology and its influence on river morphology depicts the powerful force of water, its ability to shape both aquatic and terrestrial systems, and alludes to the interactions in social-ecological systems. This process of bank erosion, though still ongoing, has been largely minimized by altered hydrology along the Platte River, leading to reduced disturbance and increased woody encroachment (Williams 1978, Johnson 1994). Figure 7 provides insight into the historical processes that structured the Platte River and what they looked like.

Temporal scale

Time-lapse imagery augments the ability to capture change at multiple temporal scales to observe and monitor natural systems, as well as communicate ecological patterns and processes. Understanding the natural world relies on the elements and patterns we can detect and the relationships among these interconnected ecological dynamics. They are also dependent upon the scale at which they are observed. Grain and extent define these scales and our understanding of natural systems (Peterson and Parker 1998). Time-lapse camera systems are controllable and manually adjusted to vary time intervals, thereby capturing the river system at high, moderate, and low temporal frequencies (Fig. 8). The difference in ecological elements, rhythms, and variability discerned at each scale of observation offers insight into the importance and value of documentation across a range of scales and the capabilities presented through the applications of time-lapse imagery. Broadly, ecological rhythms are environmental processes or biological occurrences with defined periodicity, such as phenology, diel cycles, and life history strategies. For example, regarding image acquisition, a high temporal extent and a low grain captures changes in hydrology, geomorphology, and seasonality, depicting ecological rhythms and interannual fluctuations (Fig. 8, coarse scale) and thus, is valuable for assessing systems over time, including restoration initiatives, and landscape impacts of climate change. At a moderate temporal extent and grain, time-lapse imagery is capable of capturing variations within seasons, fluctuations in streamflow, and the influence of environmental factors that are applicable for evaluating the response of biotic and abiotic elements to weather, such as variations in hydrology and water quality, the rate of vegetation phenophase, and processes within a season (Fig. 7, moderate scale). At a fine scale, comprised of high temporal frequency and short temporal extent, time-lapse imagery can capture rapid processes, in-depth details, and occurrences that may be too sensitive to observe extensively in person, such as the roosting patterns of Sandhill Cranes (Fig. 8, fine scale). The temporal versatility of time-lapse exemplified by a range of scales makes it a valuable tool for research, but moreover it is a valuable mechanism to communicate relationships and processes that can be challenging to understand when observation is temporally limited in extent and/or grain.

Spatial scale

Ground-based time-lapse imagery offers a method of data collection to bridge the divide between human observation (fine detail, low spatial extent, moderate temporal frequency) and satellite remote sensing (coarse detail, high spatial extent, low temporal frequency). The ability to scale up data for analysis is particularly beneficial for climate change research and

Fig. 7. Time-lapse imagery illustrating river morphology and erosion of the Platte River stream bank over time at Plum Creek Complex.

Fig. 8. Static time-lapse data sequences showing examples of temporal scale with conceptual data graphics and paired time-lapse imagery.

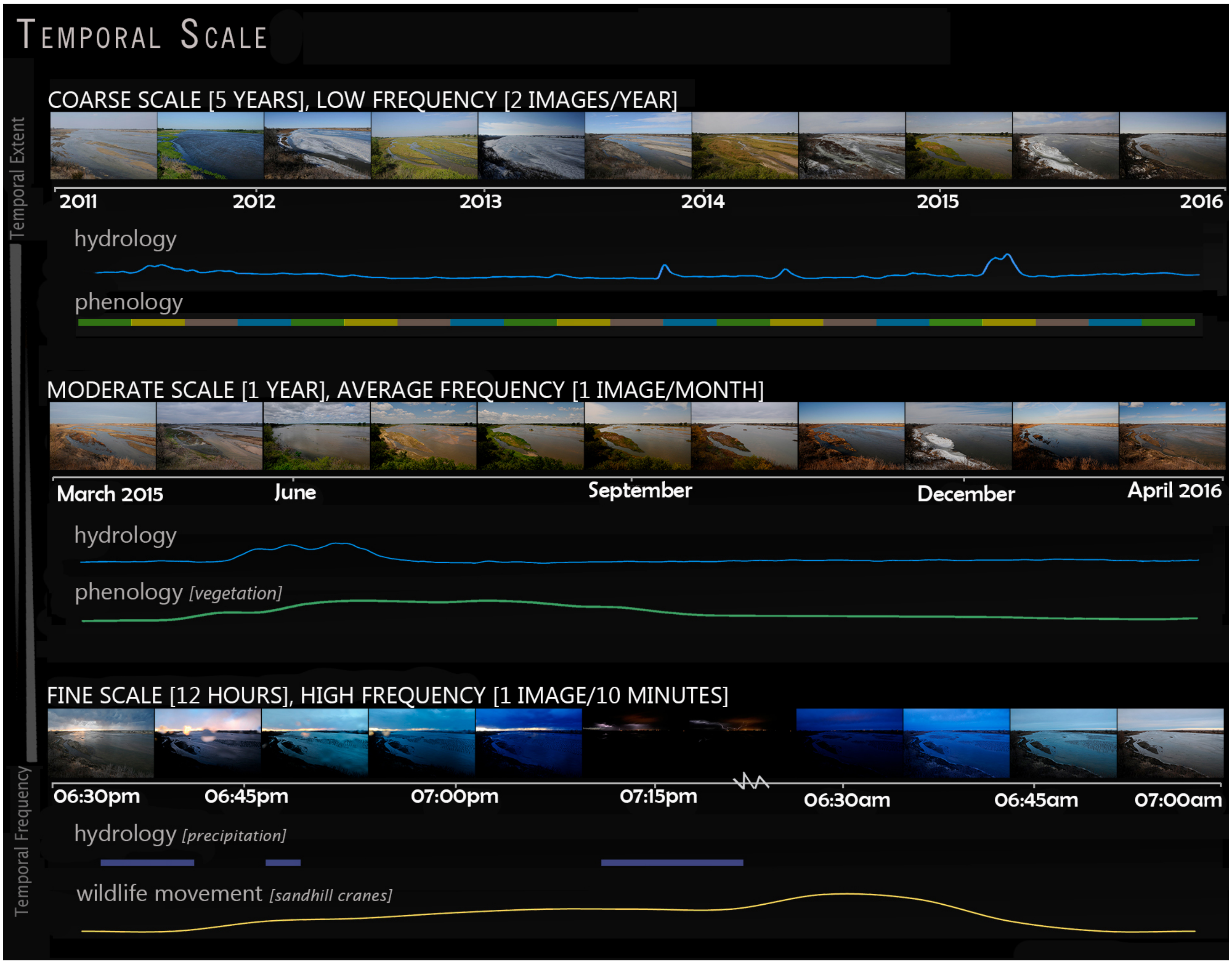


Fig. 9. Scaling up of in-person, time-lapse imagery and satellite remote sensing observations.

understanding the response of biotic and abiotic factors. Figure 9 illustrates a simplified portrayal of scaling up in spatial resolution from differing methods of data acquisition. Human observation concentrates on a fine scale, such as details of an individual species, whereas satellite imagery documents a larger system at a bird's eye view. Time-lapse imagery captures a landscape or community, substantiating a more continuous spatial alignment. Furthermore, although the oblique view captured by time-lapse can be challenging to quantitatively characterize, the perspective can be more interpretable, tangible, and relatable to public audiences and thus, can aid in understanding.

System comparison
http://www.ebrinbuck.com/ATZ.html

Although DRW is further downstream than RRC and thus, has a delayed response of approximately one week for high water events, the general hydrology at both sites is responding similarly to heavy precipitation upstream of the two locations, as seen in the time-lapse images. However, it's evident looking at the data graphic that levels of atrazine are higher at DRW following the increased water levels. The ability to see the changes side by side, visually and graphically, allows comparison between sites to guide our understanding of how watersheds are changing through time and space (Fig. 10). In a broader context, we can infer and educate about how different aspects of a river basin function, such as movement of human-use contaminants through a river and the benefits of wetland filtering.

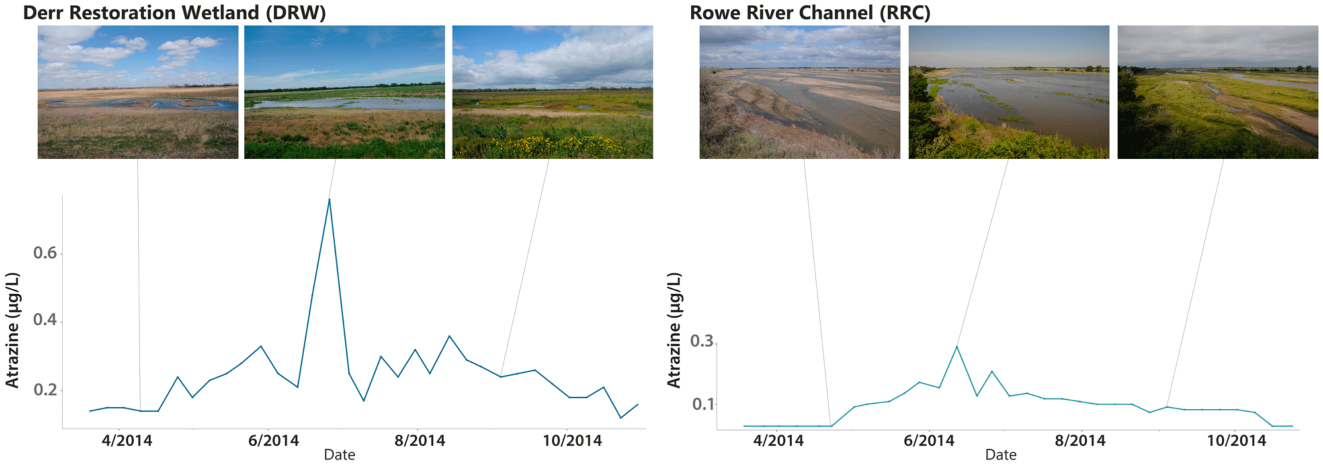
DISCUSSION

Across multiple spatio-temporal scales, environmental change and human impacts to the natural world have increased the importance of monitoring and understanding ecosystems (Sagarin and Pauchard 2010, Folke et al. 2011). Innovative methods of documentation and knowledge sharing are needed to conserve ecosystems and sustain our natural resources. In a water-stressed system within the Great Plains of Nebraska, we utilized time-lapse imagery for two purposes; to collect data and to depict ecological change. Our results demonstrate the duality of digital time-lapse imagery and its ability to function as an expressive aesthetic and as a means of observational evidence.

Proximal sensing is an increasingly applied technique in ecological research for monitoring systems, assessing biotic and abiotic change, and evaluating management decisions (Crimmins and Crimmins 2008, Richardson et al. 2009). Time-lapse camera systems offer high-resolution and ease of use, and they are able to acquire data at a range of temporal and spatial scales and to archive and reference imagery for future examination (Webb 2010). Utilizing digital time-lapse cameras as passive sensors, we demonstrate that time-lapse imagery is an effective tool to characterize vegetation phenology and quantify water inundation. Findings suggest that time-lapse cameras are capable of documenting systems previously unmonitored or infrequently measured because of the spatial and temporal constraints of existing methods, including human observation and satellite imagery. For example, hydrologic equipment, such as stream gauges, can require in-person measurements, familiarity with scientific tools and methodologies, and furthermore, are limited in their application because they are designated for one use. The application of time-lapse imagery to monitor aquatic systems can provide near-continuous data collection of hydrologic changes, in addition to various other datasets, such as vegetation encroachment or sandbar dynamics, while simultaneously offering visual confirmation of landscape changes. Our preliminary findings are suggestive of the capabilities of time-lapse imagery to augment data collection, to increase the spatial and temporal capacity to quantify system changes, and to support the findings of previous studies (Sakamoto et al. 2012, Inoue et al. 2015).

In addition to expanding monitoring scales, the proficiency of time-lapse imagery to document change and defy the human-perception of time makes it a powerful communicative tool. Most environmental challenges facing society today, such as climate change impacts, requires the attention and awareness of diverse societal actors to find solutions and gain support for research (Sunderland et al. 2009). Imagery compels society to confront issues by documenting a moment in time and making environmental problems visible. Time-lapse imagery documents change over time, in which the sequential alignment of individual frames compresses human-experienced time into a more tangible and perceptible timeframe (i.e., days to years illustrated within seconds to minutes). The synthesis of data visualization and time-lapse imagery offers a communicative duality to coalesce the interpretable aesthetics of imagery with the quantitative reinforcement of data to convey complex ecological dynamics. Time-lapse data sequences presented both visual and invisible change over time and offered potential to link the two in new and

Fig. 10. Time-lapse data sequences at Derr Resotration Wetland and Rowe River Channel showing fluctuations of Atrazine from March to November of 2014. Atrazine is a commonly applied herbicide for agricultural producers.



interesting ways: researchers to further comprehend anomalies, scientists to inform policy, land-stewards to guide management, teachers to augment learning objectives, and informal educators or organizations to raise awareness and interest in environmental issues.

Time-lapse data sequences take advantage of the prevalence of online environments to improve access and inform diverse audiences. When presented in a digital format, time-lapse data sequences incorporate interactive elements allowing for flexibility and efficiency to transcend the static limitations of traditional communicative approaches. In contrast, traditional media, such as newspaper and hard copies, is often inherently static, and thus, constraining, representationally limiting, isolated from key societal actors, and inadequate to overcome complexity and design challenges. An author or editor is often required to make a decision with regard to translating a fact or message in static media, i.e., depicting one moment in time and space or generalizing a concept to an average, restricting the scale to one spatio-temporal point, and limiting the potential to communicate process and complexity. The malleability of time-lapse data sequences does not adhere to a rigid format. The malleability is capable of representing complexity and transitioning between time and space, a key factor in exploring and assessing natural systems. This structure can enable content to be extended in novel ways, organized in an interactive framework, and viewed as various arrangements by way of animation, dynamic elements, or hyperlinks (Eveland 2003). User-defined actions allow an individualized pace to view or reexamine content (skimming vs. in-depth reading) to aid in comprehension. This interactivity has the ability to facilitate multidimensional exploration, selectivity, and engagement (Liu and Schrum 2009, Vervoort et al. 2010) to create explanative environments, encourage pattern recognition, make inferences, and foster understanding of the interconnectedness of content and concepts (Eveland 2003, Andrienko et al. 2010). Facilitated by interactivity, active engagement has been shown to have a positive impact on learning and learner satisfaction, in addition to increasing inquiry and interest in scientific-related fields (Liu and Schrum 2009, Chou et al. 2012). Our resulting preliminary examples suggest that the flexible nature of time-lapse imagery in a digital environment may be better apt to convey the nonlinearity, transitions, and shifting states inherent in complex systems.

Extending beyond traditional learning approaches, digital time-lapse data sequences enable flexible access for knowledge sharing and integrative experiences. Portable devices such as tablets, laptops, and cellphones, have presented opportunities for mobile knowledge sharing and engagement through a nature-technology interface and have emerged as a commonly used tools for integrative indoor/outdoor experiences and mobile learning (Hwang and Wu 2014). Recent studies have found that mobile electronics are pedagogically beneficial and can enhance a user's experience, knowledge, and motivation (Park 2011, Hwang and Wu 2014), to aid in generating a sense of place and act as a catalyst to foster sustainable action. Time-lapse data sequences delivered by a portable digital platform can connect individuals by facilitating context awareness and content adaptivity. Context awareness, the familiarity with a physical location, situation, or people, is achieved through visually immersing individuals or audiences into a place through graphics and imagery connected to their physical location. Content adaptivity, the ability to direct materials and information to appropriate individuals (i.e., age, learning objective), is enabled through the malleability of time-lapse data sequences and a wide range of applications and capabilities to tailor narration and learning experiences (Pea et al. 2011). For example, an individual can visit a physical location, such as a park or nature center, and through wireless internet, cell service, or preloaded devices can access historical evidence and/or real time data to guide explorative learning, observe changes over time, and create relational understanding. By digital access to time-lapse data sequences, the connection to the park can continue even after an individual leaves the physical location to enable a more in-depth experience. This technology-nature interface presents opportunities to network experiences and engage outside audiences. This could be a student visiting a location on a field trip, staying engaged with the site while at school, and then sharing their connection to the place at home. Portable applications of digital time-lapse sequences offer opportunities to strengthen connection and contribute to local knowledge bases, a consideration for understanding social-ecological systems (Gerhards and Schaffer 2010).

Digital time-lapse imagery offers a technique capable of dual purposes: (1) a tool to monitor systems, document change, obtain quantitative data, and fill a gap in scale, and (2) through digital time-lapse sequences, as a communicative medium coupled with data visualization to inform audiences, spark interest, and facilitate novel perceptions. The versatility in applications can capture and illustrate ecological dynamics, with the aim of aiding in the understanding of natural systems. Reinforcing graphical representations with visually telling imagery, time-lapse data sequences offer the potential to reveal latent changes, depict a more holistic conceptualization of social-ecological systems, and elucidate informative yet beautiful patterns, processes, and relationships (Gray et al. 2012) to further blur the line of separation between art and science.

Responses to this article can be read online at:
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