Conservation Biology

Essay

Ten ways remote sensing can contribute to conservation

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Abstract: *In an effort to increase conservation effectiveness through the use of Earth observation technologies, a group of remote sensing scientists affiliated with government and academic institutions and conservation organizations identified 10 questions in conservation for which the potential to be answered would be greatly increased by use of remotely sensed data and analyses of those data. Our goals were to increase conservation practitioners' use of remote sensing to support their work, increase collaboration between the conservation science and remote sensing communities, identify and develop new and innovative uses of remote sensing for advancing conservation science, provide guidance to space agencies on how future satellite missions can support conservation science, and generate support from the public and private sector in the use of remote sensing data to address the 10 conservation questions. We identified a broad initial list of questions on the basis of an email chain-referral survey. We then used a workshop-based iterative and collaborative approach to whittle the list down to these final questions (which represent 10 major themes in conservation): How can global Earth observation data be used to model species distributions and abundances? How can remote sensing improve the understanding of animal movements? How can remotely sensed ecosystem variables be used to understand, monitor, and predict ecosystem response and resilience to multiple stressors? How can remote sensing be used to monitor the effects of climate on ecosystems? How can near real-time ecosystem monitoring catalyze threat reduction, governance and regulation compliance, and resource management decisions? How can remote sensing inform configuration of protected area networks at spatial extents relevant to populations of target species and ecosystem services? How can remote sensing-derived products be used to value and monitor changes in ecosystem services? How can remote sensing be used to monitor and evaluate the effectiveness of conservation efforts? How does the expansion and intensification of agriculture and aquaculture alter ecosystems and the services they provide? How can remote sensing be used to determine the degree to which ecosystems are being disturbed or degraded and the effects of these changes on species and ecosystem functions?*

Keywords: applied research, biodiversity, priority setting, remote sensing

Diez Maneras en que la Detección Remota Puede Contribuir a la Conservación

Resumen: *En un esfuerzo por incrementar la efectividad de la conservación por medio del uso de las tecnologías de observación de la Tierra, un grupo de científicos de detección remota afiliados con instituciones académicas y gubernamentales y con organizaciones de conservación, identificaron diez preguntas de conservación para las cuales el potencial de ser respondidas se ampliaría al usar datos de detección remota y el análisis de esos datos. Nuestros objetivos fueron incrementar el uso de detección remota por parte de quienes practican la conservación para apoyar su trabajo, incrementar la colaboración entre las comunidades de la ciencia de la conservación y la de detección remota, identificar y desarrollar usos nuevos e innovadores de la detección remota para avanzar en la ciencia de la conservación, proporcionar dirección a las agencias espaciales sobre cómo misiones satelitales futuras pueden apoyar a la ciencia de la conservación, y generar apoyo del sector privado y del público para el uso de datos detección remota para dirigirnos a las diez preguntas de conservación. Identificamos una lista inicial amplia de preguntas con base en una encuesta de correos electrónicos en cadena. Después usamos una estrategia colaborativa e iterativa basada en un taller de trabajo para reducir la lista a estas preguntas finales (que representan diez temas relevantes en conservación): ¿Cómo puede usarse la observación global de la Tierra para modelar la abundancia y distribución de las especies? ¿Cómo puede mejorar la detección remota el entendimiento de los movimientos animales? ¿Cómo pueden usarse las variables de los ecosistemas detectados a distancia para entender, monitorear y predecir las respuestas ambientales y la resiliencia a estresantes múltiples? ¿Cómo puede usarse la detección remota para monitorear los efectos del clima sobre los ecosistemas? ¿Cómo puede el monitoreo ambiental en casi tiempo real catalizar la reducción, de amenazas, la gobernación y el cumplimiento de las regulaciones, y las decisiones sobre manejo de recursos? ¿Cómo puede la detección remota informar a la configuración de redes de áreas protegidas en extensiones espaciales relevantes para las poblaciones de especies clave y servicios ambientales? ¿Cómo pueden usarse los productos derivados de la detección remota para monitorear y evaluar la efectividad de los esfuerzos de conservación? ¿Cómo altera la expansión e intensificación de la agricultura y la acuacultura a los ecosistemas y a los servicios que proporcionan? ¿Cómo puede usarse la detección remota para determinar el grado al que los ecosistemas se están degradando y perturbando y los efectos de estos cambios sobre las especies y las funciones de los ecosistemas?*

Palabras Clave: biodiversidad, investigación aplicada, marco de prioridad, teledetección

Introduction

Since the U.S. National Aeronautics and Space Administration (NASA) launched the Landsat 1 spacecraft in 1972, satellite and airborne technology for observing Earth from space (henceforth, remote sensing) has played an increasingly important role in detecting, mapping, understanding, and predicting changes in the environment. Early applications mainly assessed land-use and land-cover change, such as deforestation in the Amazon (Skole & Tucker 1993) and global changes in the distribution of cropland (Ramankutty & Foley 1999). More recently, remote sensing has been used, for example, to map carbon stocks in the Amazon (Asner et al. 2010), identify critical bird breeding habitat (Goetz et al. 2010), and assess the effects of anthropogenic light on seabirds (Rodrigues et al. 2012). Nevertheless, remote sensing research largely has focused on areas other than the conservation of biological diversity (Turner et al. 2003; National Research Council 2007).

Recent papers identified remotely sensed metrics (e.g., primary productivity, sea surface height, and land cover [Pettorelli et al. 2014]) that may be associated with ecological response variables ranging from probability of extinction (Di Marco et al. 2014) to genotype (Madritch et al. 2014). Programmatic efforts by NASA (e.g., Ecological Forecasting Program), the Committee on Earth Observation Satellites (CEOS), and the Group on Earth Observations–Biodiversity Observation Network (GEO-BON) focused attention, raised funds, coordinated data collection, and facilitated meetings and working groups on the application of remote sensing to conservation of biological diversity. We complemented those publications and efforts by engaging members of the conservation science and remote sensing communities in identifying 10 conservation questions to which remote sensing can be applied at both a tactical and a strategic level. Our objectives were to increase conservation practitioners' use of remote sensing and collaboration between the conservation science and remote sensing communities, identify and develop new and innovative uses of remote sensing for advancing conservation science, provide guidance to space agencies on how future satellite missions and supporting airborne campaigns can support conservation, and generate support from the public and private sector in the use of remote sensing data to address the 10 conservation questions.

Methods

We convened 30 individuals with expertise in conservation science and remote sensing who were affiliated with academic, governmental, and nongovernmental organizations (NGOs). To identify the participants, we worked with a small group of remote sensing scientists and conservation practitioners to first develop an extensive list of potential participants and then, from this list, to identify a narrower set of individuals with collective expertise in both terrestrial and aquatic ecosystems and in diverse scientific and geographic areas. The participants included 7 individuals from academic institutions, 12 scientists employed by the U.S. government, and 11 individuals employed by international conservation NGOs. We then used the modified Delphi process developed by Sutherland et al. (2006) to engage participants in pre-workshop data collection, a 4-day workshop, and post-workshop collaboration to finalize the 10 questions.

Prior to the workshop, in an effort to expand the diversity of expert opinions, we asked each participant to interview 5 colleagues with diverse backgrounds and expertise on conservation challenges that have the greatest potential to be answered through an influx of remote sensing. This process was roughly analogous to snowball sampling, which is common in survey design and implementation. Participants were asked to focus on conservation questions that can be addressed with either current technologies or technologies that plausibly could be developed in the near future. Participants interviewed over 100 experts and generated 360 questions. Most questions focused on conservation; some, despite instructions, focused on desired advances in remote sensing technology.

The full list of 360 questions was sent to all 30 participants. Each was asked to vote for the 10 conservation questions and the 2 technical questions for which they considered the answers most relevant to the practice of conservation. The 183 questions that received at least one vote were retained.

In January 2013, 30 participants and 2 leaders convened in a week-long workshop to distill the 183 questions to 10. The group first established 4 criteria for retaining questions and 3 criteria for prioritization. We required that each question identify a clear conservation application, focus on use of remote sensing, focus on a specific challenge but remain broadly applicable, and that the answer to the question potentially have a clear link to conservation practice. Each question that met these criteria was then prioritized categorically (low, medium, or high) on the basis of whether it provided information for informed conservation action and whether its answer would be broadly applicable.

To identify high-priority questions, we divided the participants into 3 groups of 10 and the questions into 3 equal sets. We asked each group to review one set of questions, identify the questions that met the above criteria, and prioritize those questions. The medium- and high-priority questions were exchanged among groups and again prioritized. This process was repeated such that after 3 rounds, each set of questions had been rated by each group, with 25 questions remaining. During the process, participants were given the opportunity to combine similar questions and reword questions to fit the criteria.

Each participant then voted for 5 of the 25 questions, with the option to cast multiple votes for questions they considered to be of highest priority. The 10 questions with the greatest number of votes were identified and discussed to ensure that the set reflected consensus and to identify the conservation theme represented by each question. The 10 questions represented a broad, but not exhaustive or mutually exclusive, set of themes that reflected current issues in conservation to which remote sensing could contribute substantially. The themes included species distributions and abundances, species movements and life stages, ecosystem processes, climate change, rapid response, protected areas, ecosystem services, conservation effectiveness, agricultural and aquacultural expansion and changes in land use and land cover, and degradation and disturbance regimes. Some themes overlapped, but participants preferred to keep overlapping questions distinct to highlight each theme.

The order in which questions are presented does not reflect a ranking. We did not identify separate questions for terrestrial, freshwater, and marine environments because each question encompassed the 3 realms.

We used the following, generally accepted characterization of spatial resolution for terrestrial applications: low or coarse resolution, >1 km (e.g., advanced very high-resolution radiometer [AVHRR]); moderate, 250 m–1 km (e.g., moderate resolution imaging spectroradiometer [MODIS]); high, 30 m (e.g., Landsat); and very high, approximately a few meters (e.g., IKONOS, Quickbird, and airborne remote sensing campaigns). Spatial resolution for open-ocean applications (e.g., ocean color, harmful algal blooms) tends to be coarser, but for coastal marine ecosystems (e.g., seagrass and corals) very high spatial resolution is often useful. We used the above characterization with reference to all realms. The variable level of detail among questions reflected diverse investment and experimentation in the application of remote sensing to different conservation questions.

Results

Species Distributions and Abundances

For the theme species distributions and abundances, the question experts identified was, how can global Earth observation data be integrated into models of species distributions and abundances to inform conservation action?

Development and validation of accurate, spatially explicit predictions of species distributions and abundances across a range of spatial and temporal scales requires integrating data on intrinsic biological factors, extrinsic environmental drivers, and historical and current species distributions and abundances (Elith & Leathwick 2009). Remote sensing provides data on extrinsic environmental drivers such as land cover, primary productivity (e.g., the normalized difference vegetation index [NDVI], chlorophyll concentration [ocean color or productivity]), and elevation and bathymetry. However, remote sensing observations often used to predict species distributions globally have spatial resolutions of approximately 0.5–1.0 km, which are coarser than the resolutions at which many taxa interact with the environment. Data at global extents but with finer spatial and temporal resolution are vital to understanding the distributions and abundances of certain species. Such data are needed to estimate values of variables including fractional land cover (i.e., proportion of area covered by different types of land cover), density of human-made structures, habitat quality for given species, land and sea surface temperature, coastal and open ocean chlorophyll-a, dates of soil freeze and thaw, fire dynamics, phenology, topography, and vertical vegetation structure. Many of these variables are derived from existing multispectral sensors (e.g., MODIS) and other instruments, but global coverage of other variables may require the deployment of new sensors such as satellite-based light detection and ranging (lidar) or 3-dimensional surface mapping and imaging spectrometers (National Research Council 2007) for better discrimination of features of heterogeneous terrestrial and marine ecosystems. Derivation of data at finer spatial and thematic resolutions also may require development of new products that integrate Earth observations and ancillary data, such as consistent and complete data on primary and secondary roads.

Species Movements and Life Stages

For the theme species movements and life stages, the question identified was, how can remote sensing improve the understanding of the processes controlling spatial and temporal dynamics of animal movements?

Long-distance movements, such as the migrations of the monarch butterfly (*Danaus plexippus*), common wildebeest (*Connochaetes taurinus*), humpback whale (*Megaptera novaengliae*), and many other species are well recognized as ecological phenomena that are extremely difficult to conserve (Wilcove & Wikelski 2008; Mueller et al. 2011) because, for instance, their role in maintaining local and global patterns of species distributions and ecosystem function is not well understood (Jeltsch et al. 2013) and little is known about how climate change may affect species' movements (Wilcove & Wikelski 2008). Additionally, it is unknown how spatial and temporal environmental variability (e.g., the phenology of primary productivity, water availability, topography, fruiting patterns in tropical forests, weather, and climate) affect long-distance animal movements. Most long-distance movements are a response to seasonal resource variation in which species exploit resource peaks in geographically distant seasonal habitats (Alerstam et al. 2003). Understanding the variation in such patterns across temporal and spatial scales, plus the effects of human actions on such patterns, is essential to understanding and conserving movement processes (Katzner et al. 2012).

Remote sensing can provide information about spatial and temporal environmental variation that affects animal movement (Pettorelli et al. 2014) and about land-cover changes that remove or reduce the quality of migration corridors (Wegmann et al. 2014). Movements of relatively large animals have been linked to remotely sensed observations, such as those of net primary productivity and topography (Bohrer et al. 2012). However, data on variables correlated with animal movements, such as phenology, climate, and food and water availability, are needed at finer spatial, thematic, and temporal resolution, particularly to model small-scale and high-frequency movement. Moreover, the scale and type of remote sensing observations must correspond to the scales at which animals perceive their environments through, for example, olfaction, sight, or echolocation.

Ecosystem Processes

The ecosystem processes theme was covered by the question, how can remotely sensed ecosystem variables be used to understand, monitor, and predict ecosystem response and resilience to multiple stressors?

Ecosystems and ecosystem processes are constantly changing in response to natural and anthropogenic disturbances, but it is not always clear how ecosystems will respond to single or multiple disturbances. For example, there is no clear understanding of the capacity of terrestrial, freshwater, and marine ecosystems to absorb nitrogen from human activities or how nitrogen facilitates the development of unproductive aquatic zones and changes in terrestrial ecosystem productivity.

Remote sensing offers cost-effective information on ecosystem extent, status, trends, and responses to stressors over large areas. For example, remote sensing can contribute to quantifying agricultural and atmospheric nitrogen inputs and associations between outbreaks of insects and forest productivity and nutrient retention (e.g., Townsend et al. 2012). Similarly, Landsat-derived maps of coral bleaching are an indicator of substantial stress and a potential loss of ecosystem function (Baker et al. 2008). Earth observation missions that provide high spatial resolution and frequent revisits are most useful for documenting long-term effects of extreme events, such as severe storms, on ecosystem structure, function, and productivity, but increased spatial and temporal resolution imagery would likely result in a finer scale understanding of ecosystem responses to these events.

Climate Change

The climate-change theme was addressed by the question, how can remote sensing be used to monitor the rate, magnitude, and spatial and temporal effects of climate on ecosystems?

Changes in climate can alter ecosystem state and functions (Chapin et al. 2010; Kasischke et al. 2013). Greater integration of paleoecological and paleoclimatological data, contemporary observations of ecosystem status and trend, and environmental models can help researchers estimate the ecological and economic effects of climate change and thus allow societies to develop and assess adaptation and mitigation plans.

Remote sensing can detect environmental changes that potentially reflect climate change at multiple spatial scales, from local patterns of disturbance, to regional changes in snow depth, to global changes in ice cover. In addition, some satellite remote sensing missions provide long-term records of land and sea surface temperature and of vegetation, from which indices useful for understanding the dynamics of climate change can be derived. Data on other high-priority variables, such as evapotranspiration (Mu et al. 2011) and soil moisture (Entekhabi et al. 2010), are or soon will be consistently and globally measured by remote sensing. As climate forcings strengthen over time, long-term satellite data records will help inform and improve projections of the effects of climate change on biological diversity. Understanding the temporal variability and trends in vegetation processes and their relation to climate forcings requires consistent time-series data on vegetation derived from multiple sensors (e.g., Cao et al. 2008 or see the Long-Term Data Record project at http://ltdr.nascom.nasa.gov/cgi-bin/ltdr/ltdrPage.cgi). Long-term, multiscale observations on phenology, precipitation, snow cover, extent of glaciers and polar ice, movement of tree lines, and other phenomena can help researchers characterize relations between climate change and ecosystems and species that are high priorities for conservation. The global coverage of satellite products implies a spatial extent that can allow consistent modeling of ecosystems across extensive regions over time, which matches the temporal scale of climate-model projections. However, the greatest challenge to improving models of the effects of changing climate on ecosystems is the lack of available in situ time-series data on the components of ecosystems for use in conjunction with remotely sensed climate information. Although these data are often collected, they are rarely made available to the broader conservation community.

Rapid Response

The rapid response to ecosystem threats theme was addressed under the question, how can near real-time ecosystem monitoring catalyze threat reduction, governance and regulation compliance, and resource management decisions.

Accurate and timely information is key to making effective conservation decisions. Some decisions, such as responses to wildfires (Davies et al. 2009), droughts, oil spills, and illegal resource extraction activities (e.g., fishing Kourti et al. 2005; and logging Hansen et al. 2013) require information within hours or days. Near real-time ecosystem monitoring based on remote sensing can make the detection of ecosystem threats more accurate and catalyze rapid response. One such example is the Fire Information Resource Management System (Davies et al. 2009), which provides near-real time global fire alerts on the basis of MODIS active fire-detection data. Another example is the coral reef bleaching alert system, which is based on sea surface temperature anomalies derived from AVHRR (http://coralreefwatch.noaa.gov/satellite/index.php).

Greater access to free or affordable data from government (Landsat, Sentinel) and private (Satellite Pour l'Observation de la Terre [SPOT], Quickbird) satellites and unmanned aerial vehicles (UAVs), improved analytical capacity, faster data-sharing networks, and the proliferation of users with mobile devices and access to digital data streams even in remote locations means that near real-time ecosystem monitoring is feasible and potentially can improve the ability of institutions to rapidly deploy enforcement or response personnel. Such data and enforcement also can increase transparency, which in turn may deter illegal activities. Integrating near real-time ecosystem monitoring and community-based monitoring can facilitate effective natural resource management while ensuring that local customs and rights are respected.

Protected Areas

Experts addressed the protected areas theme with the question, how can remote sensing inform configuration of protected area networks at spatial extents sufficient to maintain ecologically functional and resilient populations of target species and maintenance of ecosystem services?

Protected areas rarely are delineated on the basis of information about ecosystem services, ecological functions, and the area requirements of resilient populations. Rather, they typically reflect political, jurisdictional, opportunistic, or land-cover or land-use boundaries. As a result, protected areas can be too small to conserve the species and ecological processes they were established to protect (DeFries et al. 2010). In part to overcome this constraint, the matrix surrounding protected areas also must be managed (Urquiza-Haas et al. 2011).

Remote sensing data can help define the extent and configuration of potential protected areas to meet the needs of the species and ecosystem processes they were designed to protect (Wegmann et al. 2014). Additionally, remote sensing can contribute to monitoring the status of protected areas by providing information on vegetation condition, areas of human disturbance, and the location and spread of non-native invasive species (Nagendra et al. 2013).

Ecosystem Services

The ecosystem services theme was covered with the question, how can remote sensing-derived products be used to value and monitor changes in ecosystem services?

Interest in understanding ecosystem services has increased globally in the last decade (Jack et al. 2008; Wunder et al. 2008). Quantifying and mapping the status of services and assigning market values to provisioning, regulating, supporting, and cultural services are key to devising market-based incentives to conserving such services (e.g., supply clean water, reduce carbon emissions from biomass conversion, and prevent soil erosion). Market incentives such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) and payments for ecosystem services (PES) can be viable options for ensuring the future provision of such services while effectively monitoring the results of conservation efforts. For example, remote sensing can be used to document, monitor, and ultimately predict the extent and condition of forest within a given region under current conditions and future policy scenarios (Busch et al. 2013).

Beyond REDD+, analysis of remotely sensed vegetation cover can establish baselines for provisioning regulatory and cultural services in PES schemes. However, remote sensing typically has not been used to establish baselines for supporting services. In one of few examples, the government of Rwanda has explored the feasibility of a payments for water services scheme to protect vegetation cover at the headwaters of rivers in Rugezi and ensure sustained flows of water for drinking, agriculture, manufacturing, and energy production (Willetts 2008). Regular monitoring of ecosystem services such as carbon sequestration, provision of clean water, sustainable fisheries, and agricultural productivity with remote sensing will enable evaluation of whether market-based schemes provide sufficient incentives to conserve ecosystem services and other elements of biological diversity.

Conservation Effectiveness

For the conservation effectiveness theme, experts identified the question, how can remote sensing and associated analytical tools be used to monitor and evaluate the effectiveness of conservation efforts?

For over a decade the conservation community has advocated for quantitative evaluation of conservation effectiveness to adapt strategies for law enforcement, governance, and conservation of both livelihoods and species and their habitats (Ferraro & Pattanayak 2006). Monitoring conservation effectiveness is intended to provide evidence whether the money spent on conservation initiatives and actions met benchmarks of success.

Remotely sensed information can play a substantial role in determining whether investment in protected areas, ranger patrols, conditional payment schemes, and governance training is correlated with status and trend of natural resources. Multiple sources of remotely sensed data such as multispectral satellite sensors, aerial videography, acoustic ground stations, and small UAV imaging surveys contribute to assessment of the effectiveness of conservation actions. These actions may include the creation of protected areas (Sieber et al. 2013), reduction of anthropogenic levels of light (Rodrigues et al. 2012), or sustainable management of ecosystems and the services they provide (Duan et al. 2013).

Agricultural and Aquacultural Expansion and Changes in Land Use and Land Cover

The agricultural and aquacultural expansion and changes in land-use and land-cover theme was addressed by the question, how does the rate and pattern of expansion and intensification of agriculture and aquaculture alter ecosystems and the services they provide?

It is a great challenge to meet society's growing food needs while mitigating the undesirable effects of agricultural expansion (Foley et al. 2011). Agriculture covers about 38% of Earth's land surface and is the most extensive land use on the planet (Ramankutty et al. 2008). To accommodate this expansion, 70% of Earth's grassland, 50% of savanna, 45% of temperate deciduous forest, and 27% of tropical forest has been cleared or converted (Ramankutty & Foley 1999; Ramankutty et al. 2008). Agricultural expansion affects both species and ecosystem functions, such as carbon storage and maintenance of soil nutrients. Similarly, aquacultural expansion alters ecosystem functions and can introduce non-native species to aquatic and terrestrial systems (Food and Agriculture Organization 2010).

A major step in understanding the potential effects of agriculture or aquaculture on species and ecosystem functions is to systematically assess the rates and locations of expansion and intensification. The global coverage and the spatial and temporal resolution from satellite observations allow mapping of these small- to large-scale changes. The combination of images with high temporal and low spatial resolution, such as those from MODIS, with images with high spatial and low temporal resolution, such as those from Landsat, are relevant to assessing agricultural systems and the open ocean. Images with high temporal resolution (daily for MODIS and *visible infrared imaging radiometer suite* vs. bimonthly for Landsat) capture the timing of vegetation changes, such as changes in phenology, and changes in coastal chlorophyll levels associated with algal blooms and riverine discharge. However, more frequent high-resolution imagery would be a tremendous advance. More nations are launching satellites with high spatial resolution (≤30 m), but it is a challenge to coordinate and calibrate the imagery from these systems to increase the frequency of observations.

Degradation and Disturbance Regimes

Experts covered the degradation and disturbance regimes theme with the question, how can remote sensing be used to determine the degree to which ecosystems are being disturbed or degraded and the effects of these changes on species and ecosystem functions?

Although satellite remote sensing can detect many types of disturbance that manifest in changes in land cover, ecosystems also can be disturbed without a corresponding change in land cover, making such disturbances more challenging to detect. For example, detectable land-cover conversion may not accompany changes in composition, structure, and function, including changes in vegetation and soils caused by varying levels of livestock grazing, changes in species composition and vegetation structure caused by non-native invasive species, increased tree mortality caused by insect outbreaks and air pollution, and myriad effects of global climate change.

Landsat data can characterize, for example, changes in grasslands on the Mongolian steppe due to grazing by domestic livestock (Karnieli et al. 2013), and, although global availability of hyperspectral data is limited, much progress has been made in the use of hyperspectral data to assess changes in coral reef ecosystems and function (Hochberg 2011). Multisensor approaches may be particularly useful for assessing changes in ecosystems, especially when combined with ancillary data such as field observations and topographic or bathymetric data. Such approaches may increase understanding of the ecological ramifications of disturbances and help researchers identify thresholds of disturbance above which there are substantial effects on species and ecosystems and determine how disturbances affect processes such as carbon sequestration and nutrient cycling.

Discussion

Through a collaborative, expert-driven process, we identified 10 conservation questions that can be addressed, in part, through a variety of remote sensing technologies, analyses, and levels of expertise. The themes and questions complement and reinforce issues highlighted by Sutherland et al. (2009) and Fleishman et al. (2011). Further, our process explicitly integrates the use of remote sensing into identifying and, ultimately, answering the questions.

As with previous priority-setting exercises (Sutherland et al. 2009; Fleishman et al. 2011), we acknowledge that the professional knowledge of 30 core participants and consultation with additional experts does not fully represent the views of all scientists, practitioners, and policy makers active in conservation science and Earth observation. However, we believe that by purposefully selecting participants with a breadth of technical, thematic, and geographic expertise and by conducting interviews with multiple colleagues we identified shared priorities and will catalyze global discussion of conservation challenges that can be addressed with remote sensing.

With the launch of the Landsat 8 mission in February 2013, the first launch of the European Space Agency (ESA) Sentinel missions in April 2014, and abundance of global, multidate satellite imagery, we believe this is the ideal time to increase focus on remote sensing for conservation applications. The shift toward more systematic global acquisitions and open access to all imagery will enable scientific research and operational monitoring in support of conservation.

As prototypes of new technologies are developed and their utility assessed (e.g., satellite-based lidar, very high-resolution optical systems, and easy-to-use, inexpensive UAV platforms), we suggest that their transition from being the object of research by a few scientists to being used by many practitioners be promoted and that efficient data acquisition and delivery systems, such as that of Landsat, be emulated. However, the ability to incorporate remote sensing into conservation decision making will depend on the cost and availability of data. Many space agencies, such as NASA, the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, and the ESA, provide all or some of their data for free, but free data from other sources can be difficult to acquire.

We hope our presentation of questions will encourage the conservation community to increase its application of remote sensing. Incorporating remote sensing into conservation practice relies not only on data but on closer collaboration between the conservation and remote sensing communities. To this end, during the workshop, participants launched the Conservation Remote Sensing Network (CRSNet) (www.remote-sensing-conservation.org/networks/crsnet). The mission of the CRSNet is to increase conservation effectiveness through enhanced integration of remote sensing in research and applications. The CRSNet will address 4 themes: capacity development, research and collaborations, communications, and best practices. We hope CRSNet can bring together conservation scientists, remote sensing scientists, and remote sensing practitioners to foster collaborations, increase capacity, and generate support for addressing the 10 questions. These collaborations also will create opportunities to advance the use of remote sensing data for conservation and allow remote sensing scientists to prioritize their research to meet the needs of field-based conservation programs. The CRSnet is tightly linked to parallel ongoing activities in remote sensing (CEOS Biodiversity, www.remote-sensing-biodiversity.org, www.ceos.org) and species conservation (GEO-BON, http://www.earth-observations.org/geobon.shtml).

For remote sensing to most effectively contribute to conservation, the conservation community must provide their requirements for environmental parameters to those who are developing satellite missions. For example, the conservation community could clarify whether derived estimates of vegetation biomass are needed, or whether fractional vegetation cover would suffice. The probability of answering the 10 questions also may depend on development of new remote sensing technologies and derived data by the Earth observation community. For example, the conservation community has long called for consistent, regularly updated, global maps of land use and land cover; continuous fields maps (e.g., vegetation continuous field); and a space-based lidar mission to provide consistent and systematic data on vegetation structure. We hope broad dissemination of the results of this initiative will spur academic and government scientists and institutions to work more closely with conservation NGOs to develop tools, data, analytical methods, and the capacity to apply them to solve conservation challenges.

To help facilitate conservation practitioner access to cutting edge solutions, we challenge the government, donor, NGO, and academic communities to use their collective financial and human capital more efficiently to solve the questions presented here. We suggest that collaborative efforts first build remote sensing capacity within the conservation community, similar to previous efforts to increase GIS capacity. Additionally, we suggest making an effort to better link remote sensing with field data, including wider access to free or low-cost medium- and high-resolution satellite images and developing funding opportunities that promote the use of remote sensing to compliment field-based projects. We also encourage membership in the CRSNet to help achieve its mission.

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