50 YEARS WITH IMPACT
Journal of Applied Ecology
British Ecological Society 1913 2013 CELEBRATING 100 YEARS

Journal of Applied Ecology 2014, **51,** 839–848 doi: 10.1111/1365-2664.12261

REVIEW

Satellite remote sensing for applied ecologists: opportunities and challenges

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Summary

1. Habitat loss and degradation, overexploitation, climate change and the spread of invasive species are drastically depleting the Earth's biological diversity, leading to detrimental impacts on ecosystem services and human well-being.

2. Our ability to monitor the state of biodiversity and the impacts of global environmental change on this natural capital is fundamental to designing effective adaptation and mitigation strategies for preventing further loss of biological diversity. This requires the scientific community to assess spatio-temporal changes in the distribution of abiotic conditions (e.g. temperature, rainfall) and in the distribution, structure, composition and functioning of ecosystems.

3. The potential for satellite remote sensing (SRS) to provide key data has been highlighted by many researchers, with SRS offering repeatable, standardized and verifiable information on long-term trends in biodiversity indicators. SRS permits one to address questions on scales inaccessible to ground-based methods alone, facilitating the development of an integrated approach to natural resource management, where biodiversity, pressures to biodiversity and consequences of management decisions can all be monitored.

4. *Synthesis and applications*. Here, we provide an interdisciplinary perspective on the prospects of satellite remote sensing (SRS) for ecological applications, reviewing established avenues and highlighting new research and technological developments that have a high potential to make a difference in environmental management. We also discuss current barriers to the ecological application of SRS-based approaches and identify possible ways to overcome some of these limitations.

Key-words: biodiversity, Earth observations, environmental management, natural capital, sensor, technology, wildlife management

Introduction

With the world's population now exceeding 7 billion people, increasing pressures are being put on our planet to secure sufficient food and space for each inhabitant (Gordon *et al*. 2012). Yet the Earth is a finite system, and as a growing proportion of natural resources are being harvested for human consumption, less energy and less space are being left to the remnant components of biodiversity (Smil 2013). Faced with habitat loss and degradation, climate change, overexploitation and the spread of invasive species, many species have struggled and are still struggling to adapt to the rapid rate of environmental change (Pereira *et al*. 2010). Serious concerns have been voiced about the implications of biodiversity loss for human well-being, particularly for the world's most marginalized and impoverished communities (Millennium

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Ecosystem Assessment 2005), leading to several high-profile political commitments to promote the conservation and sustainable use of biological diversity (Collen *et al.* 2013).

Conserving biodiversity, however, requires data. The ability to monitor the state of our natural capital and the impacts of human activity on these resources is fundamental to designing appropriate and optimized management strategies. In particular, to rise to the challenges posed by global environmental change, the scientific community needs to be able to access global, long-term, reliable information on spatio-temporal changes in the distribution of direct and indirect anthropogenic pressures to biological diversity; in the distribution, structure, composition, and functioning of ecosystems; as well as evidence of the effectiveness of various management actions.

Over the past 30 years, satellite remote sensing (SRS) has shown increased utility for informing the state of, and pressures on, biodiversity at landscape, regional, ecosystem, continental and global spatial scales (Roughgarden, Running & Matson 1991; Turner *et al.* 2003; Duro *et al.* 2007; Gillespie *et al.* 2008; Horning *et al.* 2010). Regional to global land cover products derived from the information captured by sensors on-board long-term satellite missions, such as Landsat, the Terra and Aqua Earth Observing System satellites, and the Polar-orbiting Operational Environmental Satellite (POES) series are widely accessible and offer a relatively inexpensive and verifiable means of deriving complete spatial coverage of environmental information for large areas in a consistent manner that may be updated regularly (Strand *et al.* 2007). Very high spatial resolution (pixel size <10 m^2) commercial optical sensors have provided new opportunities for habitat mapping at a finer spatial scale than previously possible (see e.g. Clark *et al.* 2004; Nagendra *et al.* 2013). Hyperspectral imagery has improved opportunities for plant species identification, soil properties monitoring and habitat mapping, as well as plant condition assessment (Ustin *et al.* 2004; Clark, Roberts & Clark 2005; Pu 2009). Instruments such as synthetic aperture radar (SAR) and light detection and ranging (LiDAR) are increasingly being used in ecology and natural resource management, providing significant opportunities for estimating aboveground biomass and the structure of woody vegetation (Vierling *et al.* 2008; Goetz *et al.* 2009; see also Fig. 1). Today, the archive of terrestrial satellite imagery from the Landsat system spans more than four decades at spatial resolutions of 15–82 m. Spatial resolutions across all sensors range from roughly 50 cm to 10 km, with bi-monthly information available for several sensors (CEOS 2012; see also Table S1, Supporting Information).

Developments in satellite and sensor technology, as well as progress in techniques and algorithms to process SRS images, are relatively rapid and continuous. New combinations of SRS data with methodologies such as support vector machines (Mountrakis, Im & Ogole 2011) and multisensor image fusion (Stathaki 2008) are constantly tested for application, while investigations for developing new indices to monitor vegetation have been occurring for decades (Bannari *et al.* 1995; Pettorelli 2013). Similarly, case studies helping to identify ecological issues that can be informed by the use of SRS are accumulating (Table 1), meaning our ability to inform environmental and wildlife management using SRS is constantly improving. Here, we provide an up-to-date, interdisciplinary perspective on the future prospects of SRS for ecological applications, reviewing established avenues and highlighting new developments that have a high potential to make a difference to practitioners and policy-makers. Although SRS is increasingly popular in applied ecology, the data are still underused. Hence, we also discuss current barriers to the democratization of SRS-based approaches and identify possible ways to overcome some of these limitations.

Established avenues

MONITORING ABIOTIC CONDITIONS AND DISTURBANCES

The physical characteristics of an environment are fundamental to determining its level of biological diversity. SRS is a primary source of information for the monitoring of abiotic conditions, such as rainfall, temperature, winds, elevation and bathymetry (Horning *et al.* 2010). Examples of sources for rainfall estimates include the Tropical Rainfall Measuring Mission (TRMM), the Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT) from the University of Reading, Meteosat Second Generation (Schmetz *et al.* 2002) and near real-time multisensor precipitation estimation from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT, www.eumetsat.int). Information related to land and sea surface temperatures is routinely collected by sensors on-board POES, Aqua and Terra. Ocean winds and oceanic fronts can be monitored using radar scatterometers (Brown *et al.* 2005; Kachelriess *et al.* 2013). Sea surface height can be accessed from the data collected by altimeters on-board satellites, and space-borne altimeters can be used in combination with vessel-based echo soundings to derive bathymetry maps (Becker *et al.* 2009). SRS can also provide relevant information on the occurrence, extent and impact of environmental disturbances, such as flood (Hoque *et al.* 2011), drought (Rojas, Vrieling & Rembold 2011), fire (Justice *et al.* 2002; Lentile *et al.* 2006) or defoliation (Eklundh, Johansson & Solberg 2009).

LAND COVER AND SHALLOW BENTHIC CLASSIFICATION

Understanding species distributions, and being able to predict their potential shifts, relies on being able to characterize the set of conditions that drive occupancy. Doing so requires information on species presence, and on the environmental conditions and resources available to the

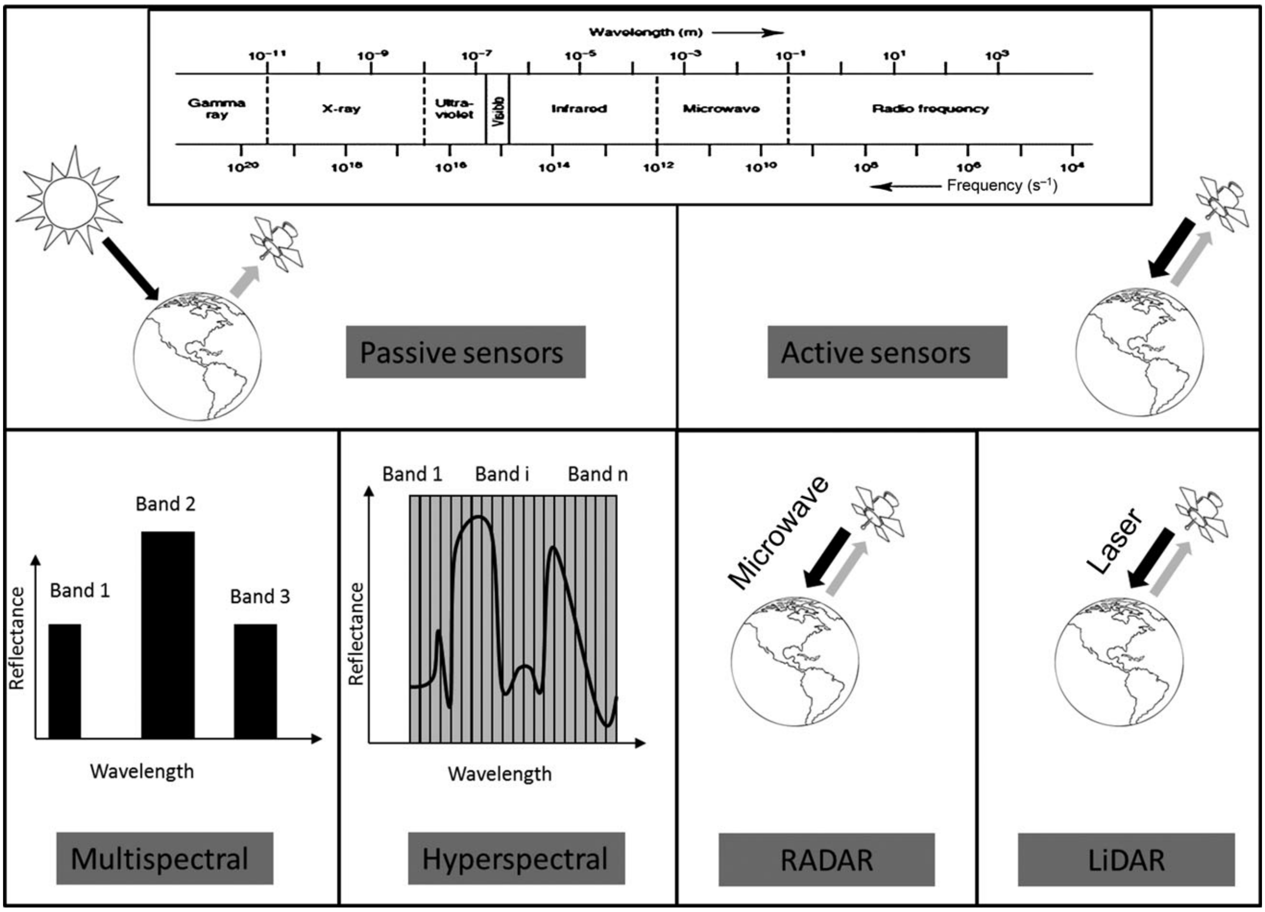

Fig. 1. Main sensor types on-board satellites. Passive sensors measure natural radiation emitted or reflected by the Earth: reflected sunlight is the most common source of radiation measured by these sensors. Multispectral imagery is produced by sensors that measure reflected energy within several specific broad bands of the electromagnetic spectrum; hyperspectral sensors, on the other hand, measure energy in narrower and more numerous bands than multispectral sensors resulting in a relatively continuous measurement of a portion of the electromagnetic spectrum. Active sensors emit an electromagnetic pulse and later measure the energy bounced back to them: RAdio Detection And Ranging (radar) sensors on-board satellites use longer wavelengths (microwaves) and are side looking (off-nadir), while light detection and ranging (LiDAR) sensors emit laser pulses (usually at 1064 nm) and are nadir viewing.

organisms of concern. Deriving maps detailing the biophysical cover of the Earth's surface from SRS is among the oldest applications of satellite data to inform applied ecology with, for instance, the first global land cover products produced in the 1990s (DeFries & Townshend 1994; DeFries *et al.* 1998). The ability of SRS to map habitats at broad scales is now widely recognized (Horning *et al.* 2010) and goes beyond the purely terrestrial realm; for example, SRS can be used for mapping and monitoring seagrass meadows, mangroves and coral reefs (Dierssen *et al.* 2010; Giri *et al.* 2011; Kachelriess *et al.* 2013).

PRIMARY PRODUCTIVITY DYNAMICS

Primary productivity is a major 'supporting' ecosystem service, required for the production of many other ecosystem services. Changes in spatial and temporal patterns of primary production dynamics can be used to detect habitat modification and landscape change (Garbulsky & Paruelo 2004; Garonna *et al.* 2009). Many satellite-based vegetation indices, formed from combinations of reflectance captured by sensors on-board satellites, have been shown to relate indirectly to terrestrial primary productivity (Bannari *et al.* 1995); among these, the Normalized Difference Vegetation Index (NDVI) has been associated with the highest number of ecological applications (Pettorelli 2013). The NDVI provides decades of information about temporal and spatial changes in vegetation distribution, productivity and dynamics, allowing the coupling of vegetation with animal distribution, abundance, movement, survival, reproductive parameters and population dynamics (Pettorelli *et al.* 2011). In the marine environment, the productivity of certain phytoplankton taxa can also be inferred from SRS data, using information on ocean colour (Muller-Karger *et al.* 2005). Similarly to the terrestrial realm, primary productivity distribution as inferred from SRS data has been shown to influence benthic community patterns, being correlated with the distribution of migratory marine species (Kachelriess *et al.* 2013).

Table 1. Non-exhaustive list of examples illustrating how SRS can be used to tackle environmental challenges

Environmental challenge	Sensor	Reference
Species distribution mapping	ETM+ and Quickbird	Fretwell *et al.* (2012)
Invasive species detection	TM & ETM+	Bradley & Mustard (2006)
Invasive species detection	IKONOS	Fuller (2005)
Invasive species detection	Hyperion	Pengra, Johnston & Loveland (2007)
Migration route prediction	AVHRR	Boone, Thirgood & Hopcraft (2006)
Informing reintroductions	AVHRR	Freemantle *et al.* (2013)
Overgrazed areas mapping	AVHRR	Otterman *et al.* (2002)
Mangrove coastal retreat monitoring	PALSAR	Cornforth *et al.* (2013)
Fire monitoring	MODIS	Justice *et al.* (2002)
Assessing fire risk	AVHRR	Maselli *et al.* (2003)
Drought probability assessment	AVHRR	Rojas, Vrieling & Rembold (2011)
Flood monitoring, mapping and management	RADARSAT	Hoque *et al.* (2011)
Oil slick detection and monitoring	RADARSAT, MODIS, AVHRR	Klemas (2010)
Air quality assessment	GOME-2, MODIS & MOPITT	Hao *et al.* (2011)
Insect-induced defoliation mapping	MODIS	Eklundh, Johansson & Solberg (2009)
Land cover change monitoring	TM, ETM, ETM+	Hansen & Loveland (2012)
Deforestation	MODIS & ETM+	Briant, Gond & Laurance (2010)
Habitat fragmentation	TM	Heilman *et al.* (2002)
Land degradation	AVHRR	Prince, Becker-Reshef & Rishmawi (2009)
Forest degradation mapping	MODIS	Garonna *et al.* (2009)
Forest degradation mapping	HRG	Souza *et al.* 2003
Urbanization tracking	DMSP/OLS	Zhang & Seto (2011)
Urbanization tracking	SAR	Taubenbock *et al.* (2012)
Natural resource extraction detection	ETM+	Duncan *et al.* (2014)
Natural resource extraction detection	ATSR	Casadio, Arino & Serpe (2011)
Tracking the effect of climate change on ecosystem functioning	AVHRR	Pettorelli *et al.* (2012)
Carbon stock mapping	GLAS, MODIS, SRTM, QSCAT	Saatchi *et al.* (2011)
SRS-based platform for the global monitoring of protected areas	MODIS, HRG, Landsat	Dubois *et al.* (2011)

ATSR, Along Track Scanning Radiometer; AVHRR, Advanced Very High Resolution Radiometer; DMSP/OLS, U.S Air Force Defense Meteorological Satellites Program/Operational Linescan System; (E)TM, (Enhanced) Thematic Mapper; GLAS, Geoscience Laser Altimeter System; GOME-2, Global Ozone Monitoring Experiment 2; HRG, high-resolution geometrical; MODIS, Moderate-Resolution Imaging Spectroradiometer; MOPITT, Terra's Measurements of Pollutants in the Troposphere; PALSAR, Phased Array type L-band Synthetic Aperture Radar; QSCAT, Quick Scatterometer; SAR, Synthetic Aperture Radar; SRTM, Shuttle Radar Topography Mission.

New avenues

VEGETATION 3-D STRUCTURE

Vertical vegetation structure is a key component of habitat quality for many species, often required for reliably quantifying natural capital assets and flows of ecosystem services, for example, to track the flow of carbon (see e.g. Troy & Wilson 2006; Müller & Brandl 2009; Swatantran *et al.* 2012). RAdio Detection And Ranging (radar) and LiDAR sensors, which are remote sensing systems that send out their own pulses of electromagnetic radiation and then interpret the returning (or backscattered) radiation from the remote target being sensed (Fig. 1), are key to the monitoring of vegetation 3-D structure from space. Data collected by radar sensors tend to be used for monitoring deforestation and forest degradation (Lucas *et al.* 2013) as well as forest regrowth (Kasischke *et al.* 2011); these are also commonly used to support carbon mapping exercises (Goetz *et al.* 2009). LiDAR provides a unique capability to measure the three-dimensional vertical structure of vegetation (Lefsky *et al.* 2002; Lefsky 2010; Asner *et al.* 2012), although proxies of vegetation height can also be derived from radar data using differential interferometry algorithms (Lavalle, Simard & Hensley 2012). LiDAR and radar data can be combined to improve the quantification of the vertical and volumetric dimensions of vegetation structure (Bergen *et al.* 2009; Mitchard *et al.* 2012). Currently missing, however, are LiDAR sensors on-board satellites. The Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud and land Elevation Satellite (ICESAT) provided LiDAR measurements from 2003 to 2009 but is no longer operating. The ICESAT-2 mission is planned to launch in 2017. SRS data collected by active sensors are often not affordable and/or not easily accessible to the biodiversity community. This situation represents a significant reduction in opportunities for SRS to support natural resource management (Koch 2010; Turner *et al.* 2013).

HUMAN-INDUCED THREATS TO BIODIVERSITY

A wealth of studies provides strong support for the important role of SRS in the monitoring of anthropogenic threats to biological diversity and ecosystem services: deforestation (see e.g. Hansen & Loveland 2012), atmospheric pollution (see e.g. Beirle *et al.* 2011; Hao *et al.* 2011), land degradation and fragmentation (see e.g. Asner *et al.* 2004; Prince, Becker-Reshef & Rishmawi 2009; Nagendra, Rocchini & Ghate 2010), urban expansion (see e.g. Taubenbock *et al.* 2012; Alvarez-Berrios, Pares-Ramos & Aide 2013) and extraction activities (minerals and oil; see e.g. Casadio, Arino & Serpe 2011; Duzgun & Demirel 2011; Oom & Pereira 2013) have all been successfully monitored using SRS (see also Table 1). Anthropogenic threats to the marine realm have also been monitored from space. Ocean acidification processes can be informed from calcium carbonate measurements derived from sensors on-board Terra (Balch *et al.* 2005); oil spills can be detected and monitored using synthetic aperture radar or infrared sensors (Leifer *et al.* 2012); hyperspectral data can be used to discriminate hydrocarbons and track oil spills (Hörig *et al.* 2001); SRS information coupled with data from active vessel monitoring systems permit the monitoring of illegal, undeclared or unreported fishing (Corbane *et al.* 2010; Kachelriess *et al.* 2013). Much remains to be done to validate these approaches across a spectrum of ecosystems and conditions. However, evidence so far clearly highlights the benefits and feasibility of SRS-based methodologies for threat monitoring.

TRACKING AND BETTER UNDERSTANDING MOVEMENT PATTERNS

Movement is a key behavioural adaptation to spatio-temporal variability in resource availability. Migration is among the most studied type of movement, with migrating species playing a key ecological role in the maintenance of global biodiversity, allowing the transfer of energy and genetic information between ecosystems. Studies suggest that airborne migrants and aerially foraging animals are highly responsive to environmental changes in the atmosphere (Shamoun-Baranes, Bouten & van Loon 2010), meaning that gaining a better understanding of the factors affecting migratory populations throughout their migratory cycles is likely to be of critical importance to conservation planning. The potential opportunity provided by radar technology to learn more about the spatio-temporal distribution, the flight characteristics and patterns of habitat use of flying animals has been recently highlighted (Ruth 2007; Chilson *et al.* 2012). At present, this research largely relies on information collected by portable sensors (see e.g. Zaugg *et al.* 2008; who developed an automated identification procedure for birds using data collected by portable radar devices) and sensors operating from ground-based stations (see e.g. Kelly *et al.* 2012; who used NEXRAD weather radars to explore animal phenology at the continental scale). Such studies suggest that radar sensors on-board satellites could successfully support the emerging field of radar aeroecology in the near future. Another even more promising avenue for SRS to contribute to movement ecology is associated with the increasing accessibility of GPS-tracking devices (see e.g. Loarie, Craig & Asner 2013; Dodge *et al.* 2014). The combination of detailed data on animal movement with frequent SRS-based information on environmental conditions indeed makes it possible for a unified framework to explore the determinants of movement patterns at multiple spatial and temporal scales (Nathan *et al.* 2008).

MONITORING SPECIES FROM SPACE

Detection of specific animal and plant individuals using information collected by satellites is still not commonly achieved, although successful examples have started to accumulate. Moderate (<100-m ground sampling) resolution satellite images have for example been used to map the spatial extents of cheatgrass *Bromus tectorum* (Bradley & Mustard 2006); moderate and very high resolution satellite images were used to detect the presence and size of emperor penguin *Aptenodytes forsteri* colonies (Fretwell & Trathan 2009; Fretwell *et al.* 2012); very high resolution satellite images were also recently used to count southern right whales *Eubalaena australis* breeding in Argentina (Fretwell, Staniland & Forcada 2014). Likewise, recent efforts to map the distribution and estimate population sizes of elephants *Loxodonta africana*, wildebeest *Connochaetes taurinus* and zebra *Equus quagga* in the Masai Mara National Park, Kenya, demonstrated that GeoEye-1 satellite imagery (spatial resolution of 1·65 m) was suitable for the detection of medium to large-sized wildlife as well as informing population estimation exercises in open savanna (Zheng 2012). High-resolution imagery coupled with object-oriented image analysis was also shown to successfully support marmot *Marmota sibérica* population monitoring in Mongolia, through the detection of active marmot mounds (Velasco 2009). A particularly promising avenue for SRS-based species detection arises from many successful uses of hyperspectral data for identifying canopy plant species (see e.g. Carlson *et al.* 2007; Adam & Mutanga 2009; Pu 2009; Cho *et al.* 2010), especially invasive species (see He *et al.* 2011 for a review). Although in its infancy, direct monitoring of species from space clearly shows potential and represents an exciting development for both remote sensing and applied ecology.

Challenges ahead

The potential for SRS to support natural resource management has never been greater; however, several issues limit this potential. First, although many satellite products are freely available, a significant proportion of products are not (Turner *et al.* 2013). Further, SRS-based data analyses can be expensive given logistical requirements (i.e. hardware, software, qualified staff and training) for the processing and analysis of large data sets. Altogether, costs can be considerable and are hampering widespread application of satellite monitoring in applied ecology and management (Strand *et al.* 2007; Leidner *et al.* 2012; Turner *et al.* 2013). In addition to free SRS products, open-source software solutions, such as R (R Development Core Team 2013), QGIS (QGIS 2013) or GRASS (GRASS Development Team 2013), are on the rise. The frequent complexity or even lack of clear documentation as well as missing training opportunities, however, originally hindered use of open-source software solutions. But this is constantly changing with open-source software increasingly used for training across disciplines (Rocchini & Neteler 2012).

Secondly, integration of *in situ* data from local ecologists and expert knowledge from remote sensing analysts is limited, leading to SRS frequently being underused and undervalued (Nagendra *et al.* 2013). The use of SRS data by biodiversity monitoring experts necessitates them to work at the interface between ecology and remote sensing, and in many cases, it can be hard for them to understand the benefits and drawbacks of particular SRS products or to locate relevant remote sensing data sets. Without common references and centralized platforms, integration will always be restricted. Yet, the goal is for SRS to become a standard element of the ecologist's toolbox.

Thirdly, users from biodiverse regions would immensely benefit from acquiring SRS data, particularly from active sensors or from very high spatial resolution sensors. Yet, these users often have limited access to imagery and the tools to process it. These limitations are shaped by sensor coverage, data costs and local capacity as well as security issues. In South Asia, for example, security considerations limit access to very high spatial resolution SRS data (Nagendra & Rocchini 2008). Likewise, high spatial resolution data, hyperspectral and LiDAR spaceborne data provide patchy and largely non-existent coverage for most biodiverse regions, especially in the tropics.

Fourthly, temporal mismatch between users' needs and the availability of SRS-derived products can create frustration. Many scientists and managers want to be able to access environmental data for the current year, yet SRS-based products are sometimes made available years after data collection (although this data latency issue is improving).

Fifth, the desire to focus on the delivery of global products has so far dictated the type of SRS-based data sets commonly supported by space agencies and commercial companies. Nationally optimized SRS products are rare, while the identification of national packages (detailing the best SRS products available at the national scale for each country) has not been undertaken for most countries. Yet, management operates at a range of spatial scales, with the national scale being key for policy implementation (Collen *et al.* 2013). Providing scientists and practitioners with easy access to reliable and nationally adequate SRS products could support the emergence of more SRS-based management approaches. Such a role could be filled by national space agencies, national environmental centres or government bodies.

Finally, the potential for SRS to support wildlife and environmental management is likely to be best achieved when effective collaborations between experts in remote sensing and experts in biodiversity monitoring are developed. Such collaborative work is, however, rare due to (i) the paucity of a shared interdisciplinary space to facilitate collaboration; (ii) semantic gaps and the lack of common reference frames; (iii) issues arising from mixed spatial scales; (iv) logistical difficulties associated with information transfer and management; and (v) difficulties associated with defining research objectives that are rewarding and scientifically valuable to members of both disciplines (Pettorelli, Safi & Turner 2014).

Future directions

Sensors are continuously being launched by space agencies (Table 2). Between 2012 and 2027, space agencies that are members of the Committee on Earth Observation Satellites (CEOS) will be operating or planning 268 individual satellite Earth observation missions (CEOS 2012). Although data collection priorities can always be discussed and enhanced, the real challenges are about increasing use and usefulness of SRS, for the benefit of natural resource management (Strand *et al.* 2007).

Most biodiversity researchers and conservation practitioners lack the financial resources to acquire large amounts of SRS data, especially if they need information over wide geographical extents or long periods of time (Leidner *et al.* 2012). It is therefore evident that making government-funded SRS freely available to biodiversity monitoring projects, and indeed all users, is a key step to facilitate progress by the research and applied communities (Turner *et al.* 2013).

In situ data availability is also a strong determinant of the future performance of SRS products, as *in situ* data are necessary for satellite data validation and ecological forecasting modelling exercises. These data are, moreover, needed to explore how SRS data correlate with on-the-ground data on trends in different biodiversity groups (e.g. Laurance *et al.* 2012). Yet, *in situ* data sharing is currently limited; this situation could be linked to the need for greater scientific recognition for those who share their biodiversity data. Frameworks for recognizing and rewarding those making their data available exist (for instance, citing authors or creators of data sets in scientific journals; Reichman, Jones & Schildhauer 2011) and need to be widely implemented. In addition, platforms inspired by the BIO_SOS project (www.biosos.eu), facilitating the integration of *in situ* data and SRS, need to become more common. To make SRS products more accessible, the sharing of new algorithms and work-flows that support the analysis and interpretation of SRS data also needs to be improved (Michener & Jones 2011).

Table 2. Examples of upcoming missions relevant to natural resource management. Details on the technical specifications of these upcoming missions are also provided

Mission	Launch date	Use
Vegetation and Environment monitoring on a New Micro-Satellite (VENμS)	2014	Earth images at high spatial resolution and high repeatability dedicated to vegetation monitoring
ALOS-2	2014	Radar Earth observation satellite used for cartography, regional observation, disaster monitoring and resource surveying
Soil Moisture Active Passive (SMAP)	2014	Will rely on active radar and a passive radiometer data to provide global measurements of surface soil moisture and soil freeze/thaw state
Sentinel-1A	2014	Will ensure the continuity of C-band SAR data, building on ESA's and Canada's heritage SAR systems
Sentinel-2A	2015	Will provide continuity for the current SPOT and Landsat missions
Sentinel-3A	2015	Will provide ocean colour and land reflectance data; sea, land and ice surface temperature data; active fire and burnt area data; and sea surface topography data
Amazônia-1	2014	Will carry an optical instrument called AWFI, operating in the visible and near infrared band, with a spatial resolution of 40 m
Global Precipitation Measurement (GPM)	2014	International satellite mission capturing precipitation measurements from space, providing observations of rain and snow world-wide every 3 h
Environmental Mapping and Analysis Programme (EnMAP)	2016	Hyperspectral Earth observation satellite that will provide detailed information on waterways, vegetation, land usage and surface geology
ICESAT-2	2017	Follow-up mission to ICESat will contain an improved laser altimeter called ATLAS (Advanced Topographic Laser Altimeter System) designed to measure ice-sheet topography, sea ice freeboard as well as cloud and atmospheric properties and global vegetation

There are many underused products and algorithms that could benefit environmental and wildlife management (e.g. fractional vegetation cover products, radar and hyperspectral imagery, differential interferometry algorithms). Similarly, environmental and wildlife management needs could trigger a variety of remote sensing research avenues. Better and stronger communication channels need to be established between the remote sensing community, conservationists and environmental managers to increase collaborative work and develop a coordinated, effective research agenda. Recent efforts towards this, such as the DLR-funded CEOS workshop in Munich (October 2012) and the NASA-funded workshop to identify the top 10 conservation questions that can be addressed using remote sensing (January 2013) are encouraging, as is the growing attendance for conservation remote sensing discussions at conferences such as the International Congress for Conservation Biology (ICCB) in 2011 and 2013. Specific platforms facilitating exchanges of information and networking opportunities between these communities, such as the Group on Earth Observations Biodiversity Observation Network (GEO BON) or the Group on Remote Sensing for Biodiversity within CEOS (www.remote-sensing-biodiversity.org), need to continue flourishing, while user-friendly, intuitive and centralized data portals need to be developed to further enhance communication and exchange of experiences about SRS products. National and international operational systems, demonstrating the concrete benefits of SRS for environmental managers, also need to appear, as these platforms could constitute a stepping stone for the development of integrated biodiversity monitoring systems. Recent initiatives such as the Digital Observatory for Protected Areas (DOPA; http://dopa.jrc.ec.europa.eu/) have demonstrated that the implementation of a global, SRS-based biodiversity monitoring framework aiming to assess, monitor and forecast the state of, and pressures on, protected areas is not out of reach (Dubois *et al.* 2011), paving the way for a better integration of SRS and field-based information.

Finally, capacity building is a key requirement for increasing SRS audience and for getting SRS data to receive the recognition they deserve at the political level. There is no single recipe to increase capacity. Solutions could include developing online resources documenting best practices and channelling relevant information on product reliability and access on key portals; favouring the emergence of contextualized training opportunities in SRS manipulation and analysis tailored for practitioners (see e.g. www.animove.org); promoting the emergence of a new generation of scientists able to carry out integrated, multidisciplinary approaches by increasing the availability of joint graduate programmes at the interface between remote sensing and ecology; continue improving the flexibility and user friendliness of open-source software while pushing for their increased use in training options; and identifying 'centres of excellence' at the national and international levels actively promoting the use of SRS, by, for example, developing internship programmes attended by relevant staff from institutions in need.

As research continues to broaden the scope for SRS to support wildlife and environmental management, stronger links between the ecological and remote sensing communities are key to insure that SRS finally meets its full potential in terms of informing the state of, and pressures on, biodiversity. While terrestrial and marine earth observatories are increasing, SRS-based earth observatories need to catch-up, in number, accessibility and use. Such advances are important, for there will be no shortage of challenges ahead.

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Received 24 October 2013; accepted 27 March 2014
Handling Editor: E.J. Milner-Gulland

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Table S1. Examples of some remote sensing sensors currently onboard active civilian satellites and presentation of their key specifications (i.e. launch date, spatial resolution, revisiting interval, relevant website).