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Monitoring mangrove forests: Are we taking full advantage of technology?

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ABSTRACT

Mangrove forests grow in the estuaries of 124 tropical countries around the world. Because in-situ monitoring of mangroves is difficult and time-consuming, remote sensing technologies are commonly used to monitor these ecosystems. Landsat satellites have provided regular and systematic images of mangrove ecosystems for over 30 years, yet researchers often cite budget and infrastructure constraints to justify the underuse this resource. Since 2001, over 50 studies have used Landsat or ASTER imagery for mangrove monitoring, and most focus on the spatial extent of mangroves, rarely using more than five images. Even after the Landsat archive was made free for public use, few studies used more than five images, despite the clear advantages of using more images (e.g. lower signal-to-noise ratios). The main argument of this paper is that, with freely available imagery and high performance computing facilities around the world, it is up to researchers to acquire the necessary programming skills to use these resources. Programming skills allow researchers to automate repetitive and time-consuming tasks, such as image acquisition and processing, consequently reducing up to 60% of the time dedicated to these activities. These skills also help scientists to review and re-use algorithms, hence making mangrove research more agile. This paper contributes to the debate on why scientists need to learn to program, not only to challenge prevailing approaches to mangrove research, but also to expand the temporal and spatial extents that are commonly used for mangrove research.

1. Introduction: recalling the importance of mangroves

Mangroves are groups of trees, palms and shrubs that grow in the estuarine margins of 124 countries around the world (Duke et al., 2006; FAO, 2007), and cover between 150,000 and 188,000 km^2 (Barbier, 2015; Costanza et al., 2014). Inhabitants of mangrove forests include the Royal Bengal tiger (*Panthera tigris tigris*), crocodiles and myriad birds, reptiles, amphibians, crustaceans and, of course, humans. With so many species depending on mangrove forests, it is important to know how humans alter and use these ecosystems.

Humans use mangroves in direct (e.g. building materials, food and medicinal purposes) and indirect ways (e.g. carbon sequestration, protection from extreme weather events, fish nurseries and land building) (Barbier, 2015; Donato et al., 2011; Kainuma et al., 2010; Lee et al., 2014). These uses and services make mangroves worth up to \$194,000 ha^{-1} yr^{-1} (Costanza et al., 2014). Despite the importance of these forests, best (and most recent) estimates declare that between 1980 and 2001 global areas of mangroves declined 30–50%, and 16% of mangrove species may be facing extinction (Donato et al., 2011; Duncan et al., 2016; FAO, 2007). Furthermore, sea level rise is expected to submerge entire forests by 2115 (Lovelock et al., 2015), which only increases the need for better management and monitoring strategies.

In-situ mangrove monitoring is a challenging task. Because these ecosystems are hard to access, surveying can be costly and time-consuming, but in-situ monitoring is still regarded as an important source of information (see e.g. Moritz-Zimmermann et al. (2002)). Remotely sensed data provides a complementary source of information and is increasingly being used as such. For example, Lee et al. (2014) found that the Web of Science had more than 8000 indexed studies on mangroves and most of them used some sort of remotely sensed data. Their study also highlights how mangrove research is shifting from fine-scale projects (i.e. in-situ monitoring) to continental and global scale analysis. It is in the latter where remote sensing tools are most useful (see Section 2).

Earth observation satellites are excellent remote sensing tools for mangrove monitoring. They consistently (i) gather information over large areas, (ii) revisit places on a monthly, weekly, or sometimes even daily basis, and (iii) use visible and non-visible sections of the electromagnetic spectrum to make quantitative measurements of light interactions with surface features (Chuvieco and Huete, 2010; Yang et al., 2017). Satellites also provide information and insight on spatial extent (e.g. land cover change), distribution (e.g. species), and temporal

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changes of mangrove forests (e.g. phenology). The collection of this information over decades is what makes satellites an invaluable tool for mangrove monitoring.

Today, more than 300 earth observation satellites from more than 15 countries are operational (Union of Concerned Scientists, 2017). Such satellites are operated by state agencies or private companies and, while many operators provide data at commercial rates, some offer their datasets free-of-charge. For example, the MODIS (Moderate Resolution Imaging Spectroradiometer) and AVHRR (Advanced Very High Resolution Radiometer) archives have been publicly available since 2001 and 1978 respectively. Although these sensors have a high spectral resolution, their spatial resolution (500 m and 1.1 km respectively) makes them less suitable for mangrove monitoring. In contrast, the Sentinel 2 sensor has a 10 × 10 m spatial resolution in the visible and Near Infra-Red (NIR) spectral bands. Despite being publicly available since the instrument was operational in 2015, no peer-reviewed studies to date have used Sentinel 2 imagery for mangrove research. This review, however, will focus on the Landsat (free since 2008) and ASTER archives (Advanced Spaceborne Thermal Emission and Reflection Radiometer, free since 2016). While some studies have used higher spatial or spectral resolution images for mangrove research (see e.g. Heenkenda et al., 2015; Koedsin and Vaiphasa 2013; Kamal and Phinn 2011), imagery from Landsat and ASTER is still widely used for three main reasons: (1) their worldwide coverage, (2) their archives go back to the 1980's and 1990's respectively, and (3) data is freely available to the public (Wulder et al., 2016).

Since 2000, more than 50 peer-reviewed articles have used Landsat or ASTER imagery to monitor mangroves around the world. Of these, 52% focused on just five countries (Australia, Malaysia, China, Madagascar and Mexico), while only 3% had global extent (see Table 2 in Supplementary information). The remainder of the studies focused on 19 other countries. Fig. 1 shows the countries and territories where mangrove research has been done using freely available imagery from Landsat and ASTER. Only 22 countries have used freely available imagery, indicating that researchers are not taking advantage of this resource. Some of the reasons for this may include: lack of knowledge about the availability of satellite imagery, lack of interest in mangrove ecosystems, financial or data accessibility constraints and limited skills or infrastructure.

This review does not intend to update the results presented by Heumann (2011) or Kuenzer et al. (2011); they provide insightful reviews of methods and sensors commonly used in mangrove research. Here we intend to challenge scientists to take advantage of all available imagery, processing facilities and datasets. This will result in examining more complex questions (e.g. seasonal and yearly changes, impacts of climate change and sea level rise), instead of focusing primarily on spatial extent.

Changes in the spatial extent of mangroves fail to represent other processes occurring in the ecosystem. Therefore, it is important to combine this information with biophysical variables such as forest density, leaf area index and chlorophyll content to gain a better understanding of how the ecosystem reacts to environmental pressures. Shifting the focus from purely spatial variables to an integrated view of the ecosystem requires additional information. This information may include meteorological, biophysical, field and citizen-collected data in various formats, resolutions and scales. Cleaning, compiling, processing and analysing larger datasets requires more processing power than ever before. Nowadays there are resources available to make this happen such as freely available imagery, enhanced storage and processing facilities (see Section 3.3).

This review aims to: (i) understand how researchers are currently using freely available imagery (mainly Landsat and ASTER) to study mangrove forests; (ii) explore how long-term monitoring adds to our understanding of mangrove ecosystems; and (iii) emphasize the need for scientists to acquire programming skills. To do this, we will revisit some of the questions being addressed and the time scales used to measure spatiotemporal changes. Next we examine the differences between high and low temporal resolution data, and suggest novel ways to process more information in less time. We then discuss how task automation needs to be incorporated into image processing and analysis and why researchers need to acquire programming skills to move mangrove research forward.

2. What are we looking at?

Mapping the natural extent of mangrove forests is required to quantify the services they provide as carbon sinks, fish nurseries and coastal protection (Danielsen et al., 2005; Donato et al., 2011; Lee et al., 2014). Extent mapping is also needed to analyse the threats mangroves face from climate change, deforestation and land use change (Alongi, 2008; Duke et al., 2007; FAO, 2007). Nowadays, most maps of mangrove forests are derived from remotely sensed information and are used to represent changes in extent and land cover; examples of this are discussed below.

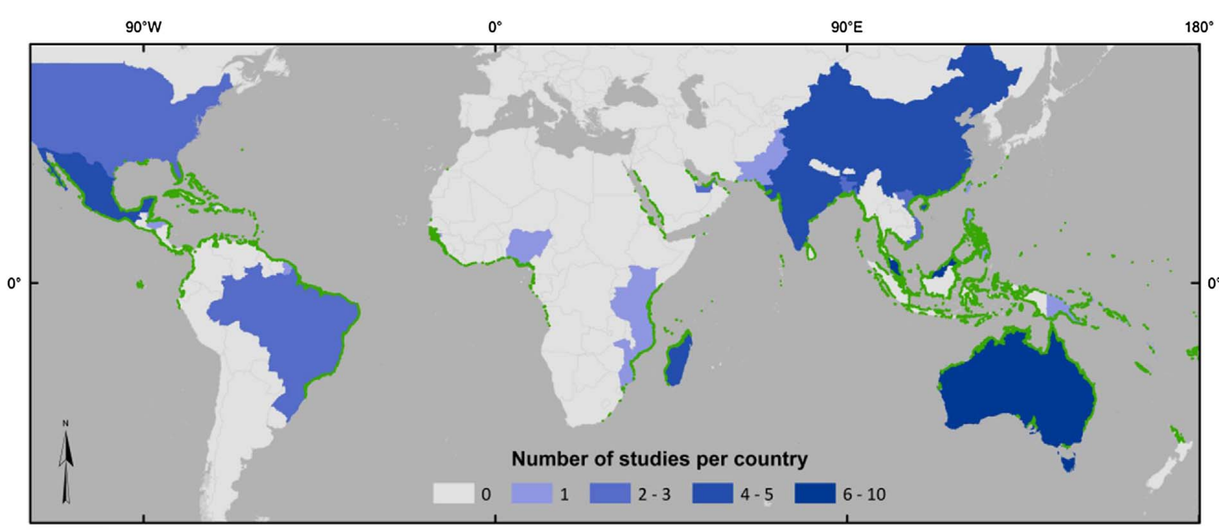

Fig. 1. Number of studies per country that used Landsat imagery (2000–2016). Approximately 65% of the studies focused on mangroves in developing countries. Global distribution of mangroves.
Source: Giri et al. (2013).