Summary

Nature as the foundation of sustainable development

Sustainable use and management of the Earth’s natural resources is a key target for nations that have ratified the UN Convention on Biological Diversity. It is also increasingly recognised as critical for sustainable business practices. Governments and the private sector therefore need to understand:

1. What elements of nature are currently present on the planet;
2. What benefits they provide for people;
3. How they are being affected by human activity and the current global environmental change crisis.

This knowledge is vital to generate and implement effective environmental policies and mitigation strategies, and ultimately support sustainable development. We summarise here how remote sensing data can be used to provide this information at a national level, in a timely and cost-effective manner; full details can be found in our report.

Concept of Natural Capital and Ecosystem Services

One means of quantifying natural resources is to use the concepts of Natural Capital and Ecosystem Services. Analogous to financial accounting, Natural Capital is the stock of environmental assets – land, air, water, species, habitats and ecosystems – that generates a flow of benefits, or ‘dividends’, to human beings in the form of Ecosystem Services – such as food, fuel, soil production, pollination, nutrient cycling and climate regulation. On one hand, some ‘stocks’ (the discrete building blocks of Natural Capital) and ‘flows’ (the ecosystem goods and services that flow from these stocks) are simple quantities, such as the amount of forest present in an area of interest and the annual primary productivity associated with this forest. On the other hand, some flows can consist of complex processes, such as the coastal protection afforded by mangroves against floods and hurricanes, or water and nutrient cycling. Some stocks and flows cannot be discretely categorised, for example water can be a stock, good or service, and they can be renewable or non-renewable.

Potential of satellite-based remote sensing

Traditional, ground-based accounting and monitoring techniques are mostly unsuitable to examine the state of, and changes in, Natural Capital and Ecosystem Services at a large scale. Problems with poor replicability and comparability between observers, and the sheer impossibility of covering the entire Earth in a time- and cost-effective manner, make in situ monitoring largely inadequate for the task. Conversely, satellite-based remote sensing has the potential for cost-efficient global monitoring of Natural Capital and Ecosystem Services from global to local scale: there is a plethora of free data available, which are mostly collected at the global scale, and always in a systematic manner.

Using satellite-based data to measure nature’s stocks and flows

Our research demonstrates how 10 types of Natural Capital (amount and condition) and Ecosystem Services can be measured from space at national and site level:

- habitat type;
- habitat distribution;
- vegetation height;
- woody biomass;
- canopy structure;
- coastal forest / mangrove degradation / afforestation;
- annual primary productivity;
- above-ground carbon;
- water cycling;
- above-ground nitrogen.
For each category we focus where possible on freely-available data derived from satellite sensors that are most suitable for each task, and describe the spatial and temporal resolutions at which data are available; we discuss the advantages and drawbacks of each method and illustrate them with an example of how this can be used in a national context, using Kenya as a case study.

**Current limitations**

This work illustrates the breadth of, and potential for, satellite-based remote sensing to measure various aspects of the Earth’s Natural Capital and Ecosystem Services. We also discuss the current issues preventing the use of this monitoring technique to its full potential, which include:

1. The need for some degree of ground-truthing and/or expert interpretation of the data;
2. The trade-off between spatial resolution and computing power/cost;
3. A bias towards optical sensing, which performs poorly under cloud cover (as experienced in the tropics/subtropics);
4. The lack of long-term, uninterrupted datasets and thus difficulty of establishing baselines;
5. The time-lag between the release of new products and use by non-specialist end-users;
6. The impossibility of measuring all types of stocks and flows remotely, such as most animal distribution.

**Recommendations**

We conclude by providing an overview of the way forward for using satellite-based remote sensing to monitor Natural Capital and Ecosystem Services. Recommendations include:

1. The development of a user-friendly data portal including guidelines on how to use satellite-based remote sensing products;
2. Awareness-raising, capacity building and interdisciplinary collaborations to help end-users understand what they need, what tools are available and how to use them;
3. Increasing the availability and affordability of satellite-based remote sensing data and pre-processed datasets;
4. The production of clear guidelines and open-source software to enable more people to use freely available data such as LiDAR data.
## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALOS</td>
<td>Advanced Land Observing Satellite</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
</tr>
<tr>
<td>CBD</td>
<td>UN Convention on Biological Diversity</td>
</tr>
<tr>
<td>GIMMS</td>
<td>Global Inventory Modelling and Mapping Studies</td>
</tr>
<tr>
<td>GLAS</td>
<td>Geoscience Laser Altimeter System</td>
</tr>
<tr>
<td>EO</td>
<td>Earth Observation</td>
</tr>
<tr>
<td>ES</td>
<td>Ecosystem Services</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ET</td>
<td>EvapoTranspiration</td>
</tr>
<tr>
<td>ETM</td>
<td>Enhanced Thematic Mapper</td>
</tr>
<tr>
<td>ICESat</td>
<td>Ice Cloud and land Elevation Satellite</td>
</tr>
<tr>
<td>INDVI</td>
<td>Integrated NDVI</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf Area Index</td>
</tr>
<tr>
<td>LiDAR</td>
<td>Light Detection And Ranging</td>
</tr>
<tr>
<td>MERIS</td>
<td>MEdium Resolution Imaging Spectrometer</td>
</tr>
<tr>
<td>MIR</td>
<td>Middle InfraRed</td>
</tr>
<tr>
<td>NDWI</td>
<td>Normalized Difference Water Index</td>
</tr>
<tr>
<td>MNDWI</td>
<td>Modified NDWI</td>
</tr>
<tr>
<td>MODIS</td>
<td>MODe rate resolution Imaging Spectrometer</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NC</td>
<td>Natural Capital</td>
</tr>
<tr>
<td>NDNI</td>
<td>Normalized Difference Nitrogen Index</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
</tr>
<tr>
<td>NIR</td>
<td>Near InfraRed</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic Atmospheric Administration</td>
</tr>
<tr>
<td>OLI-TIRS</td>
<td>Operational Land Imager and the Thermal Infrared Scanner</td>
</tr>
<tr>
<td>PALSAR</td>
<td>Phased Array type L-band Synthetic Aperture Radar</td>
</tr>
<tr>
<td>PP</td>
<td>Primary Productivity</td>
</tr>
<tr>
<td>RADAR</td>
<td>RA dio Detection And Ranging</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Imagery</td>
</tr>
<tr>
<td>SPOT</td>
<td>Satellite Pour l’Observation de la Terre</td>
</tr>
<tr>
<td>TM</td>
<td>Thematic Mapper</td>
</tr>
<tr>
<td>VIS</td>
<td>VIsible Spectrum</td>
</tr>
</tbody>
</table>
Contents

Summary ................................................................................................................................. 1
Glossary ................................................................................................................................... 4
Introduction .......................................................................................................................... 6
What are Natural Capital and Ecosystem Services? ............................................................ 7
How can we count stocks, measure their condition and monitor flows? ............................ 7
What is the aim of this report? ............................................................................................ 8
Table 1: satellite remote sensing products used to measure Natural Capital and Ecosystem Services ............................................................ 8
What to expect from this report .......................................................................................... 8
What habitat types, and how much of each, are present in the area of interest? ............... 9
How are habitats distributed in the area of interest? ........................................................ 10
What is the vegetation height in the area of interest? ....................................................... 12
How much woody biomass is present in the area of interest? ......................................... 14
BOX 1: The Normalised Difference Vegetation Index ....................................................... 15
What is the canopy structure (Leaf Area Index) of the area of interest? ....................... 16
What is the state of coastal wetlands and mangroves in the area of interest? ............... 18
What are the patterns in annual primary productivity in the area of interest? ............... 20
What is the amount of carbon stored and how is it changing in the area of interest? ....... 22
What components of the water cycle are present in the area of interest? ..................... 24
BOX 2: The (modified) Normalised Difference Water Index ........................................... 28
How much nitrogen is stored in the vegetation in the area of interest? ......................... 26
Discussion .......................................................................................................................... 29
Limitations of remote sensing for measuring Natural Capital and Ecosystem Services .. 29
The way forward .................................................................................................................. 30
Conclusion .......................................................................................................................... 31
References .......................................................................................................................... 32
**Introduction**

There is a direct correlation between human wellbeing and the state of the natural environment [1]. From the requirement of the oxygen produced by trees and their ability to absorb carbon dioxide in return, through the utilisation of wildlife and vegetation as a source of food and medicine, to the reliance on green spaces in cities to regulate microclimates and promote wellbeing, the welfare of people is tightly linked to the composition, distribution and state of nature. However, the human population is growing fast. The 7 billion people mark was reached in 2011, and, at this rate, the human population on planet Earth is predicted to reach between 8.3 and 11.1 billion people by 2050 (Figure 1). A growing population means that resource requirements also grow, and this increasing demand is eroding all components of nature. Simultaneously, global environmental change is occurring at an alarming rate: land use change, land degradation, habitat fragmentation and climate change are some of all putting further pressure on natural resources.

Sustainable use and management of the environment and its component parts, or biodiversity, is thus a priority at the regional, national and global levels [2]. The aims of sustainable management are both to protect the natural environment for future generations (for use and non-use purposes) and to foster the sustainable economic development of countries and economies. Yet, as the human population grows, these goals are becoming increasingly difficult to reconcile.

There have been several internationally-led attempts at setting targets for countries to protect their own biodiversity in a sustainable way. However, these have not been the unmitigated successes initially hoped for. For example, in 2002 parties to the Convention on Biological Diversity (CBD) agreed to set themselves the goal to reduce the rate of biodiversity loss at all spatial scales by 2010. Unfortunately, according to the Global Biodiversity Outlook 3 report, actions taken towards the CBD 2010 targets were not sufficient to address pressures on nature in most places [3]. More recently, a follow-up attempt was made by the CBD to set goals for countries for the sustainable management of natural resources: the CBD Aichi Biodiversity 2020 Targets. The 20 ambitious Aichi Targets broadly aim to protect biodiversity while supporting sustainable human development, consumption and production [2].

A key aspect of international frameworks like the CBD’s Aichi Targets is that for governments to sustainably manage their natural resources, they need to know what components of nature are present in the first place, and thus can be lost. At present, this level of information at the relevant spatial scales is not readily available. At the 2012 Rio+20 World Summit, governments recognised

![Figure 1. Predicted human population size by 2100 under various growth scenarios. Source: UNFPA](image-url)
the need to account for natural resources in order to fully recognise all aspects of their national ‘wealth’ [4]. Yet accounting for nature present on Earth is not an easy task. One way to categorise nature’s elements and functions is to combine the concepts of Natural Capital, or stock [5], and Ecosystem Services [1], or flows.

**What are Natural Capital and Ecosystem Services?**

To understand the distinction and relationship between Natural Capital and Ecosystem Services, let’s use a simple analogy. Imagine nature as a factory. To describe the factory, we need a list, or account, of the equipment present in the factory at a given time, i.e. the Natural Capital or stock; we need information on the working status of that equipment, i.e. the stock condition; we need information on the products that this equipment is capable of producing when it works, i.e. the Ecosystem Services or flows.

Therefore, the planet’s Natural Capital consists of all the physical elements of nature present on Earth. These are identifiable by the fact they are discrete, well-defined entities that can be accounted for today, such as forests, animals, rivers and lakes. Stock condition is an indicator of the ability of the stock to perform, or yield Ecosystem Services, at any time. For example, if the stock is a forest, its condition is indicated by the height of the trees, potential fragmentation, and the status of woody and green vegetation. Ecosystem Services are the flows that are yielded by the stock. Flows can be tangible goods: for example, food, medicine and clean water, which are also known as provisioning services [1]. They can also be processes, such as climate regulation, water purification or primary production, which are known as regulating or supporting services [1]. Moreover, sometimes, indicators of stock condition can also be Ecosystem Services, e.g. woody biomass correlates with fuel-wood. Flows thus consist of things that may directly and indirectly provide benefits to the human population; sometimes flows may rely on the good functioning of other flows in order to function well themselves. This is the case for example of primary production, a service necessary for the recurrence of vegetation, which yields goods such as fuel-wood or food. Primary production also directly supports the creation of woody biomass and thus the ability of forests to absorb carbon dioxide and regulate the climate.

**How can we count stocks, measure their condition and monitor flows?**

To quantify stock amount and condition (or the Natural Capital) and the flows (or Ecosystem services) across wide spatial scales, traditional survey methods involving field measurements are mostly not appropriate. It would take an impossible amount of time to survey the globe with *in situ* techniques. Even if observers managed to cover an entire country, which is a reasonable expectation for a meaningful measure of Natural Capital and Ecosystem Services, collecting all data at least approximately equivalent to that which can be collected from satellite information, the time and the associated costs required would be prohibitive. Moreover, measures would most likely be biased by the employment of varying methodologies and different observers, making quantities measured incomparable across areas.

Remote sensing, on the other hand, provides a way to take repeatable and comparable measurements of Natural Capital and Ecosystem Services at very large spatial scales [6]. It is broadly defined as the “science of identifying, observing and measuring an object without coming into contact with it” [7], and offers the potential for the most cost-effective monitoring of the Earth’s stock and flows. Data collection is also relatively rapid over large spatial scales, yielding a near-instantaneous picture, and efficient in collecting information in batches, with one dataset often providing information on more than one stock or flow. It is moreover unbiased and comparable between areas, as satellites collect exactly the same information, using the same methods, every time the sensors take a picture. Surprisingly, most satellite-based remote sensing is now inexpensive; there is a huge amount of freely-available data from which measures of
stock and flows can be derived. Many datasets relevant to Natural Capital and Ecosystem Services are in fact available directly from the internet and the cost of other images is no longer prohibitive. Using remote sensing can thus be low cost and relatively non labour-intensive [6,8–10].

**What is the aim of this report?**

ZSL aims to demonstrate how satellite-based remote sensing can be used to measure and monitor elements of the Natural Capital and Ecosystem Services at all spatial scales (Table 1). Using only free or relatively low-cost satellite imagery, we demonstrate a practical approach to measuring stock and flows from space, identify the limitations of these techniques, and provide cost-effective suggestions and recommendations for how these limitations could be addressed. Kenya is used as a case study, demonstrating that the proposed approach to measuring Natural Capital and Ecosystem Services works at the national scale. Ultimately, our aim is to make this monitoring and measurement information available and accessible to end-users such as governments and businesses so that Natural Capital and Ecosystem Services can be incorporated into national accounting systems and business planning, and ultimately support international multilateral environmental agreements and the sustainable development agenda.

**Table 1: Satellite remote sensing products used to measure Natural Capital and Ecosystem Services**

<table>
<thead>
<tr>
<th>Sensor and Satellite</th>
<th>Passive sensors (measure natural radiation emitted or reflected by the Earth)</th>
<th>Active sensors (emit an electromagnetic pulse and later measure the energy bounced back to them)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Multispectral</td>
<td>Hyperspectral</td>
</tr>
<tr>
<td><strong>Sensor and Satellite</strong></td>
<td>VEGETATION onboard SPOT</td>
<td>Hyperion hyperspectral imager onboard EO-1</td>
</tr>
<tr>
<td></td>
<td>MERIS onboard ENVISAT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TM, ETM+ or OLI-TIRS onboard Landsat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MODIS onboard Terra and Aqua</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AHVRR onboard NOAA</td>
<td></td>
</tr>
<tr>
<td><strong>What is being measured</strong></td>
<td>Natural Capital stock</td>
<td>Ecosystem services (nitrogen)</td>
</tr>
<tr>
<td></td>
<td>Stock condition (woody biomass, canopy structure)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ecosystem services (water cycle, primary productivity, carbon storage, woody biomass, canopy structure)</td>
<td></td>
</tr>
</tbody>
</table>

**What to expect from this report**

In the following section, we present the Natural Capital elements (stock), their condition, and Ecosystem Services (flows), which can be measured using satellite remote sensing. Each one is illustrated by showing an example of a typical output using Kenya as a case study.

For each stock or flow, we describe the satellite sensor and products used to obtain the data, the spatial resolution and coverage of these products, as well as the associated cost of the data (if any). For reference, we consider very high spatial resolution to be <10m, high resolution to be between >10m and <100m, medium resolution to be between >100m and <1,000m and low resolution to be >1,000m; when relevant, a relative ranking of the cost associated with the data is given as free, low ($), medium ($$) and high ($$$) costs.
The Natural Capital stock is the total of each habitat type present on Earth at given times. It can be measured as the area of each land type using land cover classification.

Currently, there are two readily-available land cover classification maps, which have been generated at the global scale. The first is called Global Land Cover 2000 (GLC2000) and is based on the VEGETATION instrument on board the SPOT 4 satellite (from the European Space Agency; ESA). The second, GLOBCOVER2009, is also global and is based on data collected by the MERIS sensor on board the ENVISAT satellite mission (also ESA).

While these two land cover maps have different spatial resolutions (1 km for GLC2000 and 300m for GLOBCOVER2009), and do not share the exact same land cover classes, it is possible to design a common legend that enables us to compare the habitat types present in both years, potentially measuring land use change at the country or continental level.

Figure 2 shows the type and amount of 8 habitat types present in Kenya in the years 2000 (left) and 2009 (right). A comparison of these two snapshots taken almost 10 years apart show that both the crop land (agriculture) and the bare soil land cover classes have expanded in this short time span, to the detriment of the tree cover and the grassland/shrubland areas. A figure like this one is very useful for a quick and simple overview of how much the extent of certain habitat types has changed over the course of a few years. However, they only represent a snapshot of two years, giving no information on how the extent of habitat type varies from one year to the next and thus on the cause for the observed changes. Moreover, because these two maps have very different spatial resolutions, it is not possible to use them to perform land cover change analysis, despite creating a common legend.

Therefore, for further investigations into variation in the extent of land cover classes over time, the GLC2000 and GLOBCOVER2009 are not enough. While land cover classification maps in different years are not necessarily available, they can be produced for given areas using various land cover classification techniques. These will be based on the output of high resolution optical sensors, such as those onboard NASA’s Landsat satellites.
The distribution and fragmentation of each habitat type in the area of interest is an important measure of Natural Capital stock condition. This requires high resolution satellite images, and performing customised land cover classifications.

Landsat imagery is produced at spatial resolutions ranging from 30m to 90m. This, combined with the long-term nature of the dataset (the first satellite of the programme was launched in 1975), makes Landsat imagery ideal for performing custom land cover classification, examining changes in the extent of various habitat types over time, or performing land use change analysis.

Because of the high spatial resolution, the level of precision achievable with Landsat data is quite remarkable. However, one potential drawback of a spatial resolution is that the amount of data can quickly become unmanageable.

While not all satellites that are part of the Landsat program are equal, a lot of the data collected is comparable and some satellites ran concurrently. This means that to rectify quality issues with Landsat 7 ETM+ images collected from 2003 onward caused by a sensor fault (rendering up to 22% missing data per image), Landsat 5 images can be used to fill in data gaps. With the launch of the latest Landsat satellite, Landsat 8, in 2013, a recent good quality dataset on land cover can now be obtained. These data are expected to remain freely-available for the foreseeable future.

A custom land cover classification was performed for the Mida Creek mangroves in Kenya using Landsat data (Figure 3); the area classified here is 9 km across. To generate these two classifications and map the extent of the Mida creek mangroves 13 years apart, data from both the Landsat 7 (April 2000; bottom left) and Landsat 8 (April 2013; bottom right) satellites were used. For comparison, Figure 3 also shows a true colour composite picture of these mangroves, which was generated in Google Earth (obtained 27/09/2013). This shows how realistic Landsat-based land cover classifications can be: every feature in the Google Earth image is correctly and easily identifiable in the 2013 land cover classification. Interestingly, these two maps show that the area of mangrove appears to have increased relative to the area of ocean, but the extent of agricultural land around Mida Creek has remained the same.
Figure 3. Land cover classification for the Mida Creek mangroves, Kenya, in 2000 and 2013.
While most conventional remote sensing products yield a two-dimensional representation of the Natural Capital stock (e.g. the location and extent of forest), LiDAR technology is able to provide three-dimensional information on vegetation. This is key when attempting to examine the height of the vegetation canopy, an indicator of stock condition, using remote sensing techniques.

LiDAR, or laser altimetry, works in a very simple way: it measures the distance between a laser-emitting device (on board a plane or a satellite) and a target surface (the top of the canopy) by calculating the time it takes for an emitted laser pulse to be reflected back and reach the emitter. Then, knowing the elevation of the area where the target surface is, the distance between the ground and the canopy can be calculated, giving a measure of the height of the vegetation. This technique is incredibly accurate and is unhindered by the presence of clouds; LiDAR has been shown capable of producing several attributes of forests, including the LAI, above-ground biomass, and canopy height and structure [11].

There are three major drawbacks to the use of this technology. First, the spatial resolution is high to very high (maximum 10-20m) and it is computationally challenging to work with large spatial extent. Second, while there is some free global LiDAR data available, very few people have the knowledge and tools to process this data, and at the moment no open-source software can process raw satellite-derived LiDAR data. Third, there is currently no operational LiDAR sensor on board any of the active satellites, since GLAS ceased to function several years ago.

As a result, most users will have to rely on pre-processed, relatively old datasets, which are either sparsely distributed or extremely expensive. For example, a free but very local dataset exists for mapping the vegetation height of mangroves in Africa (Figure 4; [12]). For data at specific sites and not currently freely-available, on the other hand, the cost of acquisition can be prohibitive: just a few km$^2$ can cost several thousand US dollars.

As remote sensing technology continues to improve, new missions are launched and ways to process data become more accessible, it is likely that more and more LiDAR datasets will be made freely-available.
Figure 4. Vegetation height around the Mida Creek mangroves, Kenya
(source: http://www-radar.jpl.nasa.gov/coastal/; [22])
How much woody biomass is present in the area of interest?

<table>
<thead>
<tr>
<th>Dataset: NDVI</th>
<th>Spatial Resolution: Low to very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Normalised Difference Vegetation Index; Box 1)</td>
<td>Global Coverage: Yes</td>
</tr>
<tr>
<td>Satellite and Sensor: Any multispectral sensor from which NDVI can be derived (e.g. MODIS or Landsat TM, ETM+ or OLI-TIRS)</td>
<td>Time series: Yes</td>
</tr>
<tr>
<td>Cost: Free</td>
<td></td>
</tr>
</tbody>
</table>

The amount of woody biomass is a key indicator of Natural Capital stock condition as it is directly linked to the amount and type of vegetation, i.e. vegetation quality, present in the habitat.

Woody biomass is also an Ecosystem Service as it can be linked to the dynamics of the carbon cycle, and dry biomass is a good proxy for the amount of fuelwood available in an area. Woody biomass is expressed as the weight of dry matter (e.g. wood, twigs) per unit area. A simple way to derive woody biomass measurements is to use the satellite-derived product called the Normalised Difference Vegetation Index (NDVI; Box 1) and a simple mathematical equation which transforms the NDVI into the amount of woody biomass present in a pixel [13]. This equation is specific to the broad habitat type of the area investigated.

For a coarse but long-term overview of an area’s woody biomass, the Global Inventory Modelling and Mapping Studies (GIMMS) Advanced Very High Resolution Radiometer (AVHRR) NDVI data can be used. While the spatial resolution (8km) is quite low, it can still yield an informative picture of the state of, and changes in, woody biomass over time, especially as the GIMMS NDVI data is continuously available between 1981 and 2011 (at c.16 day intervals).

The woody biomass stock was mapped in and around Tsavo East and West National Parks in Kenya (Figure 5). The amount of woody biomass present in the area in 1982 and 2011 seems to correlate with the GLOBCOVER 2009 land classification showing habitat that is dominated by savannah (lower woody biomass) with a few patches of forests (higher woody biomass).
Figure 5. Amount of woody biomass in 1982 and 2011, and changes in woody biomass in and around Tsavo National Parks, Kenya

**BOX 1: The Normalised Difference Vegetation Index**

The Normalised Difference Vegetation Index, or NDVI, is a popular remotely sensed metric of vegetation. Often compared to a measure of vegetation “greenness”, it has been linked to measures of primary productivity (PP), evapotranspiration, above-ground biomass or even carbon storage in above-ground vegetation.

It is derived using the red:near-infrared reflectance ratio (RED:NIR) where RED and NIR are the amount of red and near-infrared light respectively [14]. NDVI can be calculated using a simple formula:

\[
NDVI = \frac{NIR - RED}{NIR + RED}
\]

Values can vary between -1 and 1. NDVI values for green vegetation will always be between 0 and 1 and negative values usually indicate the absence of vegetation such as bare soil or snow cover; the more positive the NDVI is, the greener the vegetation is.

Because several optical sensors measure the RED and NIR spectral bands, NDVI can easily be derived at all spatial resolutions.
Canopy leaf area index (LAI) is a measure of the amount of leaves present in a given area, or canopy structure. It is defined by the area of single-sided leaf per unit of ground area in broadleaf canopies, or as the maximum projected green leaf area per unit of ground area in coniferous canopies [15,16]. Therefore, where measures of the woody biomass describe the woody component of forests, the green LAI is a direct indication of the vegetation foliage. As such it is both an indicator of stock condition, and an Ecosystem Service relating to the exchange of energy, water and carbon between the land surface and the atmosphere [15].

There are two different avenues of varying complexity for obtaining LAI estimates. Firstly, LAI can be calculated with an algorithm that uses measures of surface reflectance; these can be obtained from any optical sensors, such as Landsat TM or ETM+, and MODIS. However, the LAI calculation algorithm must be adjusted for the type of satellite sensor (spatial resolution, bandwidth, atmospheric correction, etc.) used to collect the reflectance data [17]. As a result, this method is not the simplest way to obtain LAI.

Alternatively, there is a MODIS-derived LAI product which allows direct and free access to LAI measurements. The only drawback is that the data is constrained to the spatial resolution of 1 km, and is only available between 2001 and 2012. MODIS-derived LAI has been shown to be well correlated with field-measured LAI [15] but, due to cloud cover, instrument problems and uncertainties with its retrieval algorithm, this product can also be inconsistent.

One way to side-step continuity and data-inconsistency issues with the MODIS-derived LAI product is to look at results over a large temporal scale, rather than focus on the 8-day temporal resolution at which the data is produced – such as by calculating annual averages and then considering the presence of increasing or decreasing trends in the area of interest. For example, trends in the annual LAI in and around the Tsavo National Parks were investigated for the 2001-2012 period (Figure 6). While some parts of the parks and surrounding buffers show no real changes in LAI in ten years, it is clear that some areas have seen some increase, and others a decrease.

Because satellite-derived LAI is not capable of distinguishing between the LAI of grass or trees when both are active [18], this information can be used in conjunction with maps of the woody biomass and land cover to identify areas where it is the LAI of trees that has increased rather than that of the grass. For example, in the north-west corner of Tsavo East, the LAI indicates a decreasing trend since 2001 (Figure 6), a pattern matched by trends in woody biomass (Figure 5), potentially indicating an area where the tree cover has become increasingly sparse, i.e. lower stock conditions.
Figure 6. Change in Leaf Area Index (LAI) in and around Tsavo National Parks, Kenya (2001-2012).
Mangroves are part of the Natural Capital stock as a unique type of forested woodland located principally in tropical and subtropical coastal and riverine areas [19]. Besides being home to rare and endemic wildlife and plant species, mangroves deliver several Ecosystem Services of paramount importance: protection against catastrophic events (floods, hurricanes and tsunamis) to habitats sheltered behind them [20], an ability that varies with the width of the mangrove strip [21,22], improving water quality and acting as a sink for nutrients and carbon [23].

Mangroves are however declining throughout the world. In the past two decades, it is estimated that this extremely useful but rare habitat has decreased by 35%, and that remaining areas are being heavily degraded [19]. To map the presence of mangroves, and more importantly to identify areas where degradation has occurred, freely-available multispectral or hyperspectral (optical) sensors can in theory be used but are often not enough. Because mangroves are located in tropical and sub-tropical areas, the near-permanent cloud cover and subsequent disruption to images is a severe impediment to using these free remote sensing datasets alone.

To complement optical sensors, microwave sensors like PALSAR can be used to map where vegetation change, such as degradation or afforestation, is occurring. Because it uses RADAR technology, cloud cover is not an obstacle to data collection. However, SAR images are not free and it can be prohibitively expensive to assess medium to large areas.

Nevertheless, SAR imagery is capable of identifying areas of degradation and afforestation, and those areas where a significant change in biomass has occurred [24,25]. For example, the location of the coastal forest of the Lamu region, Kenya, makes it difficult to map vegetation using optical sensors (Figure 7, left); there is too much permanent cloud cover and finding unaffected images is nearly impossible. Using SAR technology (Figure 7, right), mapping of degradation and afforestation of the coastal forest and the mangroves present in Lamu is possible. Particularly, there is clear evidence of recent deforestation very close to the mangrove habitat, indicating the potential threat of encroachment on this rare and unique ecosystem in the near future.
Figure 7. Land classes (left; in 2011) and changes in vegetation between 2007 and 2010 (right), in the coastal forest in the Lamu region, Kenya.
**Ecosystem Service (supporting)**

**What are the patterns in annual primary productivity in the area of interest?**

<table>
<thead>
<tr>
<th>Dataset: NDVI</th>
<th>Satellite and Sensor: Any multispectral sensor from which NDVI can be derived (e.g. MODIS or Landsat TM, ETM+ or OLI-TIRS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution: Low to High</td>
<td>Global Coverage: Yes</td>
</tr>
<tr>
<td>Time series: Yes</td>
<td>Cost: Free</td>
</tr>
</tbody>
</table>

Primary productivity is an important Ecosystem Service as it is a measure of how productive, and healthy, the vegetation is. It can be measured using remote sensing by utilizing NDVI (Box 1) and calculating an index called the annual integrated NDVI [26].

The annual integrated NDVI is a direct measure of annual net primary productivity as it is the sum of the monthly values in NDVI during the year. Annual primary productivity can thus be measured and compared between years (Figure 8, right side) and changes in primary productivity (PP) over time computed (Figure 8, left and centre).

Several pre-processed NDVI datasets exist and they come at no cost at various spatial resolutions. For example the GIMMS AHVRR NDVI data has an 8km resolution and is available since 1981. The MODIS dataset, on the other hand, is available at 1km, 500m and 250m resolutions, but only since 2001.

When compared, changes in the annual integrated NDVI at 8km (Figure 8, left) and 500m (Figure 8, right) resolutions yield similar but not identical results. For example, at 8km, a lot of the significant decrease in integrated NDVI between 2001 and 2011 detected at the 250m resolution seems to disappear; it is still identified as a decrease, but does not appear significant. Similarly, small patches of significantly increasing annual integrated NDVI shown at the 250m resolution are not shown to be significant at the higher spatial resolution of 8km.

Which dataset is best to employ for these analyses is dependent on whether the interest is in the long-term change in primary productivity, at the cost of spatial precision, or in the fine-scale changes in primary productivity, but at the cost of potential long-term trends.
Figure 8. Annual Primary Productivity (PP) in 2001 and 2011 (right), and changes in annual PP between 2001 and 2011 (left and centre), in and around Tsavo National Parks, Kenya. Two spatial resolutions are shown for the change in PP: 8km (GIMMS) and 500m (MODIS).
**Ecosystem Service (regulating)**

**What is the amount of carbon stored and how is it changing in the area of interest?**

<table>
<thead>
<tr>
<th>Dataset: NDVI</th>
<th>Satellite and Sensor: Any multispectral sensor from which NDVI can be derived (e.g. AVHRR GIMMS, MODIS or Landsat TM, ETM+ or OLI-TIRS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution: Low to High</td>
<td>Global Coverage: Yes</td>
</tr>
<tr>
<td>Time series: Yes</td>
<td>Cost: Free</td>
</tr>
</tbody>
</table>

Carbon can be stored in many forms on Earth, including, for example, in terrestrial vegetation, soils, as black carbon residues from fires or in harvested products [27]. Knowing the size of carbon pools is critical for understanding the ability of systems to mitigate climate change as the potential emission of carbon produced by their destruction. As the strength of the climatic change the planet will experience in the future depends on the amount of greenhouse gas present in the atmosphere, of which CO2 is a major component, identifying areas that have a high potential for naturally storing carbon in the vegetation is very important. This knowledge can help inform policies for greenhouse gas emissions and climate change mitigation strategies; for example, highlighting forested areas that should remain intact at all costs.

Remote sensing can be used to estimate the size of carbon pools in the vegetation of specific areas. As carbon storage is directly linked to the above-ground biomass, it can be estimated using the NDVI [28] (Box 1). Although there is a large acknowledged uncertainty associated with estimating carbon pools from above-ground biomass, the consensus is that carbon represents 45-55% of biomass depending on the habitat type [29]. In addition, for some habitat types, such as acacia-dominated savannah in East Africa, more precise estimates of carbon can be derived using habitat-specific mathematical formulas.

In Tsavo East and West National Parks, where the habitat is mostly comprised of acacia-dominated savannah, mapping the carbon pools during the wet season shows that, even within the national parks, there is a lot of variation in the amount of carbon stored in the vegetation (Figure 9, top left and right).

An estimation of the change in carbon pools between 1982 and 2011 at the 8km resolution shows that in the last three decades most of the national parks and surrounding buffer has seen an increase in carbon storage linked to above-ground biomass (Figure 9, bottom). Therefore, overall the Tsavo East and West National Parks are acting as a carbon ‘sink’, increasing carbon storage in the vegetation through time.
Figure 9. Carbon pool in 1982 and 2011, and changes in carbon pool between 1982 and 2011, in and around Tsavo National Parks, Kenya; derived from the AHVRR GIMMS NDVI dataset (8km resolution).
Water cycling is a complex but essential Ecosystem Service. Water circulates and forms closed hydrological cycles, and the resulting terrestrial cycle is of critical importance to both humans and wildlife. For example, it impacts short-term weather patterns and long-term climatic conditions, the growth of vegetation and forestry, food production and availability, and ecosystem carbon and nutrient storage capabilities. There are some parts of the water cycle that can be measured using satellite remote sensing. This is the case for liquid water and the vegetation and soil evapotranspiration (ET).

Liquid water can be measured using the Normalised Difference Water Index (NDWI) [30] and the Modified NDWI (MNDWI) [31]. Both indexes are similar, but not equal, to the NDVI. For example, the MNDWI uses the GREEN band instead of the RED band and the MIR instead of the NIR band (Boxed 1 & 2); this way it can distinguish between vegetation, built-up areas and above-ground water pools.

The MNDWI was used to identify the location of two lakes bordering Tsavo West National Park, Kenya, on its west side (Figure 10). While there clearly are missing data in the MNDWI dataset (the black pixels), this index was able to identify the location of the two water bodies.

ET is the process by which precipitation is returned to the atmosphere; this is done through plant transpiration and soil evaporation. It is the second largest component of the terrestrial water cycle, after rainfall [32], and therefore has a huge influence on water availability on Earth. Water released into the atmosphere also has a large impact on cloud formation, which in turn impacts temperature and precipitation. ET can be measured from space and a pre-processed dataset is made available from data from the MODIS sensor on board the Aqua satellite, at weekly, monthly and annual temporal resolutions.

Because ET is a measure of both land and vegetation transpiration, high values are usually found where the vegetation is denser or where water bodies are present. For example, the annual ET in and around the Tsavo National Parks is highest where the two lakes are located, and at the south-eastern sections of the parks, which are close to the Indian Ocean (Figures 10 & 11). Because the lakes are permanent water bodies, they are highlighted in the maps of ET in 2000 and 2012 (Figure 11). Similarly, areas of highest woody biomass, such as tree cover, also seem to have a permanently high ET footprint (Figures 5 & 11).
Figure 10. Water bodies identified using the MNDWI on the border of Tsavo West National Park, Kenya.

Figure 11. Annual evapotranspiration in 2000 and 2012, and changes in annual evapotranspiration in and around Tsavo National Parks, Kenya.
The nitrogen content of plant foliage is essential to the good functioning of some of their key physiological processes, such as photosynthesis and respiration [33]. It is thus directly related to Natural Capital and other Ecosystem Services, such as the woody biomass or the primary productivity. Spatial variation in foliar nitrogen is caused by local tree species composition, soil type and disturbance history or temperature, while temporal variation is a function of short-term climate disturbance or plant exposure to rising CO₂[33].

In the last decade, technological advances in remote sensing, and specifically ‘spectroscopy’, have opened the door to measuring the content of nitrogen in plant foliage from space. The hyperspectral imager on-board the EO-1 satellite, Hyperion, is capable of measuring the chemical constituents of the Earth’s surface by recording many adjacent wavelengths on a continuous spectrum. This is different from multispectral sensors, like MODIS or AVHRR, which only measure a set of discrete wavelengths such as the NIR or MIR.

Foliar nitrogen can be derived using two bands of the >200 bands that are captured by Hyperion. A simple equation [34] is then used to transform these raw measurements into an index of nitrogen content: the Normalized Difference Nitrogen Index or NDNI.

Although free, Hyperion data have the main disadvantage of not offering global coverage of the Earth; only ‘strips’ of data are available across the globe (Figure 12). For example, only a small area of the Tsavo National Parks has been covered by the Hyperion sensor (Figure 12). As a result, limited information exists on foliar nitrogen content from space-borne monitoring. This image shows that nitrogen is consistently low in areas covered by crops (red polygons), but is variable, being both low and high in areas identified as having tree cover (blue polygons). In fact, the highest nitrogen content of Tsavo West National Park is found in land classified as grassland/shrublands (Figure 12).

As an alternative to the Hyperion sensor on-board the EO-1 satellite, AVIRIS, an airborne spectrometer, can also be used to obtain nitrogen measurements. However, AVIRIS data acquisition is feasible at the local scale only and is not free.
Figure 12. Foliar nitrogen as indexed by the Normalized Difference Nitrogen Index (NDNI) in Tsavo National Parks, Kenya.
The Normalised Difference Water Index, or NDWI, and the Modified Normalised Difference Water Index, or MNDWI, are designed to measure above-ground water.

The NDWI is derived using the near-infrared:green reflectance ratio (NIR:GREEN) where GREEN and NIR are the amount of green and near infrared light respectively [31]. NDWI can be calculated using the following formula:

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR}$$

With this index, water features have positive values, while vegetation and soil have zero or negative values. However, in regions with a built-up land background, the NDWI does not perform as well, with built-up features having positive values too. To correct for this potential issue, the MNDWI can be used.

The MNDWI is derived using the middle-infrared: green reflectance ratio (MIR:GREEN) where GREEN and MIR are the amount of green and middle infrared light respectively [31]. MNDWI can be calculated this simple formula:

$$MNDWI = \frac{GREEN - MIR}{GREEN + MIR}$$

With this index, water has a greater positive value than with the NDWI, vegetation and soil remain negative and built-up areas will show as negative as well. This is because the water and built-up area show similar reflectance values when calculating the difference between GREEN and NIR, but not when using GREEN and MIR [31].
Discussion

The potential of satellite remote sensing for helping measure the planet’s Natural Capital and Ecosystem Services is immense. This is not only illustrated by this report, but by the fact that satellite remote sensing is increasingly acknowledged as a key component of the biodiversity monitoring toolkit [35]. For example, it has been proposed as the best tool to assess progress against up to 11 of the 20 Aichi Biodiversity Targets set by the Convention on Biological Diversity (CBD) [36].

On several aspects where traditional monitoring techniques stumble, such as through bias introduced by multiple observers, poor repeatability across sites or the impossibility of working at large global scales, satellite remote sensing techniques are clearly superior. With the plethora of satellite data freely available to anyone with access to a computer and an internet connection, it is now easy and convenient to obtain a picture of the state of various types of Natural Capital and Ecosystem Services over large spatial and temporal scales. That said, there remain some serious limitations to the use of satellite-derived data to fully measure both.

In this section, we draw attention to the limitations of remotely sensed data for Natural Capital and Ecosystem Services monitoring, and offer a perspective on the way forward for measuring and monitoring the Earth’s natural stocks and flows.

**Limitations of remote sensing for measuring Natural Capital and Ecosystem Services**

Despite the many benefits of remote sensing for Natural Capital and Ecosystem Services, this monitoring method is not a panacea. We list here some limitations and challenges to consider.

1. First, while satellite remote sensing is ideal for working at large spatial scales, ground-truthing the information collected from space with field-derived data is not widely feasible. Without adequate interpretation or explanation, there is a risk that this may lead to the blind acceptance of satellite remote sensing information, with users unaware of the potential uncertainty in the data to the real situation on the ground. Users may also be inclined to believe that satellite data carries very little uncertainty, simply being naïve to the limitations of the sensor with which this data has been collected, i.e. spatial and temporal limitations in data availability across sensors (e.g. annual primary productivity patterns for the same area differ at different spatial resolutions; Figure 8). Yet, if satellite remote sensing is going to be used to support decision-making or policy-making for Natural Capital and Ecosystem Services at the national or international scales, there needs to be some understanding of the accuracy of collected data [37].

2. There is a trade-off between spatial resolution and the size of the footprint of each satellite image. For example, each Landsat image, which contains data collected at a high spatial resolution of 30-90m, is fairly small; as a result, a lot of images are required to cover the entirety of a large area. With each image, the number of pixels to handle increases, which means that the computing power necessary to handle these data increases alongside. There is also a trade-off between spatial resolution and price of acquisition. Currently, any dataset with pixel resolution greater than 30m is not free to all users. Unfortunately, there may be some cases when 30m is still too low resolution to fully capture heterogeneity in Natural Capital or Ecosystem Services [38]. In addition, very high resolution images (such as 1-4m IKONOS data) can be useful to improve the output of land cover classification algorithms that use Landsat or MODIS data [39]. Finally, there is also a trade-off between spatial
resolution and temporal resolution. For satellites with high spatial resolution and small footprints it takes longer to cover the entire Earth once, and thus the time between repeated measurements of the same area is longer.

3. There is bias in the type of information that is freely-available as it is mostly multispectral data collected with optical sensors, such as the Landsat or MODIS data. This means key high resolution information that would be available through hyperspectral, LiDAR or RADAR data is not accessible to all potential users. Moreover, some regions of the world are simply not suitable for optical remote sensing. Tropical and sub-tropical areas are usually under near-constant cloud cover. This means that traditional optical sensors are useless for a part of the world which contains important and rare biomes (e.g. mangrove forests; Figure 7), and thus Natural Capital and Ecosystem Services. Yet, even if hyperspectral, LiDAR or RADAR data were purchased, their analysis still requires the use of specialist software and higher than average computer expertise. This is maybe the highest impediment to their use in measuring stocks and flows. Indeed, surprisingly, very little help is available for processing them.

4. Very few datasets are the fruit of long-term, i.e. multi-decadal, uninterrupted data collection. In fact, most datasets tend to start around the year 2000, meaning that it is difficult to measure long-term change in stock and flows, but also that establishing a suitable baseline against which to measure degradation is difficult in these situations.

5. While remote sensing is a very dynamic field, experiencing a boom in new technologies, satellites, and datasets being produced, there is a certain lag between the release of a new product and its use by non-specialist end-users. New advances will tend to be published in specialised journals, not widely accessible to all, and publications will often make heavy use of jargon which further prevents access to all potential users [37].

6. Finally, and perhaps most importantly, not all aspects of Natural Capital and Ecosystem Services can be measured remotely. A key example is animal distribution, which can be seen as both a stock and a flow, but cannot usually be monitored from space. While there are some proxies that can be used to assess animal biodiversity, such as estimating the habitat type and correlating it with knowledge of biodiversity in similar habitats and regions, remote sensing is not at present a medium for identifying species, counting species or even individuals within species. Exceptions do exist, such as in the Antarctic, where emperor penguin colonies have been mapped using satellites [40], but this is dependent on habitat type and cover.

The way forward

There are a few steps that can be taken to improve the general user’s ability to use remote sensing data to measure Natural Capital and Ecosystem Services.

First, one way to ensure that access to remote sensing data is made easier would be to create a user-friendly data portal; while websites to download several kinds of data already exist (e.g. EarthExplorer http://earthexplorer.usgs.gov/), they still require a certain level of know-how. For example, the user has to already know what data they want to acquire. However, it stands to reason that some potential users will have a problem they want to solve but will not necessarily know what data they need to solve it. Such a potential future data portal will thus need to use jargon-free descriptions of the kind of remote sensing data available for download, with a particular focus on the things that can be achieved with it. Another issue with the current data portals is the lack of transparency in the
description of the data one can acquire. A description of the spatial reference required to visualise the data, and of the pre-processing and atmospheric corrections that must be applied to the data, would be extremely useful. When further work is required before the data can be used, what is needed should be clearly stated, including a basic guideline on how to do it (e.g. a link to grey literature or published work detailing the procedure, software and tools that can process the data), in order to avoid the misuse of remote sensing products.

In addition, education and capacity building will be required to improve general users’ ability to understand what data they need, what data are actually available, and where to find those data if available. At present, this information is scattered across a wide breadth of specialist literature; as a result not everyone has access to it, and those that do may not have the specialist knowledge to extract the information. Resources containing this information could be stored on the aforementioned data portal. Organised workshops and seminars could also help train stakeholders on how they can employ remote sensing to measure stocks and flows. Resources and training in data processing using open source software would also be useful, as most procedures are currently not described in simple layman terms and require licensed software. However, one sure way to maximise the potential of satellite remote sensing for quantifying and monitoring Natural Capital and Ecosystem Services is through collaborations between remote sensing experts and ecologists [41]. While those remain rare, interdisciplinary collaborative research between remote sensing scientists and ecologists is increasingly happening (e.g. [42,43]).

Finally, at present, some datasets that are key for measuring Natural Capital stock and condition and Ecosystem Services remain unavailable to most users, either because they are not free (i.e. RADAR) or because the processing required is not clearly explained and/or requires expensive software (i.e. LiDAR). For the former issue, it is up to the agencies collecting the data to decide to make their product available to a wider range of users, although it is sometimes possible to acquire images at a reduced rate for students or charities (e.g. the European Space Agency: ESA). However, acquiring this data remains a lengthy process involving a written proposal and is likely to discourage many people. For the latter issue, some research labs clearly possess both skills and tools to create pre-processed datasets (see e.g. [12]), but processing data for the whole world to create such a dataset is a huge undertaking, potentially both time-consuming and costly. Even though some LiDAR data are slowly being made available online, it offers far from global coverage and is heavily biased towards the United States. One way to remedy this problem, and enable more people to process the free LiDAR data, would be to publish clear guidelines on the process and to develop open-source software that can do the job.

**Conclusion**

We have showed how 10 key components of Natural Capital (stock and condition) and Ecosystem Services (flow) can be successfully measured using almost exclusively free satellite-based remote sensing. By means of Kenya as a case study, this report demonstrates the incredible amount of detailed information, relevant to both policy-making and conservation decision-making, which can be collected from space with very little effort. Importantly, this work can be replicated in any part of the world. For countries for which we currently know little of the spatial distribution and state of their Natural Capital and Ecosystem Services, the proposed framework is an ideal, cost-efficient method to get up-to-date relevant information. It is also the best method for collecting comparable, unbiased data, something that is not always possible with traditional, ground-based monitoring. However, there are known limitations to remote sensing that need to be addressed if the aim is for non-specialist end-users to turn to satellite data as their first port of call for large- and not-so-large-scale monitoring of Natural Capital and Ecosystem Services.
References


The Zoological Society of London (ZSL), founded in 1826, is a world-renowned centre of excellence for conservation science and applied conservation (registered charity in England and Wales). ZSL’s mission is to promote and achieve the worldwide conservation of animals and their habitats. This is realised by carrying out field conservation and research in over 50 countries across the globe, carrying out original scientific research at our Institute of Zoology, and through education and awareness at our two zoos, ZSL London Zoo and ZSL Whipsnade Zoo, inspiring people to take conservation action.

For more information:
Dr Nathalie Pettorelli, Institute of Zoology, Zoological Society of London, Regent's Park, London NW1 4RY, United Kingdom
nathalie.pettorelli@ioz.ac.uk
www.zsl.org