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DESERTIFICATION MONITORING BY REMOTE SENSING

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Comité Scientifique Français de la Désertification
French Scientific Committee on Desertification

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French Scientific Committee on Desertification

The creation in 1997 of the French Scientific Committee on Desertification (CSFD) has met two concerns of the Ministries in charge of the United Nations Convention to Combat Desertification. First, CSFD is striving to involve the French scientific community specialized on issues concerning desertification, land degradation, and development of arid, semiarid and subhumid areas in generating knowledge as well as guiding and advising policymakers and stakeholders associated in this combat. Its other aim is to strengthen the position of this French community within the global context. In order to meet such expectations, CSFD aims to be a driving force regarding analysis and assessment, prediction and monitoring, information and promotion. Within French delegations, CSFD also takes part in the various statutory meetings of organs of the United Nations Convention to Combat Desertification: Conference of the Parties (CoP), Committee on Science and Technology (CST) and the Committee for the Review of the Implementation of the Convention. It also participates in meetings of European and international scope. It puts forward recommendations on the development of drylands in relation with civil society and the media, while cooperating with the DesertNet International (DNI) network.

CSFD includes a score of members and a President, who are appointed *intuitu* personae by the French Ministry of Higher Education, Research and Innovation, and come from various specialties of the main relevant institutions and universities. CSFD is managed and hosted by the Agropolis International Association that represents, in the French city of Montpellier and Languedoc-Roussillon region, a large scientific community specialised in agriculture, food and environment of tropical and Mediterranean countries. The Committee acts as an independent advisory organ with no decisionmaking powers or legal status. Its operating budget is financed by contributions from the French Ministry for Europe and Foreign Affairs, the Ministry for the Ecological and Inclusive Transition, as well as the French Development Agency. CSFD members participate voluntarily in its activities, as a contribution from the French Ministry of Higher Education, Research and Innovation.

More about CSFD
www.csf-desertification.eu

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Foreword

Mankind is now confronted with an issue of worldwide concern, i.e. desertification, which is both a natural phenomenon and a process induced by human activities. Our planet and natural ecosystems have never been so degraded by our presence. Long considered as a local problem, desertification is now a global issue of concern to all of us, including scientists, decision makers, citizens from both developed and developing countries. Within this setting, it is urgent to boost the awareness of civil society to convince it to get involved. People must first be given the elements necessary to better understand the desertification phenomenon and the concerns. Everyone should have access to relevant scientific knowledge in a readily understandable language and format.

Within this scope, the French Scientific Committee on Desertification (CSFD) has decided to launch a series entitled *Les dossiers thématiques du CSFD*, which is designed to provide sound scientific information on desertification, its implications and stakes. This series is intended for policy makers and advisers from developed and developing countries, in addition to the general public and scientific journalists involved in development and the environment. It also aims at providing teachers, trainers and trainees with additional information on various associated disciplinary fields. Lastly, it endeavors to help disseminate knowledge on the combat against desertification, land degradation, and poverty to stakeholders such as representatives of professional, nongovernmental, and international solidarity organisations.

These Dossiers are devoted to different themes such as global public goods, remote sensing, wind erosion, agroecology, pastoralism, etc., in order to take stock of current knowledge on these various subjects. The goal is also to outline debates around new ideas and concepts, including controversial issues; to expound widely used methodologies and results derived from a number of projects; and lastly to supply operational and academic references, addresses and useful websites.

These Dossiers are to be broadly circulated, especially within the countries most affected by desertification, by email, through our website, and in print. Your feedback and suggestions will be much appreciated! Editing, production and distribution of *Les dossiers thématiques du CSFD* are fully supported by this Committee thanks to the support of relevant French Ministries and AFD (French Development Agency). The opinions expressed in these reports are endorsed by the Committee.

ROBIN DUPONNOIS

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Preamble

This second edition proudly follows up on the first one that was prefaced by Hubert Curien and we are fully indebted to the authors of that trailblazing publication[1]. Here the authors outline the fundamentals of satellite remote sensing, while also highlighting recent trends, particularly the development of many different types of sensors —including radar—and of images, covering large parts of the globe as well as very small detailed areas using civilian drones, which the authors refer to as 'personal remote sensing'. They also provide examples of various uses of this technology in dryland regions, from the global to the plot scale.

Readers will thus discover, based the latest findings, myriad images that satellites generate in terms of geographical and topic-oriented data. But this vast amount of data can only be used in conjunction with studies and field measurements that are vital for properly interpreting the images.

The spotlight is naturally on Earth observation in areas with low rainfall. Images from sensors operating in the visible portion of the electromagnetic spectrum—which have been available for more than 40 years—are thus preferred. Long-term trends can in this way be measured and interpreted, as reflected by recent discussions on the regreening of the African Sahel.

The specific features of dryland regions are fully taken into account, particularly the extent of the soil surface, which is crucial in these regions. From a spatiotemporal perspective, it has sparse vegetation cover and generates windborne dust that impacts local Sahelian farmers' fields as well as the global climate system.

Earth observation has become much more widespread and accessible over the past 10 or 20 years. It was previously limited to specialists but has now broadened to encompass direct beneficiaries, including environment surveillance specialists, particularly those who analyse and monitor desertification in arid and semi-arid areas.

This *Dossier* contains abundant information on tools available to the general public, along with (free) images and data. A list of websites is provided at the end of the document with the aim of enhancing access to remote sensing images. This will hopefully foster environmental monitoring and hence facilitate the governance of these drylands.

MICHEL-CLAUDE GIRARD

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MEMBER OF THE *ACADÉMIE D'AGRICULTURE DE FRANCE*

1. The first edition was *Les dossiers thématiques du CSFD N°2*, published in 2005.

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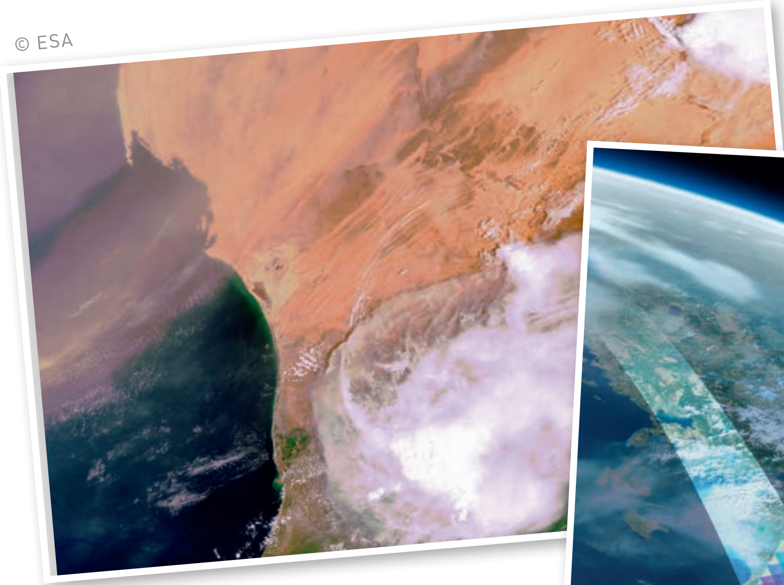

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Satellites and environmental surveys

Earth observation satellites have gradually increased our capacity to monitor the environment—including drylands—over the past 40 years.

In 2016, about 100 satellites were in operation—or were about to be—generating a broad spectrum of Earth images of the atmosphere, continents and oceans, etc. This has given rise to a highly diverse range of technologies that are being used for different applications, such as meteorology and urban planning.

This *Dossier* presents some basic concepts and examples of the use of Earth observation satellites in combating desertification, thus providing a first overview of the possibilities offered by remote sensing. The aim is to introduce readers to the topic, while offering tips for further reading, including manuals and specialized sites mentioned in the 'For further information' section (see p. 38).

TWO TYPES OF EARTH OBSERVATION SATELLITE

Two main types of satellite are currently orbiting and scanning our planet: (1) geostationary satellites —mainly meteorological satellites—orbit the Earth in the same direction, always staying above the same spot on Earth, and (2) near-polar orbiting satellites that revolve around the Earth from pole-to-pole.

→ FOCUS | Remote sensing

Remote sensing encompasses all instruments and techniques that produce satellite or aerial images from which information on the Earth's surface—including the atmosphere and oceans—can be extracted without direct contact.*

Remote sensing satellites collect electromagnetic radiation from the Earth's surface via small surface components, or so-called 'pixels' (picture elements), which are assembled in an orderly grid pattern to form images. These measurements are related to the physical nature of the observed surface and provide information on the processes under way there. Satellite images generally include several spectral channels or bands since the satellite sensor captures measurements at several wavelengths.

* Adaptation of the definition from the French *Commission interministérielle de terminologie de la télédétection aérospatiale* (1988).

Geostationary satellites orbit the Earth at 36,000 km altitude and rotate in the same direction and speed as the Earth, observing the entire side of the planet from a fixed position (e.g. see below a complete image of one side of the Earth taken by the Meteosat 8 satellite). These satellites, which acquire images every 15 min, track cloud movements (as illustrated in weather reports), in addition to many of the parameters required for weather forecasting models (surface temperature, atmospheric water vapour content, etc.). However, despite this high image acquisition frequency, they provide a very low spatial resolution[2], i.e. where the pixel size—or smallest area on the ground detectable by the sensor—typically ranges from 1 to 8 km^2.

▲ **4 August 2015. First image captured by the SEVIRI sensor.** (*Spinning Enhanced Visible and InfraRed Imager*) from the MSG-4 Meteosat Second Generation satellite. © Eumetsat, 2015

2. Terms defined in the Glossary (page 44) are underlined and highlighted in blue throughout this *Dossier*.

Near-polar orbiting satellites are the most widely used and enable more detailed observations, particularly for environmental monitoring, with spatial resolutions of up to 50 cm but lower acquisition frequencies (lower 'repeatability' or higher 'revisit times', ranging from 1 day to several weeks. They closely monitor different features along their track as they orbit the Earth at a much lower altitude. Their sensors capture images continuously along the track within the width of the so-called 'swath'. As the Earth obviously continues to rotate around its axis throughout this time, the satellite monitors a nearby swath with each orbit. The tracks wrap around the Earth like wool yarn on a ball, and after a number of rotations the satellite will have observed the entire surface of the Earth before repassing over the same positions.

The acquisition frequency is related to the time between two satellite passes over the same area. However, some satellites are capable of "oblique scanning" (aiming at a neighbouring track), which locally increases the repeatability. Note that the orbits of many near-polar orbiting satellites are chosen to be synchronized with the sunlight cycle (i.e. so-called 'sun-synchronous' satellites). They pass over a section of the Earth at the same solar time and thus observe the flyover area under similar lighting conditions between passes, which facilitates signal interpretation.

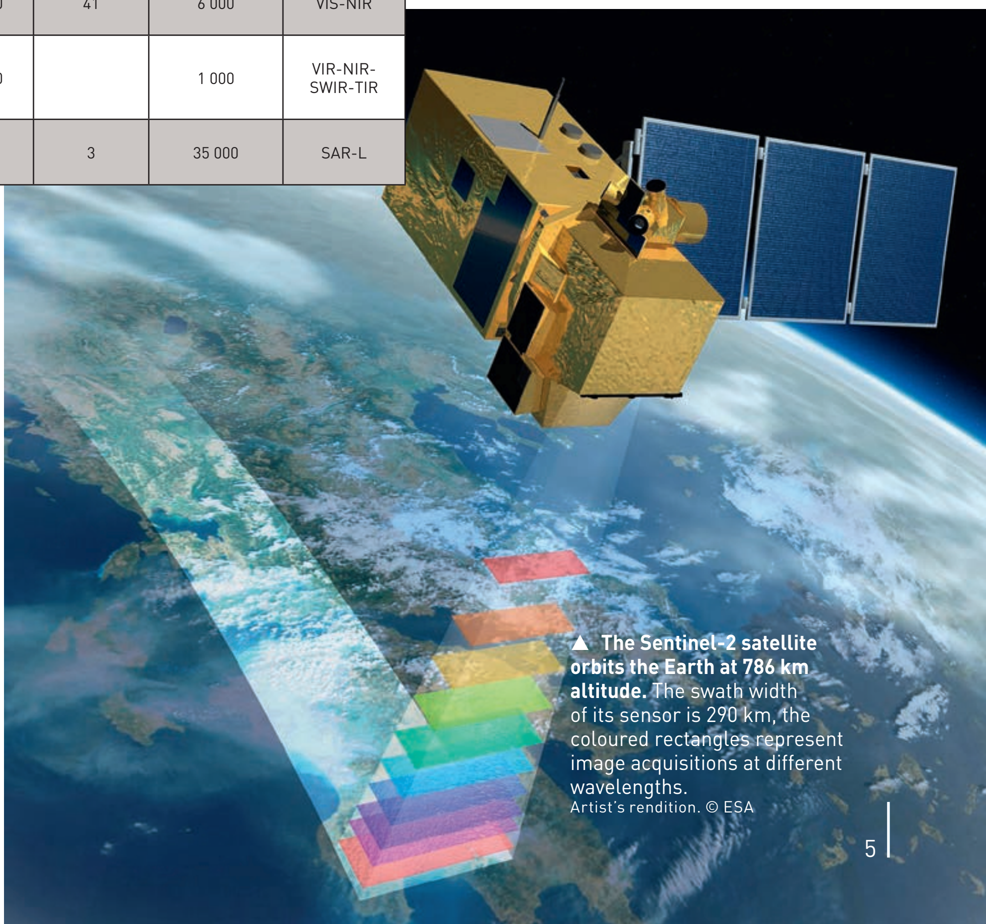
The image below represents a second generation near-polar orbital satellite (Sentinel-2, European Space Agency, ESA) while also illustrating the satellite track, swath width and altitude in orbit.

The adjacent table shows some of the recent satellite and sensor systems mentioned in this *Dossier* as well as their main features.

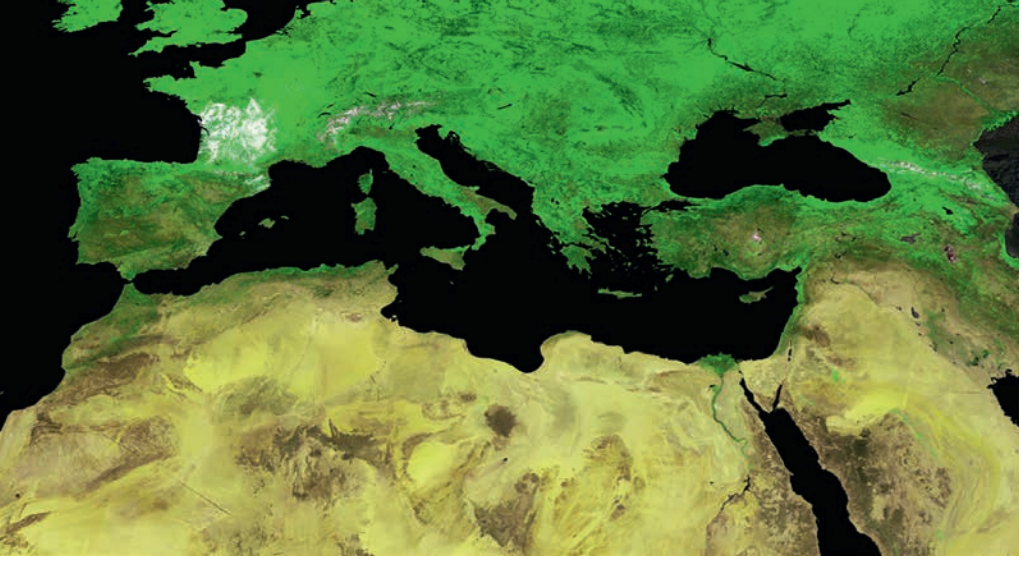
Satellite	Sensor	Country**	Altitude (km)	Swath (km)	Revisit (days)	Maximum spatial resolution (m)	Spectral range***
SPOT-7 - *Satellite Pour l'Observation de la Terre*	NAOMI	France (EADS)	694	60	26	1,5	VIS-NIR
Landsat-8	OLI	USA (NASA)	705	185	16	30	VIR-NIR-SWIR
Envisat* Environmental Satellite	MERIS	Europe (ESA)	783	300	35	300	VIS-NIR
Sentinel-1	SAR-C	Europe (ESA)	693	400	12	5	Radar Band-C
Sentinel-2	MSI	Europe (ESA)	786	290	10 (ultimately 5)	10	VIR-NIR-SWIR
Proba-V-Project for On-Board Autonomy	VGT-P	Europe (ESA)	820	2 250	1	100	VIR-NIR-SWIR
Terra	MODIS	USA (NASA)	705	2 330	2	250	VIR-NIR-SWIR
ADEOS*-Advanced Earth Observing Satellite	POLDER-1	Japan (NASDA)	787	2 400	41	6 000	VIS-NIR
NOAA-19-National Oceanic and Atmospheric Administration	AVHRR	USA (NASA)	870	2 000		1 000	VIR-NIR-SWIR-TIR
SMOS-Soil Moisture and Ocean Salinity	MIRAS	Europe (ESA)	758		3	35 000	SAR-L

* Satellites that are no longer operational.
** EADS: Airbus Defence and Space, France
NASA: National Aeronautics and Space Administration, USA
ESA: European Space Agency
*** VIS: Visible spectrum (0.4–0.7 µm)
NIR: Near infrared spectrum (0.7–1.6 µm)
SWIR: Short-wave infrared wavelength (1.6–4 µm)
TIR: Thermal infrared radiation (4–15 µm)
SAR-L: Synthetic aperture radar–L band

◀ **A few recent examples of satellite/sensor systems used for Earth observation**
This table specifies the main characteristics of the sensors mentioned in this *Dossier* and the satellites (or platforms) on which they are deployed. Satellites often have multiple onboard sensors, although not reflected in this deliberately limited list. Satellites involved in long-term programmes are often pooled in similar series (e.g. SPOT-1 in the current SPOT-7 series), as also is the case for the Landsat series 1 to 8 (only the last one is mentioned in this table).
For further information: https://directory.eoportal.org/web/eoportal/satellite-missions



▲ **The Sentinel-2 satellite orbits the Earth at 786 km altitude.** The swath width of its sensor is 290 km, the coloured rectangles represent image acquisitions at different wavelengths.
Artist's rendition. © ESA



▲ **Mediterranean Basin viewed from space.** Note the clear contrast between the green vegetation along the northern coast and the arid terrain on the southern side of the Basin.
Synthesized PROBA-V/VEGETATION image, June 2013.

The high variability in the spatial resolution of the different sensors is due to the diverse range of sensor/satellite combinations that are implemented according to their target use, e.g. for global climate modelling or detailed mapping of urban infrastructure. In recent years, the advent of increasingly finer resolution images (less than 1 m) offered by private operators (GeoEye, Digitalglobe) is gradually leading to the replacement of aerial photographs to address the needs of companies in telecommunications, construction, public works and distribution (supermarkets, etc.) sectors, etc.

WHAT IS THE PURPOSE OF REMOTE SENSING?

Satellite Earth observation technologies—in conjunction with ground measurements and scientifically valid models—enable the study, modelling and monitoring of environmental phenomena, as well as the monitoring of resources (particularly food crops, etc.) at different spatiotemporal scales. They serve as an objective, exhaustive and permanent information base. These technologies offer situation monitoring and assessment and pave the way for early warning systems.

Remote-sensing data are also essential for the development and implementation of land surface functioning models, particularly for drawing up scenarios and forecasts at various time scales (see adjacent Focus). They can also be used to assess initiatives by contributing to the assessment of their results. They help politicians, decision-makers and other economic and social stakeholders take short-term measures required in response a given situation, but also to identify appropriate medium- and long-term strategies that could enhance sustainable development. Moreover, they enable these stakeholders to benefit from feedback. Understanding and monitoring desertification mechanisms, defining plans to combat desertification and assess initiatives undertaken are thus part of this type of application.

MULTIPLE EARTH OBSERVATION PROGRAMMES

National and international Earth observation programmes have been implemented since the 1960s, including Landsat (1972), SPOT (since 1986) supplemented by Pléiades since 2011, while recent major programmes include RADARSAT (since 1995), Terra and Aqua (2007), SMOS (Soil Moisture and Ocean Salinity, 2009), Envisat (Environmental Satellite) and the Sentinel series that was launched in 2014.

Meteorological satellites that provide observations for the World Weather Watch should also be mentioned, including European satellites such as Meteosat (1977) and MSG (Meteosat Second Generation in 2002) and MetOp (Meteorological Operational series, since 2006), in addition to US satellites such as GOES (Geostationary Operational Environmental Satellite since 1975), NOAA-AVHRR (National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer, since 1978), etc.

→ FOCUS | Remote sensing and modelling

The analysis and mathematical and/or physical representation of environmental phenomena (e.g. water cycle, vegetation growth, climatic mechanisms, etc.) enables the design of relatively complex models of these phenomena. The models are then used to forecast floods, crop yields, future weather conditions, etc.

Remote sensing data provide information on variables as diverse as stream height, vegetation cover growth rate, surface temperature, etc. This periodically acquired information subsequently serves as input in models of various types that simulate variations in a system or resource, thus helping to refine forecasts.

The development of Earth observation programmes is ongoing at an accelerated and coordinated pace. This reflects the priorities that States, institutions or international organizations give to this technology and its trends, thus enabling them to observe various phenomena with ever greater precision. The EU Copernicus programme is emblematic of this leap forward with the Sentinel satellite series currently being deployed. In addition, France plays a spearheading role in this progress, often through multilateral cooperation, and above all via its involvement in the European Space Agency (ESA). The private sector is also increasingly involved. For example, the SPOT satellite programme—originally a French public initiative with a contribution from Sweden and Belgium—was gradually taken over by the private sector up to SPOT 6, i.e. the first fully private satellite.

New satellites have an increasingly fine spatial resolution, while forming a seamless series with older satellites to facilitate long-term monitoring of phenomena such as desertification. In recent years, there has been a trend towards increased acquisition frequency (e.g. Sentinel-2 has been offering 5-day coverage for any point in the world since 2017), higher spatial resolution, as well as free provision of environmental monitoring data. Currently, only very high resolution recent data has to be purchased.

These national or joint multinational efforts could lead to overlaps and gaps. To effectively address this issue, space agencies first set up a forum—the Committee on Earth Observation Satellites (CEOS, 1984)—and then another forum with broader scope—the Integrated Global Observing Strategy (IGOS)—with other agencies providing different types of data. Finally, at the political level, the G8[3] World Summit on Sustainable Development in 2002 gave rise to the Group on Earth Observations (GEO), a partnership of governments and international institutions to build a Global Earth Observation System of Systems (GEOSS).

Within a span of about 50 years, space observation systems have made it possible to acquire extremely large and *a priori* heterogeneous image archives. Significant efforts have been made internationally (including through CEOS and GEOSS) to make these archives interoperable at minimal cost and readily accessible to users, e.g. mainstream mobile phone applications for viewing maps and satellite images, vehicle GPS, etc. More targeted scientific, institutional and operational applications have also benefited from similar digital image processing progress (georeferencing, radiometric correction, etc.), thus further facilitating their use.

Some satellites have fixed systematic image acquisition schemes (e.g. every 16 days for Landsat), while others, because of their oblique viewing capability, make it possible to rapidly observe one or more areas requested by a user. An increasing number of systems offer this flexibility to better address the demand. There is an overall improvement in the acquisition repeatability, which facilitates monitoring of relatively rapid changes, e.g. phenological stages (growth stages) of natural vegetation and crops.

Moreover, it is possible to coordinate the simultaneous use of several satellites, for instance within the framework of charters on major hazards, to enable priority monitoring of areas affected by a natural or industrial disasters (earthquake, flood, etc.).

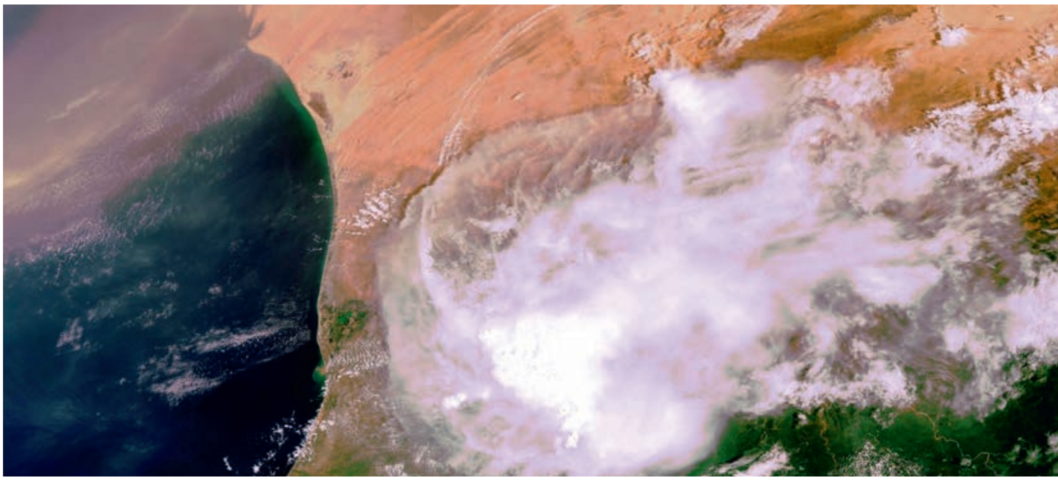
The following chapters of this *Dossier* present the different parameters that can be observed by satellite, as well as the use of satellite images in various operations to combat desertification.

▲ **Arid landscape in Cape Verde.**
Y. Boulvert © IRD

3. G8 members include France, USA, UK, Russia, Germany, Japan, Italy and Canada.

Fundamentals of remote sensing

The basic concepts summarized in this chapter will enable readers to approach remote sensing and its uses with sufficient knowledge to understand its potential and limitations.



▲ **Excerpt from a European Envisat satellite image acquired on 16 September 2010 over Mauritania. Differences in ground colour between regions are clearly visible with the MERIS sensor. A sandstorm over the ocean can be seen.** © European Space Agency (ESA)

This chapter provides an overview of the physical concepts needed to understand remote sensing and its uses. Many reference documents in French and English provide further information on these techniques (see p. 38).

SAMPLING, SPECTRAL SIGNATURE AND REVISIT

Electromagnetic spectrum and radiation sources

The electromagnetic spectrum observed by on-board instruments, which carries the information that remote sensing seeks to analyse, is divided into different domains ranging from short to long wavelengths (denoted λ). Remote sensing only uses some of these domains for both physical and technological reasons, such as the transparency or absorption of atmosphere and clouds, whose disruptive effects are minimized and/or corrected by selecting suitable wavelength domains.

These domains primarily involve the visible (0.4–0.7 µm), near (0.7–1.6 µm) and mid-infrared (1.6–4 µm), and thermal infrared (4-15 µm) radiation characterizing the heat emitted by the 'Earth system' (i.e. the Earth and its atmosphere as a unit). This set of domains is sometimes referred to as 'optical' because of the observation instrument technology. Then comes the wide microwave or 'radar' radiation domain, which occupies a millimetre to decimetre wavelength band.

There are two main types of remote sensing system:

- **Passive systems** measure radiation emitted by the Earth system first in the visible and infrared range, and then (as technology advances) in the microwave range.
- **Active systems** emit their own radiation sources —mainly in microwave and Lidar domains (laser remote sensing)—and measure the radiation returned by the target being analysed.

Electromagnetic radiation measured by sensors aboard satellites can thus:

- **result from the diffusion of incident radiation** from a natural source such as the sun (visible and near infrared domains) or from the satellite (active microwave domain)
- **or be emitted directly by the Earth as a result of its temperature**, mainly in the thermal infrared domain (associated with the ground temperature with a maximum thermal Earth emission) and in the passive microwave domain, which also results from the ground temperature modulated by several major physical phenomena (e.g. soil moisture for the SMOS satellite, see p. 20).

In almost all cases, different phenomena are involved in the received signal, e.g. soil conditions, vegetation activity, water colour and the atmosphere. Several measures are therefore necessary to extract the sought-after information. This generally entails choosing wavelength domains where the impact of the monitored phenomenon prevails over that of other phenomena.

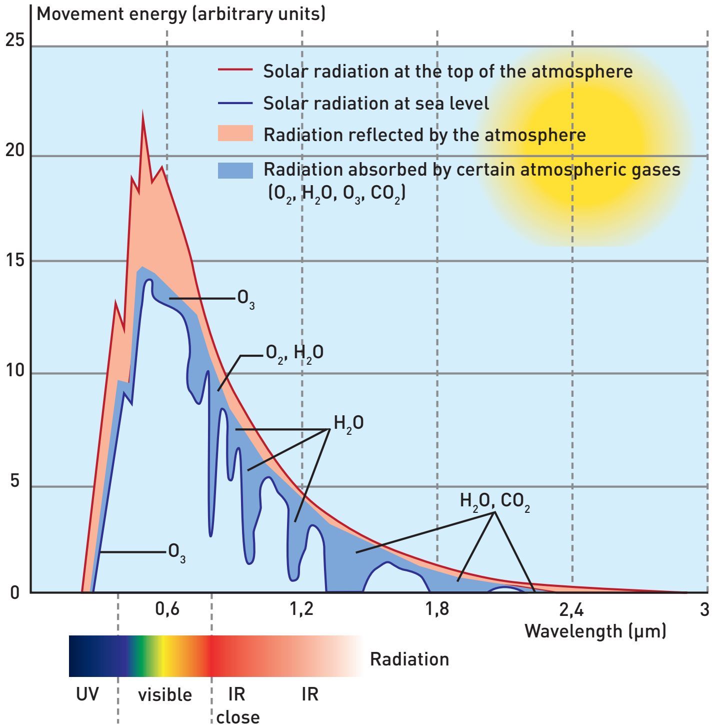
Observation in thermal infrared and microwave domains (active or passive) can be done at any time of the day or night. The atmosphere and clouds have very little effect on the electromagnetic spectrum in the microwave domain. Radar can thus be used for both night and day observations in open or cloudy areas.

Electromagnetic waves generally interact to a high extent with objects when their size is of the same magnitude as their wavelength. In particular, in the active microwave domain (with a millimetre to decimetre wavelength magnitude), vegetation and ground roughness could markedly contribute to the backscatter signal, depending on their characteristics and the wavelengths involved. Some specific cases of interest for desertification studies are mentioned in the next chapter.

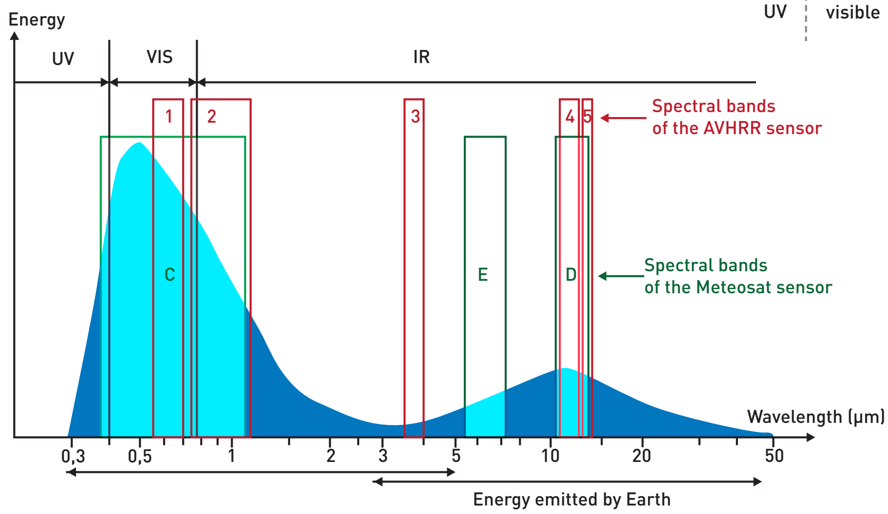
Sampling, resolution and correction

The signal is not continuously measured by the sensor (e.g. on a photographic device), but rather for small elements called 'pixels'. Raw sensor images are not in standard cartographic projection form because of the imaging geometry of the satellite. Image processing software tools are available to restore images to conventional projections. However, this task is becoming unnecessary for users because the images are provided with standard projections ('georeferenced'), or are even corrected for deformations due to the relief ('orthorectified').

In addition to these geometric corrections, radiometric correction is also required to avoid the inevitable imperfections of the observation device, which are especially due to the atmosphere, as well as observation angles, optical effects within the device, the detection physics, etc. This treatment covers radiation measured in the satellite to the surface emitted radiation value, while excluding atmospheric effects. These corrections have long been problematic for users due to the limited availability of the atmospheric data needed for the treatment, but the situation is changing as image providers now often perform this correction. The surface emitted radiation value is generally not directly used, but rather a normalized value, i.e. the ratio between this value and the energy received at the surface. This 'reflectance' value ranges from 0 to 1 for highly absorbent and highly reflective objects, respectively.



▲ **Solar radiation at the top of the atmosphere and at sea level.**
© Université Virtuelle Environnement et Développement durable (UVED)



◀ **Electromagnetic radiation emitted by the Earth.**
In blue: spectrum of radiation emitted by the Earth and the reflected solar radiation spectrum. The figure also highlights the five spectral domains explored by the NOAA AVHRR satellite sensor and those explored by the Meteosat 1-7 satellite sensor (C, D, E bands).
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For further information: http://eduscol.education.fr/orbito/pedago/tempe/tempe3.htm

Spectral signature concept

Optical instruments measure radiation in several wavelength domains, which means that a number of values are provided for each pixel, thus constituting the spectral signature of the target object at a given time. Hence the image data consists of several ‘channels’ or ‘spectral bands’, each corresponding to a wavelength measurement. This concept can be extended to active and passive microwave systems via which electromagnetic radiation emitted or backscattered at several wavelengths can be collected, but also as a function of the signal polarization.

As the sought-after information (e.g. the extent of vegetation cover) cannot be obtained from a single channel, it is usually necessary to extract it by processing the different spectral signature channels of each pixel, or even by introducing exogenous data (measured or known independently of the observation system).

Time required for complete coverage

As already explained, a swath is the width of the ground strip observed at a given time by an on-board instrument, which actually records strips all around the Earth, ultimately covering it entirely after the so-called ‘repeatability’ (or ‘revisit’) time. The latter can therefore be defined as the theoretical period of observation of a given point on the ground (we say ‘theoretical’ because some lateral viewing devices enable focusing on certain points to the detriment of others, while on the other hand cloudiness in the optical domain can mask the point to be observed). The revisit time is a key component in the physical foundations of remote sensing.

DIFFERENT TYPES OF IMAGE

There are several main image categories depending on the measurement instrument technology.

Optical images

Optical images use so-called passive technologies that collect the signal naturally reflected or emitted by the target. The very rapid technological progress achieved in recent years has led to very significant resolution gains in the optical domain—especially at short wavelengths (visible and near infrared domain, typically 0.4-1.1 µm).

Very high resolution images (less than 1 m) enable detailed monitoring of highly anthropized environments and infrastructure. They also provide information on the vegetation spatial structure (e.g. the tree and shrub distribution), which is important in the study of desertification processes. However, these images are generally expensive and only cover small areas. In combating desertification, they are mainly used to obtain very local information when focusing specifically on an area of interest and then, where relevant, applying the collected information on a broader scale.

High-resolution images (typically 10-30 m) generally shed light on local landscapes while identifying the main phenomena affecting them. Agricultural plots of about 1 ha and larger may be distinguished on such images. Composite information is obtained, particularly in semiarid environments—soil contributions are often predominant in signals of sparse and/or inactive vegetation.

▼ **Sandstorm over the Red Sea.**

The advantage of medium (50-250 m) and low resolution (from 500 m) images is that they have a very wide swath with a repeatability of about a day. They can generally highlight weekly changes in vegetation, even under cloud cover. Time series images can thus be programmed as they provide a very interesting source of information for monitoring environmental changes (see an example regarding the Sahel on p. 25).

Thermal infrared images, which are generally of lower resolution than shorter wavelength images, contain information related to the surface temperature of the observed targets, modulated by their own specific emissivity parameter. This temperature information depends on energy exchanges between the surface and the surrounding environment, which are linked to key phenomena such as evapotranspiration and vegetation stress levels.

Microwave images

Active microwave images can achieve high resolution through the so-called synthetic aperture radar (SAR) technique. Objects that most interfere with the incident wave are those in the same size range as the wavelength, which may be of interest in studying the surface roughness and vegetation in semiarid areas. Metal objects and open water areas also reflect the incident wave while moist soils tend to absorb it. As with optical images (but in a less intuitive way), the pixel response therefore contains information related to many surface parameters. For example, wavelengths that differ significantly from the size of sand grains under some conditions make it possible to obtain images of structures hidden by the sand, e.g. fossil hydrological networks, buried archaeological sites, etc. (see p. 21).

The resolution of passive microwave images is typically about 10 km. These images only shed light on phenomena at the subregional scale. They however provide types of information that are hard to access with sufficient accuracy by other systems. Therefore, despite its low resolution (a 3-day revisit frequency and better than 50 km spatial sampling), the SMOS system designed by the Center for the Study of the Biosphere from Space (CESBIO) provides valuable information on soil surface moisture (see p. 20).

It may be advantageous to develop combined systems, including both types of sensor, or two sensors of the same type with different features. For example, France and Italy have jointly developed the high-resolution Optical and Radar Federated Earth Observation (ORFEO) space observation system, with Pléiades (France) being the optical component and COSMO-SkyMed (Italy) the radar component. Finally, as part of the Copernicus programme, Europe (ESA/EU) is developing the Sentinel satellite series mentioned above, which contains various types of information system.

Data and product providers tend to sidestep swath constraints by providing users with the ground surface they need by mosaicking several (types of) image. This 'turnkey service' is generally very convenient for most applications, but scientists should remember that in such cases not all points in the delivered image were observed at exactly the same dates or under the same observation angle and atmospheric conditions, etc. They should thus avoid using methods that explicitly or implicitly assume that these conditions are consistent.

DATA ACCESS

The situation regarding access to Earth observation data, products and services is rapidly and profoundly changing, as illustrated during the first decade of the 21st century with the advent of mainstream products such as Google Earth. These consumer products and services are generally not—except in special cases—those needed by scientists, engineers and decision makers, including those involved in combating desertification. The Google Earth Engine is a platform designed to meet their needs (see p. 40). In addition to this consumer offer, there is currently a rapid increase in the supply of conventional, multi-wavelength and multi-resolution satellite images, which provide a wealth of information that can be used by scientists. To an increased extent, these images are free, e.g. as is the case with Sentinel images.

Some public distribution systems provide digital data and products free of charge, while others, whose funding involves private investment, market them (see p. 40). The mainly French SPOT system is a unique case—the products are commercially marketed, but archived images prior to a certain date may be accessed free of charge if they are not to be used for commercial applications.

A growing number of countries are acquiring (or already have or will) national or regional satellites thanks to the combination of national and/or regional interests, the rapid increase in space technology expertise, technological progress and lower manufacturing costs. These satellites are generally wholly or partly purchased from large companies in industrialized countries (with increasing involvement of national teams and/or technology transfer operations) or resulting from North/South or South/South agreements between States. For example, with regard to Africa, a continental cooperation has been established between Algeria, Nigeria and the Republic of South Africa, with the first being the launch of the AlSat-1 satellite in 2002, under the responsibility of the Algerian Space Agency (ASAL).

There is generally relatively easy access to data from these satellites but this access may be reserved or open. These new ‘space States’ sometimes join forces with major Western corporations to distribute their data, e.g. those of the FORMOSAT satellite, which are available via Airbus Defence & Space (ex- SPOT Image).

It is very likely that major changes in the massive and free data dissemination policy of the European Copernicus Programme (ESA/EU) will be required with respect to the types of products that are operationally available in this area.

In addition, the *Centre national d’études spatiales* (CNES) and the French scientific community have developed a project on scientific thematic clusters, including Theia which is devoted to land surfaces. This Theia thematic cluster provides a comprehensive range of certified quality images, methods and services to scientific communities and public policy stakeholders. Studies on the impact of anthropogenic and climatic pressures on ecosystems and territories is a major focus of this cluster.

These national measures are beneficial for desertification studies, which require access to long time series data for both local and vast areas (e.g. data from the SPOT archives have been available since 1986) (see Spot World Heritage p. 40).

DERIVATIVE INDICATORS AND VARIABLES

Desertification is the result of complex interactions between humans and their environment. A set of specific indicators is therefore generally used to detect desertification situations, understand the mechanisms involved, define short- and medium-term control policies, predict changes in related phenomena and analyse feedback. The definition of such indicators is a long-term process requiring close collaboration between technology managers, scientists and decision-makers. For example, with regard to desertification, the relevant United Nations agencies involved in the United Nations Convention to Combat Desertification (UNCCD) recently identified the most representative and relevant indicators at the national level, i.e. the percentage of degraded land in relation to total land, the extent of vegetation cover and the soil organic carbon content.

Remote sensing is a major source of information for calculating environmental indicators, providing access to physical information such as albedo, vegetation indices, surface roughness, surface temperature or soil moisture.

→ FOCUS | Remote sensing and geomatics

Geomatics encompasses all of the tools and methods used to acquire, represent, analyse and incorporate geographic data. Geographic information systems (GIS), for instance, are used in an increasing number of fields: land-use planning, infrastructure management and networks, transport and logistics, insurance, telecommunications, engineering, social networks, etc.

Remote sensing images are an increasingly important source of geographic data used in geomatics. They can be directly processed in GIS, but are generally managed using specific image processing software, which includes all of the necessary display and analysis functions (geometric and radiometric correction, index creation, land cover classification, etc.).

▲ **In this optical sensor image, the Salar d'Uyuni salt flats in Bolivia clearly stand out as a white area due to its much higher albedo than the surrounding landscape.** © Google Maps, 2016

Albedo

Albedo is the ratio of the amount of light reflected by an object to the total amount of light it receives. It is expressed by a number between 0 (no reflected light) and 1 (total reflected light). Albedo is a major factor in energy and radiation balances as it controls the amount of solar energy absorbed by a surface. The albedo of a given geographical area may vary during the year for a given geographical area as a result of various physical phenomena, such as soil moisture, various phenological vegetation stages and wind deposits (or even as a result of adverse effects such as the presence of clouds for low-resolution images).

The interpretation of this value and its spatiotemporal variations is linked to desertification processes. The albedo of bare ground decreases as its water content or roughness increases. Similarly, the albedo of land with vegetation depends on the extent of vegetation cover and its chlorophyll activity. Substantial research has been carried out on the relationship between albedo and desertification, particularly from the climate perspective, but no definitive conclusions could be drawn because this relationship is indirect.

▼ **Arid landscape, Namibia.** The coastal Namib Desert is located in southwestern Namibia and is considered to be the oldest desert in the world. J.-Y. Meunier © IRD

Vegetation index

Albedo may incorporate the entire solar radiation spectrum, but certain objects and their states can be characterized by analysing the reflection of this radiation across different spectral bands. Green vegetation, due to its chlorophyll activity, thus has low reflectance in the red spectral wavelength domain (600-700 nm, denoted R), as well as high reflectance in the near infrared domain (0.8-1.1 µm, denoted IR) due to the structure of green plant tissues (incomplete parenchyma).

When chlorophyll activity decreases, R increases while IR decreases. The curves shown on the next page show that reflectance increases (all other things being equal) when chlorophyll activity is more intense. This remarkable property of green plants has facilitated the development of several vegetation indices using these bands, with the normalized difference vegetation index (NDVI) being the most commonly used.

$NDVI = (IR-R)/(IR+R)$

This index is, however, hard to apply in arid environments. Indeed, ecosystems are characterized by the relatively sparse and inactive vegetation cover. Most of the signal therefore comes from the ground. The impact of the vegetation state on the vegetation index remains low and can be disrupted by a diverse range of variations related to the soil.

Interpretation is particularly difficult when studying vast regions over long time intervals, often using several satellites, because the consistency of these long series is never perfect. A typical example is the debate on 'Sahel greening' (see p. 26).

Surface roughness

The roughness parameter serves to quantify the irregularity of a surface, which can be due to the ground surface or to the vegetation cover. The extent of surface roughness depends on the extent of its irregularity. This naturally presupposes that an order of magnitude of the irregularity dimension has been defined to determine whether or not the target object is rough. For example, a regular sand surface is smooth at the centimetre scale but may be rough at the tenth of a millimetre scale.

If the roughness influences the reflectance in the visible domain, then it is generally assessed by radar remote sensing. Radar emits microwaves and measures the power at which an object reflects them (so-called 'backscatter'). The backscatter increases with the surface irregularity and is all the greater when the size of the irregularities mentioned above is in the order of magnitude of the wavelength of the emitted radar microwaves. Roughness is an important parameter in calculating sensitivity to wind and water erosion and surface water flow.

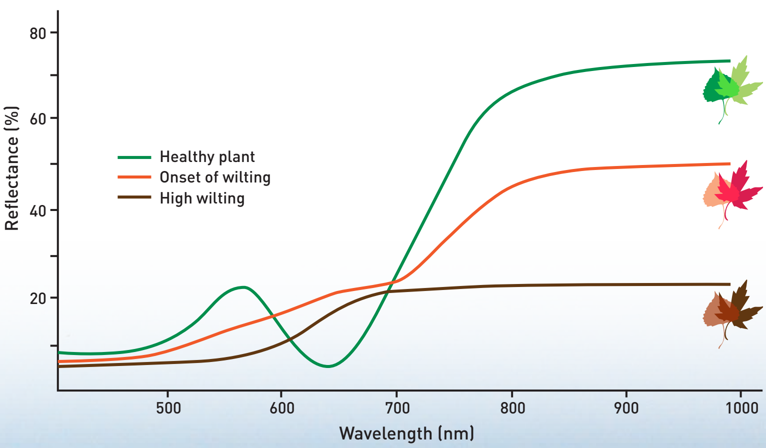
▼ **Soil erosion in South Africa.** A form of gully erosion in pastures overrun by *Acacia iberiasna*, Potshini catchment area, Bergville region.
J.-L. Janeau © IRD

Surface temperature

The surface temperature is the result of energy exchanges at the Earth's surface and is estimated by thermal infrared radiation measurement. Its value depends more or less directly on many factors, with the main ones being the albedo, which determines the absorbed energy, as well as the soil surface moisture, the amount of active vegetation present and its water stress level, which determines evapotranspiration. Like these energy exchanges, the temperature of a surface varies according to the observation time. With geostationary satellites (meteorological satellites), surface temperature patterns may be monitored over large areas but at low resolution. Higher resolution observations (60 m) are currently only possible with Landsat spacecraft.

Soil moisture

Soil surface moisture can be estimated by radar (ERS, Envisat, Sentinel-1 satellites) provided that the roughness impact can be isolated, or more recently by passive remote sensing in the microwave domain, but at very low resolution (ESA SMOS satellite designed at CESBIO, see p. 20). Soil moisture governs energy exchanges with the atmosphere, particularly through its role in evapotranspiration. Its assessment and temporal monitoring are therefore important in hydrology and agronomy, particularly in ecosystems in arid and semiarid regions where this parameter is generally low, and it is a desertification early warning sign.



▲ **Variations in the spectral response of vegetation according to its physiological state.** Source: Paris 1 University e-learning.

→ FOCUS | Field observations

It is essential to collect information relevant to the subject under study—and accurately georeferenced by GPS—in order to match the data contained in satellite images with the actual field conditions on the ground. For example, a land-use map may be drawn up by image processing based on a set of ground points visually established in the field according to different classifications (forest, farmland, permanent grassland, urban area, etc.), which in turn will be used to develop the mapping treatment. The quality of the resulting map is verified by comparing the classes assigned to each of a different set of points (including the percentage of well ranked points). These points will have been viewed on the ground during the same field survey. They are therefore essential for validating products obtained by remote sensing (maps, measurements, statistics, etc.).

Accurate measurements of parameters such as the leaf-area index or the senescence of the vegetation cover are sought for some applications. Reflectance measurements obtained by instruments such as spectrometers or field spectroradiometers are then used to calibrate the satellite data according to the ground parameters. The latter device determines the reflectance curve of the target in a range of wavelengths that varies according to the model. The curves shown in the adjacent figure cover the visible to near-infrared range.

▲ **Example of a recent portable spectroradiometer (SVC HR-768si) for measuring reflectance in the visible to medium infrared range.**
With permission of the Spectra Vista Corporation (SVC), Poughkeepsie, New York.

Desertification monitored via satellite images

A wealth of satellite information can be used to assess the impact of desertification, measure and even predict its temporal changes, including extension, stabilization and regression.

Some of this information is global and encompasses the entire planet while other data can be used to zoom in to levels as tiny as a farmer's field. This information —regardless of whether it concerns green vegetation densities, temperature or moisture levels—is organized according to a geographical grid to form images. This process is exemplified by the remote sensing data applications outlined hereafter.

METEOROLOGY AND MONITORING CLIMATIC EVENTS

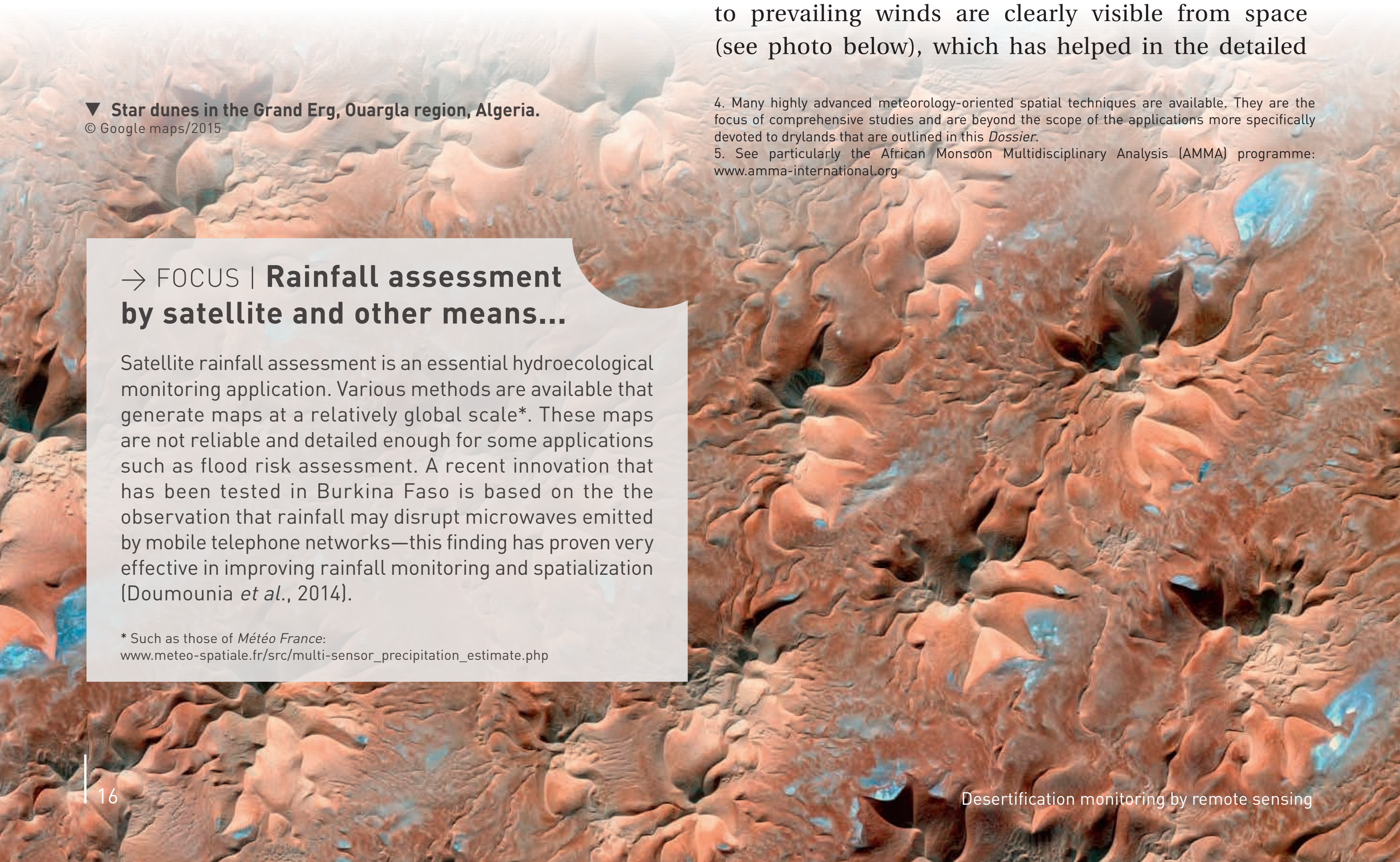
The most widely used satellite images in the world provide information on cloud, wind, moisture and surface temperature distributions on the Earth's surface (see map on next page). The resulting distribution maps are used in meteorology as they provide information for short-term (weather reports) and medium-term (weather warnings) forecasting models as well as models for studying the climate and its long-term changes[4].

This is of course also the case in dryland regions and satellite weather images are very useful for monitoring rainfall, droughts and their expansion range. For instance, recent research on the African monsoon phenomenon—which is responsible for the rainfall regime in West Africa—has galvanized the international scientific community by making a major contribution to remote sensing databases[5]. In these regions, early drought warning systems through satellite monitoring of crop production are already operational (see p. 24).

MONITORING AND UNDERSTANDING TYPICAL WIND PHENOMENA IN DRYLAND REGIONS

One striking feature of dryland regions is the prevalence of sand deposits over vast areas. The advent of satellite images has enabled observation of sand formations, ergs and large dune fields, barkhan dunes and smaller nebkas, which are easy to identify thanks to their generally high albedo (see p. 13). The typical shapes of these sand structures and their orientation in relation to prevailing winds are clearly visible from space (see photo below), which has helped in the detailed

4. Many highly advanced meteorology-oriented spatial techniques are available. They are the focus of comprehensive studies and are beyond the scope of the applications more specifically devoted to drylands that are outlined in this *Dossier*.
5. See particularly the African Monsoon Multidisciplinary Analysis (AMMA) programme: www.amma-international.org



▼ **Star dunes in the Grand Erg, Ouargla region, Algeria.**

→ FOCUS | Rainfall assessment by satellite and other means...

Satellite rainfall assessment is an essential hydroecological monitoring application. Various methods are available that generate maps at a relatively global scale*. These maps are not reliable and detailed enough for some applications such as flood risk assessment. A recent innovation that has been tested in Burkina Faso is based on the the observation that rainfall may disrupt microwaves emitted by mobile telephone networks—this finding has proven very effective in improving rainfall monitoring and spatialization (Doumounia *et al.*, 2014).

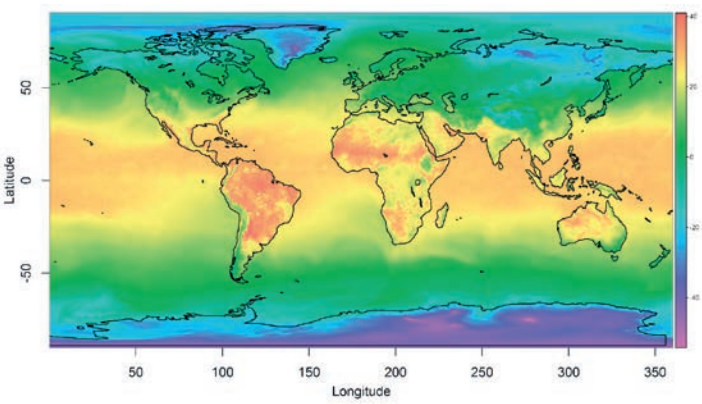
* Such as those of *Météo France*: www.meteo-spatiale.fr/src/multi-sensor_precipitation_estimate.php

mapping of these wind formations and even their (usually minor) displacement (2-3 m/year at most).

The dunes of the great Saharan ergs have thus remained relatively stationary for several thousands of years—they are not moving long distances to encroach on the Sahel, contrary to some beliefs that confuse desertification and 'desert advances' (Dia *et al.*, 2010; Escadafal *et al.*, 2011).

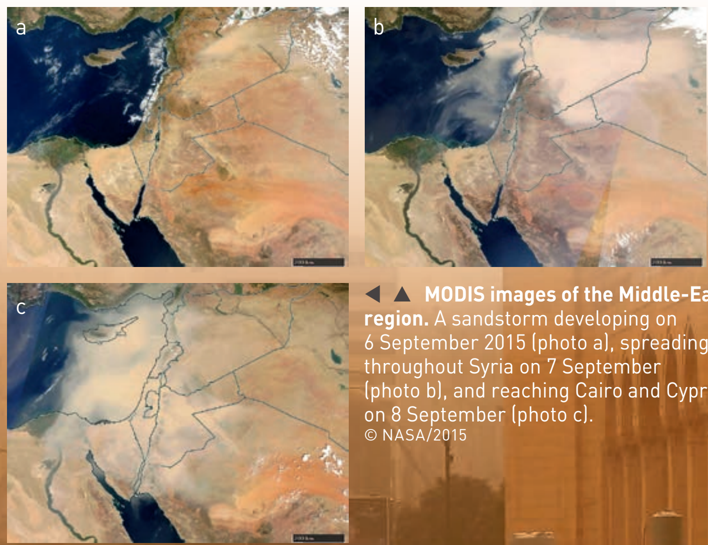
Under windy conditions, sand and dust become airborne and are carried into the atmosphere, often resulting in light to severe sandstorms—typical features of wind erosion in these regions (Mainguet & Dumay, 2011). Their onset, development and extent are hard to assess and monitor from the ground. Dusts and aerosols (particularly from the Sahara) have been studied by scientists since the 1950s because of their marked impact on the environment (e.g. on crops) but also on human health (e.g. respiratory and eye diseases), air navigation and, more generally, the climate. Recently there have been increased efforts to gain greater insight into where these dusts and aerosols come from, where they go and what they do. Satellite images quickly proved efficient in identifying and tracking sandstorms and measuring their magnitude, which is very difficult to do from the ground (see photos below).

The regions where these storms start may be identified on successive time-sequenced images, thus facilitating monitoring of the dust source areas while pinpointing the most active ones (see map on next page).

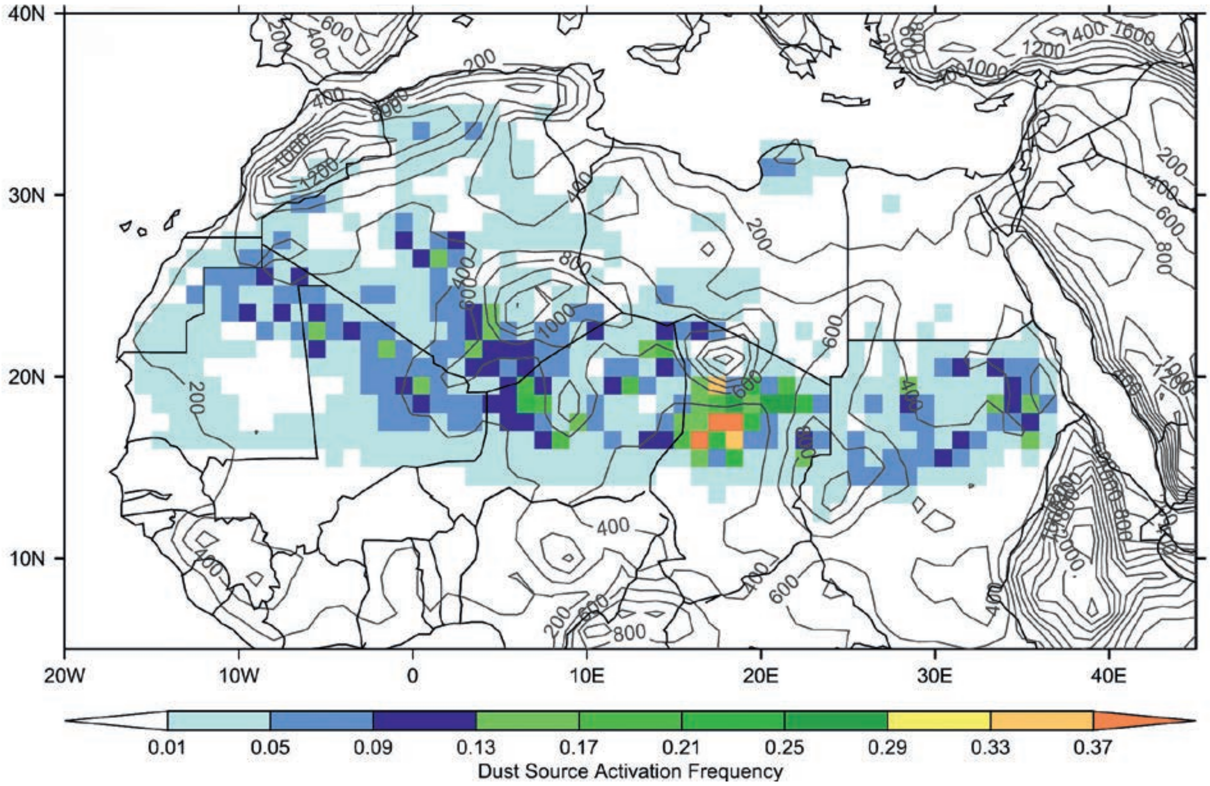


▲ **Global surface temperature map, 29 October 2014 at 18:00 GMT.**
© NOAA

▼ **Dust-laden sky over Beirut (Lebanon), 8 September 2015.**
© Hurriyet Dailynews, 2015

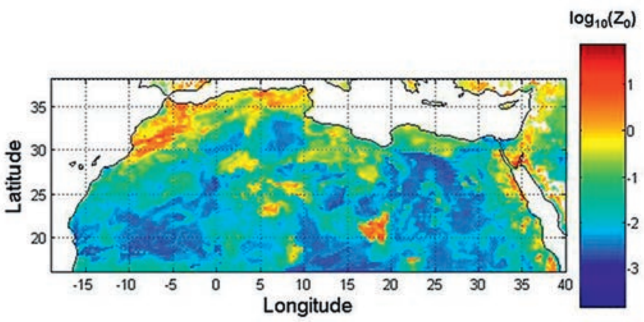


◀ ▲ **MODIS images of the Middle-East region.** A sandstorm developing on 6 September 2015 (photo a), spreading throughout Syria on 7 September (photo b), and reaching Cairo and Cyprus on 8 September (photo c).
© NASA/2015



▲ **Activation frequency of dust sources detected by the SEVIRI sensor aboard the European Meteosat 8 satellite.**
Northern Chad seems to be the most dust-producing region.
From Schepanski *et al.*, 2012.

Predicting sand and dust storms is much more complicated, however, because they form when strong dry winds blow over drylands covered with fine particles that can be carried away in large quantities by these winds. The ground wind speed, which is responsible for blowing loose sand and dust particles from the dry surface, depends of course on the weather conditions. The minimum speed (threshold) that must be reached to initiate this sand/dust lifting phenomenon depends on the soil and surface roughness. As such, modellers—who develop prediction methods—measure this roughness via satellite images (see below).



▲ **Map of aerodynamic roughness lengths at ¼° × ¼° resolution based on POLDER-1 satellite data supplemented with a geomorphological analysis of surface conditions.**
From Marticorena *et al.*, 2006.

MONITORING HIGH SOIL MOISTURE VARIATIONS

The amount of soil water available for plants is essential information to be able to understand the climate and ecology of dryland regions. Currently the most widely used tool for this purpose involves monitoring surface temperature variations in the thermal infrared domain via satellite sensors. This enables identification of situations where surface moisture is present, and such surfaces are generally colder than the surrounding environment. Conversely, when it gets warmer, if the surface is being cultivated, the crop cover will be hampered by water stress.

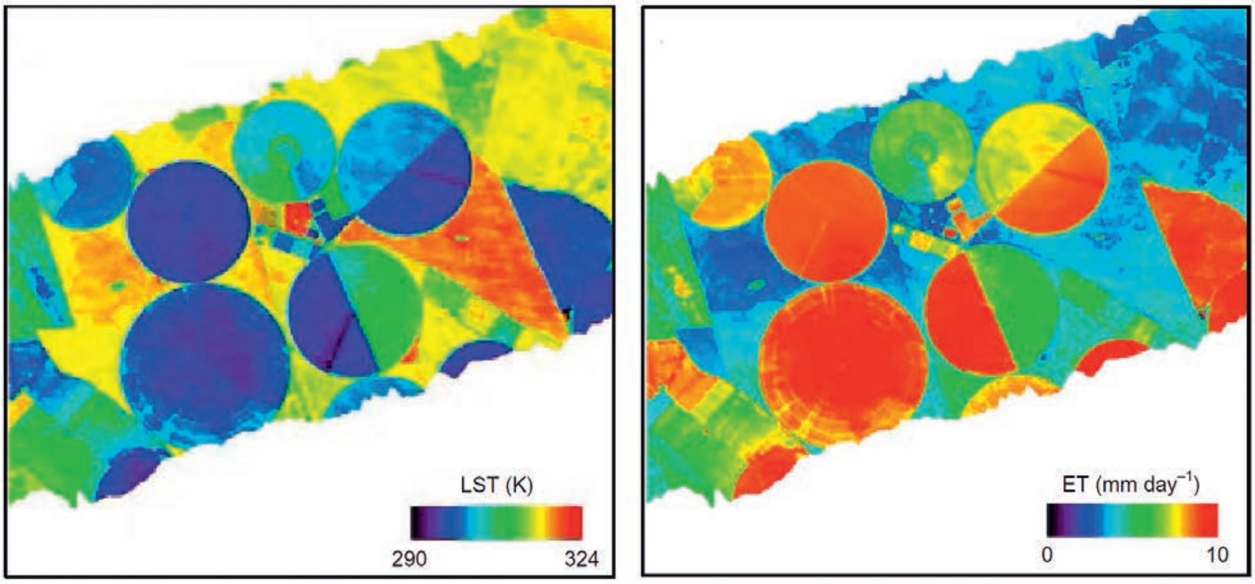
Monitoring irrigated fields

Monitoring surface temperature variations is particularly well suited to irrigated areas, as illustrated by a study of the Barrax region in Spain (see next page) using satellite data that are accurate enough to monitor individual plots (Landsat Thematic Mapper). The coldest surfaces on the left (in blue) correspond to fields that had just been irrigated using a large-scale pivot irrigation system. The corresponding daily evapotranspiration intensity (on the right) was calculated according to temperature differences between the crop and the ambient air. Naturally, the wettest fields have the highest evaporation rate.

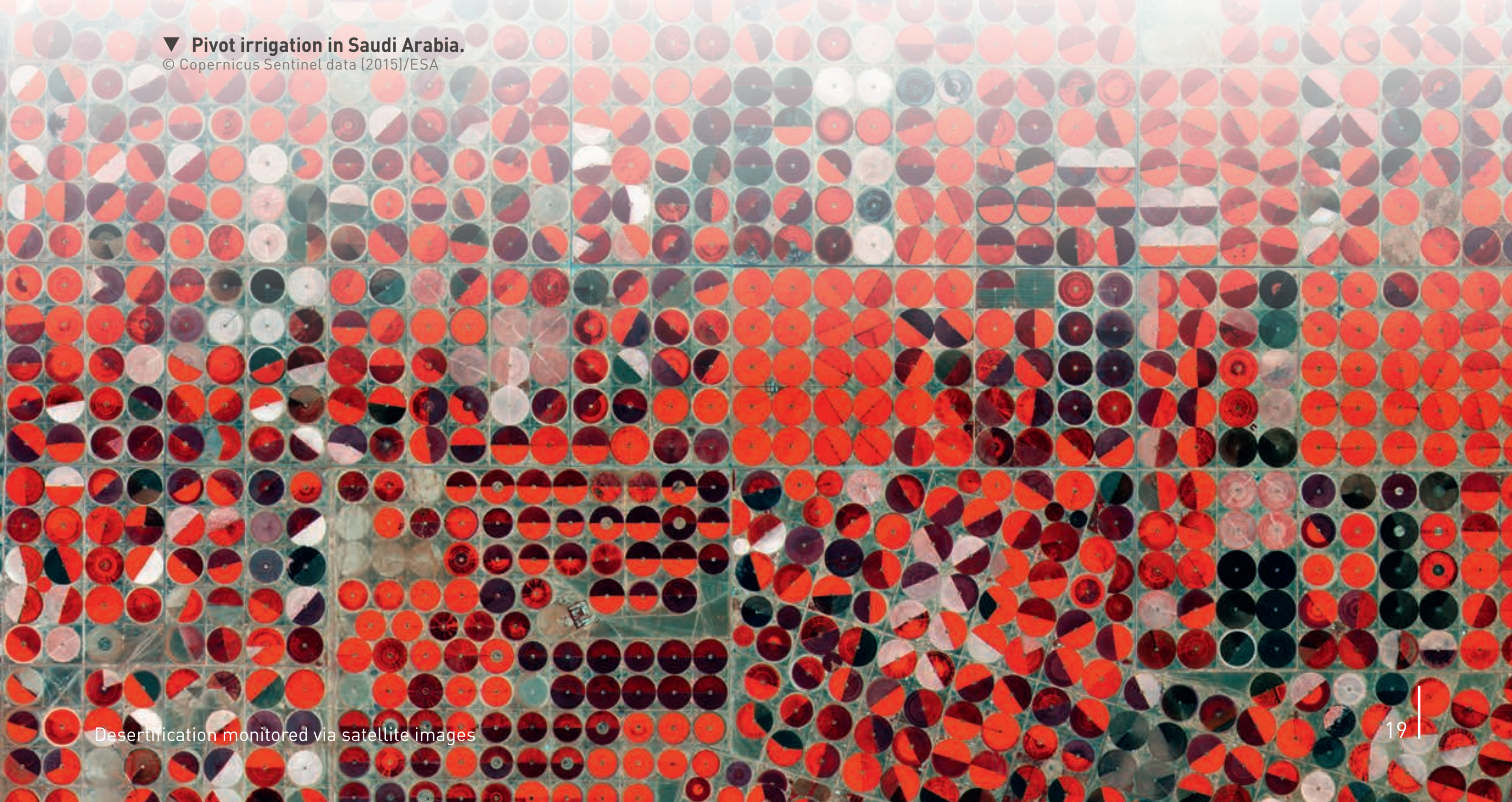
These estimates must be validated against field data from micrometeorological equipment deployed in the field. The correspondence between ground measurements and the satellite estimates can thus be verified at specific points in crop fields. Here remote sensing shows its tremendous driving force —making it possible to go from these few accurate field measurements to an actual evaporation map and thus to accurately calculate how much water is consumed at a given time in a given area.

By repeating this type of evaporation estimate over time, water consumption may be calculated over the agricultural season at the level of a field, a set of fields, an irrigated area or even a region. This information is essential for good water resource management and is particularly crucial in areas under dry climatic conditions where these resources are limited and need to be closely managed.

A recent study carried out on an irrigated area in the Marrakech region of Morocco showed that such estimates of actual crop water consumption rates are accurate enough to be compared with water quantities normally available to farmers through the irrigation network. When consumption at the field level exceeds these quantities, it means that the crop has benefited from supplementary water inputs from undeclared wells and boreholes (Chehbouni *et al.*, 2008).



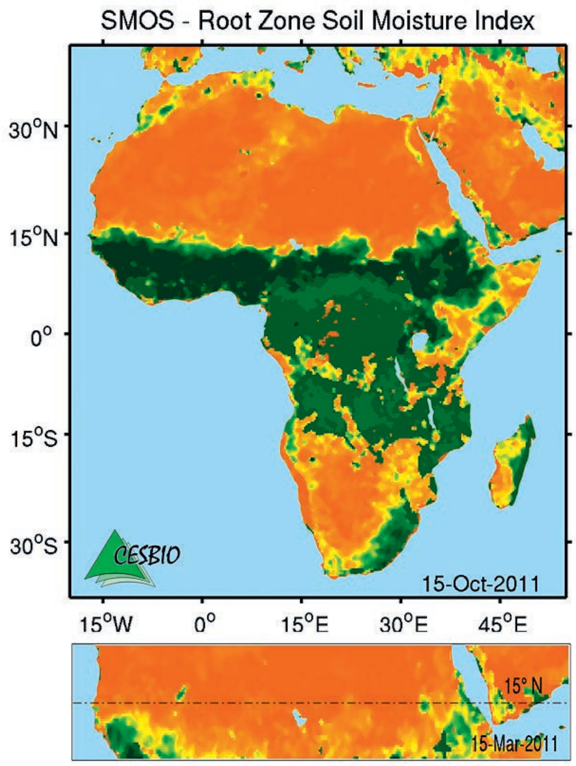
▲ **On large pivot-irrigated fields in the Barrax region of Spain, measured surface temperatures (left photo) enabled calculation of the daily evapotranspiration rate (right photo), i.e. the amount of water that the crop uses per day.**
LST (K): land surface temperature (°K)
ET: evapotranspiration (mm/day)
From Lagouarde *et al.*, 2012.



▼ **Pivot irrigation in Saudi Arabia.**
© Copernicus Sentinel data (2015)/ESA

Monitoring soil moisture on a continental scale

This estimate of the water status of cropping areas has recently been supplemented by new global passive microwave data from the SMOS (Soil Moisture Ocean Salinity) satellite that was launched in 2009. The resolution is not greater than 40 km due to the signal weakness, but the generated data nevertheless enable assessment of the soil moisture content. A moisture index in root zones was therefore developed (combining surface moisture and modelling of evaporation and water infiltration processes). The following map shows this moisture index calculated for the whole African continent from the SMOS data of October 2011. The index ranges from 0 for dry conditions to 1 for wet conditions. Note that an exceptionally harsh drought affected the Horn of Africa region during this period. The map also shows the wet conditions—normal at this time of year—in the western Sahel. For comparison, the thumbnail image below this map, which focuses on the 15° latitude N area, highlights the dry conditions in the Sahel during March while the southeastern Sudan and central Mali regions remained wet.



▲ **Map of soil moisture indices in Africa in October 2011 (1 = maximum). The resolution is around 40 km. The thumbnail image at the bottom is an excerpt for conditions in the Sahel in March 2011.**
From the CESBIO SMOS team.

For further information: www.cesbio.ups-tlse.fr/SMOS_blog/?page_id=2589
Contact: Ahmad Albitar (CESBIO), ahmad.albitar@cesbio.cnes.fr

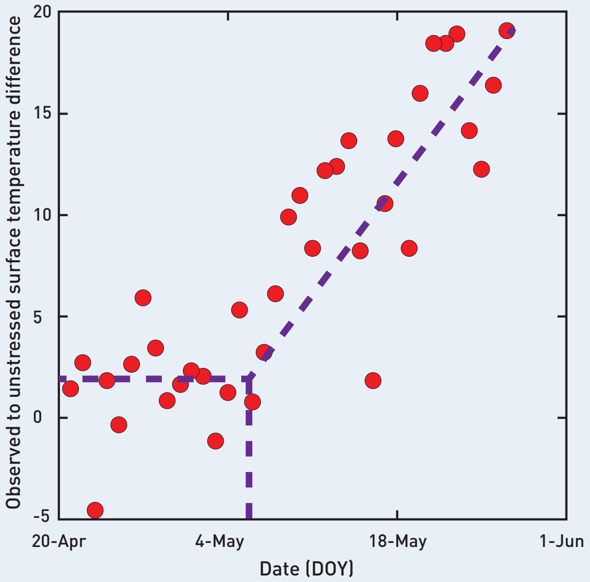
This new source of information therefore seems promising for drought monitoring and early warning, and the soil moisture data are also essential to fuel climate prediction and change models.

→ EXAMPLE | Use of satellite data combined with a wheat crop energy balance model in Morocco

An energy balance model allows—based on meteorological information gathered by ground stations and information on the extent of vegetation cover from satellite data—to calculate the theoretical surface temperature of a crop when it grows on land with a good water supply. Satellites can also measure the actual surface temperature. It is then interesting to monitor changes in the difference between these two temperatures.

The graph below shows that this difference, as measured on a wheat crop in Morocco, was stable until May 6 and then increased rapidly. The vegetation therefore became warmer than expected, which is a sign that the crop is lacking water and is therefore under water stress. This type of information can be used, for instance, to determine the right time to irrigate.

From Boulet *et al.*, 2007.



Locating deep water resources

In most drylands remote from major river basins, shallow and deep groundwater abstraction and management is essential for supplying water to people, livestock and for irrigation development. Satellite imagery applied to hydrogeology can be used with two distinct objectives, i.e. to enhance knowledge on aquifer systems based on surface conditions, and to help set up catchment structures in the most suitable areas that are often not visible at the surface.

From raw or processed images, or by combining images and digital terrain models, efforts are being made to define the structure, reservoir limits and possible links with neighbouring aquifer systems. The 'vegetation, soil moisture (see previous paragraph), geology and geomorphology' combination can be used to map an infiltration potential and thus delineate the main recharge areas where water percolates into the ground. All of these parameters are useful for calibrating and validating hydrogeological models designed to simulate and manage changes in groundwater resources.

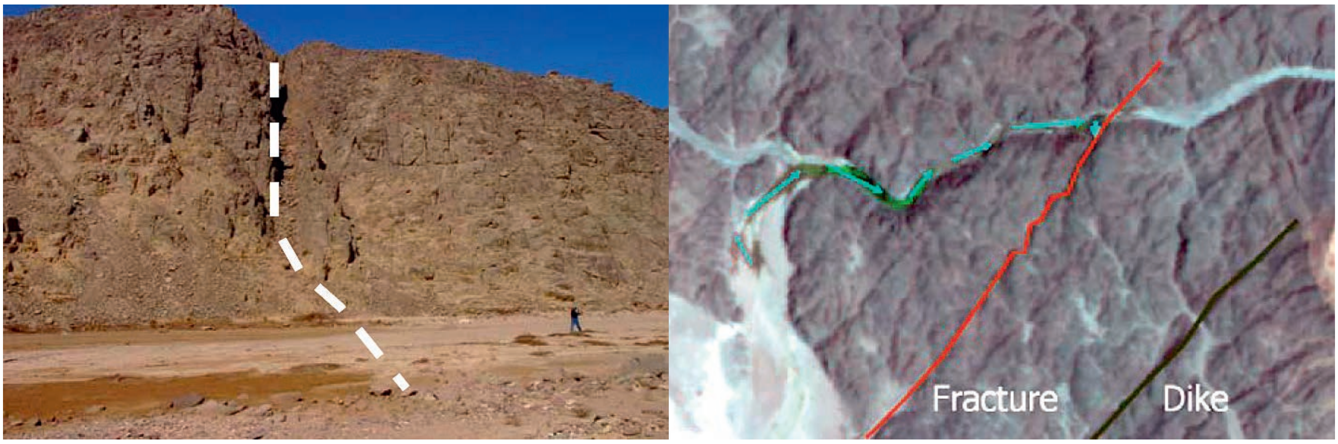
It is essential to find permanent water resources in arid areas. Two cases concerning shallow aquifers are particularly representative—the identification of fracture zones and of old watercourses buried under dunes.

Fractured and altered bedrock formations

One of the oldest uses of remote sensing in the hydrogeological field to help in the identification of fracture zones, which are useful clues for hydrogeologists to locate aquifers. This approach has, for instance, been successfully applied in Africa since the 1970s. Fractures or veins are readily recognizable in areas with exposed bedrock (see below). They can also serve as a drain or hydraulic barrier and are often suitable sites for drilling.

The approach is more complicated when the bedrock is covered with a relatively thick altered layer, as is often the case. Then alignment patterns are generally sought on the remote sensing images, even though they do not always correspond to fractures. Image processing techniques (enhancement, filters, etc.) are then used combined with statistical calculations and field validations. These discontinuities (fractures, veins, etc.) are often conducive to the alteration and thus thickening of the broken and fissured area that is favourable for groundwater storage and circulation.

More generally, this alteration zone may play a major role when there are few productive fractures, a situation that can be studied by combining image findings (visible and radar) and geomorphological expertise using digital terrain models (DTMs, i.e. 3D representations of the landscape based especially on satellite images).



▲ **Bedrock fractures: loss of stream flow due to a fracture crossing the El Mellaha wadi, Eastern Sahara (Egypt).**
There are interrupted traces of surface moisture along the fracture on the left and an area of vegetation and moisture that vanishes at the fracture observed on the right on the multispectral SPOT 5 image.
From Chorowicz & Guillande, 2009.

Buried ancient riverbeds

The first radar images acquired by the NASA Space Shuttle in 1982 over the Eastern Sahara (Egypt) revealed structures buried under the sands. Radar radiation passes through the desert sands and is reflected by the underlying rocks, sometimes revealing ancient riverbed buried under the dunes (Schaber *et al.*, 1986). This is interesting for gaining insight into the history of these landscapes while also being very useful for locating surface water bodies. Indeed, these old riverbeds, which are nowadays covered by a thick layer of very permeable sand, constitute high-quality aquifers but with very limited lateral expansion. The precise location of these aquifers may effectively help guide the installation of potential catchment structures.

This approach is illustrated in the adjacent figure, which corresponds to an overlay of two images: (1) a colour image in the visible domain showing the current sandy surface and a pivot irrigation system fed by groundwater wells, and (2) a grey radar image revealing, at depth, the meanders of an old river that justify the location of these wells.

▶ **Central pivot irrigation discs (circular irrigated areas generated by rotating central pivot irrigators) in the Saudi Arabian Desert.** An old hydrographic network buried under the sands was revealed by the overlaid radar image. © DLR TanDEM X/2010
For further information: www.dlr.de/blogs/en/desktopdefault.aspx/tabid-5919/9754_read-204/blogmonth-7/blogyear-2010

▼ **Air region. Niger.**
P. Blanchon © IRD

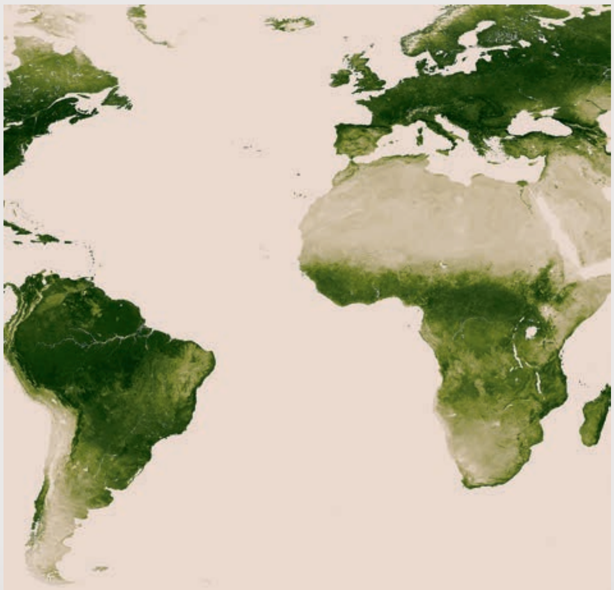
Extent of green vegetation

The most widespread application of civil remote sensing satellite imagery—apart from meteorological and climate research uses—is for vegetation index measurement and monitoring. Using the reflective properties of light from plants, this index is based on the contrast between red and near infrared reflected radiation. Various vegetation indices exist and the normalized difference vegetation index (NDVI) is the most well-known (see p. 14) and is used to produce green vegetation cover maps. In many studies based on this principle, NDVI has generally facilitated identification of areas where vegetation has developed and those where it was sparse or absent.

NDVI may be sensitive to variations in the soil spectral signature when surveying areas with low vegetation cover. Indices that disregard the soil characteristics have been proposed to overcome this disturbance (e.g. the soil-adjusted vegetation index [SAVI] and the modified soil-adjusted vegetation index [MSAVI]), but they are hard to work with because they are based on additional parameters that are not easily calibrated for vast areas.

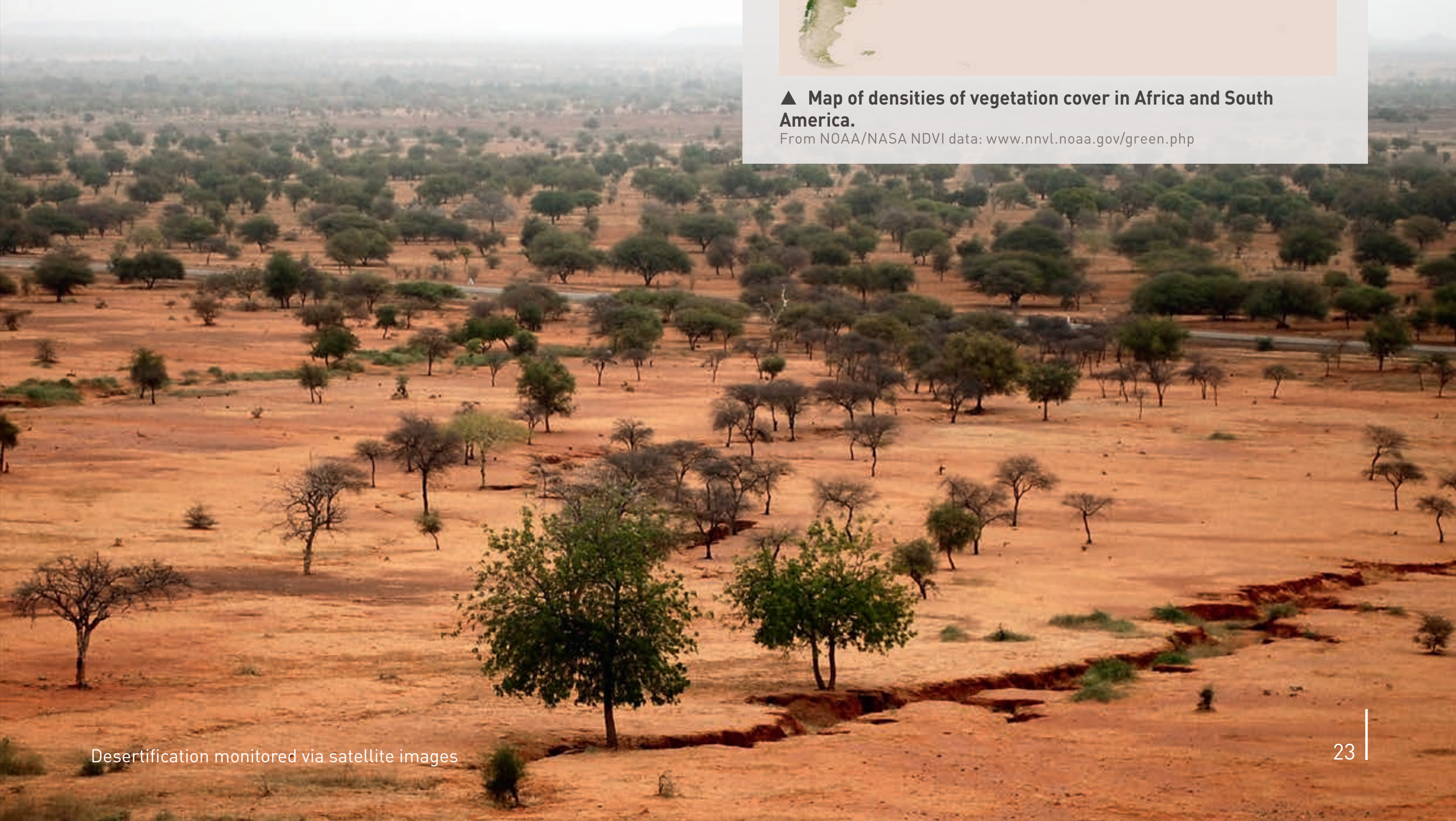
→ FOCUS | **NDVI: a desertification monitoring indicator recommended by UNCCD**

The extent of vegetation cover is an indicator for monitoring the state of desertification in terrestrial areas, as recommended by the United Nations Convention to Combat Desertification (UNCCD). However, the figure below illustrates that it is hard to distinguish between the semiarid and arid regions on the edges of the Sahara, which typically have low vegetation cover, and totally desert regions such as the large ergs and regs in the middle of the Sahara. Caution is therefore required when using NDVI, which has been shown to be more suitable for areas with greener medium-to-dense vegetation cover than for the regions of interest in this *Dossier*.



▲ **Map of densities of vegetation cover in Africa and South America.**
From NOAA/NASA NDVI data: www.nnvl.noaa.gov/green.php

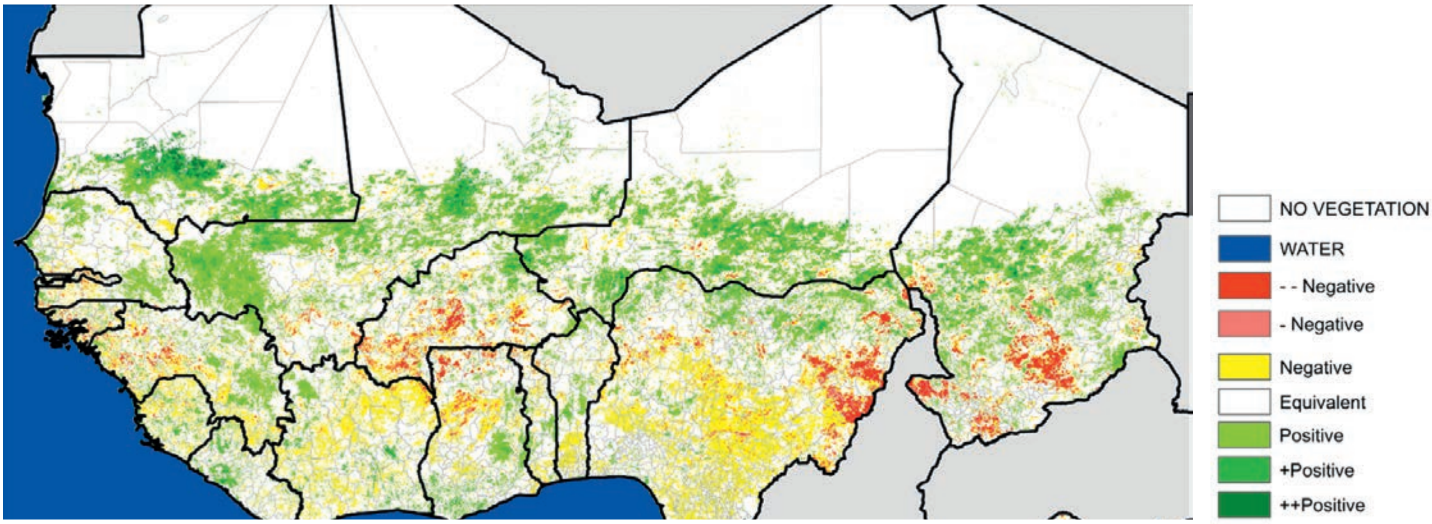
▼ **Sahelian landscape**



Short-term operational monitoring – early warning systems

Drought monitoring information is particularly important for avoiding food crisis situations and is currently one of the operational applications of satellite monitoring methods based on the vegetation index. This monitoring is carried out in Africa by regional organizations such as AGRHYMET (see p. 41) using data from NOAA-AVHRR series satellites, as well as via the Vegetation sensor aboard SPOT satellites.

In the example in the figure below, the vegetation growth pattern is monitored at regular intervals (usually 10-days) and deviations from previous year highlight areas where vegetation has grown to a greater or lesser extent than average. Alert situations arise when these more sparsely vegetated zones cover vast areas, which in turn must be monitored to determine their changes. This monitoring is complemented by meteorological data to gain further insight into the situation and analyse possible scenarios.



▲ **Standardized vegetation index for West Africa.** Colours indicate deviations from the historical average during the last 10-day period of July 2013.
Source: AGRHYMET, from Traoré *et al.*, 2014. www.sciencedirect.com/science/article/pii/S2212094714000279

▼ **Air region, Niger.**
P. Blanchon © IRD

→ EXAMPLE | Use of remote sensing for monitoring impacts of natural resource management projects

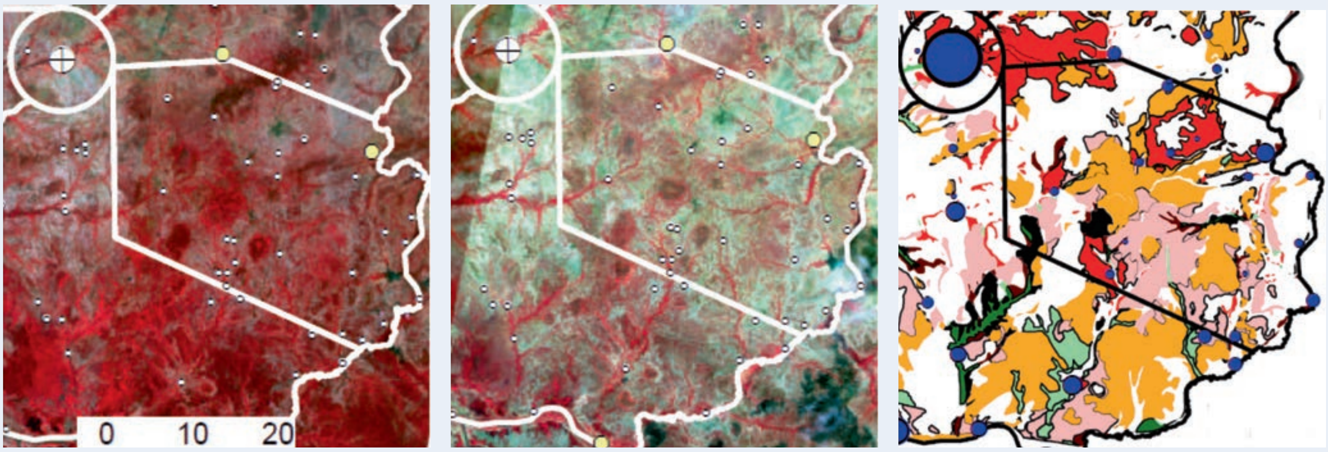
The German Corporation for International Cooperation (GIZ) has used remote sensing images to monitor the impacts of its natural resource management programmes in the Sahel based on an initial situation.

Spatiotemporal changes in vegetation cover, human settlements, tracks and ponds in southern Mauritania were monitored through a comparison of SPOT satellite images from the 1989-1999 period. This analysis of differences between satellite images over a 10-year period was used to map vegetation and rainfed crop patterns. The results of visual interpretations of the satellite images were presented in the form of detailed maps so as to monitor changes in areas where projects were under way, as well as their medium-term impacts.

The excerpt presented in the images below concerns the area east of Sélibaby (circle), the regional capital. On the change map (right) obtained from the 1989 (left) and 1999 (centre) images, an increase in degraded land (represented by colours ranging from pink to red) is illustrated, while new crops have emerged in the south (in green). The scale is in kilometres. But it should be kept in mind that it is very tricky to analyse change patterns in an area from only two images. Indeed, care must be taken to compare dates with similar rainfall levels in order to highlight variations due to changes in the environment, not just rainfall variability.

The conclusion of this analysis was that land degradation had increased by nearly 14% over the entire area, mainly due to overgrazing and tree cutting, while the annual crop cover had decreased overall. Fortunately, the limitations of this pioneering application example—where images are not taken in identical seasons thus making them hard to compare—are now being overcome thanks to the increasing availability of images.

For further information: Kußerow *et al.*, 2002, in the framework of the *Atlas du Guidimakha* (GTZ/ECO – IRAM).



Monitoring and understanding medium- and long-term fluctuations

Vegetation index maps can be produced regularly for large areas using images from the different series of satellites that have been continuously orbiting the Earth for nearly 40 years (see p. 4). This is essential in dry areas where seasonal variations in vegetation occur (as in temperate environments), but above all where there is high interannual variability. Only analyses spanning several decades—combining field data, rainfall and the NDVI index—can efficiently highlight environmental degradation or enhancement, which is not a temporary trend. This approach has been applied especially in the African Sahel, sometimes with contradictory results between studies. Changes observed from space can only be understood by correlating the findings with field data and measurements.

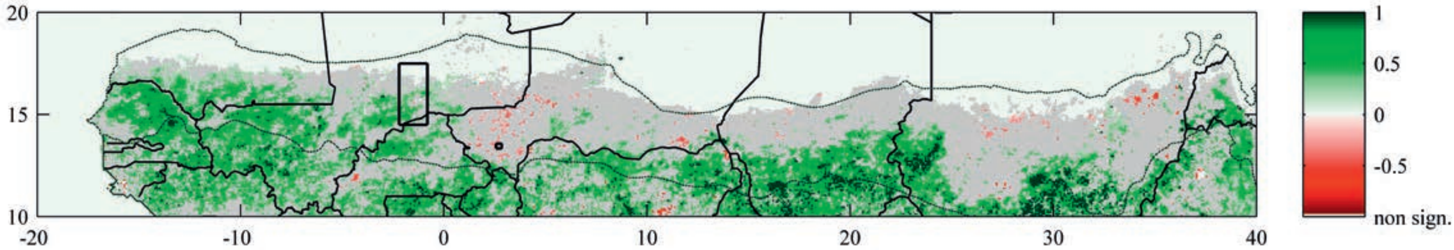
Indeed, satellite images alone do not facilitate decision making. Linking satellite measurements with the actual situation on the ground is a key challenge. Indeed, the satellites used in this case had a 9 x 9 km spatial resolution, and it is generally hard to obtain a field vegetation measurements covering the same area at the time of the satellite pass. Moreover, the atmosphere is not always transparent—with the presence of clouds and dust—which complicates correlation of the spatial and ground measurements.

In a recent study, the ground vegetation cover rate was compared with the satellite vegetation index at two reference sites: one in Gourma in Mali and the other in the Fakara region of Niger (Dardel *et al.*, 2014). This comparison concerned the 1981-2011 period and was based on a field measurement system that was operational at these sites throughout most of the study period (see photographs below).

To contextualize this study, the map below shows the results regarding variations in the vegetation index over the 1981-2011 period for the entire Sahelian region. It clearly illustrates the regreening phenomenon under way in this region, as shown by the high proportion of green in this region on the image, so over the 30 year period taken into account there was an average trend towards an increase in the vegetation index. There is therefore an overall regreening trend throughout the Sahel, indicating that no desertification has taken place. Experts agree that this regreening is mainly due to an increase in average rainfall over this period.

There were nevertheless disparities, so the two sites studied here had different fates. Most of the vegetation cover consisted of annual plants, on average increasing in Mali while decreasing in Niger. In both cases, the satellite measurements were confirmed by field observations. However, the findings of previous studies were sometimes contradictory.

▲ **Measuring the extent of vegetation cover on sandy soils at the Louguéré Kilouki dune site in northern Mali.**
Left: dry season.
Right: rainy season.
© P. Hiernaux



▲ **Mean changes in the satellite vegetation index (NDVI GIMMS-3) over the 1981-2011 period.**
Red: decline in vegetation cover.
Green: increased vegetation.
Grey: no clear trend.
From Dardel *et al.*, 2014.

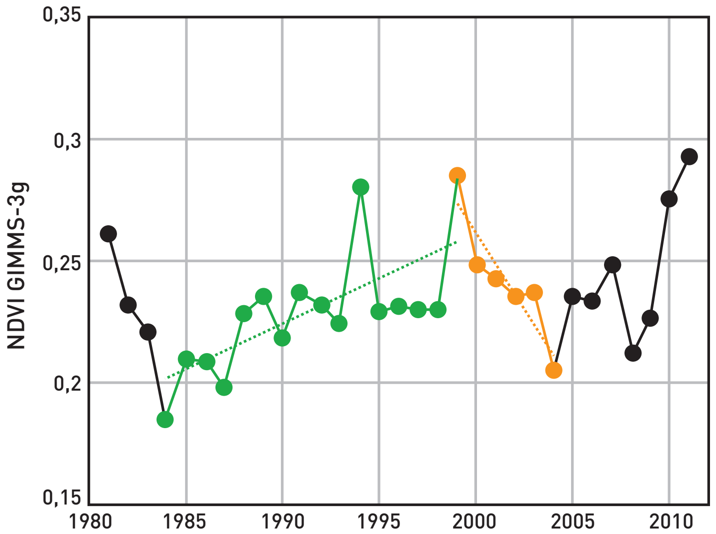
The adjacent graph provides an explanation for this —the conclusions differ markedly depending on the period considered. This graph shows the importance of the period considered to highlight trends. Over the 1984-1999 period, the conclusion is that the vegetation regenerated, whereas on the contrary over the 1999-2004 period the vegetation cover appears to have degraded.

This satellite image time series enables monitoring of vegetation cover and detection of trends, but appropriate field observations are needed for validation, while being very careful in their interpretation. Moreover, given the high interannual variability in the vegetation cover—linked particular to the rainfall variations—it is hard to reveal patterns between two arbitrarily chosen years. Time-series data are much more effective in documenting this variability and in calculating trends, as shown in the figure below. Statistical methods for detecting breaks in time series also enable identification of pivotal periods.

→ FOCUS | **What vegetation index should be used for dry periods?**

NDVI is the most widely used vegetation index, particularly because it can be calculated from all kinds of image. All that is required is data in the red and infrared spectral bands (see p. 8). However, many other indices have been proposed that combine more spectral bands through a more elaborate process. As the vegetation in dry regions is often not green, specific indices such as the soil tillage index have been tested. This simple ratio between two mid-infrared bands has proven effective in estimating the abundance of herbaceous straw and litter in the Sahel during the dry season.

From Jacques *et al.*, 2014.



▲ **A vegetation index time series (NDVI GIMMS-3g) for the 1981-2011 period, Gourma region in Mali.**
From Dardel *et al.*, 2014.

▼ **Gourma region, Mali.** Sandstone *'doigts de fiancée'*. A 'Far West' landscape, where highest mountains of Mali stand like sentinels of the Sahel.
J.-C. Leprun © IRD

Assessing land degradation by long-term monitoring of land productivity dynamics

It is generally recognized that long-term variations in land cover clearly reflect land productivity trends. The frequency of vegetation monitored over long periods is a good indicator of changing ecological or production conditions—soil fertility, water supply and land use. It is therefore a measure of the response of ecosystems to external impacts, whether induced by human activity or due to natural variability, while also providing information on land degradation. Indeed, the reduction or loss of productivity—mainly biological and/or economic—is a common feature in the different definitions of land degradation. Land productivity is therefore essential information for monitoring land degradation.

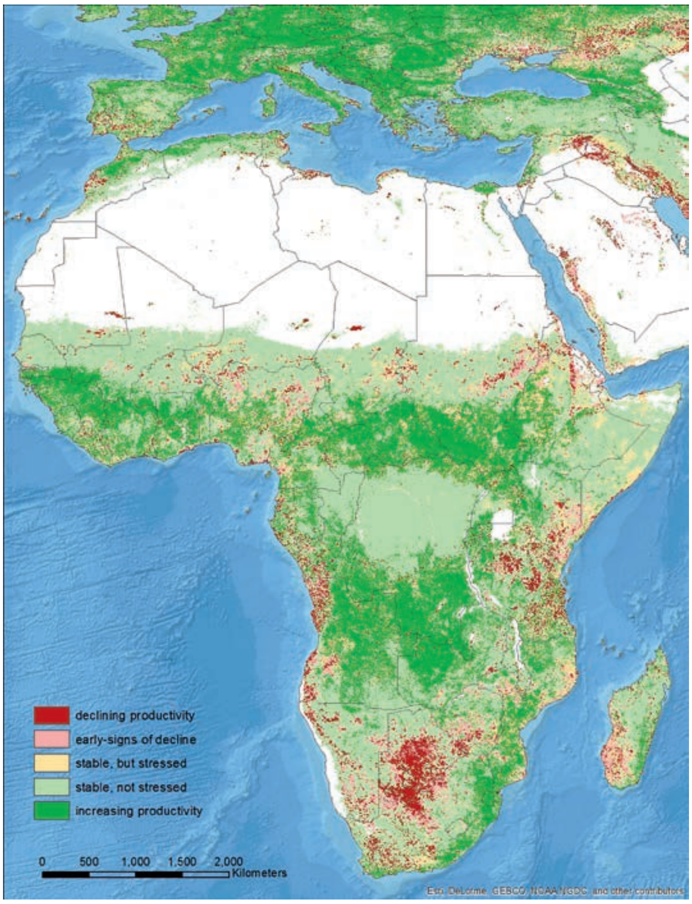
In the case presented here, time-series images were used to determine the overall NDVIs over the 1999-2013 period[6]. For each image pixel, the biomass measurement—which was integrated over a season—was compared to the normally expected production level (compared to the pixels of similar ecosystems).

The biomass productivity dynamics map produced for Africa (see next page) shows five classes of production variation (ranked from increasing to decreasing). It is an indicator of apparent changes in the capacity of land to maintain primary production over the 15 year monitoring period.

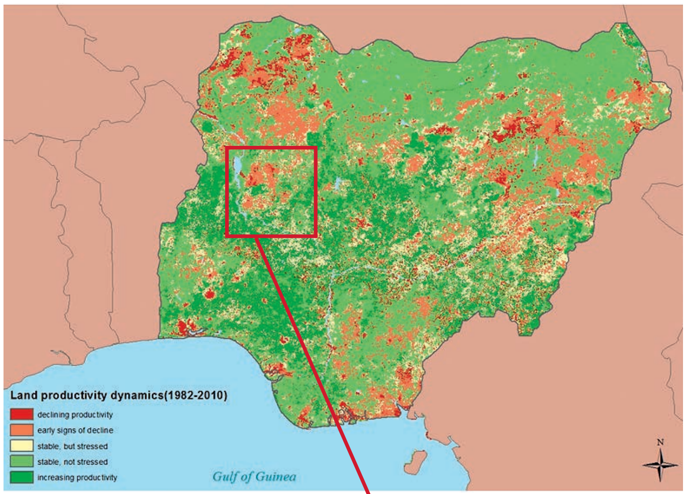
This information could then be analysed in more detail against available local data on observed environmental changes and their potential causes, such as overuse of agricultural land (see the Nigerian example on the next page). Consistent evidence then facilitates assessment and mapping of ongoing land degradation. Several combined stress factors often hamper sustainable land use in areas where the vegetation productivity dynamics are declining. These stress factors may be natural (e.g. drought) or human-induced (e.g. land impoverishment due to overly demanding crops). Areas impacted in this way should be considered for further analysis.

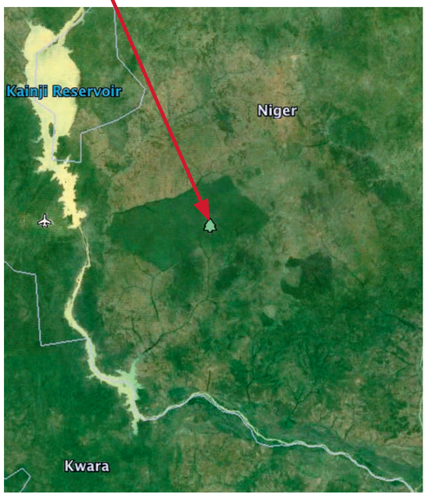
6.Time-series NDVI data from SPOT VGT images processed by the European Commission Joint Research Center, in collaboration with the experts and institutes involved in compiling the new World Atlas of Desertification: http://wad.jrc.ec.europa.eu

▼ **A rural landscape in South Africa.** Grazed pastureland in the Drakensberg foothills region on acidic sandy soils. This landscape shows, on the right, that smallholder farmers with traditional Zulu huts are using the land. There are signs of degradation (mid-slope) following the dismantling of terraces. On the left, a natural meadow has been colonized by shrub species, probably due to the fact that burning is less systematically used for controlling invasive species and/or to the northern exposure, which leads to a higher warming rate favourable for shrub species such as acacia. A ravine developing within the colluvium may be seen in the foreground.
V. Chaplot © IRD



▲ **Map of productivity dynamics in Africa, 1985-2010.**
The five classes indicate areas of stability, growth or decline. These results were obtained by processing a series of SPOT VEGETATION NDVI images, 1999-2013. From Cherlet *et al.*, 2015.





▲ **Interpreting variations – an example in Nigeria.**
Kainji Dam in Nigeria has enabled expansion of cropland around the Dagida Wildlife Reserve (green area on the map above, indicating long-term productivity stability). The map suggests that the capacity of land to sustain this cropland expansion is declining, while highlighting the need for further analysis to identify possible causes and whether these factors are actually spurring land degradation.
From Cherlet *et al.*, 2015.

Land-use changes are often the most striking environmental changes and are fairly easy to detect by remote sensing (see next page). This trend may be noted when, for instance, tree or shrub (bush) stands are cleared for cultivation. This land-use change —which results in changes in vegetation cover— obviously has impacts on food (increased agricultural production) and supplies of fuelwood (which is becoming increasingly scarce), etc. Moreover, the water cycle is generally also impacted—increased runoff, gully deepening and pond filling.

Burnt areas (slash-and-burn cultivation, bush fires) are land-use changes that are highly visible on satellite images. The contribution of fires to the global carbon cycle has also been demonstrated.

→ FOCUS | **Detecting and surveying forest and bush fires**

Fires are an important environmental management component, particularly in Africa and Asia where they are part of cultural practices.

Using MODIS (Moderate Resolution Imaging Spectroradiometer) images available in near-real time (within hours post-acquisition), NASA has developed a fire warning and information programme that aims to achieve global reach: the Fire Information for Resource Management System (FIRMS) programme, relayed by the Food and Agriculture Organization of the United Nations (FAO).

For further information:
https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms

▼ Cleared field in in a dry forest area near Odienné, Côte d'Ivoire.
C. Lévêque © IRD

→ EXAMPLE | **Land-use changes along a tributary on the right bank of the Niger River in the Sahelian region**

A sharp increase in the flow coefficient of tributaries along the right bank of the Niger River occurred during the severe drought period in the Sahel. This phenomenon was also observed in all monitored basins in the Sahel region. Jean Albergel (1986) had already reported this situation in experimental watersheds in Burkina Faso. This has been called the 'Sahelian hydrological paradox' (see below) as a follow up to the *Analyse Multidisciplinaire de la Mousson Africaine* (AMMA) programme.

The maps on the right were produced by photo-interpretation from CORONA images (1965, top) and SPOT scenes on Google Earth (2010, bottom). They show the extent of land-use change between the two dates in the Dargol Basin, i.e. a tributary along the right bank of the Niger River (Burkina Faso, Niger), with a catchment area of 7,000 km².

The adjacent graph also shows the very sharp increase —between these two dates—in the flow coefficients of the three Sahelian tributaries along the right bank of the Niger River, i.e. the coefficients quadrupled in 50 years, while the flows more than tripled. The processes involved are of variable spatiotemporal scales, and should be carefully explained, since cropping at the regional scale appears to correspond to a very substantial increase in runoff, while at a very local scale, weeded fields are places with the highest water infiltration. Local soil crusting—although very sandy—explains this process and the very high degree of flooding caused.

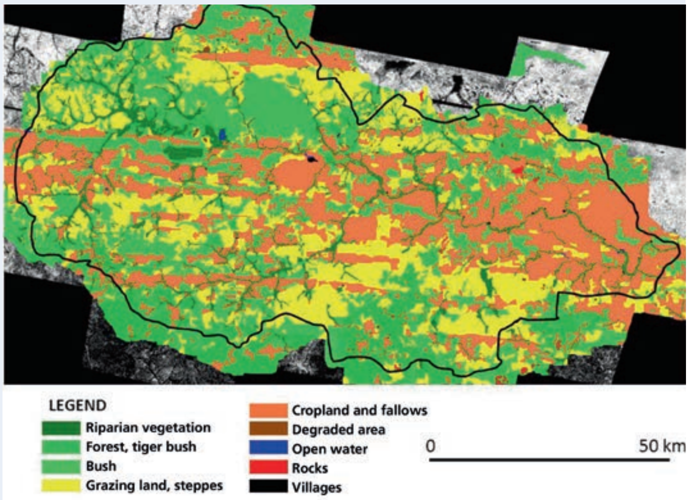
For further information: Descroix *et al.*, 2012; Descroix, 2018.

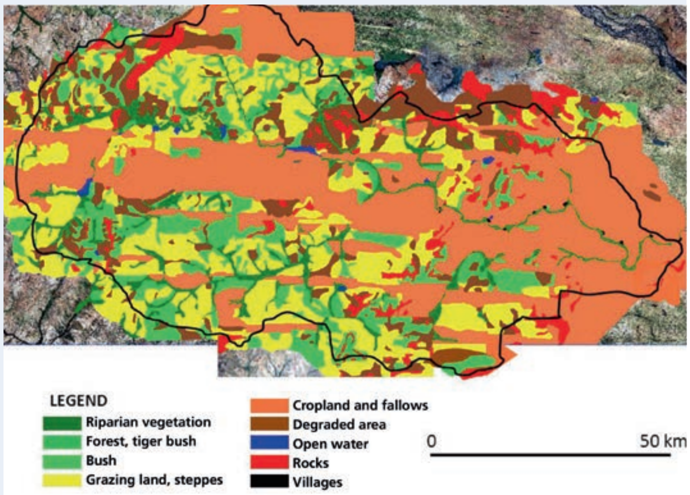
The Sahelian paradox

Since the 1950s, hydrologists have documented an increase in runoff coefficients in many parts of the Sahel. One of the consequences of this phenomenon is that, despite the low rainfall during the 1970-2010 period, the amount of water in ponds and rivers has increased—this is called the 'Sahelian paradox'. This paradox is in apparent contradiction with the regreening of the Sahel, since the decrease in vegetation cover is the hypothesis generally put forward to explain the increase in erosion and therefore runoff on the resulting degraded surfaces.

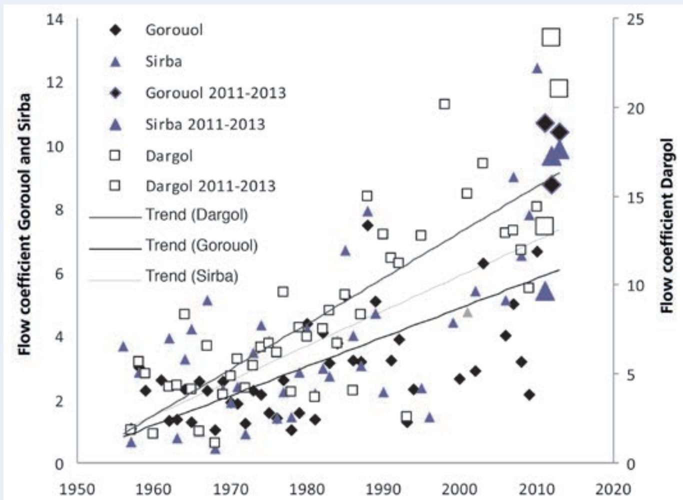
These two theories can be reconciled by analysing field data from the Gourma region in Mali. Indeed, it can be hypothesized that degradation affecting only a small part of the landscape, such as some surface soils, may be responsible for increasing runoff coefficients, while the overall signal indicates that regreening is under way in the Gourma region.

For further information: Dardel *et al.*, 2014.





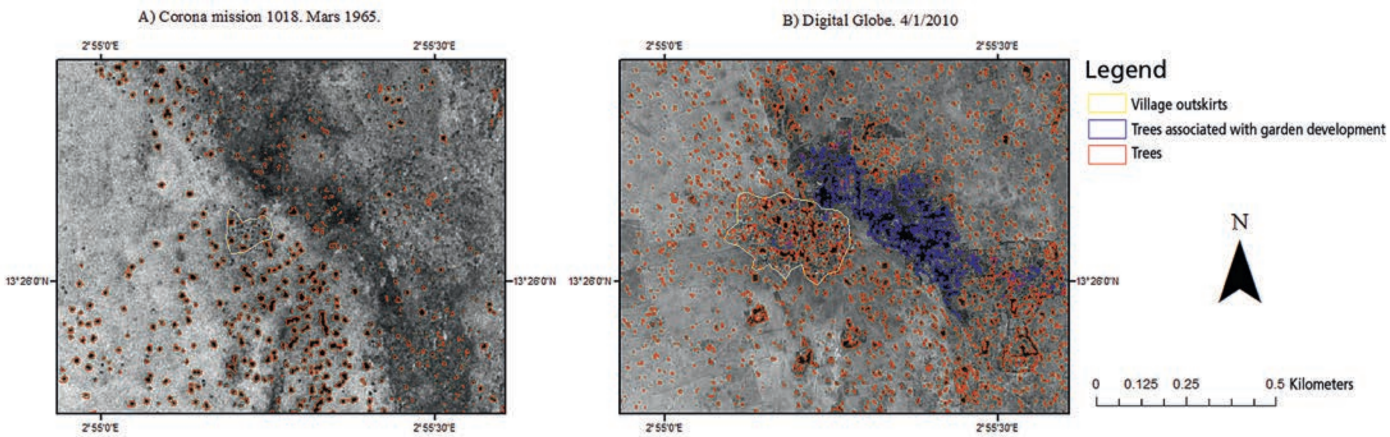
▲ **Land-use changes between 1965 and 2010 in the Dargol Basin (Burkina Faso, Niger).** From Descroix, 2018.



▲ **Variations in flow coefficients of three Sahelian tributaries along the right bank of the Niger River.** From Descroix, 2018.

Remote sensing imagery from the latest satellites is increasingly detailed and—like aerial photos—the very high resolution images produced makes it easier to identify specific objects in landscapes shaped by human activities, e.g. fields with hedges, trees and plantations, roads and infrastructure, dwellings and their extension patterns. Online mapping sites such as Google Maps for the whole world or the *Geoportail* for France use this type of image (see p. 40).

Access to declassified very high resolution photographs taken by military satellites in the 1960s enables comparisons with images from present-day civilian satellites of comparable resolution. Several studies have taken advantage of this opportunity to examine changes in agricultural landscapes in Sahelian Africa. In southern Niger, for instance, increased human pressure has clearly had a significant impact on the environment, within only two generations. This generally involves an extension of land clearing, a decrease in bush stand density in flatland areas (so-called 'tiger bush'). The expansion of villages and the development of gardens may also be noted, as reflected in the example of the village of Zindarou, by an increase in the number of trees—and therefore vegetation cover—around the village (see images below). This information on land-use trends is essential for analysing and gaining insight into environment-society relationships, etc.



▲ **Changes in the vegetation patterns around the village of Zindarou in southern Niger between 1965 and 2010.**
From San Emeterio *et al.*, 2013.

▼ **A typical flatland tiger bush area around Sofia Bangou Pond near the village of Banizoumbou, 60 km east of Niamey, Niger.**
J. Asseline © IRD

The advent of civil drones heralds the dawn of 'personal remote sensing'

While many recently launched commercial satellites produce increasingly detailed images (less than 1 m resolution), the development of unmanned aerial vehicle (UAV) systems (or so-called 'drones'[7] has added a new personal dimension to remote sensing, similar to how the advent of personal computers revolutionized the computer field.

This broad field—which derives from military applications—is expanding rapidly with the emergence of simpler and cheaper civilian models, while the cheaper models serve more as gadgets or hobby applications. All of these tiny aircraft can be used to take photographic and/or video images at low altitude, or even very close to the ground. Moreover, the image features depend mainly on the type of onboard camera, the stabilization of the platform and the navigation system. The great advantage over today's best satellites is that centimetre spatial resolutions are available, which is very interesting for monitoring ground surface conditions.

▲ **A drone with an onboard camera in flight.**
©2015 Hootsuite Media Inc.

This new and expanding field has applications devoted to scientific monitoring of arid environments. For example, kite-borne imaging was first attempted in Tunisia in 1984 (Escadafal, 1989), and the technique is now used to develop digital landscape models for erosion monitoring (Feurer *et al.*, 2012). This kite technology is also available in a motorized delta wing version (IRD Pixy drone). More recently, very high resolution images obtained from a modern drone were used in Morocco to map agricultural land impacted by erosion (see adjacent image). The complex geometry problems associated with these views taken at highly variable angles have now been solved by the use of very powerful software tools that are able to geometrically correct and 'mosaic' the series of quasi-automatically acquired images.

Note that operational airborne video applications have been developed since the late 1990s for monitoring refugee camps (e.g. Kenya, Cambresy & Souris, 2000), and there has also been a boom in applications for humanitarian and emergency purposes.

Observation and aerial mapping resources are thus now accessible to individuals and small groups to meet immediate local needs (e.g. for media reporting[8]). This form of 'personal remote sensing' is likely to develop as a tool for monitoring/assessing desertification control actions.

▲ **Digital drone image showing traces of recent erosion around La Glalcha village, Souss region, Morocco.**
From Oleire-Oltmanns *et al.*, 2012.
For further information: Irène Marzolff, 2011 / http://imaggeo.egu.eu/view/738

7. But the name 'drone' makes most people suspicious of these aircraft because of the poor reputation of military drones.
8. www.africanskycam.com

→ FOCUS | **The right to view others from the sky**

Increasingly sophisticated and invasive technological devices that provide operators with close-up views without being in close proximity to the target is in derogation of civil laws to protect property owners from the intrusive view of neighbours on their property. New legal measures have emerged to overcome this issue, and the most documented cases are currently in developed countries, but everyone is concerned.

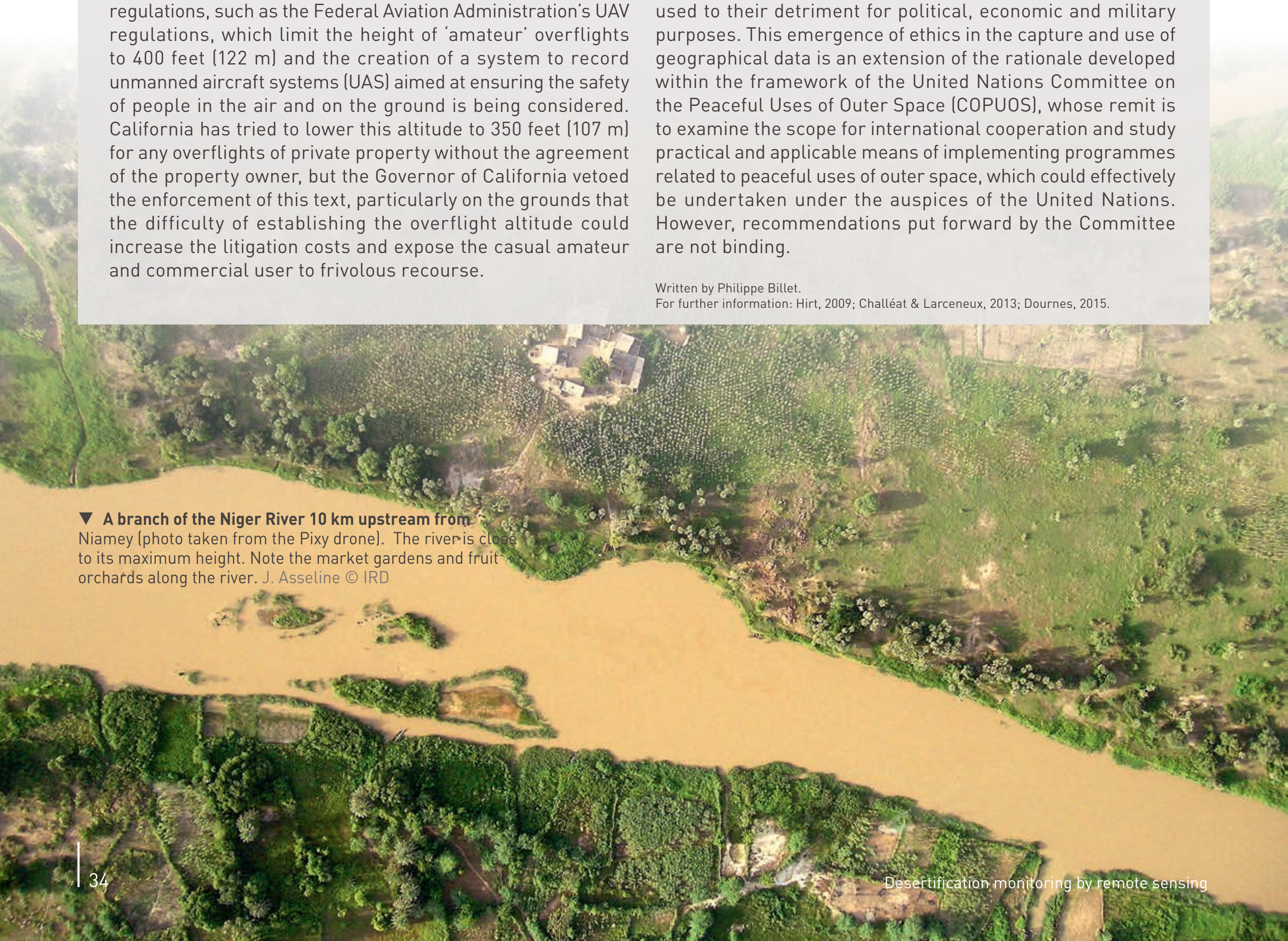
For example, the online Google Street View service—which provides images of streets and places where people, vehicles, yards and gardens are partially visible—has been found to violate privacy rights despite software applications that blur personal features, since personal data (people and vehicle license plates) and distinctive signs in the vicinity of sensitive institutions such as schools, hospitals, retirement homes, courts and prisons are not completely anonymized (*Trib. Féd. Lausanne, 31 May 2012, Case n° 1C_230/2011, Google Inc*).

Legal issues of a completely different nature arise when the observation point is high above the target. Beyond the problem of image rights on one's property and usage, access to sensitive data (location and configuration of a military building, a nuclear power plant, etc.) warrants restrictions. Unless a specific derogation specifying the use that may be made of photographic images and digital recordings has been issued, the French Civil Aviation Code prohibits «aerial photography by camera, film or any other sensor zones listed by interministerial decree» (Article D. 133-10., the list defined in the annex to the decree of 15 May 2007 is classified as *Défense Confidentiel*). This concerns drones as well as any other aircraft (paragliders, etc.). Other countries, such as the United States have specific regulations, such as the Federal Aviation Administration's UAV regulations, which limit the height of 'amateur' overflights to 400 feet (122 m) and the creation of a system to record unmanned aircraft systems (UAS) aimed at ensuring the safety of people in the air and on the ground is being considered. California has tried to lower this altitude to 350 feet (107 m) for any overflights of private property without the agreement of the property owner, but the Governor of California vetoed the enforcement of this text, particularly on the grounds that the difficulty of establishing the overflight altitude could increase the litigation costs and expose the casual amateur and commercial user to frivolous recourse.

Image blurring—whereby information in an image is deliberately obscured—varies according to the type of data to be protected. Yet paradoxically this intervention places a spotlight on the importance of the site, which would otherwise likely be overlooked. Disclosure is therefore necessary for privacy protection of the site, without which no criminal sanctions would be possible, since a breach of secrecy offense (national defence, etc.) is only committed if the site is officially protected in this respect. This raises the delicate question of the dissemination of aerial and satellite images which are beyond the jurisdiction of the overflown States. It is only once on the ground that the images are punishable, provided that their marketing, possession or interpretation are identified, which is almost impossible due to the widespread access to online information. However, most of the data is not subject to this prohibitive common law regime, but may be officially disseminated when it is of public origin, particularly under the INSPIRE orthoimaging directive (dir. No. 2007/2/EC of 14 March 2007 establishing an infrastructure for spatial information in the European Community) or the national so-called 'Geoportal' systems set up by many States.

However, this data "communitization" does not give such data the status of common things, which are not owned and anyone can use them. This situation sheds light on the attitude of some indigenous communities, which criticize the tendency of Western States to be involved in geopiracy, whereby geographical information about their area is collected and used without the consent of the communities, and their areas are often even set within boundaries that do not have any historical reality for the community, while geographical information is used to their detriment for political, economic and military purposes. This emergence of ethics in the capture and use of geographical data is an extension of the rationale developed within the framework of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), whose remit is to examine the scope for international cooperation and study practical and applicable means of implementing programmes related to peaceful uses of outer space, which could effectively be undertaken under the auspices of the United Nations. However, recommendations put forward by the Committee are not binding.

Written by Philippe Billet.
For further information: Hirt, 2009; Challéat & Larceneux, 2013; Dournes, 2015.



▼ **A branch of the Niger River 10 km upstream from** Niamey (photo taken from the Pixy drone). The river is close to its maximum height. Note the market gardens and fruit orchards along the river. J. Asseline © IRD

▲ **Photo taken from the Pixy drone: village of the Zulu community of Posthini, crossed by a deep ravine, KwaZulu Natal region, South Africa.**
J.-L. Janeau © IRD

Towards widespread and accessible use of satellite images?

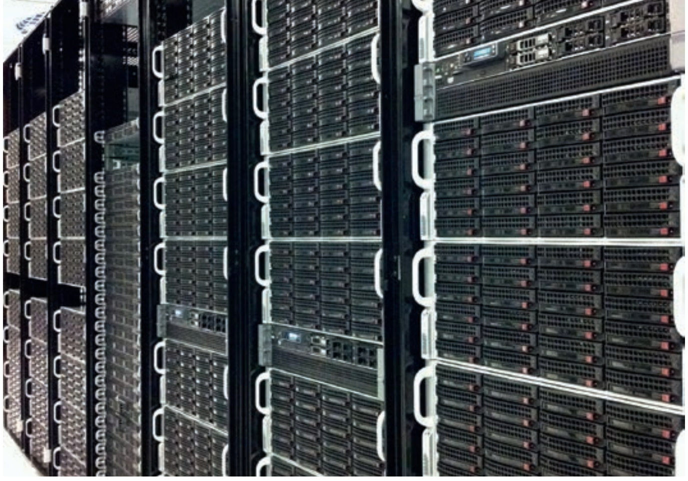
The great advantage of satellites is that they collect data—generally in the form of images—spanning the entire Earth's surface, including the most remote and inaccessible locations. They are cost-effective and images may be obtained repeatedly over time, which makes it possible to measure changes and evolutionary patterns. While these measurements obviously need to be validated by spot checks on the ground, it clearly would be impossible to carry out such exhaustive surface monitoring solely through field surveys.

▲ **A rural scene in an argan tree stand. Southern Morocco.**
G. Michon © IRD

The amount of satellite information transmitted to receiving stations is increasing daily and reaching staggering volumes. For example, Sentinel satellites —which Europe is deploying as part of the Copernicus programme—will alone produce 4 terabytes of image data per day! (see Focus on next page).

One current challenge is to make effective use of this digital manna from heaven, while making it usable and useful for those who need it. This is a real challenge and a source of great hope in technically underdeveloped dryland regions. Indeed, the many currently available applications (including those mentioned in this *Dossier*) highlight that remote sensing can be a major asset in meeting the challenges of these regions, not to mention the ever-increasing number and diversity of ongoing developments.

Satellite remote sensing, combined with ground measurement networks and various types of modelling, has now emerged as a powerful operational and readily applicable tool to provide information on desertification and its dynamics.



▲ ***Johns Hopkins University Data Center.***
Courtesy of Flickr user.

This is the result of three parallel advances:
- **A triple technological revolution:** (1) the industrial space technology revolution has prompted the building and launching of increasingly cost-effective efficient environmental observation satellites, while enabling users to receive and process raw satellite data into a usable form; (2) the Internet revolution has led to the rapid widespread proliferation of high-speed communications and their public and private uses, thus facilitating massive streamlined exchanges of digital information while ensuring the widest possible public access to this data; and (3) the information revolution has fostered the development of huge databases and facilitated access to powerful information processing tools, including those on mobile terminals (tablets, smartphones, etc.).
- **A scientific revolution and applications, with:** (1) the development and improvement of valid models to develop relevant indicators through the 'assimilation' of satellite and ground data, and (2) the operational implementation of these models in centres that use both satellite and ground-based measurement data, such as weather forecasting models, crop forecasting models, forest fire risk and propagation models, etc.
- **A revolution in public and private awareness** that takes into account the importance of environmental issues, at local to global levels, as reflected in the United Nations Convention to Combat Desertification with regard to drylands.

Major private operators managing 'big data' (including Google, of course) have emerged as new players in this global environmental monitoring field, but the use of field knowledge and the participation of end users of these observation data is still a major challenge. Meeting this challenge will surely be facilitated by the emergence of so-called 'personal remote sensing' based on the use of civilian drones.

The ability of decision makers, development stakeholders and especially civil society to appropriate remote sensing and geomatics tools to facilitate the management of their lands will be crucial to guide them towards achieving greater sustainability while ensuring that ecosystems provide better services to those who inhabit them. The overall enthusiasm for these tools should be encouraged by leveraging the widespread movement to make data and processing applications available to the general public. This trend will make it possible to produce information at the grassroots level, in addition to that available via major channels of national and international bodies in charge of geographical and environmental information[9]. We sincerely hope that this *Dossier* will contribute to this effort.

→ FOCUS | **An ever-increasing amount of satellite images**

The total volume of satellite images that are accessible is very difficult to determine. Many countries now produce images, and growing amounts of data—which were previously private or could be purchased—are entering the public domain. The following three examples illustrate the volume of this data:
- French SPOT 1 to 5 series satellites have generated an archive of more than 30 million images in 26 years.
- The United States Geological Survey (USGS) EROS (Earth Resources Observation System) Data Center stores more than 5 petabytes* of data from NOAA and NASA satellites.
- The new European Sentinel satellite system will generate 4 terabytes* of data per day (or 1.4 petabytes* per year).

* 1 petabyte (PB) = 1,000 terabytes (TB) = 1 million de gigabytes (GB).

9. Big data are now being used by environmental nongovernmental organizations (NGOs), such as Skytruth, which uses satellite data to monitor environmental damage caused by fishing or illegal mining activities, etc.

For further information...

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▲ **Young girls of the Bella caste working in vegetable gardens (or *bouli*). Korizeina village, Burkina Faso.**
D. Rechner © IRD

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INTERNET ACCESS TO SATELLITE IMAGES

Viewing images via Internet

Since the publication of the first version of this *Dossier*, remote sensing and geomatics have become considerably more widespread both technically—very simple tools are now accessible to anyone interested—and from a material standpoint—a plethora of images are freely available online. This is largely due to the impressive development of internet use in all fields and the high contribution of leading companies in the sector in promoting the widespread use of satellite data.

Microsoft, and especially **Google** have, on their websites, posted sets of images at different resolutions, covering the entire globe according to an automatically managed tiling system. These platforms acquire satellite images from many providers (NASA, NOAA, SPOT Image, Digital Globe, etc.) and they are georeferenced, i.e. projected on a mapping system.

Websites including **Google Maps, Bing Maps (Microsoft)** and **Flash Earth** enable anyone interested to view global satellite images directly online, while displaying the coordinates (latitude, longitude) and map information for easy reference.

The *Géoportail*, managed by the French National Institute of Geographic and Forest Information (IGN, France), offers medium resolution images covering the whole world, as well as high resolution satellite and aerial images covering France, while giving users the possibility of displaying a high number of thematic maps (geology, hydrography, relief, administrative and cadastral boundaries, etc.).

One step further—users with a solid basic understanding of remote sensing may gain direct access to petabyte-scale satellite data via the **Google Earth Engine**. Google manages images from this platform through its Cloud, which is constantly being enriched with newly acquired images, especially from the Copernicus European Earth Observation Programme (see opposite). Access to global-wide series of images (especially acquired by Landsat satellites) is free and user-friendly. Experts can also run a online image processing programme—one of its flagship applications has been to analyse global changes that have occurred over the last 30-40 years.

The **European Space Agency**, in collaboration with the *Université catholique de Louvain* (UCL, Belgium), have set up a geoportal that provides free access to series of global land-cover maps for dynamic monitoring of changes in vegetation cover.

Science On a Sphere (SOS) is an NOAA application which, once downloaded, offers an interface similar to that of Google Earth, with a broad range of features for the analysis and visualization of huge sets of NOAA satellite images (vegetation cover, temperature, etc.).

Downloading images from online catalogues

Access to satellite images is no longer exclusively reserved for professionals and many image providers now allow free data downloads. They are not as user-friendly as Google tools, but the catalogues contain an extremely huge number of images.

For instance, the range is constantly progressing so below are a number of image catalogues that are freely accessible online (as of the date of publication of this *Dossier*).

In France: Theia - www.theia-land.fr/en

Access to this new platform—which is mainly focused on scientific applications—was recently provided for the general public. It offers a collection of satellite images of France and some other parts of the world, including recent SPOT 6 and 7 satellite coverage, as well as Sentinel-2 time series images that are ready-to-use (orthorectified and corrected for ground reflectance).

As part of this initiative, the Spot World Heritage programme aims to make all SPOT 1 to 5 satellite images acquired since 1986 available free of charge. At its launch in June 2015, a first series of 15,000 images on France was made available. As the programme unfolds, images from other countries and continents, particularly Africa, will be posted online.

In Europe

Copernicus Programme managed by the European Commission
www.copernicus.eu
This programme provides access to images from the new European family of Sentinel satellites. It primarily covers Europe, but also includes global data in its Land thematic: http://land.copernicus.eu/global
Sentinel-2 satellite images from the Copernicus/ESA programme are distributed via the Copernicus website, but also through different databases. They are, for instance, available through the Amazon Cloud platform.
A portal enables users to browse this database by zooming in on the area of interest. The selection is then made in this highlighted zone, and users can also specify the period and maximum level of clouds: http://sentinel-pds.s3-website.eu-central-1.amazonaws.com/#ImagerySearch
Selected elements are 100 x 100 km tiles, compiled from the larger original 'datatakes'—the format currently managed on the ESA server.

Product Distribution Portal
www.vito-eodata.be
A catalogue of European satellite images, especially from PROBA-V and Envisat satellites, are accessible through this portal. Users only have to pay for real-time images, while those acquired 3 months earlier or more are free.

Viewing images via Internet

Google Maps: www.google.fr/maps
Bing Maps (Microsoft): www.bing.com/maps
Flash Earth: www.flashearth.com
Géoportail (IGN): http://tab.geoportail.fr
Google Earth Engine: https://earthengine.google.org/#intro
ESA/UCL Land Cover website: http://maps.elie.ucl.ac.be/CCI/viewer/index.php
Science on a Sphere: http://sos.noaa.gov/SOS_Explorer/download.html

In Africa

Sahara and Sahel Observatory (OSS)
Among its activities, OSS has developed a set of tools and services based on the harnessing of geospatial technologies, including:
- Providing support to 12 sub-Saharan African countries in developing national land-cover maps at 1/200000 resolution, validated on the country scale, and available online and in the form of printed atlases. www.oss-online.org/rep-sahel/index.php?option=com_content&view=category&id=45&Itemid=115&lang=en and http://bricks.oss-intra.org:8080/geobricks/srv/eng/main.home
- Creation of a geoportal to support the Great Green Wall initiative in the Sahara and Sahel regions to facilitate access to spatial data produced by regional and international institutes related to sustainable land management issues. http://bricks.oss-intra.org:8080/geobricks/srv/eng/main.home
- Use of geographical web services based on Open Source technologies, such as the information system for sustainable land management in Mali (ILWAC project, Integrated Land and Water Management for Adaptation to Climate Variability and Change— http://ilwac.oss-online.org/ml-ilwac-gn2_10 —and a portal on knowledge sharing on desert ecosystems and livelihoods devoted to the Middle East and North Africa (MENA) region. www.oss-online.org/mena-delp/index.php/fr

Global Monitoring for Environment and Security Initiative (GMES)
Its African component is being developed with the African Union and the European Union. OSS will be involved in monitoring the status of natural resources in direct connection with the desertification topic. A first milestone in this extensive programme is currently being achieved through the Monitoring for Environment and Security in Africa (MESA) programme that radiates from Addis Ababa through the 48 African, Caribbean and Pacific (ACP) countries. http://moi.govmu.org/mesa

AGRHYMET Regional Centre of the Permanent Interstate Committee for Drought Control in the Sahel (CILSS)
This Niamey (Niger) based centre is responsible for the distribution of cartographic products stemming from satellite data (including warning bulletins) and training and technical support activities. www.agrhymet.ne/produit.html

In the United States

Portal of the United States Geological Survey (USGS)
http://earthexplorer.usgs.gov
This portal—set up by USGS, the US government agency in charge of national satellite data archiving—provides access to a highly comprehensive catalogue. It also contains aerial photographs and declassified images. Most of the data is open access (free), but some archive images require pre-processing prior to downloading (for a fee). The interface is quite user-friendly but, due to its sheer extent, a degree of learning is necessary to browse, identify interesting data and prepare for downloading.

NASA Earthdata website
https://worldview.earthdata.nasa.gov
This NASA website is designed to enable users to view and download near-real-time global images (MODIS sensor) from its Aqua and Terra satellites. It is particularly interesting for monitoring current environmental events (sandstorms, forest fires, floods, droughts, etc.), owing to its multi-temporal feature, as particularly highlighted when browsing images captured daily using a calendar cursor.

For an overview of major Earth observation programmes

US National Aeronautics and Space Administration (NASA) Visible Earth website
http://visibleearth.nasa.gov
This site provides a catalogue of NASA Earth images.

European Space Agency (ESA) website
https://earth.esa.int

Note that it is hard to get simple information from either of these sites as they are extremely dense and packed with technical terminology.

TUTORIALS

European Space Agency (ESA)

ESA provides students and the general public access to its EDUSPACE website, which is available in eight languages. It offers an introduction to remote sensing and open access to European satellite data. The LEOWorks software package can also be downloaded free of charge, which includes a tutorial on basic image processing.
www.esa.int/SPECIALS/Eduspace_EN (English)
www.esa.int/SPECIALS/Eduspace_FR (French)

Another site showcases ESA's many Earth observation activities, along with the satellites and sensors discussed in this *Dossier*: www.esa.int/Our_Activities/Observing_the_Earth

Other resources for teachers and students (non-exhaustive list)

EOEdu 'Observing our planet'
A short guide to remote sensing is available at:
http://eoedu.belspo.be/en/guide/index.htm (English)
http://eoedu.belspo.be/fr/guide/index.htm (French)

FEGEPRO – *Fédération des professeurs de Belgique Francophone*
Explanations specific to Google Earth (which also has its own help pages).
www.fegepro.be/pages/google_earth.html

Government of Canada
A course (and the corresponding downloadable manual) on the fundamentals of remote sensing, available on the Natural Resources Canada website:
www.nrcan.gc.ca/earth-sciences/geomatics/satellite-imagery-air-photos/satellite-imagery-products/9271 (English)
www.rncan.gc.ca/sciences-terre/geomatique/imagerie-satellitaire-photos-aeriennes/imagerie-satellitaire-produits/9272 (French)

Portal for course material of the *École National des Sciences Géographiques* (ENSG, Champs-sur-Marne, France)
Many educational materials (university level) can be accessed freely
www.ensg.eu/?lang=en
***Planète Sciences Midi-Pyrénées* Association (Toulouse, France)**
General public news: http://regard-sur-la-terre.over-blog.com

Pocket Guide of CNES (Toulouse, France)
https://cnes.fr/en/page-intermediaire/Pocket%20Guide (English)
https://cnes.fr/fr/page-intermediaire/Dossiers%20de%20vulgarisation (French)

NASA Earth observations and global change
http://neo.sci.gsfc.nasa.gov

Introductory course on remote sensing, and vademecum on remote sensing by M.-C. & C. Girard (AgroParisTech, France)
https://tice.agroparistech.fr/coursenligne/courses/TELEDETECTION/?id_session=0
https://tice.agroparistech.fr/coursenligne/courses/VADEMECUMTELEDETECTI/?id_session=0

Recent multilingual course of the European SEOS project (including English and French)
http://lms.seos-project.eu/learning_modules#

IMAGE PROCESSING AND GEOMATICS SOFTWARE

For basic processing

Specialized software is needed to advance further to manipulate, import and sketch the boundaries of images, in short, to perform geomatics-type processing. For instance, the **Google Earth** application (especially the **Google Earth Pro** version) is straightforward and easy to use and can be downloaded free of charge. This software allows you to view, process and print satellite images available via Google, while other materials can also be added, such as topographic maps, images from alternative sources. Moreover, files containing geographic information in KML format—an international standard that Google Earth has helped popularize—may also be imported/exported.

▲ **Students working in the Wahlé Daba Community Development Centre (Balbala, Djibouti).**
L. Pasquier Doumer © IRD

For more complex processing

Many commercial software packages are available for more comprehensive and advanced processing, but their evaluation would be beyond the scope of this *Dossier*. Moreover, some freeware programmes have emerged in the framework of university courses in remote sensing. Many programmes are no longer available, but one especially interesting freeware application devoted to satellite image analysis, i.e. (developed at Purdue University, USA), is still available online in a light version (in English only).
https://engineering.purdue.edu/~biehl/MultiSpec/index.html

On the Sentinel Application Platform (SNAP), ESA proposes free efficient Toolboxes that have been developed specifically for processing and analysis of Sentinel satellite data.
http://step.esa.int/main/toolboxes/snap

Orfeo ToolBox: This library of satellite image processing modules has been developed by CNES for the most adventurous users with more specific needs, and it benefits from improvements made by a community of highly experienced users. The so-called Monteverdi interface provides user-friendly access to certain common functions (e.g. classification).
www.orfeo-toolbox.org

GIS freeware and open source software

QuantumGIS (QGIS): is currently the most widely used free and open source GIS (supported by government agencies).
https://www.qgis.org/en/site
This very comprehensive GIS (especially as it includes many plugins) is not very straightforward to learn but it is constantly improving through input from a large community of developers and users. It is available in several languages, with abundant online documentation and tutorials. This is an interesting option for anyone interested in getting started in this field without requiring any financial outlay, but the learning curve could be quite long, timewise!

Geographic Resources Analysis Support System (GRASS): this free and open source GIS software has been evolving since the 1990s, with menus and tutorials offered only in English.
https://grass.osgeo.org

OSGeo provides an attractive comprehensive environment of open-source geomatics software tools. The most commonly used tools are Virtual Machine based.
http://live.osgeo.org/en

▲ **Market gardening in Niger.**
F. Boyer © IRD

Glossary

Active remote sensing. The remote sensing system emits and measures the electromagnetic signal return (radar principle).

Atmospheric absorption. This phenomenon is attributable to the various gases and particles in the atmosphere that absorb electromagnetic radiation energy. It varies according to the nature of the gases involved and their properties, while also depending on the spectral wavelengths.

Diffusion. This is the result of the interaction of particles and molecules (water droplets, dust, fumes, aerosols) on incident and reflected electromagnetic radiation. It depends on the nature of the wavelengths, turbidity and thickness of the atmosphere (through which radiation must pass).

Geometric correction. This correction can compensate for distortion caused by satellite movements, while also being used to transform an image so as to represent it as a plane in a given cartographic projection.

Passive remote sensing. The remote sensing system only records the energy reflected or emitted by objects on the ground.

Radiometric correction. Correction of recorded measurements while taking the specific characteristics of the instruments as well as the effects of atmospheric disturbance on electromagnetic signal transmission into account. The aim is to reproduce luminance or reflectance values related only to the observed object (i.e. 'ground' values, as opposed to 'top of atmosphere' values for uncorrected data).

Reflectance. Ratio of reflected radiation intensity to that of incident radiation on a surface (target).

Sensor. An instrument that captures energy from the target scene and emits a corresponding measurable electrical signal.

Spatial resolution. The pixel size on the ground—it thus has a geographical dimension that dictates the size of the smallest discernible element on the ground surface. It can be likened to the minimum distance separating two objects on the ground for them to be distinguishable. This is the defining parameter for recognizing objects by their shape.

Spectral signature. A set of measured values for the same object at different wavelengths.

Swath. Area of the scene monitored on the ground whose width ranges from about 10 to 100 km depending on the type of on-board sensors and the satellite's altitude.

LIST OF ACRONYMS AND ABBREVIATIONS

See Table on page 5 for satellite names and abbreviations.

AGRHYMET	*Centre Régional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle*, Niger
AMMA	African Monsoon Multidisciplinary Analyses Programme
AVHRR	Advanced Very High Resolution Radiometer
CEOS	Committee on Earth Observation Satellites
CESBIO	Center for the Study of the Biosphere from Space, France
CNES	*Centre National d'Études Spatiales*, France
CSFD	French Scientific Committee on Desertification
ESA	European Space Agency
GBEP	Global Bioenergy Partnership
GEOSS	Global Earth Observation System of Systems
GIMMS	Global Inventory Modeling and Mapping Studies
GIS	Geographic information system

GPS	Global positioning system
IRD	*Institut de recherche pour le développement*, France
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration, USA
NDVI	Normalized difference vegetation index
NOAA	National Oceanographic and Atmospheric Administration, USA
OSS	Sahara and Sahel Observatory, Tunisia
SAR	Synthetic Aperture Radar (RSO in French)
SMOS	Soil Moisture and Ocean Salinity Programme
UNCCD	United Nations Convention to Combat Desertification
USGS	United States Geological Survey

Abstract

In 2016, roughly a hundred civil remote sensing satellites were monitoring the Earth from space. These satellites collect data—usually in image form—on the entire Earth's surface, including the most remote and inaccessible areas. They accomplish this task regularly at reasonable cost, thus allowing users to measure, model and monitor the evolution of the environment on different spatiotemporal scales. Remote sensing (all technology and techniques that produce satellite or aerial images) has a broad range of applications in different fields, such as meteorology, environmental science and urbanism.

In the desertification setting, remote sensing provides critical support to help gain insight into the mechanisms involved in this phenomenon. The vast amount of local to global information produced enables scientists to analyse the effects of desertification and measure the stabilization or regression trends over time. Early warning systems and integration of the data in models can even help predict these trends. This information is essential for the development of scenarios and forecasts for various periods, in turn facilitating short-term decision making and the formulation of medium- and long-term strategies to ensure sustainable development.

This *Dossier* begins with a presentation of a few physics concepts that are essential for understanding remote sensing, and a description of the main parameters that can be monitored by satellite. Several recent examples regarding the various possible uses of satellite images for the purpose of combating desertification are then proposed. The *Dossier* concludes by offering a guide on practical ways to advance in remote sensing via freeware and satellite images provided free of charge by French, European, and American space agencies.

Keywords:
remote sensing, desertification, vegetation cover, land surface state, early warning system, monitoring/assessment, decision support

Résumé

En 2016, une centaine de satellites civils observent la Terre depuis l'espace. Ils permettent de recueillir des données, le plus souvent sous forme d'images, sur toute la surface de notre planète y compris dans les endroits les plus inaccessibles. Ils le font à un coût modéré et de façon répétée dans le temps, ce qui permet de mesurer, de modéliser et de suivre les évolutions de notre environnement à différentes échelles spatiales et temporelles. Les applications de la télédétection (ensemble des appareils et des techniques produisant des images satellitaires ou aériennes) sont ainsi variées — météorologie, environnement, urbanisme, etc.

Dans le contexte de la désertification, la télédétection apporte une aide irremplaçable pour la compréhension de ce phénomène. De multiples informations — du local au global — fournies par les satellites permettent de diagnostiquer les effets de la désertification, de mesurer son évolution dans le temps — extension, stabilisation, régression. Les systèmes d'alerte précoce et l'assimilation de données dans des modèles permettent même de prévoir des évolutions. Elles sont essentielles à l'établissement de scénarios et de prospectives à diverses échéances et contribuent de ce fait à la prise de décisions à court terme ainsi que la définition de stratégies à moyen et long termes dans un objectif de développement durable.

Ce dossier présente tout d'abord quelques notions physiques indispensables à la compréhension de la télédétection et les principaux paramètres observables par satellite. Il nous fait ensuite découvrir différentes utilisations possibles des images satellitaires au service de la lutte contre la désertification, au travers de plusieurs exemples récents. Il se conclut sur un guide pratique pour aller plus loin, grâce aux logiciels libres et aux images mises à disposition gratuitement notamment par les agences spatiales françaises, européennes et américaines.

Mots clés :
télédétection, désertification, couvert végétal, état des surfaces, alerte précoce, suivi-évaluation, aide à la décision

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