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Continental Surfaces

Space data in support of land resource management
Water resources, agriculture, forest, urban areas

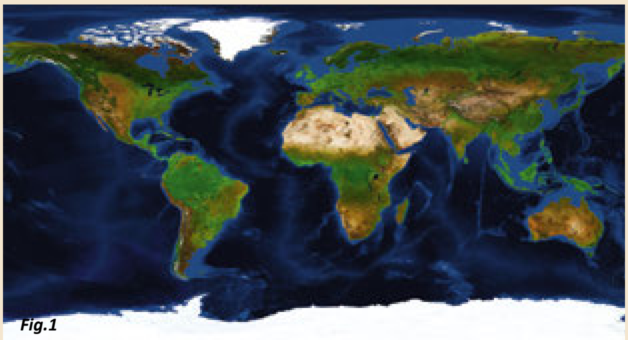

Fig.1

Global change covers both climate change, environmental changes related to human activities (modification of the land use and land cover, urbanization, fossil energy consumption, pollutant release, etc.), and the induced consequences (erosion, flooding, impacts on continental and coastal ecosystems, displacement of animal populations and prevalence of disease areas, etc.). Climate change is now a reality, and there is a growing awareness in the opinion of the potential environmental, economic, and geopolitical impacts in the short term. At the same time, the role played by anthropogenic effects and greenhouse gas in climate change has been highlighted (see Climate Change 2007, 2013: Synthesis report from Intergovernmental Panel on Climate Change).

In terms of the processes involved, the interactions between water and carbon cycles and climate play a crucial role. As for land, the nature of surface and its vegetation cover (continental biosphere) greatly influence the exchanges of water, CO_2, and energy between the soil and atmosphere and hydrological cycles (runoff, infiltration/evaporation, etc.), with in return “retroactive” effects on climate. Coastal areas are prone to climate change due to their internal biophysical systems (for example, exchanges with the atmosphere) and their interactions with the neighboring continental systems.

Furthermore, 1.4 billion people still lack access to drinking water and more than 3 billion have infections related to the poor water quality. By 2025, two-thirds of the world’s population could be subject to water stress. Several regions of the world including Europe present the risk of water resource overuse, increased by repeated droughts. Faced with this issue, the analysis of the impact of human activities and climate change on this resource has become essential. Continental water is strongly influenced not only by climate change but also, and to a stronger degree, by the direct impact of human activities (artificial storage, use for agriculture and industries, domestic water supplies, stream morphological change, land use change, etc.). Access to water is a major issue of sustainable development, affecting economic development, social welfare and environmental dynamics.

This context has led the scientific community and CNES to propose the following recommendations to the CNES prospective seminar in 2014:

i) to design in collaboration with ISRO, the Indian Space Agency, a project of an IRT space mission (high-spatial resolution and high revisits with a global coverage);
ii) to continue the important partnership with NASA/JPL for the SWOT mission;
iii) to continue to support the BIOMASS mission;
iv) to support the exploitation of the SMOS mission;
v) to continue the preparation of the use of SENTINEL-2 data with the “flagship” experience called SPOT-4 Take five;
vi) to continue to support and develop the national THEIA land data center. Following new membership in 2015, THEIA has now 12 institutional partners.

A new thermal infrared mission to adapt agricultural and natural ecosystems, coastal and inland waters and urban management to climate change

Through the energy exchanges of continental or oceanic surfaces, surface temperature provides critical climate information. In particular, it allows, through evapotranspiration, the access to the water cycle and the functioning of the continental biosphere.

Missing in the panorama of the space missions in orbit today, CNES has signed a cooperation agreement with ISRO for the development of an original IRT space mission (such as the recent French projects MISTIGRI and THIRSTY) combining a high spatial resolution (50-100 m) and a high revisit rate (from one to three days). Phase A has started in early 2016 with a joint mission group involving French scientific experts covering all of the mission’s objectives (agriculture, urban, coastal and inland waters). A seminar on space contribution for the management of water resources is planned in the first quarter of 2017.

SWOT – new measures for the overall quantification of continental water bodies

NASA and CNES are proposing, with the SWOT mission, to use interferometry techniques in Ka-band to make measurements with a wide swath (120 km) and an increased resolution (in the order of 10 m with the high resolution mode). SWOT will provide a global inventory of all terrestrial surface water bodies whose surface area exceeds 250 m × 250 m (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m. SWOT will allow the access to global storage change in terrestrial surface water bodies as well as the estimation of the global change in river discharge, both at sub-monthly, seasonal, and annual time scales.

In 2015, key steps have been achieved: i) the selection of an international scientific team ii) NASA is now in development phase (Phase C) and CNES should decide Phase C in July 2016. Moreover, as part of the SWOT Downstream Preparatory Program, France – through the CLS and LEGOS – has been selected to coordinate the work package relating to water and snow of the Land Monitoring Copernicus service in order to produce surface water height in lakes and rivers from the LEGOS Hydroweb database which has been industrialized. A downstream ecosystem with the AFD and OIEAU (Office International de l'Eau) is built around the Congo basin with CICOS *(Commission Internationale du Bassin Congo Oubanghi Sangha)* involving scientific laboratories, industry and CNES. This union should provide new measures and hydrological monitoring tools to basin organizations.

BIOMASS – a look at our forests to monitor and measure biomass from space

The BIOMASS mission (7th ESA Earth Explorer Core Mission) was selected on February 18, 2015, and planned for launch in 2021. The P-band SAR mission will provide global maps of forest biomass and height (at 200 m resolution) and forest disturbance (at 50 m resolution) every six months to reduce the major uncertainties in carbon fluxes linked to land use change, forest degradation and regrowth, to provide support for international agreements (UNFCC and REDD+), to infer landscape carbon dynamics and supporting predictions, to initialize and test the land component of Earth system models, and to provide key information on forest resources, ecosystem services, biodiversity, and conservation.

THEIA Land data center and SENTINEL-2

With the decision to launch the VENµS project, in 2004, CNES began helping the French and European user community get ready for the arrival of SENTINEL-2 (S2). CNES was deeply involved in SENTINEL-2 image quality and Level 1 processing and developed a very efficient and robust level 2A (L2A) product (atmospheric correction and cloud masks) included in the MACCS processor. As of 2008, we have begun to distribute L2A time series of S2-like images to users (based on the FORMOSAT-2 and LANDSAT satellites) so that they start learning how to use the time series. Later on, with the SPOT-4 & 5 (TAKE 5) experiments managed by CNES with help from ESA, S2-like time series were distributed to almost 1 000 users in 2013 and 2015. Six years of LANDSAT (5, 7, 8) L2A data over France are also available and are already used by 150 users.

The new THEIA Land data Center, set-up by nine French public organizations, was responsible for these productions and distributions. THEIA is also about to release the first L2A products from SENTINEL-2A, to be produced on a routine and near real-time basis for 5.4 M km^2. These zones were selected through a call for proposals open to the French public user community. This production is done using the MACCS software. This software is also the core of the MACCS-ATCOR Joint Algorithm, proposed by CNES and DLR to ESA for a global production of SENTINEL-2 data.

Meanwhile, in the THEIA framework, large algorithm development efforts were undertaken to develop fully automatic procedures to provide higher level products. The first two of these products will be issued at the end of 2016 with the first year of SENTINEL-2 data, to deliver snow cover maps and fully automatic land cover maps over France with 20 classes at 20-meter resolution. Some other methods initially developed within the THEIA framework, such as monthly composites, crop masks and biophysical variables have been implemented into the ESA SENTINEL-2 for Agriculture project.

Fig. 1: Used to provide accurate measurements of the main characteristics of Earth's vegetation cover, the Vegetation instrument on board Spot-4 and Spot-5 is part of the European Vegetation program. *© CNES/ made by UCL*

Fig. 2: Areal view of a river. *© Thinkstock*

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Continental Surfaces

Contribution of space measurements in the description and monitoring of the water cycle

Water is a key factor in the integrated functioning of the critical zone and continental surfaces. Monitoring energy and water budgets at all levels thanks to surface temperature is essential to understanding the interdependent processes induced by environmental (climate change) and human constraints (population growth, resource depletion, land pressure, increasing water consumption, etc.) and ultimately meet societal challenges (food security, water management, maintenance of biodiversity, hydrological risks, etc.).

Several complementary recent or projected assignments aim to provide water cycle variables: evapotranspiration using thermal data, surface moisture using microwaves, free surface water heights using altimetry.

SMOS provides soil moisture based on surface moisture measurements [1]. Used in conjunction with thermal power, it gives access to the latent heat flux and the key variables of surface function, monitors large-scale crop stress, and ultimately provides critical information for resource management. Via drought indexes, the SMOS root-zone water content (Fig. 1) provides data on the water available to plants and anticipates fine-scale stress with the TIR (Thermal Infrared). Combined with information on vegetation water content – obtained using L-band radiometry, for example – this information is used to build yield forecasting indicators. Soil moisture data can also be used for risk prediction, flood and basin water budget monitoring. [2] The first results are very promising. However, the need to access fine scales – the agricultural parcel – to ensure a continuous monitoring faces differences in the resolution or revisit rate of the various systems, and significant work on the disaggregation process [3] was required to overcome these issues.

In the thermal infrared, the scientific community still faces the dilemma of spatial resolution and revisit frequency: to date, no system offers both characteristics simultaneously. In France, the development of such a mission has resulted in several CNES projects including MISTIGRI [4] or THIRSTY in partnership with JPL/NASA. This cooperation involves many laboratories and continues today with India with the CNES-ISRO agreement. The mission's main scientific goals involve (i) monitoring the water balance and stress of terrestrial ecosystems, (ii) coastal and inland water functioning, and (iii) monitoring urban microclimates. The mission requirements are defined by original experimental and digital studies involving angular effects, the impact of atmospheric turbulence on measurement accuracy, spectral band definition, time of pass, etc. An algorithm for mapping and assessing EVASPA evapotranspiration [5] is being tested (Fig. 2). Basic specifications are a 50-80-meter resolution, a minimum of three channels in the TIR and three channels in the VNIR (Visible and Near-Infrared), with revisit times of one to three days. The space mission will be associated with a ground-based calibration and validation site network for operating methodology, TIR data and product testing.

In the microwave domain, the spatial resolution of systems such as SMOS and SMAP remains too coarse for agricultural applications. Two approaches have been adopted to overcome this constraint. The first is based on complementary systems to circumvent space-time sampling limitations. Taking the example of surface moisture, a concept combining an accurate moisture measurement (radiometry) and spatial variation measurement of moisture (radar) can be used. Other similar initiatives bypass revisit time differences using the disaggregation scheme obtained at a given date in all intermediate low-resolution data until the next high-resolution acquisition. The second approach consists in using surface evaporation efficiency to disaggregate passive microwave moisture via leaf area index measurements (cover rate) thanks to short-wavelength optical data coupled with surface temperature (thermal infrared); both are obtained with high spatial (SENTINEL, SPOT, ASTER, etc.) and sometimes high temporal (MODIS) resolutions. Therefore, the concept of a TIR high-resolution/high-revisit mission (e.g. MISTIGRI

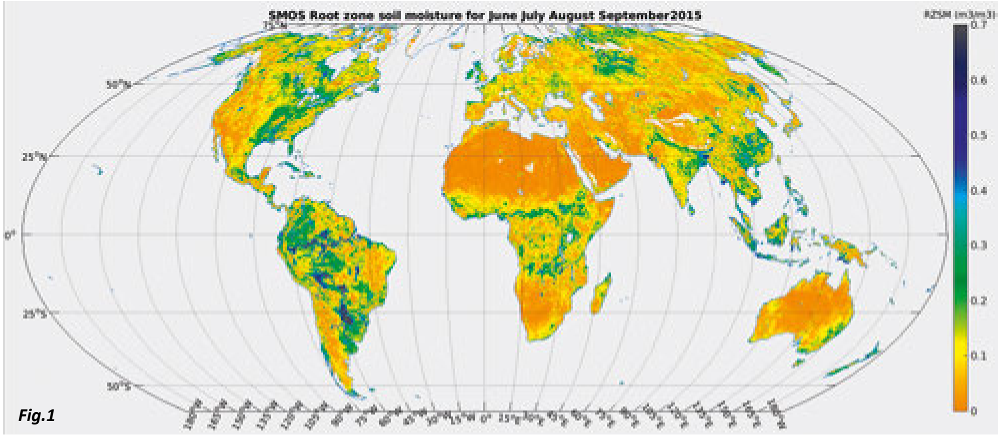
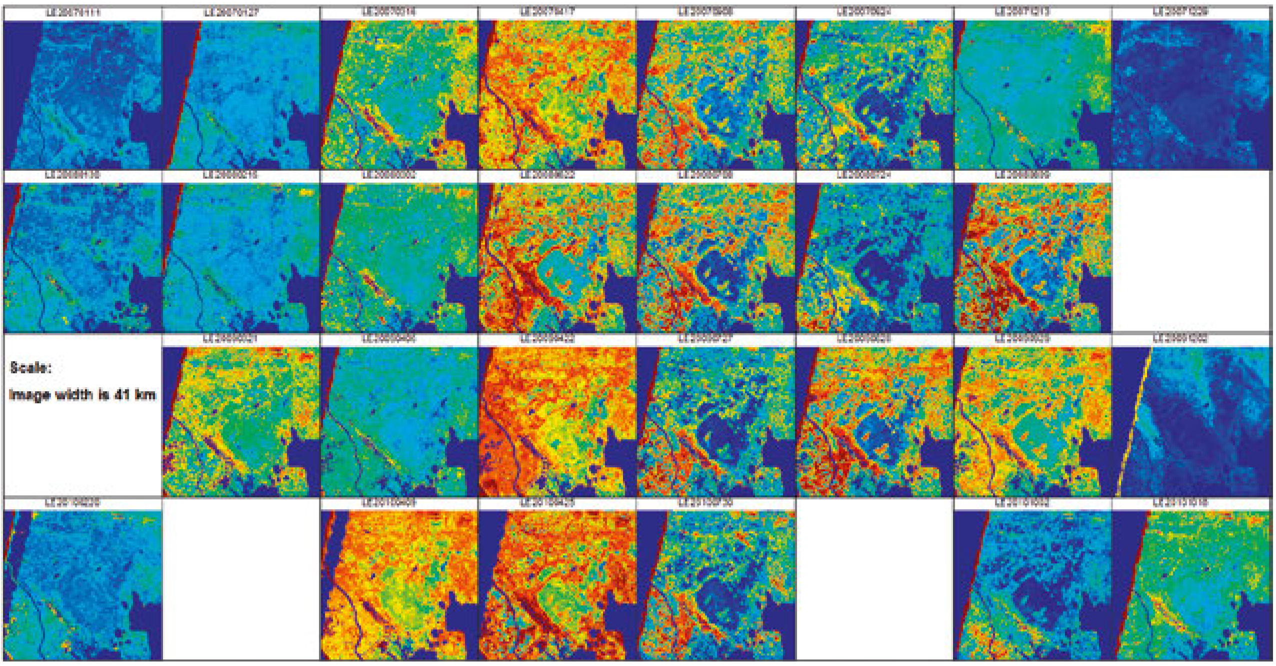


Fig. 1: SMOS Root zone soil moisture from June to September 2015 (Al Bitar *et al.*, CATDS 2016).

Fig. 2: Latent heat flux maps at 10:30 (0-500 Wm-2 from blue to red) from 2007 to 2010, over a 40x40 km area called Crau in southeastern France (based on Olioso *et al.*, RAQRS'IV 2014 meeting, Valencia).



and THIRSTY) fills a significant gap. These approaches have been validated at the scientific level and applied in the irrigation water management project in Catalonia, among others.

Significant progress in water cycle monitoring across a wide range of scales is expected from the exploitation of combined observations provided by multiple satellite sensors now available. Rainfall monitoring is crucial in arid regions, but this issue is poorly covered by TRMM-type sensors owing to surface complexity and to the atmospheric phenomena involved (with a standard error ranging from 100 to 300% according to sites and approaches). It has been demonstrated that estimates could be greatly improved by assimilating SMOS data to TRMM data. In large catchments or water surfaces with temporal variations (flooded areas, lakes, marshes, etc.), it is essential to complement water surface estimates obtained at high temporal repetition (e.g. with SMOS) with information obtained at lower frequency (due to clouds) but finer scale (in the optical domain). Another promising approach aims to combine surface data with altimeter data (JASON, and later, SWOT) to estimate volume variations.

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Continental Surfaces

Above-ground biomass mapping in French Guiana using remote sensing and environmental data

Mapping forest aboveground biomass (AGB) is becoming an important task, particularly for the reporting of forest carbon stocks and their changes. An approach for AGB mapping over the tropical forest of French Guiana was developed using regression-kriging of remote sensing and environmental data. The RMSE on the AGB estimates is of 51 Mg/ha (R^2=0.66) with 1-km resolution map. This paper summarizes the approach developed for tropical forest biomass retrieval and the main results.

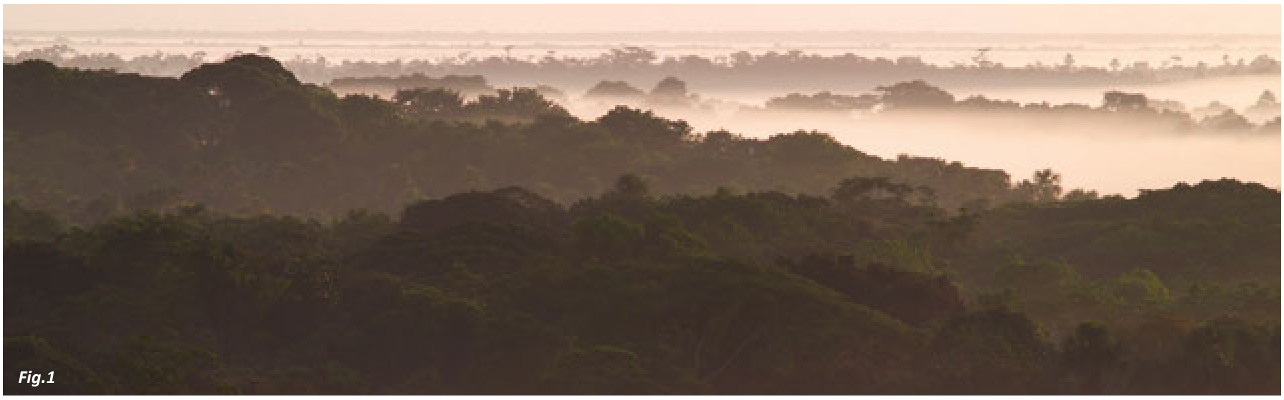
Fig.1

Forests act as carbon sources and sinks through deforestation, degradation and regrowth. The monitoring of forest carbon stocks is a pressing concern to quantify the exchange of carbon between the surface and the atmosphere, and therefore to reduce uncertainty in the global carbon budget for climate change mitigation.

A fundamental parameter characterizing the spatial distribution of carbon in the biosphere is biomass, and forests comprise ~80% of the terrestrial above-ground biomass (AGB). Among the different biomes, tropical forests hold a large fraction of the terrestrial carbon, thus playing a major role in the global carbon cycle.

In response to the need for greatly improved mapping of global biomass, the BIOMASS mission was selected by the European Space Agency for the third cycle of Earth Explorer Core missions. The BIOMASS mission is designed to map the full range of the world's above-ground forest biomass, and to quantify biomass changes during the mission lifetime, with accuracy and spatial resolution compatible with the needs of national scale inventory and global carbon flux calculations. This objective is achieved with the P-band SAR [1]. However, the BIOMASS mission will be launched in 2020 and global datasets for biomass monitoring are expected during the forthcoming decade. Meanwhile, global AGB maps have been produced using existing remote sensing data, at a resolution of 1 km by Saatchi *et al.* [2] and Avitabile *et al.* [3], and 500 m by Baccini *et al.* [4]. In [2] and [4], the main data source is from spaceborne LiDAR data acquired from the Geoscience Laser Altimeter System (GLAS).

The spaceborne LiDAR data provided the canopy heights, which are converted into AGB using known allometric equations relating height to AGB. The extension to global AGB was made using global in situ datasets and optical data such as MODIS. In this paper, we propose an improved approach based on remote sensing (lidar, radar and optical data) and environmental data to map the AGB over a large territory. The method is applied to French Guiana, which has 86 504 km² of surface area, 90% of which is covered by dense and inaccessible tropical rain forests.

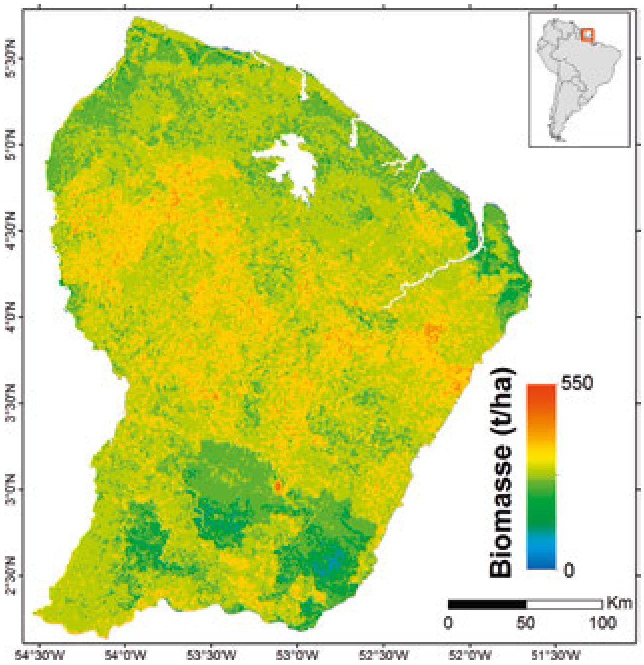

Fig.2

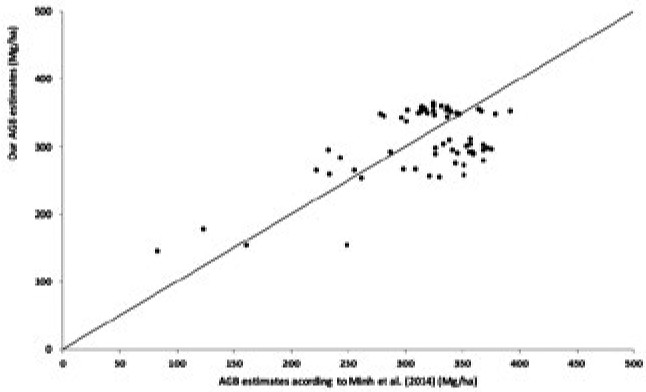

Fig.3

Fig. 1: French Guiana's forest. © *Thierry Montford*

Fig. 2: A 1-km resolution AGB map of French Guiana obtained with the regression-kriging technique.

Fig. 3: Comparison between AGB estimates obtained with the regression-kriging of GLAS data and AGB estimates obtained from the P-band airborne dataset on two sites in French Guiana (Nouragues and Paracou).

The methodology uses the canopy height map of French Guiana, produced successfully from GLAS data [5, 6] based on the three following steps: (i) finding the best linear regression between GLAS waveform-derived metrics and in situ AGB (for data with a distance between GLAS footprints and in situ AGB of 250 m x 250 m plot); (ii) developing a trend model of AGB data (in situ and the GLAS estimates) with predictors derived from optical (MODIS), radar (PALSAR), and environmental maps; (iii) improving the AGB map precision by incorporating the kriged residuals of the AGB model from step (ii). Steps (ii) and (iii) correspond to a usual kriging-regression approach.

A 1-km resolution AGB map was created with an RMSE of 51 Mg/ha (Fig. 2). The produced AGB map as well as the in situ AGB measurements were compared to three global AGB maps from the studies of Saatchi *et al.* [2], Baccini *et al.* [4], and Avitabile *et al.* [3]. The comparison with in situ data showed that the global maps have large AGB errors over dense tropical forests; they also showed very high bias. For the maps of Saatchi and Baccini, AGB was underestimated by ~45 Mg/ha in comparison to both our map and the in situ AGB measurements. The error was also high, with an RMSE of ~70 Mg/ha. The most recent map [3] has even larger error and bias than the previous maps, with an overestimation of AGB of ~70 Mg/ha and an RMSE > 100 Mg/ha.

The wall-to-wall AGB map was also compared to tomographic P-band radar AGB estimates covering two small sites in French Guiana (Nouragues and Paracou) [7]. The data used to obtain AGB estimates were from the P-band airborne dataset acquired by the Office National d'Études et de Recherches Aérospatiales (ONERA) in 2009, as part of the European Space Agency campaign TropiSAR to support the future BIOMASS mission [8]. The P-band radar AGB estimates were resampled to 1 km by calculating the mean AGB estimates in each 1-kilometer cell. The comparison results showed good agreement with an RMSE on the AGB estimates of 49 Mg/ha (Fig. 3).

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Continental Surfaces

Tele-epidemiology – a study of the climate-environment-health relationships

CNES and its partners have developed a conceptual approach called tele-epidemiology which consists in studying the links between the environment, ecosystems, and etiological agents responsible for diseases in human, animal, and plant populations, based on space products truly adapted to the needs of health actors.

Half the world's population is subject to the risk of emerging or re-emerging infectious diseases. The latter are responsible for 14 million deaths every year. According to WHO, they are a leading cause of global mortality as they account for nearly one third of deaths in low-income countries. The context of this situation is a world in transition where rapid environmental changes (climate change, population growth, deforestation and urbanization, agricultural intensification, globalization and increased trade, etc.) foster pathogens and their dispersal, thereby contributing to endemic and emerging diseases in humans, wild or domestic animals and plants. In addition, non-communicable diseases (respiratory and cardiovascular diseases, cancers, etc.) are responsible for a growing number of deaths worldwide according to WHO, and can be caused by organic or inorganic elements in the environment.

A conceptual approach of tele-epidemiology at CNES

Faced with these social challenges, an integrated multidisciplinary research is growing, especially around the concepts of "One Health" and "EcoHealth". This approach combines the physical, biological, social sciences and humanities and aims to understand the mechanisms involved and identify the factors that affect the spread of these pathologies (Fig. 1). These factors can be environmental, climatic, demographic, socio-economic, and/or behavioral. Some can be identified from space, which requires the development of effective methods to use remote sensing for risk factor characterization, mapping, and monitoring. Data from Earth observation satellites do not directly concern the pathogens which cause the disease, but their environment – they will therefore be used to measure these favorable factors.

CNES and its partners have worked with the countries' health authorities and with local scientists to develop tools to compile entomological risk maps for infectious vector-borne diseases (presence/absence of water points, presence/absence of larvae breeding sites, larval densities and adult mosquito densities) with high spatial and temporal resolution. The effectiveness of risk prevention could be improved by providing health authorities with these maps predicting "when and where" there will be a risk of emergence of the disease vectors and the risk level. If regularly updated, risk maps could provide useful data to optimize vector control measures. This approach was successfully implemented for the Rift Valley Fever in Senegal and for urban malaria in Dakar. It was also tested for rural malaria in Burkina Faso. Today, it is being developed for dengue in Martinique and Guyana.

An example of application: the Rift Valley Fiver in Senegal

The Rift Valley Fever (RVF) is a viral disease transmitted by the bite of mosquitoes. It is considered a major public health issue with a strong socio-economic impact in breeding areas where it occurs. Though it mainly affects animals, humans can also be infected with the disease which results in a severe pathology. It also causes significant economic losses due to death and abortion among RVF-infected livestock.

AdaptRVF is a French-Senegalese partnership project between the Dakar Ecological Monitoring Center and Institut Pasteur, the Directorate of Veterinary Services of Senegal, Météo-France, and CNES. It aims to apply the conceptual approach of tele-epidemiology to RVF in the Sahel region of Ferlo (Senegal), which is regularly affected by the disease. It was funded by the French Ministry of Ecology through its Management and Impacts of Climate Change Program.

RVF emergence corresponds to the conjunction of three factors in time and space: (i) vector proliferation (mainly

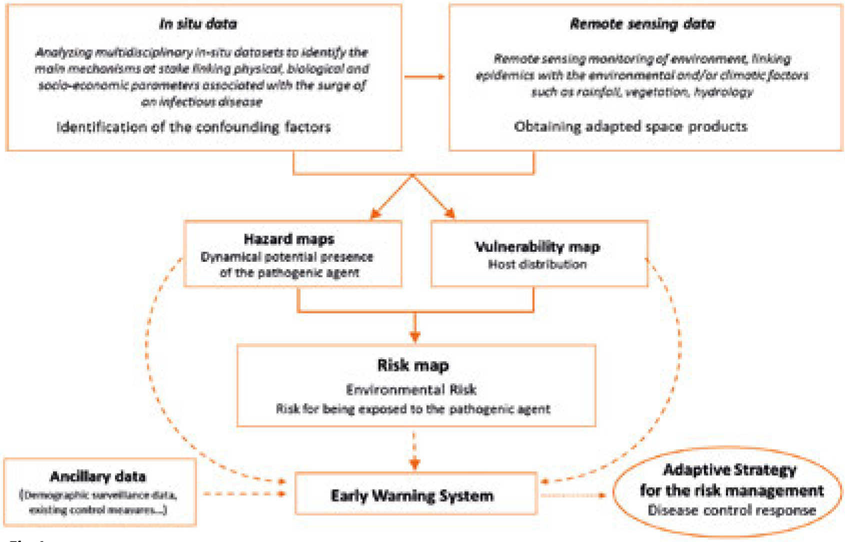

Fig.1

Fig. 1: The conceptual approach of tele-epidemiology for vector-borne diseases.

Fig. 2: The Rift valley fever entomological risk modelling.

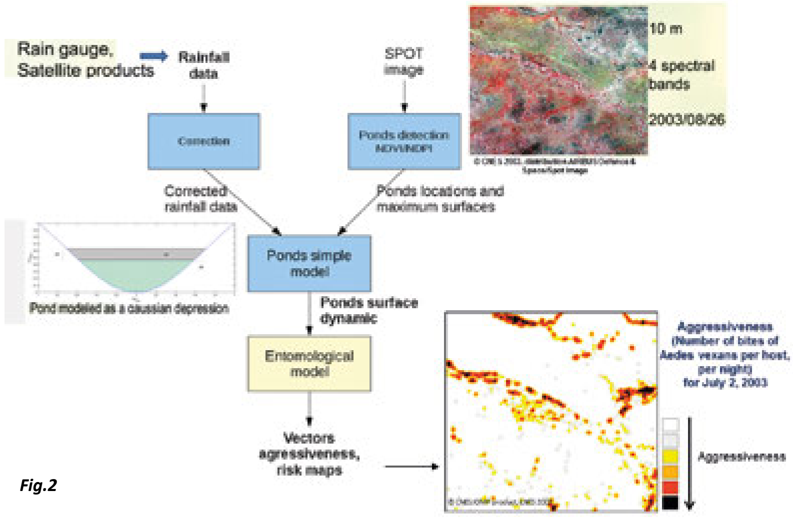

Fig.2

Aedes vexans and Culex poicilipes in the Ferlo region) depending on environmental and weather conditions (especially rainfall), (ii) virus circulation, (iii) the contact of infected vectors with cattle (host).

Satellite data have been used to identify the environmental and weather conditions which foster mosquito vector development. Here, the dynamics of ponds where hosts and vectors can be in contact must be detected and observed because they are the breeding sites of mosquitoes infected with RVF during the rainy season. Entomological studies have shown that the abundance of these vectors in the Ferlo region is directly related to the dynamic of ponds, which is itself associated with rainfall time-space variability. Therefore, rainfall distribution and spatial heterogeneity is a key parameter in the emergence of mosquitoes.

The assessment of the risk of cattle exposure to mosquito bites required the following three steps:

- Detection of temporary ponds based on SPOT-5 satellite images at 10 m spatial resolution. Nearly 1 300 ponds were identified in the study area (45 km x 45 km).
- Dynamic modelling of Zones Potentially Occupied by Mosquitoes (ZPOM) with mechanisms linking rainfall variability, pond dynamics, and mosquito density. Environmental data (presence/absence of ponds) from SPOT-5 images and meteorological data (rainfall from in situ and satellite data including TRMM, GSMaP, RFE CMORPH, PERSIANN) were used to set up a model with hydrological and entomological components (Fig. 2). This model called ZPOM produces dynamic maps with high spatial (10 m) and temporal (daily) resolution, to predict the aggressiveness risk (number of bites per host and per day) of mosquitoes infected with RVF.
- Crossing, through a GIS, the ZPOMs (vector hazard) with parked livestock positioning (vulnerability of hosts) to assess the environmental risk, *i.e.*, the risk of cattle exposure to mosquito bites.

The Directorate of Veterinary Services is then able to integrate this information into its adaptative strategy for animal health management. It includes parking livestock away from risk areas and organizing anti-vector control, vaccination, and a communication strategy towards the affected population. The transfer of this new decision-making tool to Senegalese actors for future operational use, is expected by the end of 2016.

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