Variation and uncertainty in MERIS sensor land biophysical variables at global scale

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by

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Abstract

Because of the fine spectral and spatial resolution, improved atmospheric correction, wide geographical cover, and three-day repeat cycle, MERIS has become a valuable sensor for capturing measurements and monitoring of terrestrial environments at regional and global scale, and accordingly two land biophysical variables has been designed specifically for MERIS sensor, MERIS Terrestrial Chlorophyll Index (MTCI), and MERIS Global Vegetation Index (MGVI), those variables are routinely available and have been used in optional applications, also they play an important role in ecosystem modelling and environmental studies and contribute to our understanding of biogeochemical fluxes and global climate. Hence, Proper usage of such products requires that the corresponding uncertainty information needs to be provided, furthermore, qualitative and quantitative accuracy assessment and quantifying uncertainty of these products is becoming more mandatory, but they have not been examined at global scale before. Therefore, this study aimed to quantify the uncertainties that corresponds to MTCI and MGVI at global scale using various statistical methods to provide further understanding on the sensitivity of these variables in preparation for the launch of the new sensor Ocean and Land Color Instrument (OLCI) on board of Sentinel-3 mission which is scheduled to be launched by late 2015. The study used BELMANIP2 network of sites to conduct homogenous spatio-temporal intercomparison between MERIS variables, using monthly global composites of MTCI and MGVI from 2002-2012 to investigate the variations in the MTCI and MGVI distribution for each biome of the 8 main biome classes of the earth's according to the study classification (Bare, Cropland, Deciduous broadleaf, Evergreen broadleaf, Needle leaf, Grassland, Shrubland, and Mixed forest) across the globe. The methodology consisted of (1) pre-processing of different datasets to match the original imagery and prepare for the intercomparison; (2) processing and statistical analysis of the corresponding time series datasets; (3) explore space-time intercomparison of these products at global scale; (4) correlation analysis between MERIS products and air surface temperature as independent mean to evaluate MTCI and MGVI products. The results revealed a good spatial distribution agreement between both of MTCI and MGVI between different vegetation seasons, the temporal stability investigation displayed a clear temporal continuity of both products with well-defined seasonality of each biome, the temporal consistency in MGVI tend to be more stable over the study period. The global latitudinal distribution between both products showed very reasonable results, both products covered up to relatively higher latitudes in the northern hemisphere in the month

of July than January, while the situation was reversed for the southern hemisphere. The high latitudes in the northern hemisphere triggered more correlation between MERIS products than the southern hemisphere which had very low correlation agreement between both variables. Using the temperature as a climate factor to evaluate MERIS products behaviour globally has been very useful, as it has demonstrated very realistic agreement between MGVI and MTCI towards the temperature of having the products to be more temperature dependant in the northern part of the globe than in the southern part.

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Acronyms and abbreviations

MERIS **ME**dium **R**esolution **I**maging **S**pectrometer
MTCI **M**ERIS **T**errestrial **C**hlorophyll **I**ndex
MGVI **M**ERIS **G**lobal **V**egetation **I**ndex
ESA **E**uropean **S**pace **A**gency
EO **E**arth **O**bservation
FAPAR **F**raction of **A**bsorbed **P**hotosyntheticlly **A**ctive **R**adiation
TOA **T**op **O**f **A**tmosphere
BOA **B**ottom **O**f **A**tmosphere
NetCDF **Net**work **C**ommon **D**ata **F**orm
HDF **H**ierarchical **D**ata **F**ormat
XML **E**xtensible **M**arkup **L**anguage
ENVISAT **ENVI**ronmental **SAT**ellite
BRDF **B**idirectional **R**eflectance **D**istribution **F**unction
MODIS **MOD**erate-resolution **I**maging **S**pectroradiometer
LAI **L**eaf **A**rea **I**ndex
EVI **E**nhanced **V**egetation **Index**
CEOS **C**ommittee of **E**arth **O**bservation **S**atellite
LPV **L**and **P**roducts **V**alidation supgroup
OLCI **O**cean and **L**and **C**olour **I**nstrument
OTCI **OLCI** **T**errestrial **C**hlorophyll **I**ndex
BELMANIP **BE**nchmark **L**and **M**ultisite **AN**alysisand **I**ntercomparison of **P**roducts

Chapter 1 Introduction

1.1 Background

Many years of published scientific research focused on the spectral changes experienced when vegetation undergoes changes in content of water, pigments, nutrients, and other properties. Earth observation satellites have been demonstrated as uniquely capable of synoptically covering the planet in a cost-effective and repeatable manner, producing data that are ideal to monitor and assess changes in vegetation cover and condition across many spatial and temporal scales. The relationship between spectral measurements and biophysical and chemical variables of vegetation has been defined using both statistical and physical approaches. (Coops, Michaud, Andrew, & Wulder, 2011).

Thru years connoisseurs of remote sensing have come to understand how combinations of the deliberate reflectance properties at two or more wavelengths reveal specific vegetation characteristics, also known as VIs (vegetation indices), and numerous indices have been developed for estimating leaf and canopy properties (Clevers, 2014). The biophysical variables help to determine the actual photosynthetic activity of vegetation, and the Information on the amount and spatial distribution of canopy chlorophyll is important to the study of photosynthetic efficiency, as vegetation covers around 20% of our planet, so definitely all types of plants play key role in all of the biogeochemical processes, such as photosynthesis, net primary production, evapotranspiration, and decomposition are related to the content of chlorophyll, nitrogen, water, lignin, and cellulose in leaves (T. P. Dawson, 2000).

There are nine fundamental that determine the biophysical variables which are, planimetric (x,y) location, topographic bathymetric (x, y, z) elevation, colour and spectral signature of features, vegetation chlorophyll absorption characteristics, vegetation biomass, vegetation moisture content, soil moisture content, surface temperature, and texture of surface roughness (Jensen, 1983), these fundamentals variables affect and urge the vegetation biogeophysical measurements from the satellite imagery like: (1) chlorophyll and nitrogen, (2) vegetation cover fraction and fAPAR, (3) leaf area index, and (4) canopy water content (Clevers, 2014) currently, sufficient maturity has been achieved for the estimation of LAI, fAPAR, the cover fraction, chlorophyll and water contents. Estimates of these variables play an important role in ecosystem modelling and broader environmental studies, contribute to our understanding of biogeochemical fluxes and global climate, and implement operational algorithms for delivering the corresponding products to the user community (Frédéric Baret & Buis, 2008; Vuolo, Dash, Curran, Lajas, & Kwiatkowska, 2012).

There are more than 150 vegetation biophysical variables that can be directly estimated from optical remote sensing observations (Verrelst, Koetz, & Schaepman, 2004), with emphasis on using vegetation indices that used to infer canopy biophysical variables, such as leaf area index (LAI), chlorophyll content (Cab), daily fraction of photosynthetically active radiation (fAPAR) absorbed by the vegetation, and the cover fraction (fCover), which are involved in important physical and/or physiological processes, vegetation cover (FVC), and Gross Primary Production (GPP). ENVIronmental SATellite (Envisat) which is the board that carried MERIS sensor, exposes 27 of these indices which were selected based upon their robustness, scientific basis, and applicability, they are intended for use in geographically mapping relative amounts of vegetation components, which can then be interpreted in terms of ecosystem conditions. For example the MEdium Resolution Imaging Spectrometer (MERIS) and the Moderate Resolution Imaging Spectroradiometer (MODIS), demonstrate enriched spectral and temporal resolutions, with improved atmospheric correction and wide geographical coverage. However, these sensors represent significantly different ranges of spectral wavelengths even though they have the same spatial resolution, the narrow spectral bands of MERIS covering a small range of the electromagnetic spectrum and the broad spectral bands of MODIS covering a considerably large region(Simp & Remoto, 2007).

The availability of data from MODIS and MERIS at a fine temporal resolution have contributed towards the wide usage of remote sensing data for diverse global applications (Jeganathan, C., Ganguly, S., Dash, J., Friedl, M., and Atkinson, 2010). Nevertheless, the increasing availability of time series data from 2000 from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, as well from other satellites, such as ENVISAT, has developed the inspiration to extend techniques that originally developed for MODIS biophysical data, to other sensors (Coops et al., 2011). Also, for practical reasons (e.g., obtaining sufficient cloud-free coverage on a seasonal basis), global vegetation monitoring is based on low resolution (1 km) data, which is the spatial resolution for most of MERIS and MODIS products, and that composes those tow sensors

and their biophysical variables to be most suitable for environmental management and modelling studies.
The vegetation indices (VIs) from Medium or moderate resolution imaging sensors provide consistent, spatial and temporal comparisons of global vegetation conditions that will be used to monitor the Earth's terrestrial photosynthetic vegetation activity for phonologic, change detection, and biophysical derivation of radiometric and structural vegetation parameters (Alfredo Huete, Chris Justice, Wim van Leeuwen, 1999; Clevers, 2014). There is two criteria for the design of a chlorophyll index using satellite data first, it should be easy to calculate from the sensor data recorded at the standard band setting and second, it should be sensitive to a wide range of chlorophyll contents (J Dash & Curran, 2004 , 2007).

Accordingly, there is vegetation indices that has been designed and calculated from MODIS data like the normalized difference vegetation index (NDVI) (MODIS-NDVI is referred to as the ‘‘continuity index’’ to the existing 30+ year NOAA-AVHRR-derived NDVI) and enhanced vegetation index (EVI), both are produced at 1-km and 500-m resolutions and 16-day compositing periods. Different studies has approved that the dynamic range of the MODIS VIs are presented and their sensitivities in discriminating vegetation differences are evaluated in sparse and dense vegetation areas, Whereas the NDVI is chlorophyll sensitive, the EVI is more responsive to canopy structural variations, including leaf area index (LAI), canopy type, plant physiognomy, and canopy architecture (Huete et al., 2002; Simp & Remoto, 2007; Alfredo Huete, Chris Justice, Wim van Leeuwen, 1999).

However, the narrow bands along with the short re-visiting time of MERIS make it possible to derive more accurate global maps and more effective vegetation indices than have previously been available, also for the reason of the fine characteristics of MERIS sensor, there was two vegetation variables designed for MERIS which are MTCI and MGVI (described detail fully in chapter two (literature review)). The MTCI appeared to be the most suitable index for the estimation of chlorophyll content with MERIS data after it has been applied to several species using data from laboratory and field and for each of these data there was strong positive relationship between MTCI and chlorophyll content. MERIS Terrestrial Chlorophyll Index (MTCI) is the MERIS Bottom Of Atmosphere (BOA) Vegetation Index and can be used to determine the physiological status of the vegetation. The MTCI L2 product is calculated using three red/near infrared bands of Envisat MERIS data and represents the amount of chlorophyll per unit area of ground which is related to the photosynthetic rate. It does not have a theoretical maximum value, but practical values range from 0 to about 4.2. (NEODAAS, 2014). While, MERIS global vegetation index (MGVI) is computed as a polynomial function of the rectified red and NIR reflectance. Basically, the useful information on the presence and state of vegetation is derived from the red and the near-infrared spectral band measurements. MGVI appears to reveal more information on the status of terrestrial surfaces than does the NDVI. This is due to a gain in the spatial contrast associated with a much lower noise on the computed index values, MERIS Global Vegetation Index (MGVI) is the MERIS Top Of Atmosphere (TOA) Vegetation Index and can be used to assess the presence on the ground of green vegetation. The MGVI Level 2 product is calculated using three MERIS bands (blue/red/near infrared) and corresponds to the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). It has a practical range of 0 to 1 (Zurita-Milla et al., 2009 ; Gobron, Pinty, Verstraete, & Govaerts, 1999).

1.2 Research problem

The term uncertainty refers to lack of knowledge about specific parameters, models, or factors (USEPA 1997). The definition of the retrieval algorithm performance and actual validation exercises are required to assess the uncertainties required by any assimilation system dealing with global issues (N Gobron et al., 2008). However, there is still unreducible uncertainties lies in the products that derived from satellites sensors data due to the retrieval algorithm, input data quality and sensor calibration issues (Fang et al., 2012; S. F. Almond, 2009; Curran & Dash, 2005a). Evaluation of product accuracy is a very difficult task, particularly regarding the global extent of most of the satellite products, their kilometric spatial resolution, as well as the dynamics of the vegetation (Marie Weiss, Baret, Garrigues, & Lacaze, 2007).

The number of the land products that derived from satellite sensors is increasing by time, that is causing mystification to the user community in choosing the most appropriate product to their desired application, also the number of applications that are using sensors derived products are increasing, therefore qualitative and quantitative accuracy assessment for this products is becoming more mandatory. Although modelled vegetation spectra and initial evaluation have demonstrated a strong relation between MERIS land biophysical variables identical to MTCI and MGVI, still those variables need full validation if it is to be embraced by the user community who require precise and consistent, spatial and temporal comparisons of vegetation condition (S. F. Almond, 2009). Proper usage of such products requires that the corresponding uncertainty information needs to be provided for the reason that uncertainty information of MTCI and MGVI is important for global modelling studies but usually difficult to systematically obtain at a global scale (Fang et al., 2012).

Despite attempts to validate these satellite derived products at multiple field sites, there lies amount of uncertainties in these products. For example the initial MTCI design and investigation process removed non-vegetated pixels from MERIS scenes (Curran and Dash, 2005). As a result of this process the effect of non-vegetated areas has not been considered. As an operational product, an understanding of the effect of non-vegetated areas on the MTCI is of vital importance to permit the successful interpretation of scene properties (S. Almond, 2009). Also both algorithms has limitations that can be found in details in (Curran & Dash, 2005 ; N. Gobron et al., 2004).

In all, research inspecting the variation and uncertainty of different biomes on global scale is scarce. However, understanding of how these uncertainties and variation occurs in different land biomes is very important to tree breeder, entomologist, physiologist, and ecologist. Therefore, this study attempt to quantify these uncertainty at global scale using various statistical methods to provide further understanding on the sensitivity of these variables in preparation for the launch of Sentinel 3 mission. Monthly global composites of MERIS products from 2002-2012 were used to investigate the annual and inter-annual variations in the MTCI and MGVI distribution for each biome.

1.3 Research relevancy

For different properties and field conditions, some indices provide results with higher validity than others. By comparing the results of different VIs, and correlating these to field conditions measured on-site, you can assess which indices do the best job of modelling the variability in your scene. Biophysical variables estimates are generally integrated within other process models such as hydrology or biogeochemical cycling along with other ground observations, therefore quantification of the associated uncertainties is required to properly merge these several sources of information (Frédéric Baret & Buis, 2008). Repetitive accurate physical measurements are necessary in order to quantify surface processes and to improve the understanding of vegetation seasonal dynamics and responses to environmental stress (esa, 2006).

In consequence, quantifying land products in general and for this study for MERIS products in particular comes from the need of providing the uncertainty information of MTCI and MGVI that corresponds to the main key biome classes on the earth, which is important for global modelling studies but usually difficult to systematically obtain at a global scale, also investigating the temporal stability for MTCI and MGVI on global scale, and providing qualitative and quantitative accuracy assessment.

The European space agency (ESA) has for long focused on research instruments, but is now developing five new missions called Sentinels specifically for the operational needs of the Copernicus program (previously known as GMES) (Clevers, 2014). This all comes as part of the preparation for launch of these two missions (Sentinel 2 and 3). Considering that biophysical variables driven approaches are very flexible, For example, estimates of biophysical variables from one sensor could be used to constitute the training data base for another sensor (Frédéric Baret & Buis, 2008). Hence, the performance of MERIS biophysical land variables need to be fully understood and its effectiveness to provide robust measures of canopy chlorophyll content explored, to generate consistent products between sensors. Therefore, Validation of MERIS land variables is also important across a range of vegetation types, spatial scales and different environmental conditions.

For the launch of the Ocean and Land Color Instrument (OLCI) onboard the Sentinel-3 this purpose a great potential and stimulus to go on with investigating MERIS capabilities to help assure data continuity and to encourage the use of OLCI data also for land applications like monitoring of vegetation dynamics over multi-decade time periods (Tüshaus, Dubovyk, Khamzina, & Menz, 2014). Sentinel3 mission will provide continuity of existing missions, giving sea and land data same as MERIS data quality, ensuring continuity of the MERIS measurements. Sentinel-3 has Ocean Land Color Instrument OLCI which is a push-broom type imaging spectrometer like MERIS, it was evaluated on their capability of retrieving relevant biophysical parameters using simulated top-of-atmosphere radiance data, in the study carried by (Verrelst, Rivera, Alonso, Lindstrot, & Moreno, 2012) it was demonstrated that OLCI datasets leads to improved biophysical parameter retrieval.

1.4 Research objectives

The main objectives for this study is the evaluation of MERIS products MTCI and MGVI at a global scale, and to quantify the uncertainty for the earth's key biomes at global scale to provide further understanding on the sensitivity of these variables in preparation for the launch of sentinel 3 mission.

1.4.1 Specific objectives

1. Estimate (construct) MTCI & MGVI distribution for each biome on the network of sites (BELMANIP2) at a global scale over 10 years 2002-2012
2. Compare MERIS products variation on the network of sites at global scale and identify the factors affecting their agreement or disagreement
3. Investigate the temporal stability (consistency, continuity) of these MERIS vegetation products over relatively homogenous sites
4. Evaluate (assess) the global correlation of MERIS land products among themselves and between climatic variable

1.5 Research questions

1. Can we link the MTCI-MGVI distribution trend over the study time?
2. Which of the indices can better explain the variation in its distribution?
3. How does the MTCI-MGVI correlate?
4. Does different biomes influence the correlation between the MTCI-MGVI?
5. Is there any significant anomalies in the indices distribution over time? And if yes is it influenced by the biome type?
6. Does the indices achieves the temporal stability over time?

1.6 Materials and data

MERIS products are available at different product levels. The highest level, 3, combines daily products into a time composite product that is more spatially uniform as it contains all valid data in a time composite over a defined period (Pinty et al. 2002). This study focuses on the uncertainty of the land biophysical variables derived from Envisat MERIS sensor. The study required different datasets for the purpose of the inter-comparison between MERIS land biophysical variables MTCI and MGVI. The study as well used updated version of the network of sites BELMANIP2, GLOBCOVER2009, and temperature data.

1.6.1 MERIS Terrestrial Chlorophyll Index (MTCI)

In this study, MERIS Terrestrial Chlorophyll Index (MTCI) 2002-2012 of 8-day and 10-day composite time series data with spatial resolution of (4.6 km) were use, MTCI is only available, operationally, at a medium spatial resolution (300 m), each image consist of three bands, the three bands are mean, standard deviation and count, the mean is the first band. In detail, per the MTCI data set used for this study, from 2003 to 2007 the MTCI is collected at an 8-day composite interval. And then from years 2008-2011 the MTCI is collected at 10-day composite interval. For each MTCI composite collection, whether 8-day or 10-day is considered as one (1) band. Thus, in a normal case, the 8-day composites collected until 2008, each year should have forty-six (46) bands (Table 1). And in the case of the 10-day composites, each year should have thirty-six bands (36). By reviewing the downloaded folders, these MTCI products are in latitude-longitude gridding and a GEOTIFF format. Additionally, when downloaded they come along with XML metadata file and a JPEG browse image. The MTCI dataset is consist and can be found from one source:
ftp://l3server.infoterra.co.uk/pub/global/MTCI_BIN/.

1.6.2 MERIS Global Vegetation Index (MGVI)

The data set that has been used for MGVI has temporal coverage from 2002-06-1 to 2012-04-01 at monthly interval. Each monthly image stored in the directory has four files HDF, NETCDF, XML and JPEG image. Spatial Coverage: 90 N, 90 S, 180 W, 180 E, Data Type: Optical/Multi Spectral Radiometry Low/Medium Resolution, Horizontal Resolution Range: 1.2 Km x 1.2km resampled in a "pseudo satellite" projection along track, the data used in the study are the compressed

NetCDF format files, it had many variables associated with each file, the study used the mean fAPAR variable. The data can be found at the following directory: http://earth.eo.esa.int/ml3/mgvi-plc/2002/

1.6.3 Land cover map, GLOBCOVER 2009

Global land cover map will be used for the indices comparison on global scale, from ESA GLOBCOVER project 2009, GlobCover Land Cover is a global land cover map collected by European Space Agency MERIS sensor hosted in its Envisat space- borne satellite at full resolution mode of 300m. It is further characterized by a geographic coordinates in a Plate-Carrée projection (WGS84 ellipsoid). Also, have a spatial coverage in the neighbourhood of 90°N, 180°W to upper left corner and 90°S, 180° to the lower right corner (see http://due.esrin.esa.int/globcover). And the classification is based on the UN Land Cover Classification System (LCCS). This GlobCover2009 Land Cover product was used to identify the spatial locations of the 8 main biomes classes of the earth according to this study classification, the map and its description and validation report can be found at: http://due.esrin.esa.int/globcover/.

1.6.4 CPC Global Surface Air Temperature

Monthly global surface air temperature (climate grids) dataset at 0.5 degree, from 2002-2011 has been used in this study. The unit for the temperature is (C), averaged monthly in Tif format. Illustrated from the data source that "The data sets is routinely updated around 8th of each month. Raw spatial resolution & Coverage: 0.5 deg lat x 0.5 deg lon; -89.75S -- 89.75N; 0.25E -- 359.75w". Available from 1948 till 2011 as monthly composite 912 image per year, the data set is also available at T126, T62 and 2.5x2.5 resolutions in this directory: ftp://ftp.cpc.ncep.noaa.gov/wd51yf/GHCN_CAMS/.

1.6.5 BELMANIP2 network of sites

(BEnchmark Land Multisite ANalysis and Intercomparison of Products) BELMANIP2 is an updated version of the BELMANIP network that has been built up by (Baret et al., 2006) which contain 445 site, it was built using the GLOBCOVER vegetation land cover map derived from MERIS images in 2009. The sites were homogeneous over a 10x10km² area, almost flat, and with a minimum proportion of urban area and permanent water bodies in addition to some sites resembling to bare soil areas (deserts) and tropical forests.

BELMANIP2 is used to analyse EO land products missing data (spatially and temporally), site temporal profiles, the smoothness of the products, as well as the temporal and spatial stability of the products (M Weiss, Baret, Lacaze, Block, & Koetz, 2012).

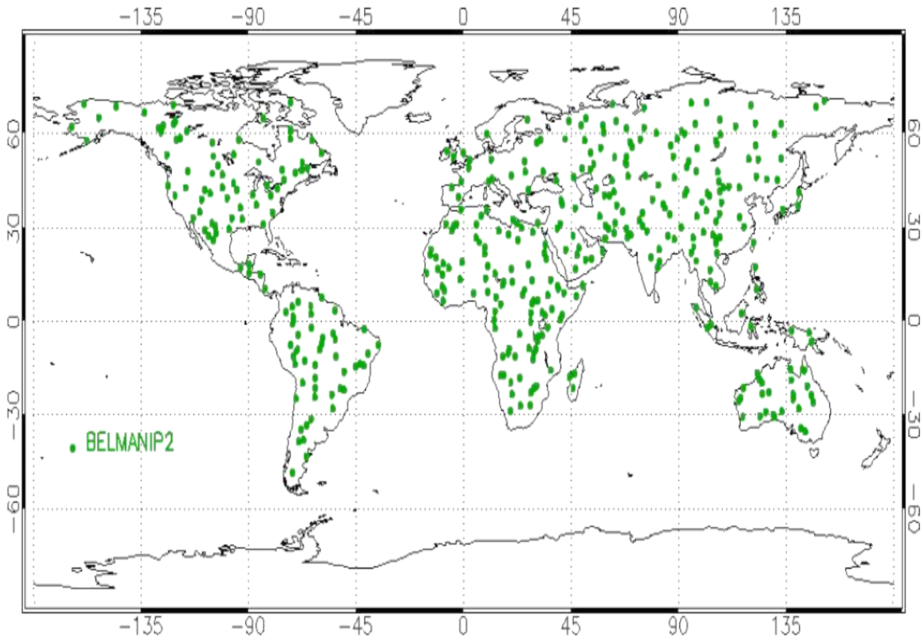

Figure 1 BELMANIP2 445 sites global distribution

The above map (figure 1) and the needed data for the network of sites can be found here: [http://calvalportal.ceos.org/web/olive/site-description.](http://calvalportal.ceos.org/web/olive/site-description)

- BELMANIP2 and DIRECT site lists can be download in Excel file format indicating site latitude and longitude for both datasets, name, web site and bibliographic references if they exist for the DIRECT sites).
- The ground validation values are provided. Values of measured variable (Leaf Area index, FAPAR, FCOVER) are provided as an average value over the 3kmx3km area represented by the site.
- Google Earth files (kml) BELMANIP2 and DIRECT site can be downloaded.

1.7 Research scheme

The work in this study has been conducted according to the following scheme.

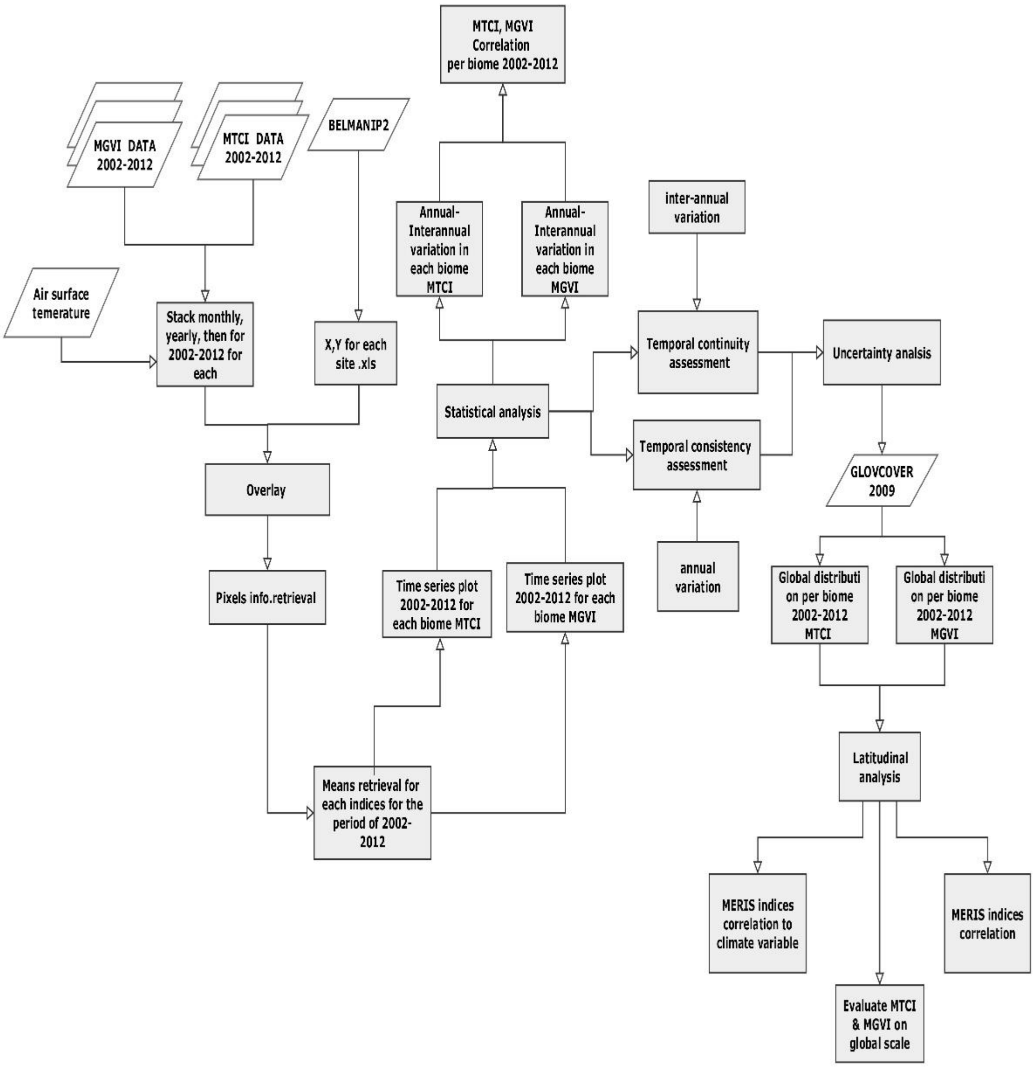

Figure 2 study workflow diagram

Chapter 2 Literature review

2.1 Land remote sensing

The "land remote sensing" era was initiated in 1972 when the first Landsat satellite, at that time known as Earth Resources Technology Satellite, was launched at Vandenberg Air Force Base in California. Since then, Earth observation satellites have revolutionized the way that scientists, politicians and the general public view the Earth. Land remote sensing data is used for deriving information like land cover maps or continuous maps on, for instance, vegetation properties. A number of applications such as forecasting weather conditions, forecasting crop yield, mapping urban areas, monitoring natural resources or addressing emergencies would not be possible without Earth observation satellites (Raúl Zurita-Milla, 2008). Monitoring vegetation dynamics gives valuable information on the condition of an ecosystem, and remote sensing can provide the necessary spatial and temporal explicit data for a continuous monitoring(Zhou & Wang, 2007). Continuous spatial information about vegetation growth and phenology is a potentially pivotal input to modelling primary productivity, biomass and natural carbon dynamics (Atkinson, Jeganathan, Dash, & Atzberger, 2012). The Remote sensing with the use of airborne or space borne spectrometers offers the potential for estimating foliar biochemical content by using methods originally developed for laboratory spectroscopy studies (T P Dawson, Curran, North, & Plummer, 1999). Compared with the direct field based sampling of chlorophyll content these remote sensing approaches are less labor-intensive, non-destructive, and offer the possibility of repetitive coverage (J. Dash, Curran, & Foody, 2009).

2.2 Benchmark Land Multisite ANalysis and Intercomparison of Products (BELMANIP)

The Committee Earth Observing Satellites (CEOS) group, Land Product Validation (LPV) supgroup, had the mission of defining standard guidelines and protocols, and cultivating data and information exchange relevant to the validation of land products since 2000 (Morisette et al., 2006). Under the observation of CEOS-LPV in 2006 the BELAMNIP network proposed as a benchmark for intercomparison of land biophysical products for first time as gathering sites from other validation networks sites such as FLUXNET, AERONET, ECOCLIMAP, and DIRECT, this initial network of BELMANIP was 397 sites with an area of 3x3km², this products intercomparison network has no limitation on spatial sampling and works with the same temporal sampling as the products, it also offers consist estimation of vegetation cycle that could be of importance for the intercomparison between satellite products as well as evaluating their accuracy on the long term. Correspondingly used for Inter-comparison between existing EO land product, it also contribute in the development of new products from past and new sensors (AVHRR archive, Sentinel 3), as well Validation against ground measurements. BELMANIP2 network of sites has been designed with limited number of homogenous sites that has no topographic effects, which make computing biome proportion of earth's surface statistics (missing data, temporal smoothness, and stability) manageable and feasible. This network of sites has been validated and used in many pervious study but on a shorter term (only few years) than this study and a smaller scale (Garrigues et al., 2008; S. F. Almond, 2009; Baret et al., 2007; Zhu et al., 2013; Morisette et al., 2006; F Baret & Weiss, 2010).

After using this set of sites in various studies, scientists have come to conclusion that BELMANIP1 has some drawbacks like deficiency in some sites as some sites that has been extracted from ARONET network are so close to urban areas, while some sites that extracted from FLUXNET are not homogenous, also observed that the network over the high latitude has excessive representation, whereas it has under-sampling for grassland and evergreen broadleaf forests (M Weiss et al., 2012).

In attempt to overcome the drawbacks from BELMANIP1 network of sites, BELMANIP2 has been proposed on special necessities as minimizing the urban and water bodies presence, extent to a limited number of sites to allow the possibility of analysis results, and to make sure has no topographic effects by reduction of size site to extent that can still allow computing of statistical analysis (M Weiss et al., 2012; Frédéric Baret et al., 2006). Depending on those requirements the BELMANIP2 has been built using GLOBCOVER2009 derived from MERIS images, aimed to represent the overall variability of vegetation types and climatological conditions at the Earth surface, BELMANIP2 consist of 445 homogenous 10x10km² sites. From different studies that has used BELMANIP2 it has been noticed that the Biome representativity and site Homogeneity has been enhanced after following the recommendations for BELMANIP2.

The study that has been carried by Frédéric Baret et al., 2007 has concluded that by using BELMANIP network the current version 3 of CYCLOPES products have been validated by comparison to ground measurements and inter-comparison to other products, and the results from their companion paper (Marie Weiss et al., 2007) indicated that the intercomparison between CYCLOPES and MODIS by using BELMANIP has helped in performing consistency of during comparison, and also stated that "The validation exercise can be used to evaluate other products or future versions of the same products and contribute to associate quantitative uncertainties as required by the user community".

Also, (Frédéric Baret et al., 2006) study where BELMANIP2 network of sites has been used to evaluate LAI and FAPAR, has concluded that using suitable approaches to conduct intercomparison between land biophysical products over BELMANIP2 sites is recommended. The same study has also indicated the benefits of BELMANIP that this type of representative network of sites could be used for validation and intercomparison of any biophysical product such as albedo or chlorophyll content, can be also used during the product calibration process, and will provide to the users quantitative evidence of the performances of the products over a very large range of conditions. (Zhu et al., 2013) have used BELMANIP2 in their research to validate and assess the effectiveness of long term global datasets of (LAI)3g and (FPAR)3g, also to test the suitability of this datasets to be used in other research disciplines, the results was very satisfying for the operated scientists. While, (Garrigues et al., 2008) used BELMANIP2 to investigate the performance of four global Leaf Area Index LAI CYCLOPES, MODIS, ECOCLIMAP, and GLOBCARBON, by intercomparing all four products spatially and temporally.

2.3 Uncertainty

2.3.1 EO products uncertainty

Among all the results, however, large variations occur and depend on the canopy type as well as on the atmospheric conditions and angular situations, the task of acquiring field measurements for validation exercises presents a range of challenges that vary in difficulty from one site to the other. Atmospheric radiative processes, absorption and scattering, affect measurements made by space-borne satellites (Nadine Gobron et al., 1999). Radiometric cross calibration of Earth observation sensors is a crucial need to guarantee or quantify the consistency of measurements from different sensors. It is a key element when analysing differences between products that are derived from measurements of different sensors (Lachérade, Fougnie, Henry, & Gamet, 2013). Obviously, the larger the uncertainties of the spectral bands, the larger the uncertainties in EO land products, and most of uncertainties caused by absorbed radiation of some gases can be avoided by choosing the narrow spectral bands in designed EO products. The actual validation exercise is performed in two steps including, first, an analysis of the accuracy of the algorithm itself with respect to the spectral measurements uncertainties and, second, with a direct comparison of the indices time series against ground-based estimations as well as similar indices products derived from other optical sensor data (N Gobron et al., 2008).

Two categories of product uncertainty information have been developed, theoretical and physical. Theoretical uncertainties are caused by uncertainties in the input data and model imperfections and are usually estimated by individual product science teams (Frédéric Baret et al., 2007). Physical uncertainties indicate the departure of product values from hypothetical true values and are obtained through independent validation studies, such as that coordinated by the Committee on Earth Observation Satellites (CEOS) Land Product Validation (LPV) community (Fang et al., 2012), it is mandated to coordinate and standardize international validation activities (Weiss et al., 2007).

2.3.2 Sources of uncertainty

The sources of uncertainty may vary due to solar and sensor geometries, surface directional reflectance, topography, atmospheric absorption and scattering, sensor electrical- optical engineering interact in complex surface measurements, calibration errors (e.g., sensor spectral calibration, even though MERIS has two specific spectral bands in the oxygen-A absorption region (channels 10 and 11), the oxygen absorption is extremely narrow, and small variations of the spectral wavelength of each pixel have a large impact on any variable derived from the oxygen-A.

In the study carried out by (O'Connor, Dwyer, & Cawkwell, 2013) the following information about uncertainty sources in Earth Observation products has been documented "Molecules of nitrogen and oxygen gas in the atmosphere cause Rayleigh scattering, the intensity of which increases at shorter wavelengths, e.g. in the blue spectrum of visible light, oxygen, ozone, other trace gases and water vapour result in signal absorption while aerosols can cause both scattering and absorption, in addition, instrument precision, calibration and off-nadir viewing create deviations in observations unrelated to vegetation dynamics". The pervious mentioned reasons along with the clouds considered to be the main reasons for delivering not accurate reflectance measurements and the gaps occurs between time series data from satellite products, also responsible for the changes that strike when applying similar index algorithm to different sensors, and the noise that can be caused by atmospheric elements like aerosols.

Fortunately, the spectral shift on the MERIS response has been well characterized (Gómez-chova et al., 2007), residual atmospheric, cloud contamination, back ground underneath the canopy (e.g., bright soil or snow cover), view-illumination geometry affects (e.g., bidirectional effects), understory vegetation and litter, canopy structure and closure and the uncertainty concern the applicability of the algorithm to range of vegetation types and environmental conditions (S. Almond, 2009; Garrigues et al., 2008; Friedl et al., 1995). Also the Errors in field measurements and error in laboratory analysis leads to uncertainty (J. Dash et al., 2010). Hence, If measurement uncertainties coming from the sensor are reasonably well known, their structure (covariance between bands and directions for example) is usually poorly documented, also another critical issue is the lack of previous information on the distribution of most land surface characteristics (Frédéric Baret & Buis, 2008).

The combined effects of time compositing and temporal smoothing of VI time series inevitably add uncertainty to studies of vegetation seasonality from remotely-sensed data (O'Connor et al., 2013). Remote sensing products associated uncertainty could be characterize by proper validation of the products before delivering to the user community according to agreed protocols from stakeholders. Also, this study by Fang et al., 2012 where it has carried uncertainty analysis between global MODIS, CYCLOPES, and GLOBCARBON LAI using triple collocation method TCM, stated that "Reasons for the different uncertainties may be due to differences in biome types, input surface reflectance, and canopy models used in each retrieval algorithm", and that Uncertainty estimates are lowest in arid regions, such as western North America, Southern Africa, mainland Australia, or Central Asia.

2.4 MERIS: Medium Resolution imaging spectrometer

MEdium Resolution Imaging Spectrometer (MERIS) exhibit enhanced spectral and temporal resolutions, wide geographical coverage and improved atmospheric correction. It created a new area of research for the use of earth observation and demonstrates new potentials and challenges for assessing the state of the global climate system. We show that 1) analysis of geophysical parameter time series provide relevant information on terrestrial surfaces states and changes 2) actual assimilation of land products opens a new research area in earth system modelling 3) temporal updates of regional and global land cover maps at the highest resolution is possible using only MERIS data. Images collected by those sensors should help addressing the challenges of automatic land cover classification of broad geographical areas. Moreover, affirm that the availability of a large number of spectral bands makes it possible to identify more detailed land cover classes with higher accuracy (Carrão, Sarmento, & Araújo, 2007; Nadine Gobron et al., 2012).

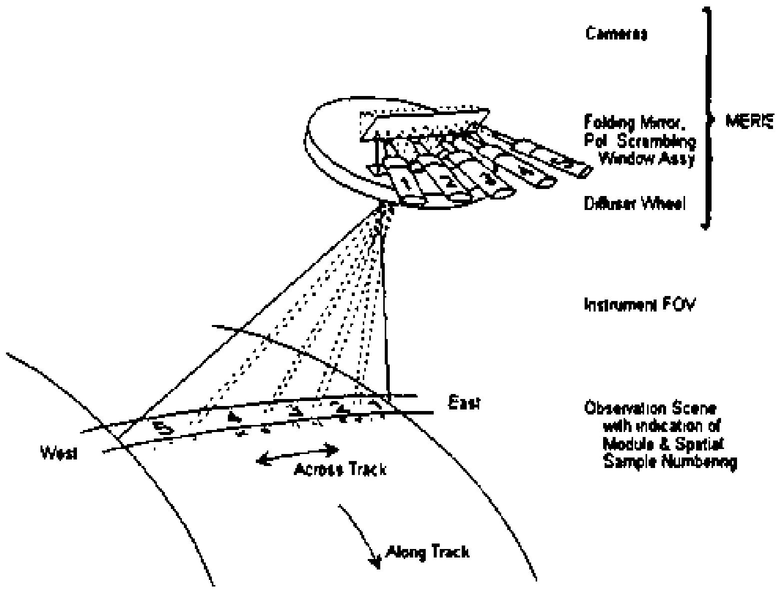

Figure 3 MERIS push-broom principle with five cameras, scanning the earth's surface. (Picture from: ESA)

The instrument consists of 5 identical cameras arranged in a fan shape configuration that together provide a 68.5° field-of-view (equivalent to 1150 km of swath width at nadir) Because of its fine spectral and moderate spatial resolution and three-day repeat cycle, MERIS is a valuable sensor for the measurement and monitoring of terrestrial environments at regional to global scales. In the standard band setting, it has eve discontinuous wavebands in red and near-infrared (NIR) wavelengths with band centers at 665 nm, 681.25 nm, 708.75 nm, 753.75 nm and 760.625 nm.

MERIS is an imaging spectrometer on board of the ENVISAT satellite has been set in the orbit orbit by the European Space Agency on the 1st of March 2002, it fulfils the information gap between the current high and low spatial resolution sensors. It is radiometrically the most accurate imaging spectrometer in space (J. Dash & Curran, 2004 ; Zhou & Wang, 2007). However, despite its enhanced spatial, spectral and temporal resolutions, MERIS is still not able to fully capture the variability present in typical European landscapes. Medium spatial resolution images of heterogeneous and highly fragmented landscapes contain a significant number of mixed pixels (Raúl Zurita-Milla, 2008). MERIS scans the Earth's surface by the so called 'push-broom' method and the design is such that it can acquire data over the Earth whenever illumination conditions are suitable (N Gobron et al., 2008). It operates in the reflective solar spectral (passive sensor) range (390 nm to 1040 nm) with 15 spectral bands within the visible and near infrared range, each capable of gathering data of ground resolution element at full spatial resolution is 300 m along track but across track it is 260 m at nadir to 420 m at the swath edge.

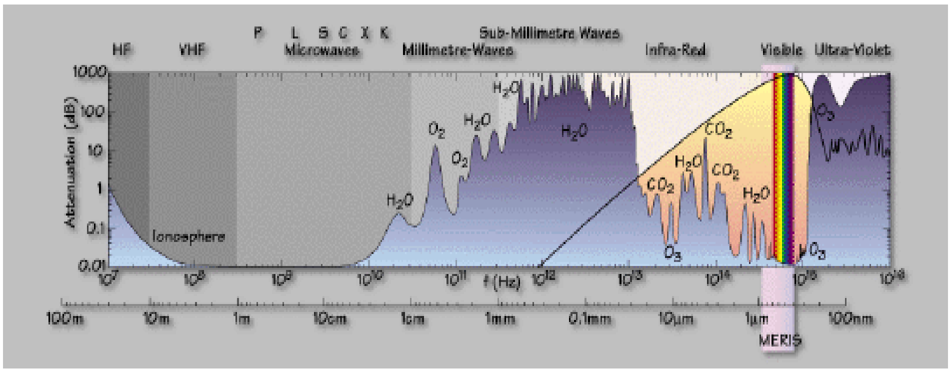

Figure 4 electromagnetic spectrum indicating dataset measured by MERIS (esa, 2006)

The Medium Resolution Imaging Spectrometer (MERIS), part of the European Space Agency's (ESA) Envisat mission, operates in 15 programmable wavebands (2.5 - 20 nm wide) in the 390 nm - 1040 nm region with spatial resolutions of 300 m and 1200 m. Because of its high radiometric resolution, relatively fine spectral resolution, moderate spatial resolution and three day repeat cycle, MERIS is potentially a valuable sensor for the measurement and monitoring of terrestrial environments at regional to global scales (J Dash & Curran, 2007b). Compared with the direct field based sampling of chlorophyll content these remote sensing approaches are less labor-intensive, non-destructive, and offer the possibility of repetitive coverage (J.Dash, Curran, & Foody, 2009).

Property	Description
Geometric	
Field-of-view	68.5⁰ cantered around nadir
Swath Width	1150 km
Localization accuracy	400m (no use of land mark)
Spatial resolution	Full resolution (FR) 300m – Reduced resolution (RR) 1200m
Spectral	
Band-to-band registration	<0.1 FR pixel
Spectral range	390-1040 nm
Spectral sampling interval	1.25 nm
Spectral resolution	1.8 nm
Band transmission capacity	15 bands programmable in Width and position
Radiometric	
Band width	programmable from 1.25 nm up30nm
Radiometric accuracy	<2% in reflectance
Dynamic rang	up to bright clouds (100%reflectance)
Single-to-noise ratio	1650:1 at 412.5 nm

Table 1 Properties and descriptions of the Envisat MERIS sensor, (Dash and Curran, 2007)

According to ESA MERIS product handbook, the sensor has three mission that can be summarized as following:
"1) Ocean mission, the principal contributions of MERIS data to the study of the upper layers of the ocean are the estimation of photosynthetic potential by detection of phytoplankton (algae), the detection of yellow substance (dissolved organic material) and the detection of suspended matter. In addition, investigations of water quality, the monitoring of extended pollution areas, and topographic observations (such as coastal erosion), should also be possible.
2) Atmospheric mission, the radiation balance of the Earth/atmosphere system is dominated by water vapour, CO_2, and clouds, as well as being dependent on the presence of aerosol. However, the global monitoring of cloud properties and their processes, is not yet sufficiently accurate. MERIS is intended to help redress this balance by providing data on cloud top height and optical thickness, water vapour column content, and aerosol properties.

3) Land mission, questions related to global change include the role of terrestrial surfaces in climate dynamics and biogeochemical cycles. Spatial and temporal models of the biosphere are currently being developed to study the mechanics of such complex systems in order to predict their behaviour under changing environmental conditions." (esa, 2006). Hence, the primary mission of MERIS is the measurement of sea colour in the oceans and in coastal areas. Knowledge of sea colour can be converted into a measurement of chlorophyll pigment concentration, suspended sediment concentration and of atmospheric aerosol loads over water. Its land mission is to study the role of terrestrial surfaces in climate dynamics and biogeochemical cycles for climate change (Raúl Zurita-Milla, 2008; Zhou & Wang, 2007; L. Bourg, L. D'Alba, 2008; ESA, 2006; J. Dash & Curran, 2004).

MERIS primary data products include calibrated instantaneous radiance estimates in each waveband at both full (300m) and reduced (1200m) spatial resolution. The secondary products include a number of geophysical and biophysical products over land, ocean, and atmosphere. MERIS data are available at three levels of processing. Level 1 data are top of the atmosphere radiances, level 2 data are atmospherically corrected top-of-canopy reflectances, as well as geophysical and biophysical products and level 3 data are derived products (e.g. mosaic of fraction of photosynthetically absorbed radiation (fPAR)) (J. Dash et al., 2007). However, mainly devoted to the ocean colour remote sensing allowing better understanding of the terrestrial carbon cycle and the interactions between biosphere and climate. It provides data with a spectrally enhanced configuration and with a quasi-daily global coverage revisit time of two to three day (Zurita-milla et al., 2011), programmable in width and position.

2.4.1 Calibration of MERIS

Sensor calibration is a method of improving sensor performance by removing structural errors in the sensor outputs (VectorNav, 2015). There are two types of calibration and associated operational scenarios: 1) Radiometric calibration is performed every two weeks using diffuser one. A monitoring of the degradation of the BRDF of diffuser one is performed every three months by deploying diffuser two and comparing the results. 2) Spectrometric calibration is performed every three months by first performing a radiometric calibration with an appropriate band settings for the spectral calibration under consideration, and deploying the erbium-doped diffuser with the same band settings on a second orbit. Two erbium spectral absorption features are used, one in the green and one in the NIR Additionally, a high-precision spectrometric calibration for the O2A absorption bands is performed by exploiting the shape of the absorption band (esa, 2006).

An accurate full radiometric calibration of any sensor is essential because it will potentially minimize the main sources of uncertainties and errors and it will make the data more suited for quantitative and multi-temporal applications. Consequently, a good radiometric calibration is a prerequisite for a correct use of the remotely sensed data (Zurita-Milla, Clevers, Schaepman, & Kneubuehler, 2007). From a strict point of view, all the radiometric corrections should be applied to the data so that the retrieval of quantitative information can be done with the highest possible quality.

The use of fully radiometrically corrected data will also facilitate multi-temporal comparisons. Therefore, a systematic application of all relevant calibration parameters will increase the long term comparability of MERIS measurements in such a way that more emphasis can be put on the retrieval of MERIS products (Raúl Zurita-Milla, 2008). The on-board radiometric calibration is designed to validate the instrument radiometric performance while MERIS is in operation. It is executed every two months when Envisat is flying over the South Pole and it consists of observing a well characterized Spectralon panel illuminated by the sun. These observations are then used to update the absolute calibration coefficients (esa, 2006).

2.5 MERIS Land products

The actual status of vegetation is represented by its spectral signature and generally characterized by a low reflectance in red and a high reflectance in near infrared. This specific feature of phenological photosynthetic active vegetation is used to calculate different vegetation indices (Klein & Menz, 2005). Retrieving leaf chlorophyll content at a range of spatio-temporal scales is central to monitoring vegetation productivity, identifying physiological stress and managing biological resources (Croft, Chen, & Zhang, 2014).

Many algorithms have been developed for the remote estimation of biophysical characteristics of vegetation, in terms of combinations of spectral bands, derivatives of reflectance spectra, neural networks, inversion of radiative transfer models, and several multi-spectral statistical approaches. However, the most widespread type of algorithm used is the mathematical combination of visible and near-infrared reflectance bands, in the form of spectral vegetation indices (Viña et al., 2011). Vegetation indices exploit the fact that live green vegetation strongly absorbs solar radiation in the red spectral band and strongly scatters it in the near- infrared (NIR) band. Monitoring and Modelling the vegetation dynamics using different multi- sensor approaches, analysed seasonal and inter-annual vegetation dynamics using vegetation indices other uses for vegetation indices could be forecasting crop yield, assessing habitat destruction and studying epidemics. (Zurita-Milla et al., 2009; Zhou & Wang, 2007; Nadine Gobron, Pinty, Verstraete, & Govaerts, 1999).

To date a number of land products have been successfully derived from MERIS as the characteristics of the MERIS fused images have used to compute two vegetation indices: the MERIS terrestrial chlorophyll index (MTCI) and the MERIS global vegetation index (MGVI). These indices represent continuous fields of canopy chlorophyll (MTCI) and of the fraction of photosynthetically active radiation absorbed by the canopy (MGVI). However, the spatial resolution provided by this sensor is not sufficient to accurately map and monitor heterogeneous and fragmented landscapes, the two indices are level 2 MERIS data products. Consequently, the ratio MTCI/MGVI is approximately equal to chlorophyll concentration Chlorophyll concentration= MTCI / MGVI (Zurita-Milla, Kaiser, Clevers, Schneider, & Schaepman, 2009 ; Jeganathan, Dash, & Atkinson, 2010). In the standard band setting, it has eve discontinuous wavebands in red and near-infrared (NIR) wavelengths with band centres at 665 nm, 681.25 nm, 708.75 nm, 753.75 nm and 760.625 nm.

Band Number	Centre (nm)	Width (nm)	Environmental variables of interest
1	412.5	10	Yellow substance turbidity
2	442.5	10	Chlorophyll absorption
3	490	10	Chlorophyll, other pigments
4	510	10	Turbidity, suspended sediment, red tides
5	560	10	Chlorophyll reference, suspended sediment
6	620	10	Suspended sediment
7	665	10	Chlorophyll absorption
8**MTCI,	681.25	7.5	Chlorophyll fluorescence
MGVI	708.75	10	Atmospheric correction
9*MTCI	753.75	7.5	Oxygen absorption reference
10*MTCI	760.625	3.75	Oxygen absorption R-branch
11	778.75	15	Aerosols, vegetation
12	865	20	Aerosols correction over ocean
13*MGVI	885	10	Water vapour absorption reference
14	900	10	Water vapour absorption, vegetation
15			

*bands used to calculate MTCI   * bands used to calculate MGVI

Table 2 MERIS band properties adapted from Curran and Steele (2005)

The characteristics of the MERIS fused images have used to compute two vegetation indices specifically designed for MERIS: the MERIS terrestrial chlorophyll index (MTCI) and the MERIS global vegetation index (MGVI). These indices represent continuous fields of canopy chlorophyll (MTCI) and of the fraction of photosynthetically active radiation absorbed by the canopy (MGVI) (Zurita-Milla, Kaiser, Clevers, Schneider, & Schaepman, 2009 ; Jeganathan, Dash, & Atkinson, 2010). The MERIS Global Vegetation Index (MGVI) product is related causally to leaf area index (LAI) and the MERIS Terrestrial Chlorophyll Index (MTCI) product is related causally to chlorophyll content (a combination of LAI and leaf chlorophyll concentration).

2.5.1 MERIS Terrestrial Chlorophyll Index (MTCI)

The MERIS terrestrial chlorophyll index (MTCI) developed by Dash and Curran and used by the European Space Agency as a MERIS level-2 product appeared to be the most suitable index for the retrieval of chlorophyll content from MERIS data and showed the highest correlation levels with leaf chlorophyll in a comparison based on laboratory and field measurements in corn and wheat canopies. The MTCI is designed to exploit the spectral reflectance in red-edge wavelengths and is particularly sensitive to the changes in chlorophyll content associated with primary productivity. The MTCI is positively related to the total chlorophyll content of vegetation, which in turn is a product of the chlorophyll concentration (amount of chlorophyll per unit area) and LAI. (J. Dash et al.,2007).

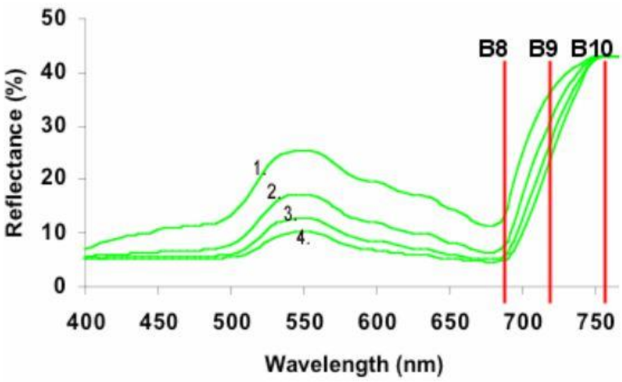

Figure 5 vegetation reflectance spectra of MERIS bands used to calculate MTCI

MERIS Terrestrial Chlorophyll Index (MTCI) is a ratio of the difference in reflectance between band 10 and band 9 and the difference in reflectance between band 9 and band 8 of the MERIS standard band setting. The MTCI is more sensitive to high chlorophyll content and less sensitive to spatial resolution and atmospheric effects than the red-edge position. The MTCI is computed as follows:

$$MTCI = \frac{R_{Band\ 10} - R_{Band\ 9}}{R_{Band\ 9} - R_{Band\ 8}} = \frac{R_{753.75} - R_{708.75}}{R_{708.75} - R_{681.25}}$$

Where R753.75, R708.75, R681.25 are reflectance in the centre wavelengths of band 8, 9 and 10 the top of atmosphere (TOA) reflectances of the MERIS bands. The MTCI appeared to be a most suitable index for the estimation of chlorophyll content with MERIS data as it has been applied to several species using data from laboratory and field and for each of these data there was strong positive relationship between MTCI and chlorophyll content. As a result the MTCI became an official MERIS level 2 product of the European Space Agency in March 2004 (J Dash & Curran, 2004 ; J. Dash et al., 2009; Zurita-Milla et al., 2009). 2014 study on estimating leaf chlorophyll density has confirmed that, the MTCI index is the best chlorophyll density estimator, is nonlinearly related to REP and is more sensitive to the changes in high chlorophyll contents. Also mentioned that literature indications of a non-negligible RMSE of MTCI chlorophyll estimates at early growth stages, related to the optical properties of bare soils, are confirmed by results of the analysis of synthetic data (Vincini, Amaducci, & Frazzi, 2014). However, it was found that the MTCI was sensitive to crop type, thus requiring re- parameterization of the algorithms for estimating Green LAI of vegetation with different canopy architectures and leaf structures. Therefore, a priori knowledge of crop type would be required for a successful application of the MTCI for Green LAI estimation in different crops types (Viña et al., 2011).

2.5.2 MERIS Global Vegetation Index (MGVI)

Given that vegetation responds to changes in the availability of nutrients and other environmental conditions through its photosynthetic capacity, vegetation productivity should be related positively to foliar chlorophyll content (Boyd et al., 2012). The APAR is derived as a product of the fraction of photo- synthetically active radiation absorbed by the canopy (i.e. fAPAR) and represents the available light energy for plant productivity and is the key variable influencing photosynthesis, transpiration, and energy balance in most carbon exchange models that known as production efficiency models of the PEMs, PAR range between 400–700 nm (Ogutu et al., 2014). The MGVI is equivalent to fAPAR, the operational MERIS FAPAR products, also called MERIS Global Vegetation Index (MGVI) the purpose of it is to identify and monitor the presence of live green vegetation over all types of terrestrial surfaces on the basis of data from the MERIS instrument, It is calculated using a combination of the blue, red and near-infrared (NIR) bands. The blue band makes the index more accurate and stable concerning external influences, the index has been designed to minimize the geometric distortion effects, atmospheric and background effects, and to maximize the correlation to the fraction of absorbed photosynthetically active radiation (FAPAR) (Klein & Menz, 2005; Nadine Gobron et al., 1999).

Provides a dynamic correction to help reduce the impact of the atmospheric and angular effects, and modelled to produce a top of canopy reflectance observed under standard illumination and geometries. However, MERIS was designed to acquire data whenever the illumination conditions are suitable the MGVI retrievals are considered valid only for sun zenith angle lower than 60°, a threshold set by the limitations of the RT model (Coops, Michaud, Andrew, & Wulder, 2011; N Gobron et al., 2008). The top of canopy reflectance is then optimized using a radiative transfer model to minimize additional influences such as soil back- ground and values are constrained so that the MGVI is as close as possible to the fAPAR associated with the plant canopy (Coops et al., 2011). There is three ingredients required to estimate MGVI: dataset of calibrated reflectances, a series of appropriate coefficients and a set of mathematical functions (Nadine Gobron et al., 2004). The MGVI has a positive linear relationship with the fraction of absorbed photosynthetically active radiation by the canopy (fAPAR). This index is computed using the TOA reflectance in three MERIS bands, blue (band 2), red (band 8) and near-infrared-NIR-(band 13). The following formula is simplest documented in the literature to describe Where $f0$ is the polynomial function and $\rho_{r68,} \rho_{r86}$ are the rectified reflectance values of bands 8 (680.9 nm) and 13 (864.8 nm).

$$\text{MGVI}= f0\ (\rho_{r68,}\ \rho_{r86}\ )$$

MGVI appears to reveal more information on the status of terrestrial surfaces than does the NDVI. The algorithm's data inputs are the calibrated MERIS L1 data in the blue (442 nm), red (680 nm) and near-infrared (865 nm) bands as well as the illumination and observation angles. In order to generate rectified bands between the latter two wave lengths, this "recitation" is done in such a way to minimize the differences between the rectified bands and the spectral reflectances that would be measured at the TOC under a standard illumination and observation geometry. The spectral index, MGVI, is generated on the basis of this rectified bands. The methodology adopted to design this algorithm relies on physically-based radiative transfer models to remove the angular, atmospheric and soil background contamination effects. This is due to a gain in the spatial contrast associated with a much lower noise on the computed index values (Zurita-Milla et al., 2009; Gobron, Pinty, Verstraete, & Govaerts, 1999; Nadine Gobron et al., 2004; Nadine Gobron et al., 2007).

The following requirements has been considered in retrieving the algorithm 1) the index should be sensitive to the amount of live green vegetation on the surface 2) To offer excellent discrimination capabilities, to distinguish various targets types 3) The performance of the index should be independent from the spatial resolution 4) The actual estimation of the numerical values of the index should require minimal computation 5) It should not be sensitive to atmospheric scattering, absorption effects, soil colour and brightness effects 6) Should not be sensetive to temporal and spatial variations in the geometry of illumination and observation. Also the MGVI has some limitation such as the vegetation characteristics in hilly or mountainous regions may or may not be very reliable, but studies has confirmed that it reveal more information on the status of terrestrial surfaces than other indices like NDVI, that is due to a gain in the spatial contrast associated with a much lower noise on the

computed index values (Nadine Gobron et al., 1999a; N Gobron et al, 2004; O'Connor, Dwyer, & Cawkwell, 2013).
In general MERIS Global Vegetation Index (MGVI) has improved geometric error correction, atmospheric interference reduction and greater sensitivity to seasonal vegetation dynamics than other existing indices such as NDVI (O'Connor et al., 2013).

2.6 MERIS Land Applications

MERIS land biophysical products has been used and validated in different applications, and that wide use of those products emphasis the need of assessing and quantifying the associated uncertainties of MGVI and MTCI. Some of the land applications that has been used MERIS products are land cover mapping and monitoring, phenology monitoring, nitrogen estimation, Gross Primary Production "GPP" estimating and Mapping C3-C4 compositions,

2.6.1 Land cover mapping

Data from current medium-spatial-resolution imaging spectroradiometers are used for land-cover mapping and land- cover change detection at regional to global scales. 15 narrow bands, facilitates the use of the most established technique to deal with mixed pixels, the linear mixing model, since the number of land-cover classes that can be unmixed is, in principle, limited by the number of bands. Two-to-three-day revisit time, allows the use of temporal patterns (e.g., vegetation phenology) to discriminate among land-cover types. Depending on the results out from this study the authors mentioned that "confident that the extracted sub pixel information might be of great utility in remote sensing monitoring activities, such as land-cover change detection or retrieval of biophysical parameters from medium-spatial-resolution data acquired over heterogeneous and frequently clouded areas" (Zurita-milla et al., 2011).
Vegetation indices like MTCI, MGVI been used also to enhance the spectral contrast between vegetated and non-vegetated land cover classes, and so may be useful as discriminating variables in classification applications. The ideal dates of MERIS data acquisition for land cover classification should, therefore, be drawn from both the high and low chlorophyll seasons. (J. Dash et al., 2007). MEdium Resolution Imaging Spectrometer (MERIS) exhibit enhanced spectral and temporal resolutions, wide geographical coverage and improved atmospheric correction. Thus, images collected by those sensors should help addressing the challenges of automatic land cover classification of broad geographical areas. Moreover, affirm that the availability of a large number of spectral bands makes it possible to

identify more detailed land cover classes with higher accuracy than would be possible with data from elder sensors (Carrão et al., 2007).

2.6.2 Phenology

ESA's MEdium Resolution Imaging Spectrometer (MERIS) sensor and several other sensors at a fine temporal resolution have contributed towards the wide usage of remote sensing data for diverse global applications and, in particular, for studies of phenology (Jeganathan, C., Ganguly, S., Dash, J., Friedl, M., and Atkinson, 2010).

The phenological cycle, as well as the effect of climate change on vegetation phenology, is species- and location-dependent. This means that global averages have limited value locally, and it is important to describe space–time changes in phenology. Long time series of FAPAR at global scale therefore provide the needed information to monitor plant phenology (Nadine Gobron & Verstraete, 2009). Also Dash et al. (2008) observed that the signal-to-noise ratio of temporal vegetation profiles from MTCI was significantly greater than the SNR of equivalent NDVI curves. Utilized time-series MTCI data to estimate phenological parameters for vegetation (Atkinson et al., 2012).Based on different studies for Zurita-Milla he confirms that, the possibility of downscaling MERIS FR images creates new opportunities to monitor vegetation dynamics (phenology) at high spatial, spectral and temporal resolution. Sub-pixel MTCI and MGVI time series can be computed from the fused images and accurate temporal profiles can be derived for individual vegetation patches or agricultural fields. These profiles can subsequently be used for a number of applications like crop yield estimation, net primary production mapping or parameterization of vegetation models(R. Zurita-Milla et al., 2009; Raúl Zurita-Milla, 2008).

2.6.3 Nitrogen estimation

According to (Ullah et al., 2012) they stated that "This study indicated that MERIS has the potential of monitoring grassland conditions over time. It is demonstrated that band depth analysis parameters (BDR, BNA, and NBDI) estimated green biomass more accurately than vegetation indices such as SAVI, NDVI and TSAVI. Although the estimation of nitrogen concentration was poor but the nitrogen density was predicted with reasonable accuracy. This study showed that band depth analysis parameters are accurate predictor of nitrogen density compared to MTCI and REIP. The successful estimation of green biomass and nitrogen density at two different time data indicate that MERIS data could be used to the monitor the condition of grassland.

2.6.4 GPP estimation

The chlorophyll content, as estimated using MTCI, is able to drive simple models to estimate GPP in contrasting land cover types when there is a detectable temporal change in chlorophyll concentrations. Moreover, due to the sampling rate of the MERIS sensor this could be achieved at a spatial resolution of 1km. The MTCI offers an alternative approach to the use of spectral indices for the estimation of GPP, and is a primarily function of the physiology of the vegetation as well as its structure. Further investigation. Further work is required to establish the physical basis for these relationships (S. Almond et al., 2010). Chlorophyll content appears a most relevant community property for estimating primary productivity, and chlorophyll- related indexes provide favorable approximations of GPP of vegetation, the MTCI is designed to exploit the spectral reflectance in red-edge wavelengths and is particularly sensitive to the changes in chlorophyll content associated with primary productivity. Envisat MTCI, which is strongly related to canopy chlorophyll content, can be used to drive simple models in order to estimate GPP across a range of ecosystems; this is particularly successful when there is a seasonal variation in photosynthetic capacity (thus temporal pattern in chlorophyll content) (Boyd et al., 2012).

2.6.5 Mapping C3-C4 compositions

Knowledge of the relative proportion of C3 and C4 grasses and its spatial variation can, therefore, be important for studies such as those that seek to model major biosphere–atmosphere exchanges and predict the impacts of environmental change on ecosystems. MTCI has been used to indicate a potential to derive estimates of the C3–C4 composition of grasslands from satellite sensor data. In particular, simple measures based on the temporal variation in the spectral response (Foody & Dash, 2007). With both the MTCI and cumulated MTCI values, the strongest relationship with the compositions was generally obtained at a relatively early date in the growing season. With the known phenology of the species involved, with C3 grasses growing more rapidly than the C4 grasses in the spring leading to enhanced MTCI values (Foody & Dash, 2010).

Chapter 3 Methods and analysis

3.1 Methods

The data used in the study has been processed and analysed according to the frame work shown in figure 6.

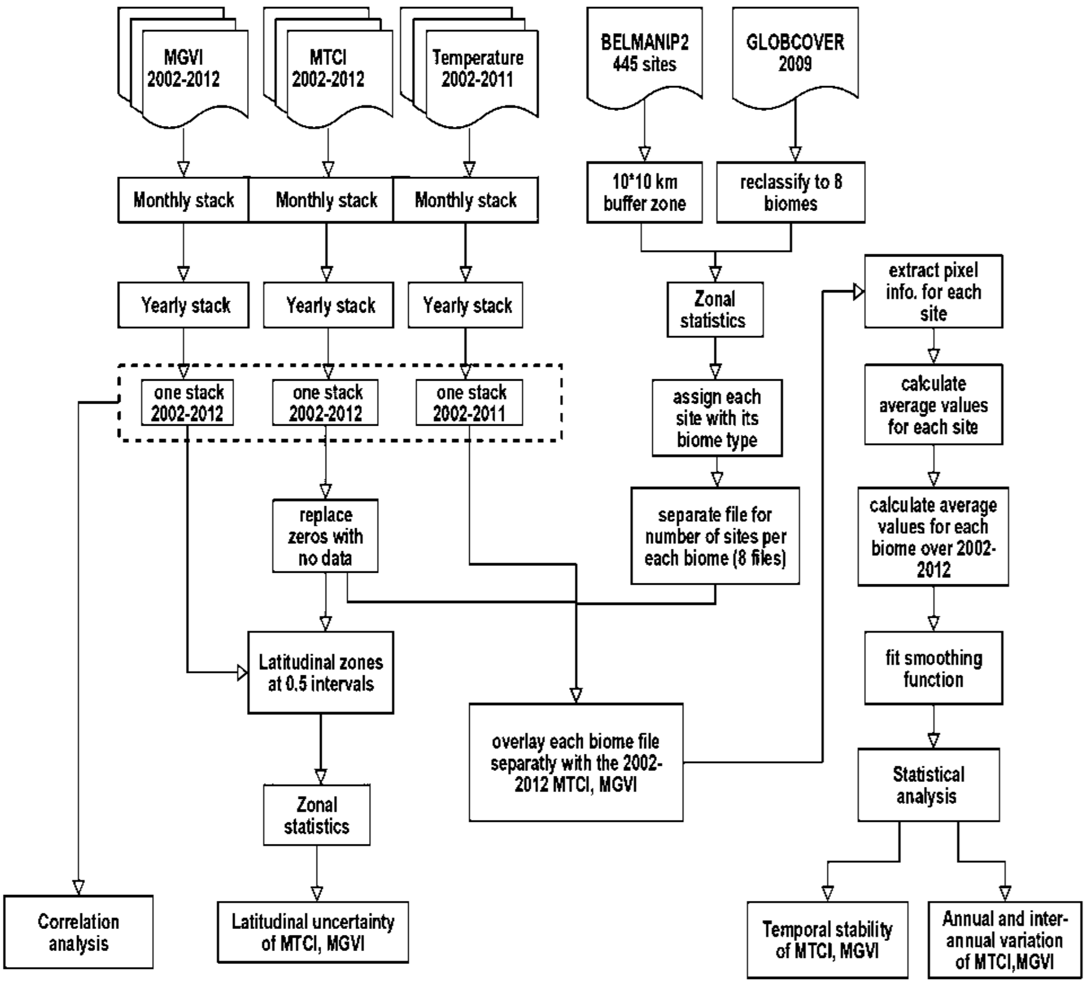

Figure 6 stages of data processing/ analysis followed in the study

3.2 Pre-processing and analysis

3.2.1 BELMANIP2 and GLOBCOVER2009

Globcover2009 map has been used to assign the land-cover type for each site, it was first reclassified from 15 land-cover classes to only 8 main classes (Biome) excluding water bodies and the sites that contain >60 % water, the 8 biomes were classified as following (Bare, cropland, grassland, shrub land, evergreen broadleaf, deciduous broadleaf, evergreen needle leave, and mixed forest). The sites has been grouped per biome and a separate file has been created for each biome as following:

Biome	No. of sites out of BELMANIP2
Bare	83
Cropland	109
Deciduous broadleaf forest	36
Evergreen broadleaf forest	55
Needle leaf forest	47
Grassland	64
Mixed forest	37
Shrubland	8
Excluded (water contained >60)	4

Table 3 Number of sites per biome from BELMANIP2 network of sites

For the BELMANIP2 network of sites previous studies has suggested that 10*10 km2 would be ideal to represent a relatively homogenous land cover surrounding each site, relatively homogeneous in terms of both vegetation type and growth stage (Weiss, Baret, Garrigues, & Lacaze, 2007, Baret et al., 2006), accordingly, a buffer zone of 10*10 km2 has been built around each site. Since the referencing system of BELMANIP2 network is GCS-WGS1984 latitude dependant, the buffer zone around the sites not strictly the same area size but relatively close.

Each of those biome classes has been overlaid with the 10 year stack image of different data sets that been used in the study (MTCI and MGVI, also temperature data) separately to extract the pixels values for each site. The number of pixels that cover each site has varied according to the site area size which was differentiated according to site distance from the latitudes under the geographic projection, and also depended on the different datasets resolution, this has not affected the study as only the overall averages values for each group of sites per biome has been used.

3.2.2 MTCI

The pre-processing of MTCI has been done mainly by two steps, first stacking, then smoothing. Initially, the 8 days composite and 10 days composite of MTCI data has been chronically stacked into monthly files then as yearly files over the 10 years 2002-2012 this created nearly cloud free final image for the 10 years life time of MERIS sensor, showing the maximum greenness, and to ensure best temporal resolution. Besides The technique of compositing data for 8 or 10 days considerably reduces noise in the surface reflection signal. The MTCI values have been checked for each site per biome type for the BELMANIP2 445 set of sites. While calculating the mean values for the biomes the zero values have been excluded during the first attempt of the smoothing process. Usually by using satellite sensor data the inevitable first step is to convert noisy temporal input vegetation index data into a smooth time-series (Atkinson et al., 2012).The study used The Savitzky—Golay smoothing on MTCI time seris data, the filter has been fitted to the MTCI global data as shown in figure 7, for each of the main 8 biome for the study. The parameters were adjusted interactively in the TIMESAT software for each biome to arrive at closely fitting results.

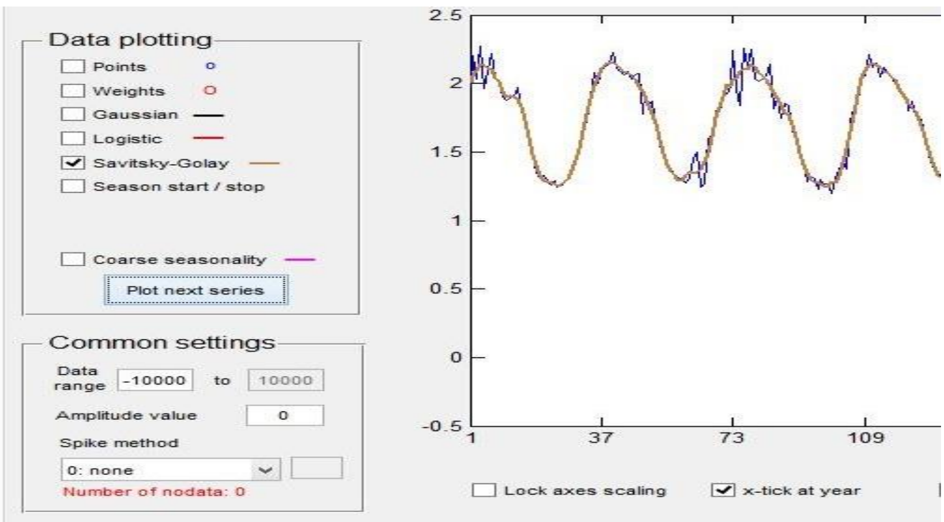

Figure 7 MTCI using Savitzky-Golay smoothing filter

In figure 7, the blue line represent the noisy MTCI behaviour over one biome extracted from BELMANIP2 network of sites for three years, while the brown line represent Savitzky-Golay best fitted line for those MTCI values which models seasonality in the time series. This filter avoid the running averages problems like widening peaks. However, it sustains the smoothing of data and preserving features of the distribution such as relative maxima, minima and width (Luo, Ying, & Bai, 2005). Also a resampling process has been done to MTCI dataset.

3.2.3 MGVI

ESA (European space agency) provided the dataset for MGVI. Please refer to chapter one of this paper for its full description. A number of pre-processing steps has been performed on the row MGVI data that has been provided by ESA to prepare it for the inter-comparison analysis. NetCDF file has been downloaded on a monthly interval for the period of 2002-2012, then annual composites contain monthly average of MGVI has been created. The original data has to be flipped and geo-referenced to get to the usual global images extent of -180E, 180W, -90S, 90N before analysis can be conducted. Each of the provided image contain several variables. According to the XML file associated with the data, in order to get the true fapar value the following equation has to be applied (value=offset+code*gain) where gain=3.937008e-03, and offset=-3.937008e-03, while the code is the current values for the images, this equation has been applied to the final stack image that used to extract biomes pixel informations. After correcting the images, the pixel information for each of the BELMANIP2 sites has been extracted and grouped per biome class as previously mentioned in table3.

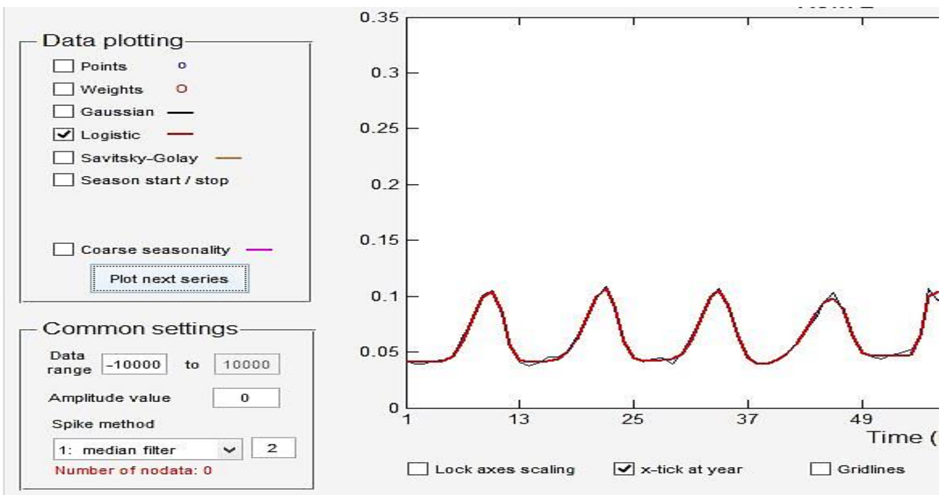

Figure 8 MGVI using logistic smoothing filter

Simple logistic smoothing filter has been applied to MGVI final data, MGVI data in general did not have much noise, and the smoothing filter has performed best fit with keeping the index features, and that was the criteria that smoothing filter type has been chosen upon for both indices.

3.2.4 Air Surface Temperature

For temperature data, the international research institute for climate and society- Colombia, has a free online data library which has different datasets, this was useful to analyse the correlation behaviour over BELMANIP2 sites between MTCI and one of the climate factors which is the temperature for its importance in determine different vegetation cycles, as well as the vegetation dynamic effect surface temperature on the long term. The surface air temperature has been retrieved from the library, the temperature data come as global images on monthly interval has the monthly mean values for surface air temperature, which has been made into annual composite as part of the standardization process to match the different datasets to prepare for the intrcomparison analysis. Then the data extent has been fixed as its extent was covering from 0E to 360W to have extent from -180E, 180W to fit and match with other datasets. And has been analysed for each biome over the BELMANIP2 network of sites in relation to the MTCI index. Initially, MTCI data had resolution of 4,6x 4,6 km2 per pixel, while MGVI had resolution of 0,5x 0,5 km2 per pixel, as a result of the different spatial resolution of each product the number of pixels that covered each site of BELMANIP2 using MTCI (5 or 6 pixels per site depending on the distance from the latitude) was bigger than the number of pixels that covered the sites using MGVI (one or two pixel per site depending on the distance from the latitude). For the performance of the correlation analysis between the three datasets of MTCI, MGVI, and air surface temperature, they were resampled and composited to a uniform of spatial and temporal frequency.

Chapter 4 Results and discussion

4.1 *Global spatial distribution of MERIS land biophysical variables*

For most application users need products that available all the time ideally with no gaps. Due to cloud occurrence, sensor problems or retrieval algorithms failure, the product might not be available all the time (Frédéric Baret et al., 2007). MTCI and MGVI have been designed to be less affected by noise from the atmosphere and soil background. However, providing uncertainty estimates for vegetation index globally is considered to be a challenging task as it requires a large number of comparable values and should cover all major vegetation types and phonological cycle.

MTCI theoretical values range between 1 to 6 and zero values represents noise, for that reason the zero values has been removed and replaced with No Data to display only the valid colocation of the index. For MGVI the theoretical values range from 0 to 1. Figure 6 shows the global cover of the valid values for MTCI and MGVI in the months of January, July respectively in the life time of MERIS sensor from 2002 to 2012.

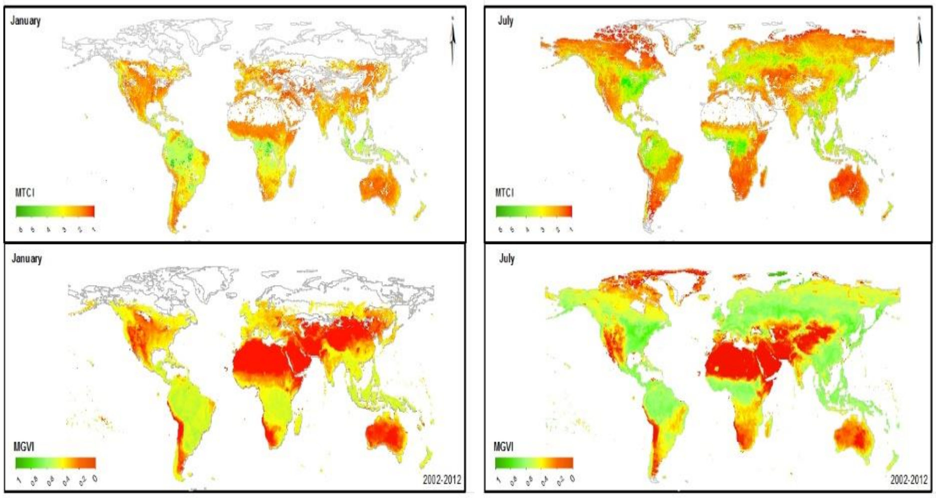

Figure 9 spatial global cover of valid colocations of MTCI and MGVI in January (right panel), July (left panel) respectively from 2002 to 2012

In figure 9, the months of January and July have been chosen as indicator of MERIS land biophysical variables global coverage correspondingly to the winter time and growing season of the vegetation. It shows that the values and coverage for both indices in January happens to be generally lower in the northern hemisphere, while it is relatively higher values in southern Hemisphere especially in the densely vegetated regions below the equator. For MTCI it has been documented in previous studies that it preforms poorly over bare soils which has also been agreed upon in this study, that the MTCI has no presence over any bare land neither in northern nor southern hemispheres, which restricted the index global coverage, and that is normally considered as MTCI is related to the chlorophyll content factor that is absent in bare soils especially in winter times. While MGVI which is related to fAPAR content has represented bare and poor vegetated soils with the lowest nominal value of MGVI, and this has resulted in extending the global coverage of MGVI than MTCI in winter timings.

On the other hand in July the values for both indices are higher in general and covers almost all regions in both northern and southern hemisphere, with peak values of both variables in the densely vegetated regions and mid latitudes in northern and southern hemispheres. Highest MTCI values are typically found in the densely vegetated regions, specifically in the regions with high vegetation chlorophyll content (Tüshaus et al., 2014). MGVI reflects high values in wider areas of the globe. The white areas in the above maps represents No data (no index coverage).

4.2 Temporal stability of MERIS land biophysical variables

Nevertheless, using the BELMANIP2 network of sites that recommended by CEOS/LPV for such global studies provide better sampling for both space and time (Marie Weiss et al., 2007). It represents the overall surface types and climatic conditions behaviour over the globe. In this study, the performance of medium spatial resolution MERIS Terrestrial Chlorophyll Index (MTCI) and Global vegetation index (MGVI) were addressed for homogenous land surfaces. By using BELMANIP2 set of sites, for each site the mean values of both biophysical variables over the 10×10 km² area has been computed to estimate the overall trend of MERIS indices and evaluate its temporal stability over the period 2002-2012 for the 8 main biome classes.

Temporal stability of MERIS land biophysical products has been investigated through two aspects 1) temporal continuity 2) temporal consistency of each product. Temporal continuity investigation is what insure the availability of the particular product ideally with no gaps throughout the produced sensor (MERIS) life time. While, temporal consistency shows the amount of variation of the product values around specific time (month, day) of a year in relation to the overall variation of this product for the whole study time.

4.2.1 Temporal continuity

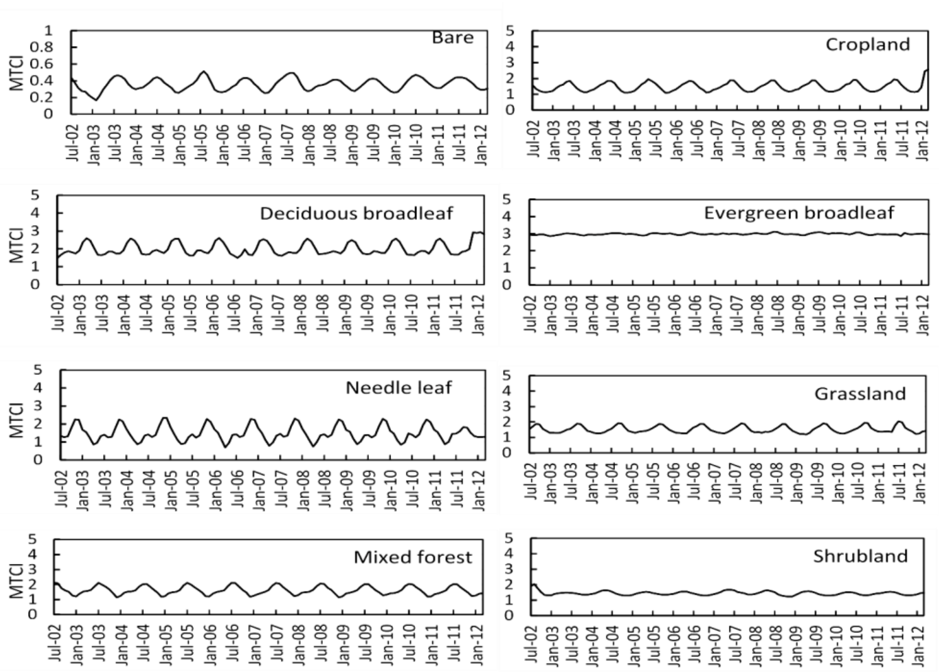

Figure 10 temporal evolution of MTCI for the period of 2002-2012, using BELAMNI2 445 sites (MTCI inter-annual variation)

Land products should generally limit gaps in their time series. Thus, we first evaluate the temporal continuity. Figures 10 and 11 show MERIS MTCI and MGVI as annual average values for the 10 years. The products has displayed good temporal continuity by means of being available all the time throughout the operating life time of MERIS sensor perfectly with no gaps. Taken January and July of each year as example of troughs and peaks of MTCI and MGVI over the years in winter and greening up seasons. In the overall trend for both indices over 10 years, the values for both indices were consistent throughout the years showing clear seasonality for all biomes with significant inter-annual variability and ideal temporal constancy. With an exception of the evergreen broadleaf forest which the seasonality was not represented clearly, both indices displayed a strong seasonality for all the other 7 biomes.

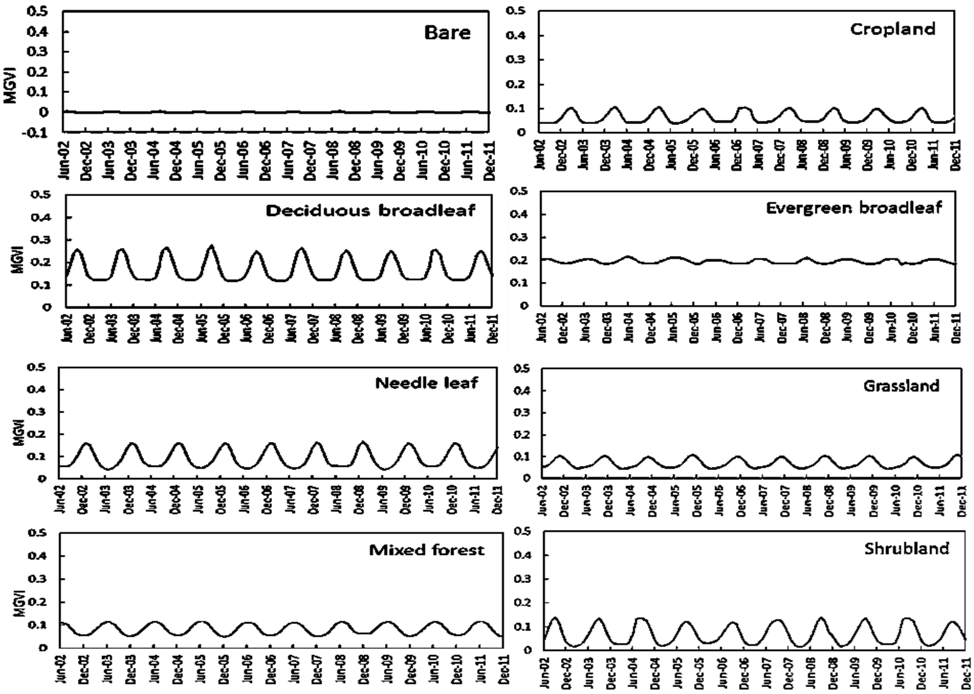

Figure 11 temporal evolution of MGVI for the period of 2002-2012, using BELMANIP2 445 sites (MGVI inter-annual variation)

Besides bare soils that had low MTCI reflectance values between 0.10-0.50, for all biomes MTCI has reflected in the range between 1 and 4. Same for MGVI which had reflectance values for all biomes between the ranges of 0 to 0.3, while only bare biome had constant values of 0 to 0.01 throughout the study time period. The difference of the bare areas reflectance values between the two indices suggested to be a result of chlorophyll that can be contained by some non-vegetated areas and can be detected by MTCI index.

However, from those figures (which qualitatively illustrate the main features observed over the 445 BELMANIP2 sites) all the biomes display relatively strong relationship between seasonality and its phasing, with values that shows the peaks and troughs of MTCI and MGVI for each biome generally consist over the 10 years.
The magnitude of both variables MTCI and MGVI is relatively similar over Grassland, shrub lands, and mixed forest keeping the reflectance's values between 1 and 2 throughout the ten years. While the forests types of evergreen, deciduous, and needle leaf had a higher reflectance's values over the study period between due to high seasonal dynamics of those biome types. Evergreen broadleaf biome type showed high consistency in the overall trend over the study time

as this biome type nature is not affected much by the seasons change between summer and winter times, keeping high values all year around. The temporal profiles for both MERIS MTCI and MGVI time series reflected the clear seasonal vegetation cycles for all biomes, all time.

4.2.2 Temporal consistency

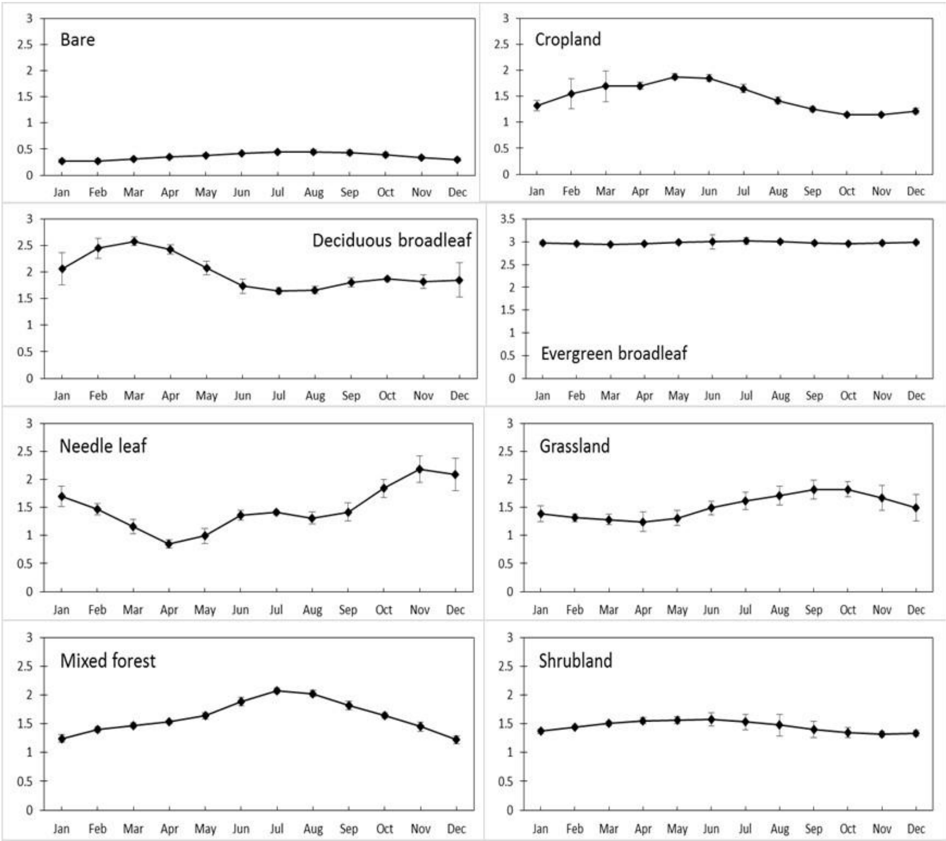

Figure 12 monthly distribution of global MTCI product estimated using BELMANIP2 sites, error bars display the variation of MTCI observation of each month for the period of 2002-2012 (Annual variation)

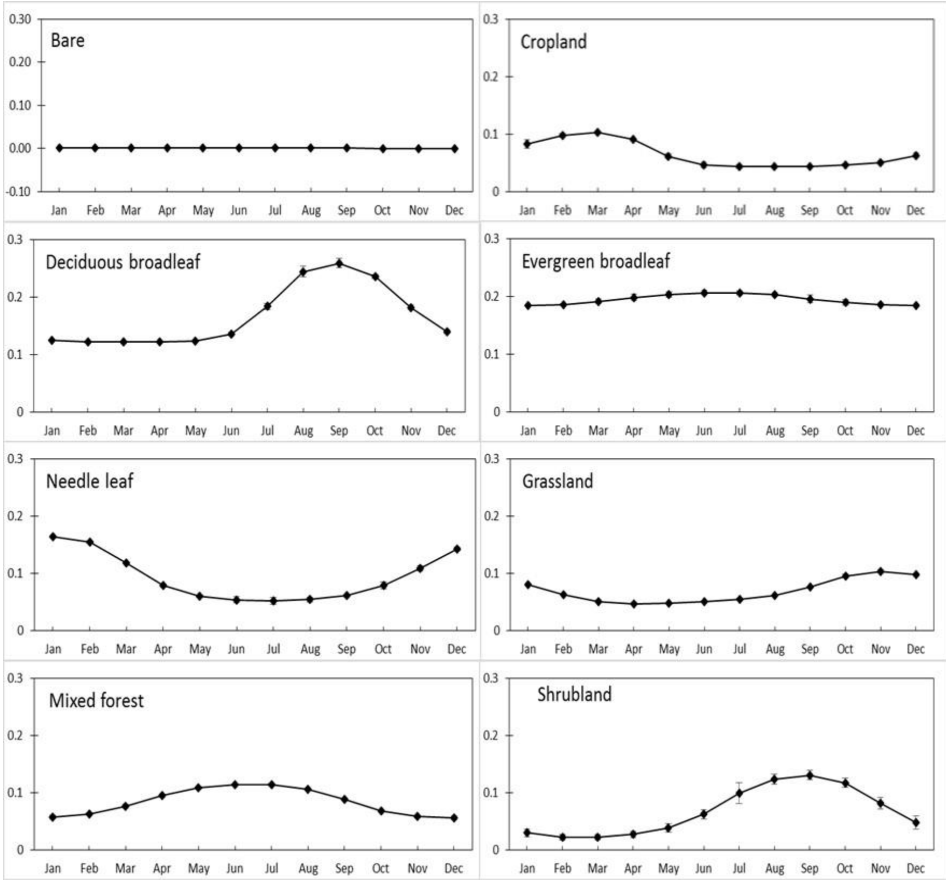

Figure 13 monthly distribution of global MGVI product estimated using BELMANIP2 sites, error bars display the variation of MGVI observation of each month for the period of 2002-2012 (Annual variation)

Figures 12 and 13, shows the annual cycle of MTCI and MGVI. The error bars on each month represent the standard deviation for the observations of this particular month over 10 years, both indices succeeded in showing the seasonal variability for all biomes using the BELMANIP2 set of sites.

The low seasonal variation of MTCI and MGVI in the bare and shrub lands biome types are due to low seasonal dynamics of vegetation indices values in general over those biomes. For bare biome class MTCI RMSE ranged from 0.02 to 0.04 and that low variation is because for the low seasonal changes of this biome as most of the bare sites from BELMANIP2 located in desert areas and that is also the reason the RMSE of MGVI over that biome been constant all the time as there is no active fAPAR to be detected by this index.

However, the errors bars for the shrub land biome show a relatively higher standard deviation from the months of June till October in both indices, which are also consider to be the growing months for those biomes that is due to the differences in the start timing for the growing seasons in different places around the globe. RMSE ranged from 0.03 to 0.1 for MTCI, and 0.004 to 0.01 for MGVI with the highest variation during greening up season months, this could also be due to the limited number of sites (only 8 sites were classified as shrub areas) that classified as shrub lands out of the BELMANIP2 network of sites.

For croplands the distribution of MTCI values over months of the year has varied due to growing and non-growing seasons, the highest variation of MTCI in cropland exhibited to be from March to September. While, in MGVI exhibit the high reflected values to be from November to May of each year. The differences between the high reflected values timing between both indices suggested to be a result of combining all the cropland sites from different climatic zones that has different phonological cycles. When taking the standard deviation bars into account the variation values range from 0.03 to 0.2 in MTCI for croplands, while it varies from 0.001 to 0.007 in MGVI. MTCI tend to have largest variation during the months of February (RMSE=0.28) and March (RMSE=0.29), for the same reason of the diverse between the phonological cycle starting time, which cause the high variation and inconsistency of the vegetation index values in those months. MGVI tends to display more temporal consistency over this biome. From October to the end of the year the winter variable play role in consist the values for both indices with almost no variation around this time of the year all through the study time period.

The highest variation of MTCI values for the global distribution of deciduous broadleaf forests happen to be in the first quarter of each year, from January to March. In reverse to MGVI which demonstrated its highest values of this biome to be in the second half of the year from June to December. For deciduous forests RMSE values for MTCI falls from 0.06 to 0.3, the highest standard deviation found in the MTCI observations globally falls within the starting months of the greening season (RMSE=0.3). For MGVI the variation of each month throughout the study time has been small and consist around 0.002 to 0.003, just showed little increase in the months of July till September to be 0.005 to 0.009. This variation between MTCI and MGVI happens for the reason of the starting time diverse for the greening up phase for deciduous forests globally, remarkably when combining different sites from both northern and southern hemispheres. Evergreen broadleaf forests showed consistency of observations values throughout months of the year in both land variables MTCI and MGVI, also the standard deviation bars displayed consist variation overtime with variation values between 0.02 and 0.04 in MTCI, and MGVI from 0.001 to 0.004.

Both indices succeed in demonstrating clear seasonality of needle leaf biome, similar to most of the other earth biomes classes seasonality cycle is different from northern and southern hemisphere. When combining both in global trend the high standard variation values would occur, the MTCI standard variation for needle leaf varied between 0.04 to 0.2, and 0.001 to 0.006 for MGVI over months of the year for the study period time. The inter-annual variation of MTCI showed the behavior of needle leaf forests to have gradually small increment followed by higher cumulative throughout the years, which has been well exhibited in the annual variation of MTCI. It showed the values to start increase gradually from May to August, followed by higher increment in the reflected values of MTCI from September onwards.

For Grassland and mixed forest MTCI and MGVI demonstrated consistent seasonality that correspond with the inter-annual variation aimed for each of those biomes, also showing generally higher dynamic range in summer that corresponds to vegetation maturity. However, the annual variation shows the growing season starts relatively earlier for grassland biome type and stays for longer time comparing to the mixed forest biome. The standard deviation values displayed great variation throughout all the months of the year with values ranges from 0.06 to 0.2.
Mixed forest land combines the characteristics of deciduous and evergreen forestland; thus, its MTCI distribution characteristics are intermediate to those of deciduous and evergreen forestland demonstrated a very clear seasonality pattern through the months of the year, and the standard devastation for this biome type has the smallest and most consist variation ranging among 0.04 to 0.07.

MTCI and MGVI generally shows harmonious temporal profiles with realistic seasonal and inter-annual variations over all vegetation types. Deciduous broadleaf forests had reversed behavior between MTCI and MGVI. MGVI observations tend to show more consistency over time than MTCI.

4.3 Latitudinal distribution of MERIS land biophysical variables

Events in plants that can be measured by vegetation indices reflectance are usually vary with latitude gradient. The dependence for both MERIS land biophysical variables variation and uncertainty on latitude were also examined. For preliminary analysis the globe was divided into latitudinal zones with even numbered parallels of latitudes. Figure 14, used MTCI global cover to show the distribution of BELMANIP2 sites around the globe, using the equator to define the sites variation in the northern and southern hemispheres.

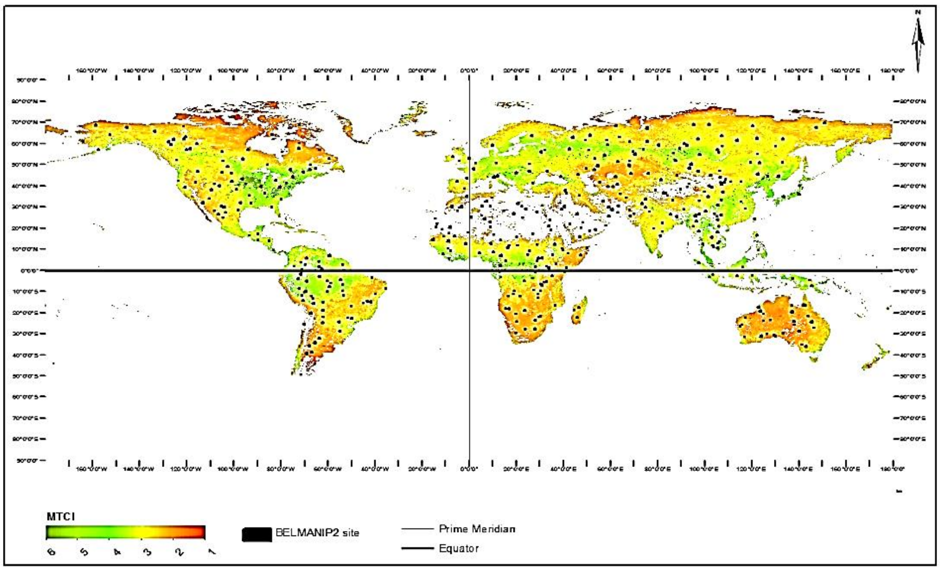

Figure 14 BELMANIP2 set of sites distribution around the equator, using MTCI global cover for July 2002-2012

4.3.1 MTCI global latitudinal distribution

By using zonal averages, spatial uncertainty of MTCI across 5 degrees latitude intervals were then computed for the globe, using the corresponding mean values MTCI for each latitudinal zone. Thus, the latitudinal distribution of the global MTCI values over the 10 years of the operating life time of MERIS has been illustrated in figure 15, demonstrating the difference between MTCI values range in January and July as examples of the global vegetation cover greening up and senescence timings.

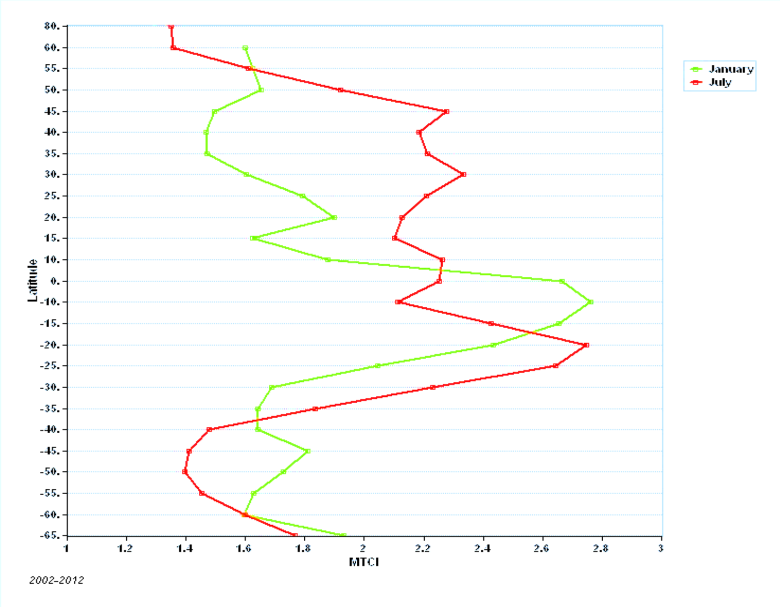

Figure 15 latitudinal distribution of global MTCI for January, July 2002-2012

The global climatic conditions vary between northern and southern hemisphere. In both seasons of summer and winter, the MTCI growth starts from the southern hemisphere at the same latitudinal zone and covers up to higher latitudes in the northern hemisphere during the summer time. In January, when the northern hemisphere is in winter and the southern hemisphere is in summer, the bulk of living vegetation, shown in green, stays close around the equator and below it, in the southern hemisphere.

While in July, the vegetation cover starts to spread over the higher latitudes above the equator. When it is summer in the northern hemisphere giving relatively high MTCI values. Still the highest of the vegetation index reflected values in the month of July can be seen below the equator, which can be explained by the densely vegetated tropical regions in that latitudinal zone below the equator.

4.3.2 MGVI global latitudinal distribution

Applying the same procedure, zonal averages were used to compute spatial uncertainty of MGVI globally across 5 degree latitudinal zones. The results achieved by using the corresponded MGVI averages for each latitudinal zone in the months of January and July.

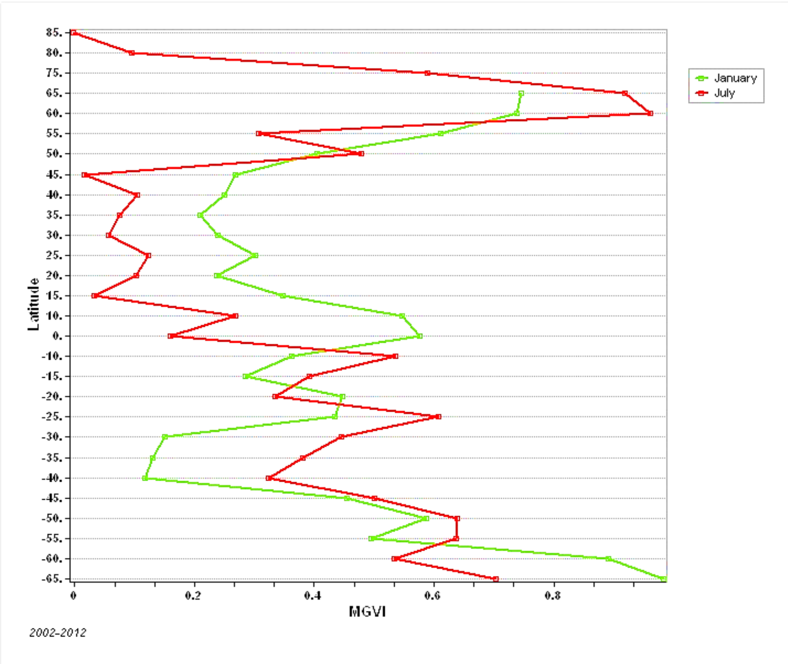

Figure 16 latitudinal distribution of global MGVI in January, July 2002-2012

MGVI behaviour across latitudinal zone had a similar pattern amongst winter and summer time. In January the MGVI index starts at higher values in the southern hemisphere, and end at lower latitude zone in the northern hemisphere (comparing to the month of July), keeping the highest for the tropical areas values around the equator.
In July the index starts to reflect at higher latitudinal zone in the northern hemisphere than January. It also has more oscillations than the index behaviour in January. The low values that are showing in the month of July in the northern latitudes above the equator are possibly a result of the big deserted area, including the African Sahara, located in those latitudes and the arid climate in this areas gets drier in the summer time, and thus relatively affecting the active photosynthetic radiation that is related to MGVI index, giving low reflectance values for MGVI.

4.4 MERIS land biophysical variables correlation on global scale

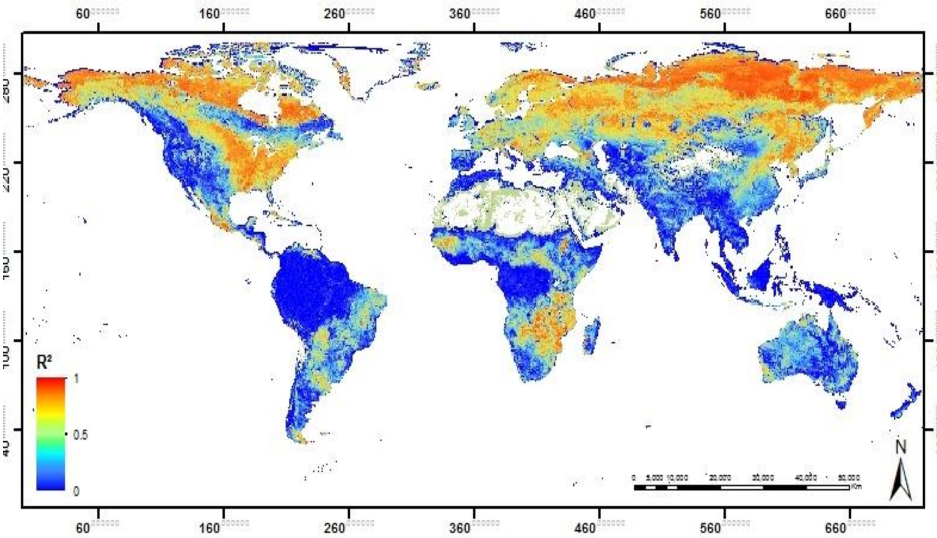

Figure 17 MTCI- MGVI pixel wise correlation map, globally using 10 years composite of both images 2002-2012

To characterize the response of vegetation measured as MTCI to vegetation measured as MGVI, the correlation between both indices has been examined using global covers from 2002 to 2012 for each index. Both of MERIS variables showed very high correlation agreement in the high latitudes in the northern part of the globe, while in the southern part the agreement between both indices was relatively low except for some parts in South America and east African coast.

Each of MTCI and MGVI is related directly to different vegetation variable, and both of them has different derived algorithm and different spectral reflectance bands composite. Accordingly, the reflectance values from MTCI and MGVI should be elevated enough to achieve good correlation agreement between both variables.

The results has given a low correlation values in the densely vegetated regions of the globe (where the differences are minor in the photosynthetic active radiation). While it has reflected a high correlation coefficients in the herbaceous areas in the northern high and mid latitudes and some parts of southern latitudes, where the vegetation cover variables can be found all year around at the same level, similar results reported at 2013 study by (Zeng, James Collatz, Pinzon, & Ivanoff, 2013).

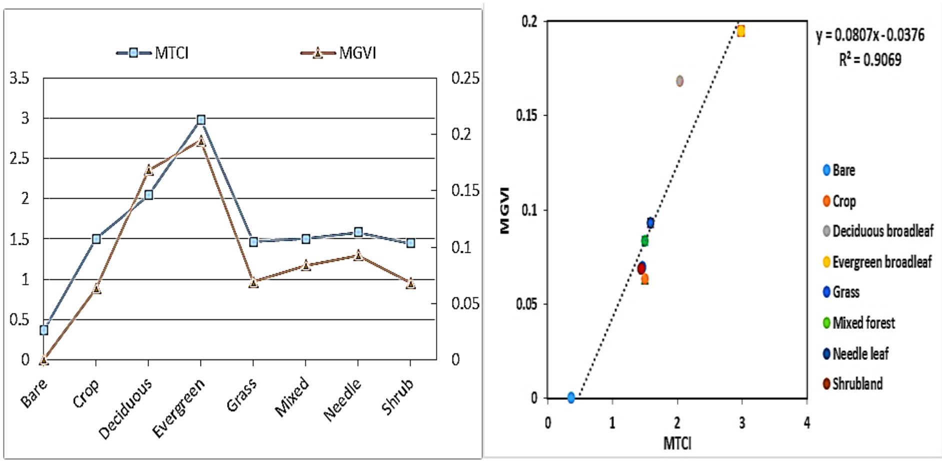

Figure 18 statistical evaluation of the overall behavior of MTCI-MGVI globally on the main biome classes of the study from 2002-2012

Both indices showed great statistical overall agreement between different biomes globally throughout MERIS sensor life time in figure 18, the analysis approved statistically significant correlation R^2 =0.9 between both indices over the different biomes that used in the study, for the whole study time period. But when reviewing the correlation between MTCI and MGVI for each biome unaccompanied not all of the biomes showed that high of agreement between both indices. Scatter plots between MTCI and MGVI products were generated for each biome class to better describe their agreement and/or differences.

Figure 19 revealed the highest correlation between both variables exhibited by mixed forest biome R^2 =0.4 and that could be due to the characteristics of this biome type that combine the features of evergreen and deciduous forest. Followed by the bare biome type with R^2 =0.3 that suggested to be a result of that both vegetation reflectance over that biome as MGVI has constant values over the bare lands close to zero all through the study time, while MTCI reflectance was minimal from 0.01 to 0.05 which limited the occurrence of error coefficient between both indices over this particular biome.
The rest of biome types showed low agreement coefficient between MERIS variables for the different theoretical values used in each index and the behavior of each index over different biomes that showed to be slightly different from the previous temporal and spatial evaluation that reported previously in this study.

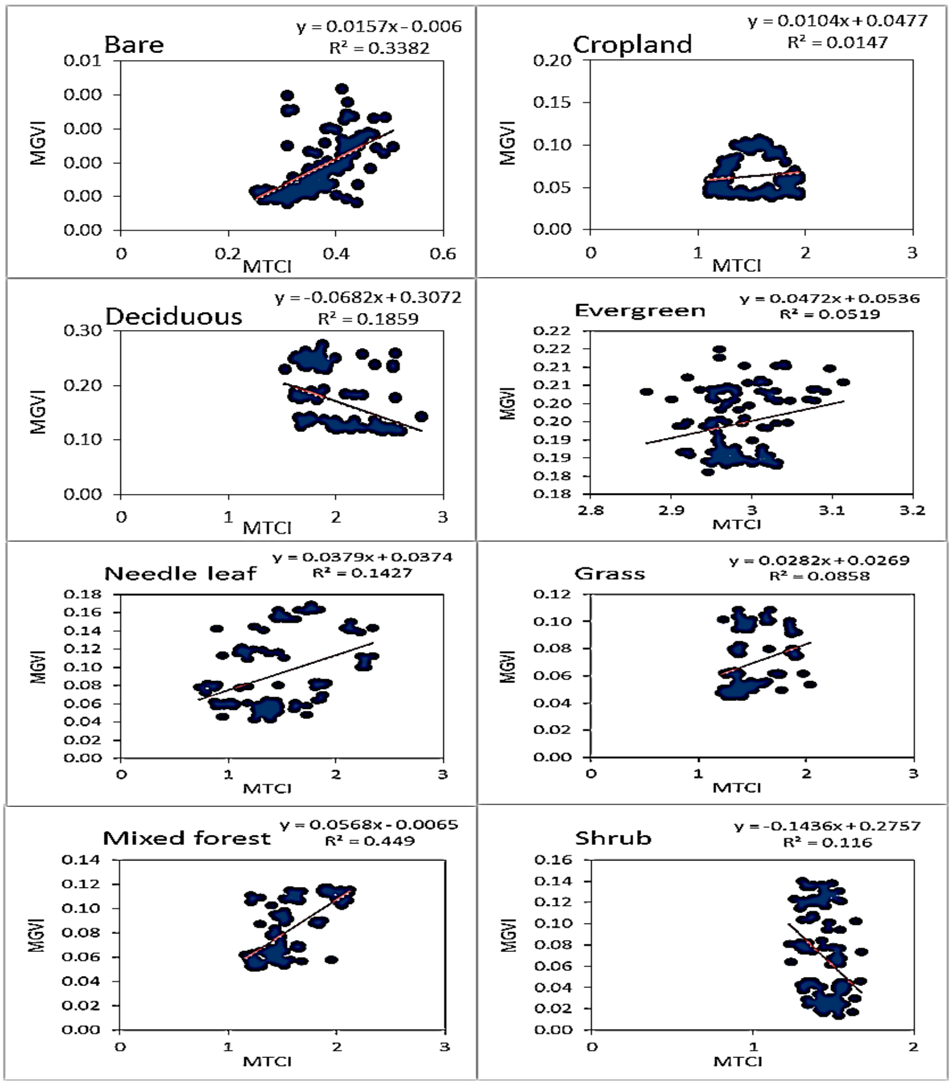

Figure 19 MERIS collection MTCI versus MGVI for the period of 2002-2012 using BELMANIP2 sites on the main surface classes for the study

The overall high agreement between both indices is typical since both variables represent green, healthy, and live vegetation, while the low agreement when looking from closer scope between MTCI and MGVI over each biome rooted in the differences in combination of spectral reflectance bands and retrieval algorithm that used to design each one of MERIS indices which has resulted in different nominal scale and different coverage method for each index that caused the low agreement between both variable when comparing different biomes.

4.5 MERIS land biophysical variables correlation with climatic variable

Temperature, solar radiation, and participation are the key climatic variables that determine the growth and cycles of vegetation, Planted areas shows temperature limitation to vegetation growth are mostly located within the northern hemisphere. Those climatic variables can also provide an independent means to evaluate existing and new datasets (Zhu et al., 2013). In higher latitudes in the northern part of the globe temperatures have been shown to trigger more variation and correlation between different vegetation indices (Sparks et al. 2005, Fisher et al. 2006; Boyd, Almond, Dash, Curran, & Hill, 2011) That has been clearly demonstrated in the maps illustrated below in figures 20 and 21, shows the correlation between MGVI and air surface temperature, MTCI and air surface temperature from 2002 to 2011 respectively.

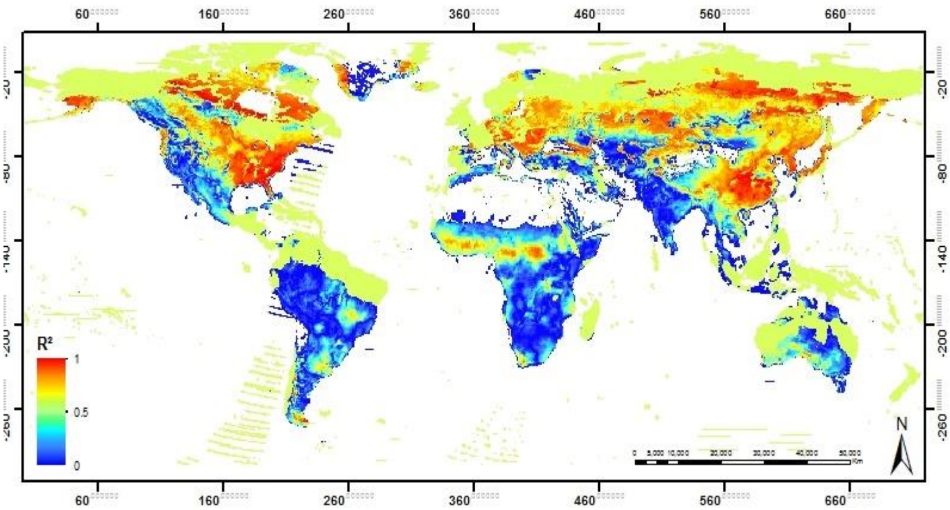

Figure 20 MGVI-Surface temperature pixel-wise correlation map 2002-2011

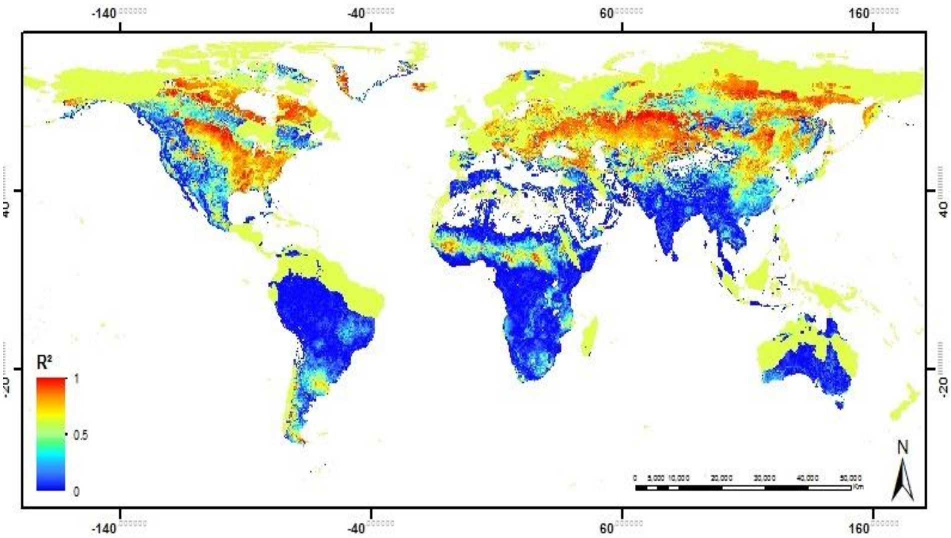

Figure 21 MTCI-Surface temperature pixel-wise correlation map 2002-2011

Vegetation photosynthetic activity and chlorophyll content in the northern latitudes has been reported to be more temperature depended, and that reflected high correlation coefficients between both of MTCI and MGVI and surface temperature in the northern hemisphere. The correlation between MGVI and surface temperature demonstrated greater spatial variability status than the correlation between MTCI and surface temperature for the reason of the difference between the global spatial coverage for the two indices, and also because MTCI has limited ability to identify vegetation statues in sparse vegetation cover, whereas, MGVI can detect all kind of vegetation covers.

However, in the southern hemisphere the association between MTCI, MGVI, and surface temperature was comparatively lower than the north, mostly only exists around the equator in the tropical regions, in general the vegetation bulks that are located in the southern latitudes below the equator are independent from surface temperature factor and not affected much by temperature changes except for small areas.

The diverse and variation in biome types that can be found in northern hemisphere has resulted in this significant agreement between the temperature as climate factor and the MERIS vegetation indices.

Chapter 5 Conclusion and recommendation

5.1 Conclusion

MERIS instrument was launched on board of ENVISAT on 2002, delivering measurements with frequency of 3 days, specifically customised to monitor land surface parameter, it has been operating until 2012. MERIS has been a valuable tool for vegetation mapping at regional scale using two land biophysical variables that have been designed especially for MERIS sensor, MERIS Terrestrial Chlorophyll index (MTCI) and MERIS Global Vegetation Index (MGVI). However, using satellite data to investigate spatio-temporal variation of different biomes at global scale is scarce in general. MERIS variables mutually has been examined at global scale in this research, this makes the study the first to characterize the spatial and temporal variation of satellite derived variables over 8 biome types at global scale, and perform 10 years intercomparison between two variables retrieved from the same sensor.

MTCI is related to vegetation chlorophyll index, while MGVI related to the fraction of absorbed photosynthetically active radiation (fAPAR), long term global datasets of both chlorophyll content and fAPAR are critical in monitor global vegetation dynamics and for modelling of energy, carbon fluxes, and mass, they are also state variables in hydrological, ecological, biogeochemical and crop-yield models (Zhu et al., 2013). That was the reason of the attempt to quantify and assess the uncertainties that are related to those particular variables. Furthermore, the significance and motivation of this study came from the worth of those variables in monitoring our earth system and model its changes. The main objectives for this study was to evaluate MERIS products MTCI and MGVI at a global scale, and to quantify the uncertainty for key biomes at global scale to provide further understanding on the sensitivity of these variables in preparation for the launch of sentinel 3 mission.

Uncertainties associated to satellite derived variables can be identified and assess by the mean of being the lack of particular information that lead to shortage or failure in the EO product measurements, it could be also referred to as differences or gaps between remote sensing data reflectance values and the corresponding ground measurements. Perhaps also to be examined through looking at satellite derived products behaviour and how well particular product can represent different vegetation types keeping its trend and pattern over time close to reality, and that what has been explored in this study using (MTCI) and (MGVI).

For the reasons of the global coverage and plurality of biomes, it was not necessity to estimate the most precise reflectances of MERIS land biophysical variables over different biome, but the study was focusing more on looking at the variability of each index behaviour over each of the main biome classes that used in the study for the whole period of MERIS sensor life time. According to the study vegetative and non-vegetative factors can influence vegetation indices reflectance values and could be source of causing uncertainties. As a result, the outcome of this study could be summarised by the following:

- This study has confirmed that MERIS products using BELMANIP2 network of sites have reached a reasonable level of maturity. However, different biome types, seasons, and latitudes has dominated the variation and uncertainty associated with MTCI and MGVI. Both indices have a great global mask, covering almost all parts of the globe with respect to the timing of the year and its effect on vegetation covers. Through the study it came to notice that MTCI perform poorly over bare soils. MTCI dataset had higher spatial resolution than MGVI dataset, which reflected higher spatial variability in MTCI global cover distribution.
- The investigation of the temporal stability for both indices demonstrated that Both of MTCI and MGVI has a very good temporal continuity over the whole life time of the produced sensor, providing a precise well-defined characterization of different biomes seasonality through their inter-annual variation performance. However, the temporal consistency with emphasis on the smoothness of the time series and the stability across years has also been evaluated. The temporal consistency inspection has described MGVI behaviour to be more consist than MTCI in all different biomes in the study over time, and that rooted in the spatial resolution differences between MTCI and MGVI datasets that used to conduct the temporal stability analysis (4.6x4.6 km^2 for MTCI, 0.5x0.5 km^2 for MGVI).
- The limited number of sites that been classified as shrublands out of BELMANIP2 network of sites (only 8 shrubland sites), has led to high inconsistency in that biome values by both MTCI and MGVI. Also there was no any site from BELMANIP2 classified as needle leaf forest in the southern hemisphere.

- The analysis for the variation of MERIS variables between northern and southern hemisphere during winter and summer seasons has given results that corresponds to realistic behaviour of satellite derived land products over vegetation cover, coats higher northern latitudes during summer time and to lower southern latitudes during winter, keeping the highest values for both indices around the equator.
- MERIS variables strongly correlated with the temperature in the northern hemisphere and in the densely vegetated parts in the southern hemisphere. However, MERIS MTCI and MGVI demonstrated to strongly correlate in the high latitudes in the northern hemisphere and some parts of the east African coast, hence, the densely vegetated areas has minor differences in the photothynthetically active, visible reflectance and that reflected low agreement between MTCI and MGVI in those areas. Also, due to the limited soil nutrient levels that related to the severity climatic conditions which affect the vegetation health and variability in the southern hemisphere.

The study has highlighted both challenges and potentials of applying MTCI and MGVI in further global analysis relating to spatial cover, latitude, vegetation season, and climatic variable, with assessment of the use of BELMANIP2 network of sites. The methodology, analysis, and results of this study could be used as a framework for the evaluation of the products coming out from the new sensor Ocean and Land Colour Instrument (OLCI) on board of sentinel3 mission that is going to be continuation of MERIS mission and will provide OLCI terrestrial chlorophyll index (OTCI) that will be based on MERIS (MTCI) heritage, expected to be launch late 2015.

5.2 Recommendation

Using BELMANIP2 network of sites has compiled spatio-temporal analysis on global scale between two different vegetation indices accessible, manageable, and more convenient to conduct, giving qualitative assessment of the main features of each product with regards to continuity, smoothness, magnitude and seasonality of each biome. Accordingly, the need of more investigation on BELMANIP2 in further studies comparing different EO products would enhance the performance of this network of sites and point out if there is shortages.

More ground experiments need to conducted on global scale, and to be compared with satellite derived variables of this study for more certain results.

Using those particular vegetation variables on BELMANIP2 network with similar methods of this study, could be replicated on regional or continental scale for more in depth and precise vision of those indices behaviour on different biomes.

Shrubland biome would be better classified under mixed forest biome type (based on previous studies) to avoid the noisy reflectance of vegetation indices caused by the misclassification. Or, it could be reported to Committee on Earth Observation Satellite (CEOS) that more sites identified as shrubland in particular need to be added to the BELMANIP2 network of sites.

Global studies are not common in general which make this study on of few that makes this an experimental study, we could not always explain the observed features. Further studies should examine the temporal consistency of MTCI on global scale, also the reversed behaviour of deciduous broadleaf forests between MTCI and MGVI needs more investigation.

References

Alfredo Huete, Chris Justice, Wim van Leeuwen, a. (1999). Modis Vegetation Index Algorithm Theoretical Basis. *Environmental Sciences*, (Mod 13), 129. Retrieved from http://www.modis.gsfc.nasa.gov/data/atbd/land_atbd.html

Almond, S. (2009). *Validation and application of the MERIS Terrestrial Chlorophyll Index*. Bournemouth University. Retrieved from http://eprints.bournemouth.ac.uk/16208/1/ALMOND_Samuel_PhD.pdf

Almond, S., Boyd, D. S., Dash, J., Curran, P. J., Hill, R. A., & Foody, G. M. (2010). *Estimating terrestrial gross primary productivity with the Envisat Medium Resolution Imaging Spectrometer (MERIS) Terrestrial Chlorophyll Index (MTCI)*. doi:10.1109/IGARSS.2010.5654088

Atkinson, P. M., Jeganathan, C., Dash, J., & Atzberger, C. (2012). Inter-comparison of four models for smoothing satellite sensor time-series data to estimate vegetation phenology. *Remote Sensing of Environment*, *123*, 400–417. doi:10.1016/j.rse.2012.04.001

Baret, F., & Buis, S. (2008). *Estimating canopy characteristics from remote sensing observations: review of methods and associated problems*. *Advances in Land Remote Sensing. New York, USA.* doi:10.1007/978-1-4020-6450-0_7

Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., Huc, M., … Leroy, M. (2007). LAI, fAPAR and fCover CYCLOPES global products derived from VEGETATION. *Remote Sensing of Environment*, *110*(3), 275–286. doi:10.1016/j.rse.2007.02.018

Baret, F., Morissette, J. T., Fernandes, R. A., Champeaux, J. L., Myneni, R. B., Chen, J., … Nickeson, J. E. (2006). Eva luation of the Representativeness of Networks of Sites for the Global Validation and Intercomparison of Land Biophysical Products : Proposition of the CEOS-BELMANIP. *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*, *44*(7), 1794–1803.

Baret, F., & Weiss, M. (2010). *Temporal consistency of CYCLOPES products*.

Boyd, D. S., Almond, S., Dash, J., Curran, P. J., & Hill, R. a. (2011). Phenology of vegetation in Southern England from Envisat MERIS terrestrial chlorophyll index (MTCI) data. *International Journal of Remote Sensing*, *32*(23), 8421–8447. doi:10.1080/01431161.2010.542194

Boyd, D. S., Almond, S., Dash, J., Curran, P. J., Hill, R. a., & Foody, G. M. (2012). Evaluation of Envisat MERIS Terrestrial Chlorophyll Index-Based Models for the Estimation of Terrestrial Gross Primary Productivity. *IEEE Geoscience and Remote Sensing Letters*, *9*(3), 457–461. doi:10.1109/LGRS.2011.2170810

Carrão, H., Sarmento, P., & Araújo, A. (2007). *Retrieving Land Cover Information from MERIS and MODIS Data : a Comparative Study for Landscape Characterization in Portugal*. *International Geoscience and Remote Sensing Symposium (IGARSS)*. doi:10.1109/IGARSS.2007.4423037

Clevers, W. (2014). Beyond NDVI: Extraction of Biophysical Variables From Remote Sensing Imagery. In I. Manakos & M. Braun (Eds.), *Land Use and Land Cover Mapping in Europe* (Vol. 18, pp. 363–381). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-7969-3

Coops, N. C., Michaud, J.-S., Andrew, M. E., & Wulder, M. a. (2011). Comparison of a regional-level habitat index derived from MERIS and MODIS estimates of canopy-absorbed photosynthetically active radiation. *Remote Sensing Letters*, *2*(4), 327–336. doi:10.1080/01431161.2010.516281

Croft, H., Chen, J. M., & Zhang, Y. (2014). The applicability of empirical vegetation indices for determining leaf chlorophyll content over different leaf and canopy structures. *Ecological Complexity*, *17*, 119–130. doi:10.1016/j.ecocom.2013.11.005

Curran, P. J., & Dash, J. (2005a). *A LGORITHM T HEORETICAL B ASIS D OCUMENT*.

Curran, P. J., & Dash, J. (2005b). *ATBD: Chlorophyll Index*. Retrieved from https://earth.esa.int/instruments/meris/atbd/atbd_2_22.pdf

Dash, J., & Curran, P. J. (2004). The MERIS terrestrial chlorophyll index. *International Journal of Remote Sensing*, *25*(23), 5403–5413. doi:10.1080/0143116042000274015

Dash, J., & Curran, P. J. (2007a). Evaluation of the MERIS Terrestrial Chlorophyll Index, *39*(1), 100–104. doi:DOI: 10.1016/j.asr.2006.02.034

Dash, J., & Curran, P. J. (2007b). *RELATIONSHIP BETWEEN THE MERIS VEGETATION INDICES AND CROP YIELD FOR THE STATE OF SOUTH DAKOTA , USA .* Montreux, Switzerland.

Dash, J., Curran, P. J., & Foody, G. M. (2009). Remote sensing of terrestrial chlorophyll content. In *Global Climatology and Ecodynamics* (p. pp 77–105). Springer Berlin Heidelberg. doi:10.1007/978-3-540-78209-4_5

Dash, J., Curran, P. J., Tallis, M. J., Llewellyn, G. M., Taylor, G., & Snoeij, P. (2010). Validating the MERIS Terrestrial Chlorophyll Index (MTCI) with ground chlorophyll content data at MERIS spatial resolution. *International Journal of Remote Sensing*, *31*(20), 5513–5532. doi:10.1080/01431160903376340

Dawson, T. P. (2000). The potential for estimating chlorophyll content from a vegetation canopy using the Medium Resolution Imaging Spectrometer (MERIS). *International Journal of Remote Sensing*, *21*(10), 2043–2051. doi:10.1080/01431160050021286

Dawson, T. P., Curran, P. J., North, P. R. J., & Plummer, S. E. (1999). The Propagation of Foliar Biochemical Absorption Features in Forest Canopy Reflectance : A Theoretical Analysis. *Remote Sensing of Environment*, *67*(2), 147–159.

ESA. (2006). MERIS Detailed Instrument Description. *European Space Agency*. Retrieved from https://earth.esa.int/pub/ESA_DOC/ENVISAT/MERIS/meris.DetailedInstrumentDescription.1_0.pdf

esa. (2006). *MERIS Product Handbook*. European Space Agency. Retrieved from http://earth.esa.int/handbooks/meris/CNTR2-7.htm

Fang, H., Wei, S., Jiang, C., & Scipal, K. (2012). Theoretical uncertainty analysis of global MODIS, CYCLOPES, and

GLOBCARBON LAI products using a triple collocation method. *Remote Sensing of Environment*, *124*, 610–621. doi:10.1016/j.rse.2012.06.013

Foody, G. M., & Dash, J. (2007). Discriminating and mapping the C3 and C4 composition of grasslands in the northern Great Plains, USA. *Ecological Informatics*, *2*(2), 89–93. doi:10.1016/j.ecoinf.2007.03.009

Foody, G. M., & Dash, J. (2010). Estimating the relative abundance of C 3 and C 4 grasses in the Great Plains from multi-temporal MTCI data: issues of compositing period and spatial generalizability. *International Journal of Remote Sensing*, *31*(2), 351–362. doi:10.1080/01431160902887339

Garrigues, S., Lacaze, R., Baret, F., Morisette, J. T., Weiss, M., Nickeson, J. E., … Yang, W. (2008). Validation and intercomparison of global Leaf Area Index products derived from remote sensing data. *Journal of Geophysical Research*, *113*(G2), G02028. doi:10.1029/2007JG000635

Gobron, N., Dash, J., Arino, O., Gascon, L. H., Muller, J., & Map, L. C. (2012). EXPLOITING TEN YEARS OF MERIS DATA OVER LAND SURFACES, 1833–1836.

Gobron, N., Pinty, B., Aussedat, O., Taberner, M., Faber, O., Melin, F., … Snoeij, P. (2008). Uncertainty estimates for the FAPAR operational products derived from MERIS — Impact of top-of-atmosphere radiance uncertainties and validation with field data. *Remote Sensing of Environment*, *112*(4), 1871–1883. doi:10.1016/j.rse.2007.09.011

Gobron, N., Pinty, B., Verstraete, M., & Govaerts, Y. (1999). The MERIS Global Vegetation Index (MGVI): Description and preliminary application. *International Journal of Remote Sensing*, *20*(9), 1917–1927. doi:10.1080/014311699212542

Gobron, N., & Verstraete, M. M. (2009). *Assessment of the Status of the Development of the Standards for the Terrestrial essential Climate Variables - Fraction of Absorbed Photosynthetically Active Radiation - FAPAR*.

Gómez-chova, L., Camps-valls, G., Member, S., Calpe-maravilla, J., Guanter, L., Moreno, J., & Member, A. (2007). Cloud-Screening

Algorithm for ENVISAT / MERIS Multispectral Images, *45*(12), 4105–4118.

Huete, a., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, *83*(1-2), 195–213. doi:10.1016/S0034-4257(02)00096-2

J. Dash a , A. Mathur b , G. M. Foody c , P. J. Curran d, J. W., & Lillesand, C. e & T. M. (2007). Land cover classification using multi- temporal MERIS vegetation indices. *International Journal of Remote Sensing*, *28*(6), 1137–1159. doi:10.1080/01431160600784259

Jeganathan, C., Dash, J., & Atkinson, P. M. (2010). Characterising the spatial pattern of phenology for the tropical vegetation of India using multi-temporal MERIS chlorophyll data. *Landscape Ecology*, *25*(7), 1125–1141. doi:10.1007/s10980-010-9490-1

Jeganathan, C., Ganguly, S., Dash, J., Friedl, M., and Atkinson, P. M. (2010). *TERRESTRIAL VEGETATION PHENOLOGY FROM MODIS AND MERIS SENSOR DATA* (Vol. 8).

Jensen, J. R. (1983). Biophysical Remote Sensing. *Annals of the Association of American Geographers*, *73*(1), 111–132. Retrieved from http://www.jstor.org/stable/2569349?seq=1#page_scan_tab_contents

Klein, D., & Menz, G. (2005). Monitoring of seasonal vegetation response to rainfall variation and land use in East Africa using ENVISAT MERIS data. *Proceedings. 2005 IEEE International Geoscience and Remote Sensing Symposium, 2005. IGARSS '05.*, *4*, 2884–2887. doi:10.1109/IGARSS.2005.1525670

L. Bourg, L. D'Alba, P. C. (2008). *MERIS SMILE EFFECT CHARACTERISATION AND CORRECTION*. Retrieved from http://earth.eo.esa.int/pcs/envisat/meris/documentation/MERIS_Smile_Effect.pdf

Lachérade, S., Fougnie, B., Henry, P., & Gamet, P. (2013). Cross Calibration Over Desert Sites : Description , Methodology , and

Operational Implementation, *51*(3), 1098–1113. doi:10.1109/TGRS.2012.2227061

Luo, J., Ying, K., & Bai, J. (2005). Savitzky-Golay smoothing and differentiation filter for even number data. *Signal Processing*, *85*, 1429–1434. doi:10.1016/j.sigpro.2005.02.002

M. A. Friedl, F. W. Davis, J. Michaelsen, M. A. M. (1995). scaling and uncertanity in the relationship between NDVI and land surface biophsycal variables.pdf. *Remote Sensing of Environment*, *45*(3), 233–246. doi:10.1016/0034-4257(95)00156-5

Morisette, J. T., Baret, F., Privette, J. L., Myneni, R. B., Nickeson, J. E., Garrigues, S., … Cook, R. (2006). Validation of global moderate-resolution LAI products: A framework proposed within the CEOS land product validation subgroup. *IEEE Transactions on Geoscience and Remote Sensing*, *44*(7), 1804–1814. doi:10.1109/TGRS.2006.872529

Nadine Gobron, Bernard Pinty, Ophélie Aussedat, Thomas Lavergne, Frédéric Mélin, M. R. and M. T. (2007). Validation of the operational MERIS FAPAR. In *… and Remote Sensing …* (pp. 2398–2403). Barcelona: IEEE. doi:10.1109/IGARSS.2007.4423325

Nadine Gobron, ophelie Aussedat, Bernard Pinty, Malcolm Taberner, M. V. (2004). *Level 2 land surface product algorithm theoretical basis document*. Ispara - Italy.

Nadine Gobron, Ophelie Aussedat, Bernard Pinty, Malcolm Taberner, M. V. (2004). *Level 2 land surface products Algorithm Theortical Basis Document*. Ispra. Retrieved from https://earth.esa.int/instruments/meris/atbd/atbd_mgvi_jrc.pdf

NEODAAS. (2014). NEODAAS - The NERC Earth Observation Data Acquisition and Analysis Service. Retrieved December 10, 2014, from https://www.neodaas.ac.uk/supportedscience/veg_indices.php

O'Connor, B., Dwyer, E., & Cawkwell, F. (2013). The implications of cloud cover for vegetation seasonality monitoring across the island of Ireland using the MERIS Global Vegetation Index (MGVI). *Irish Geography*, *46*(1-2), 25–49. doi:10.1080/00750778.2013.845489

Ogutu, B. O., Dash, J., & Dawson, T. P. (2014). Evaluation of the influence of two operational fraction of absorbed photosynthetically active radiation (FAPAR) products on terrestrial ecosystem productivity modelling. *International Journal of Remote Sensing*, *35*(1), 321–340. doi:10.1080/01431161.2013.871083

Simp, A. X., & Remoto, S. (2007). *A comparison of MERIS and MODIS data for land cover characterization*.

Tüshaus, J., Dubovyk, O., Khamzina, A., & Menz, G. (2014). Comparison of Medium Spatial Resolution ENVISAT-MERIS and Terra-MODIS Time Series for Vegetation Decline Analysis: A Case Study in Central Asia. *Remote Sensing*, *6*(1), 5238–5256. doi:10.3390/rs6065238

Ullah, S., Si, Y., Schlerf, M., Skidmore, A. K., Shafique, M., & Iqbal, I. A. (2012). Estimation of grassland biomass and nitrogen using MERIS data. *International Journal of Applied Earth Observation and Geoinformation*, *19*, 196–204. doi:10.1016/j.jag.2012.05.008

VectorNav. (2015). Calibration - VectorNav Library. Retrieved April 8, 2015, from http://www.vectornav.com/support/library/calibration

Verrelst, J., Koetz, B., & Schaepman, M. (2004). Directional sensitivity analysis of vegetation indices from multi- angular chris/proba data. *PoLAR*.

Verrelst, J., Rivera, J. P., Alonso, L., Lindstrot, R., & Moreno, J. (2012). Potential retrieval of biophysical parameters from FLORIS, S3-OLCI and its synergy. *International Geoscience and Remote Sensing Symposium (IGARSS)*, 7121–7124. doi:10.1109/IGARSS.2012.6352021

Viña, A., Gitelson, A. a., Nguy-Robertson, A. L., & Peng, Y. (2011). Comparison of different vegetation indices for the remote assessment of green leaf area index of crops. *Remote Sensing of Environment*, *115*(12), 3468–3478. doi:10.1016/j.rse.2011.08.010

Vincini, M., Amaducci, S., & Frazzi, E. (2014). Empirical Estimation of Leaf Chlorophyll Density in winter wheat canopies using

Sentinal-2 spectral resolution. *IEEE Geoscience and Remote Sensing Society*, *52*(6), 3220–3235. doi:10.1109/TGRS.2013.2271813

Vuolo, F., Dash, J., Curran, P. J., Lajas, D., & Kwiatkowska, E. (2012). Methodologies and Uncertainties in the Use of the Terrestrial Chlorophyll Index for the Sentinel-3 Mission. *Remote Sensing*, *4*(12), 1112–1133. doi:10.3390/rs4051112

Weiss, M., Baret, F., Garrigues, S., & Lacaze, R. (2007). LAI and fAPAR CYCLOPES global products derived from VEGETATION. Part 2: validation and comparison with MODIS collection 4 products. *Remote Sensing of Environment*, *110*(3), 317–331. doi:10.1016/j.rse.2007.03.001

Weiss, M., Baret, F., Lacaze, R., Block, T., & Koetz, B. (2012). *Validating GEOV1 products over the 1998-2010 period using the OLIVE tool (On LIne Validation Exercise)* (Vol. 14).

Zeng, F. W., James Collatz, G., Pinzon, J. E., & Ivanoff, A. (2013). Evaluating and quantifying the climate-driven interannual variability in global inventory modeling and mapping studies (GIMMS) normalized difference vegetation index (NDVI3g) at global scales. *Remote Sensing*, *5*(8), 3918–3950. doi:10.3390/rs5083918

Zhou, X., & Wang, X. (2007). An analysis about seasonal vegetation variety in Fujian Province (China) using ENVISAT MERIS vegetation index. *2007 IEEE International Geoscience and Remote Sensing Symposium*, 3386–3389. doi:10.1109/IGARSS.2007.4423571

Zhu, Z., Bi, J., Pan, Y., Ganguly, S., Anav, A., Xu, L., … Myneni, R. (2013). Global Data Sets of Vegetation Leaf Area Index (LAI)3g and Fraction of Photosynthetically Active Radiation (FPAR)3g Derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the Period 1981 to 2. *Remote Sensing*, *5*(2), 927–948. doi:10.3390/rs5020927

Zurita-Milla, R. (2008). *Mapping and monitoring heterogeneous landscapes : spatial , spectral and temporal unmixing of MERIS data*. Wageningen Universiteit (Nederland).

Zurita- Milla, R., Clevers, J. G. P. W., Schaepman, M. E., & Kneubuehler, M. (2007). Effects of MERIS L1b radiometric calibration on regional land cover mapping and land products. *International Journal of Remote Sensing*, *28*(3-4), 653–673. doi:10.1080/01431160600821069

Zurita-milla, R., Gómez-chova, L., Guanter, L., Clevers, J. G. P. W., Camps-valls, G., & Member, S. (2011). Multitemporal Unmixing of Medium-Spatial-Resolution Satellite Images : A Case Study Using MERIS Images for Land-Cover Mapping, *49*(11), 4308–4317. doi:10.1109/TGRS.2011.2158320

Zurita-Milla, R., Kaiser, G., Clevers, J. G. P. W., Schneider, W., & Schaepman, M. E. (2009). Downscaling time series of MERIS full resolution data to monitor vegetation seasonal dynamics. *Remote Sensing of Environment*, *113*(9), 1874–1885. doi:10.1016/j.rse.2009.04.011