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SPIE.

Event: SPIE Remote Sensing, 2018, Berlin, Germany

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Landscape heterogeneity around flux measurement stations investigated through Sentinel-2 and PROBA-V satellite imagery

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ABSTRACT

This study proposed the exploitation of Sentinel-2 and Proba-V imagery to assess the heterogeneity in the surroundings of EC stations through the multitemporal analysis of NDVI. The observations by these platforms allow computation of NDVI at 10 m (Sentinel-2) and 100 m (Proba-V) spatial resolutions. Such levels of spatial detail allowed the comparison of pixel values within two relevant geographic extents: the footprint of EC stations and the extent of satellite imagery cells commonly used to force flux modelling. The satellite platforms considered for this study exhibit different but complementary strengths. Proba-V allowed fast processing over a large number of stations in order to screen or rank EC stations as function of the spatial heterogeneity. The fine spatial resolution of Sentinel-2 allowed more in-depth spatial analysis. Three methods were implemented to explore the spatial heterogeneity with Sentinel-2 NDVI: the analysis of simple NDVI histogram, spatial heterogeneity index (SHI) and fitting a semi-variogram. The analysis with Proba-V resulted in a ranking of flux tower stations on the basis of NDVI Interquartile Range.

This study was conducted in the framework of a research programme aiming at improving estimates of net primary productivity across different biomes. The methods appeared to complement each other: histograms were simple to interpret and offered a clear view on the spread and shape of data (often bi-model in cropped sites); SHI plots enable the visualization of heterogeneity changes throughout a period of time and semi-variograms allow the analysis at different distances and orientations.

Keywords: Eddy covariance, Sentinel-2, Proba-V, Heterogeneity

1. INTRODUCTION

Measurements by flux towers are of paramount importance in understanding and quantifying carbon and energy fluxes. The growing number of eddy covariance (EC) stations around the globe represents a major asset for validating and calibrating models designed to estimate the exchange of carbon, energy and water vapor between the Earth's surface and the atmosphere.

EC stations are usually intended to be representative of a particular ecosystem of interest.[1] Therefore homogeneity within the extent of the EC tower footprint and beyond is a desired landscape condition. However the perfect homogeneity is difficult to attain in practice and the magnitude and temporal pattern of the measured fluxes is often impacted by the presence of heterogeneous arrangements of vegetated areas exhibiting different phenology patterns. This aspect influences the representativeness of a particular site,[2] the degree of energy balance closure in the measurements[3,4] and the measurements at EC towers in general.[5] In this respect, the characterization in space and time of the surroundings of EC towers can be a valuable helping element in the

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Remote Sensing for Agriculture, Ecosystems, and Hydrology XX, edited by Christopher M. U. Neale, Antonino Maltese, Proc. of SPIE Vol. 10783, 107830D · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2325620

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interpretation of the measured fluxes and the calibration and validation of models.

This study belongs to the initial phase of a larger scientific research initiative, the ECOPROPHET project (supported by the Belgian Science Policy, contract SR/00/334), aimed at improving the estimation of biomass production across diffent ecosystems in the globe (http://ecoprophet.meteo.be).

Given the relevance of EC measurements in the overal objective of the ECOPROPHET project, this study investigated the heterogeneity in the vicinity of 5 EC towers in Belgium and The Netherlands. The analyses were based on the Normalized Difference Vegetation Index (NDVI) as derived from observations by two recently launched satellite missions: Proba-V (100 m spatial resolution) and Sentinel2 (S2) (10 m spatial resolution). The features of these satellite platforms are particularly interesting for investigating the heterogeneity around EC sites as their spatial and temporal resolutions allow the discrimination of time changing landscape elements within relevant spatial extents.

2. OBJECTIVES

The main objective of this study was to investigate the heterogeneity of the landscape at different points in time and over different spatial extents around EC measurement sites on the basis of multidate NDVI derived from Proba-V and S2 observations. Moreover, we wanted to determine the differences in the analyses related to the use of one or the other satellite platform.

3. METHODS

3.1 Landscape heterogeneity

The studied variable in the analysis of landscape heterogeneity was NDVI. The use of NDVI values around the flux measurement stations was rooted in the assumption that:

- NDVI can be adopted as a surrogate of surface flux *i.e.* the spatial and temporal patterns of NDVI around the EC measurement sites are related to the distribution of sources/sinks of the fluxes measured at the EC sites.
- Homogeneous areas exhibit low NDVI variability.
- Heterogeneous areas exhibit low spatial autocorrelation.

In following these ideas, the assessment of heterogeneity was based on indicators of dispersion and spatial autocorrelation. Those indicators were derived from NDVI images for the years 2016 and 2017 where at least 80% of the cells contained in the considered area were labeled as good quality values. The analyses were performed over different spatial extents. More details are provided in section 3.3. The indicators under consideration were:

1. Central tendency and dispersion statistics: In particular, the mean, median, standard deviation and the inter-quartile range (IQR).
2. Mean Spatial Heterogeneity Index (SHI).[6] SHI is as an indicator of variability whereby each NDVI value was compared to those of the neighbouring cells (8-cell neighbourhood). The obtained SHI values are then aggregated across the spatial extent under consideration. The calculations are as follows:

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$$SHI_{ij} = \sum_{a=-1}^{1} \sum_{b=-1}^{1} |NDVI(i,j) - NDVI(i+a, j+b)| \quad (1)$$

$$MeanSHI = \frac{1}{m.n} \sum_{i=1}^{m-1} \sum_{j=1}^{n-1} SHI_{ij} \quad (2)$$

where $NDVI(i,j)$ indicate the value of the i^{th} row and j^{th} column of the NDVI image; m and n are the number of rows and columns, respectively.

3. Fitting a semi-variogram. The spatial structure of NDVI as represented by a semi-variogram model contains information about the landscape heterogeneity. The sill of the semi-variogram is of particular importance as it is related to the NDVI variance as a function of distance; its value is directly related to spatial heterogeneity.[7]

   Semi-variogram were derived from contrasting landscape conditions (crops and forest) in order to verify the expression of spatial heterogeneity in semi-variogram models. An interesting feature of semi-variogram models is the option of considering omni-directional variance between points in the study area or focusing in particular directions. Both possibilities were explored.

The analyses enumerated above were mainly conducted on S2 images. The spatial resolution of S2 is an appealing feature to derive landscape indicators in areas in the order of magnitude of the footprint of EC towers. The conduction of similar analyses in a large number of EC sites scattered all over the world might be of interest for many application but requires a considerable effort to acquire, screen and process S2 images. This aspect motivated the use of Proba-V 100 m resolution in this study. The idea behind considering both satellite platforms is the conduction of preliminary analysis/ranking of EC measurement sites on the basis of Proba-V NDVI and then proceed to a more in-depth analysis with S2 imagery for a smaller number of sites. This idea was implemented in this study as well.

3.2 Study sites

The study was conducted in EC measurement sites in Belgium. The sites belong to the ICOS Belgium network (`www.icos-belgium.be`). The geographical location of the study sites is shown in the map of Figure 1. Table 1 presents the geographical coordinates of the EC towers and the cover type according to the CORINE land cover map[8] and the Ecoclimap Second Generation database (EC-SG). Aerial views of the sites extracted from GoogleEarth™ are presented in Figure 2.

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Table 1. Geographical coordinates of the EC towers in the study sites and land cover classification according to the CORINE land cover map and the Ecoclimap-SG database

Site	Acronym	Longitude	Latitude	CORINE	Ecoclimap_SG
Vielsalm	BE-Vie	5.9981	50.3051	Mixed forest	Temperate needleleaf evergreen
Maasmechelen	BE-Maa	5.6315	50.9802	Moors and heathlands	LCZ9: sparsely built
Lonzee	BE-Lon	4.7461	50.5516	Non-irrigated arable land	Winter C3 crops
Brasschaat	BE-Bra	4.5206	51.3092	Mixed forest	Temperate broadleaf deciduous
Loobos	NL-Loo	5.7436	52.1666	Coniferous forest	Temperate needleleaf evergreen

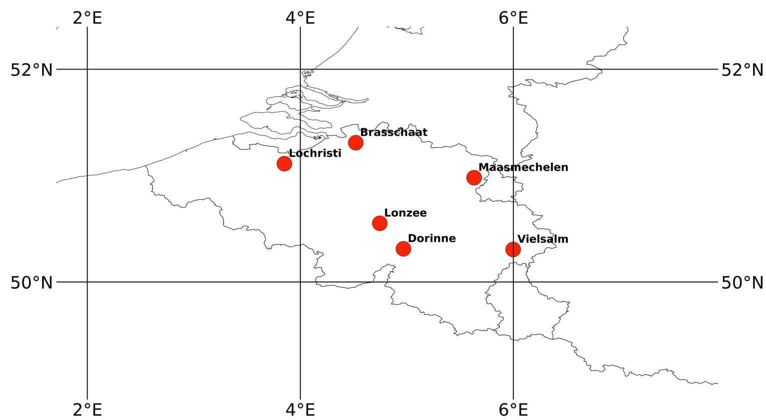

Figure 1. Geographical location of the study sites

3.3 Spatial extent of the analyses

Square shaped areas centered at the location of the EC towers were delimited to constraint the extent of the analysis. Three sizes were considered: 4 (100 x 100 m),25 (500 x 500 m) and 100 hectares (1000 x 1000 m). This analysis scheme is illustrated in the Figure 3. The Figure also shows an example of S2 NDVI image over one of the study sites where the boundaries have been clipped in accordance to the considered spatial extents.

The definition of these spatial extents is somewhat arbitrary and intended to ease and uniformize the analysis over sites exhibiting different conditions. Nevertheless, an analysis of the footprint climatology for comparison purposes is performed for some sites by following the method proposed by Kljun.[9]

3.4 Datasets

3.4.1 Remote sensing data

The S2 and Proba-V NDVI datasets were obtained from the Proba-V Mission Explotation Platform (MEP) (https://proba-v-mep.esa.int/). This platforms provide access to the full archive of the Proba-V mission and a dataset of processed S2 images covering Belgium and a fraction of the neighbouring countries. The Proba-V data used in this study had a 100 m spatial resolution.

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Figure 2. Real-color views of study sites extracted from GoogleEarth™

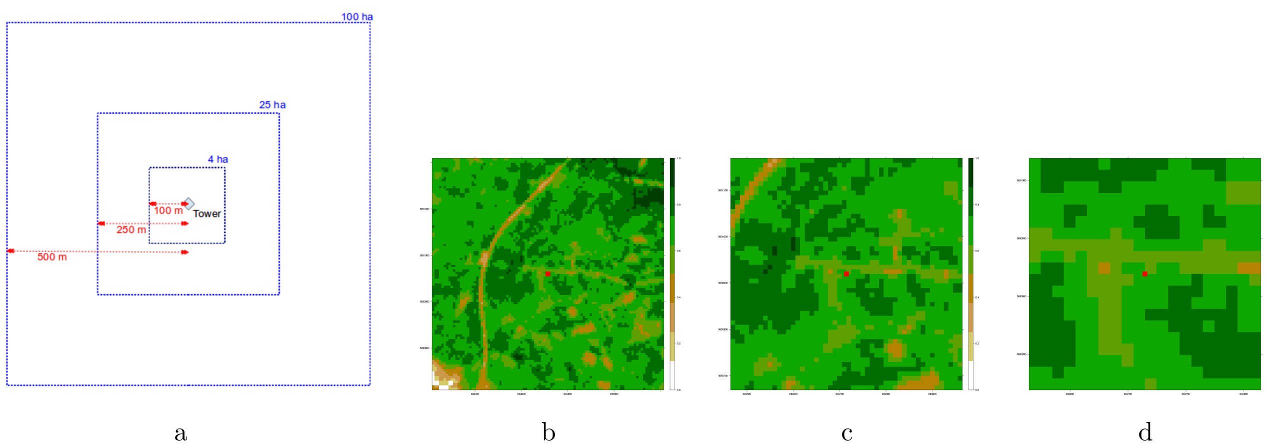

Figure 3. Scheme on area delimitation around stations (panel a) and examples of cropped Sentinel2 NDVI images covering 4, 25 and 100 hectares (b, c and d, respectively) around the station - Site in images: Maasmechelen (July, 7 2015)

The selection of the actual set of S2 NDVI images used in the study was conducted on the basis of the cloud and shadow masks supplied with the S2 NDVI product.

4. RESULTS AND DISCUSSION

The histograms allowed a first appraisal of the spread of NDVI values in the vicinity of the flux towers. Figure 4 shows histograms for winter and summer NDVI for Brasschaat (Scots pine) and Lonzee (agriculture crop) within the three areal extents considered. From the visual inspection of this Figure, it can be learned that the histogram in Brasschaat in unimodal in both seasons and for the three spatial extents. In both seasons the histogram is

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negatively skewed (over the 100 hectares domain skewness=-0.28 in the winter, -1.4407 in the summer) which can be related to dominant presence of evergreen vegetation in comparison to other land cover types. Lonzee exhibited a more contrasted situation which can be related to multiple vegetation cycli ocurrying simultaneously in cropped sites. This impacted the shape of the histograms, particularly in the two largest spatial extents. The winter is characterized by the dominance of low NDVI values due to scarce vegetation in the agriculture fields in that period. The intensive growth in some parcels results in a big contasts in NDVI values which are expressed in bi-modal histograms.

A complementary view on this can be gained from the aggregated SHI plots. Figure 5 shows the spread of SHI values computed for different dates and over the three different spatial extents in Maasmechelen and Dorinne. The magnitude in SHI values in the smaller extent is notably lower in the smaller extent (4 ha) in Dorinne as compared to the other considered spatial extents. Except for the notably lower SHI values in the smaller extent (4 ha) in Dorinne, no big difference related to spatial extent is suggested by the values displayed in the images. This can be related to the local character of SHI, *i.e.* the individual SHI values are computed by sequentially comparing the NDVI value of each cell to that of its adjacent neighbourgs and therefore, the spatial extent of the analysis might not have a great impact.

An interesting feature of these plots is the visualization of possible changing conditions along a time line. The SHI boxplots time series indicate lower values in 2016 than in 2017. The visual analysis of the NDVI images suggested that this difference might be due to differences in weather conditions in 2016 and 2017. Figure 6 shows a sequence of NDVI images over an area of 100 hectares around the Maasmechelen EC measurement site. Those images show that 2016 was a *greener* year and thus the contrast between adjacent pixels was low, the site was more homogeneous. In a dryer year (2017), the patchy arrangement in the NDVI images could be related to the presence of vegetation with different levels of sensitivity to dry conditions, heterogeneous soil storage or topographic conditions. The verification of these and other drivers of heterogeneity is relevant when interpreting the measurements at the EC tower.

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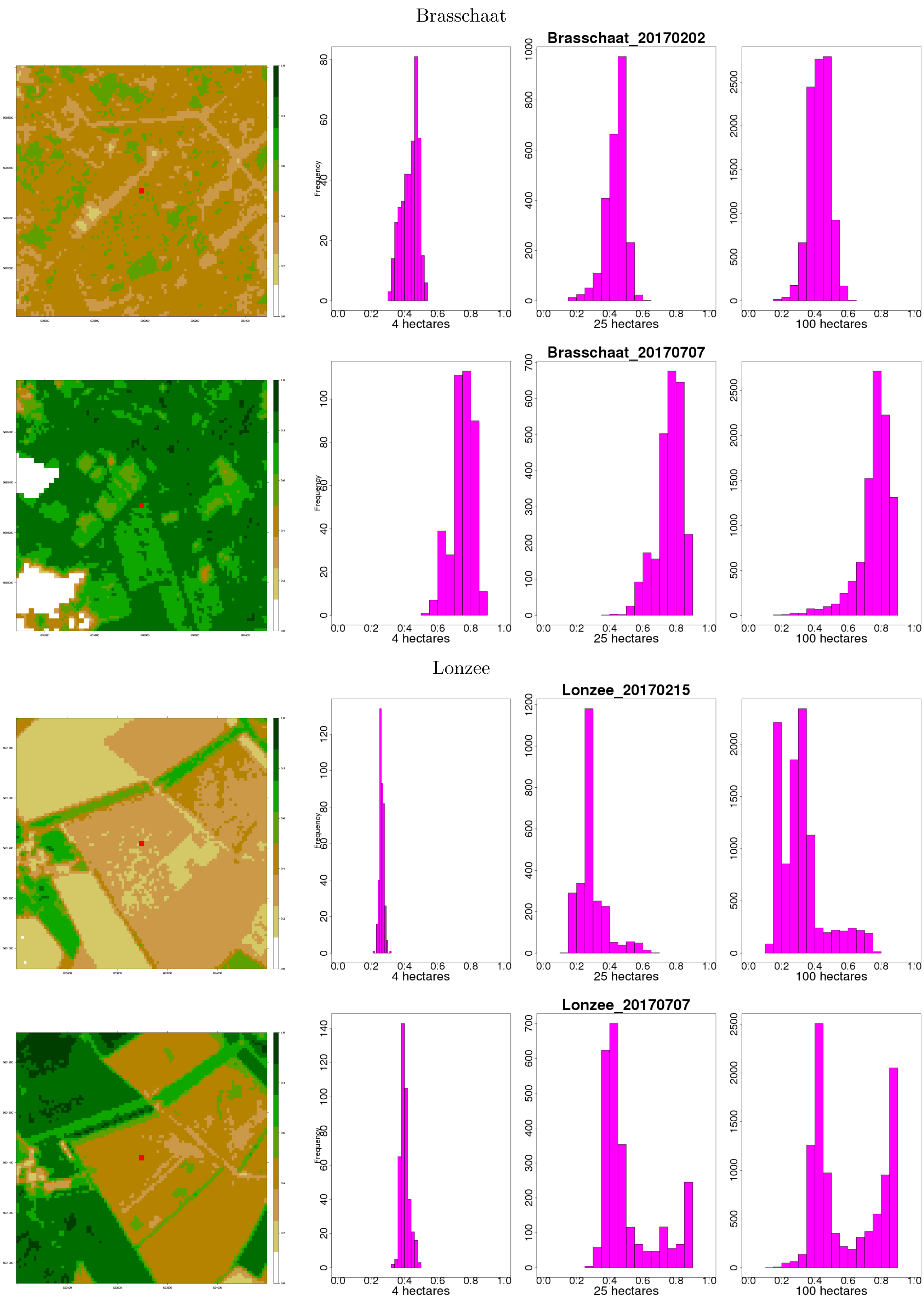

Figure 4. Histograms for winter and summer NDVI images at Brasschaat and Lonzee

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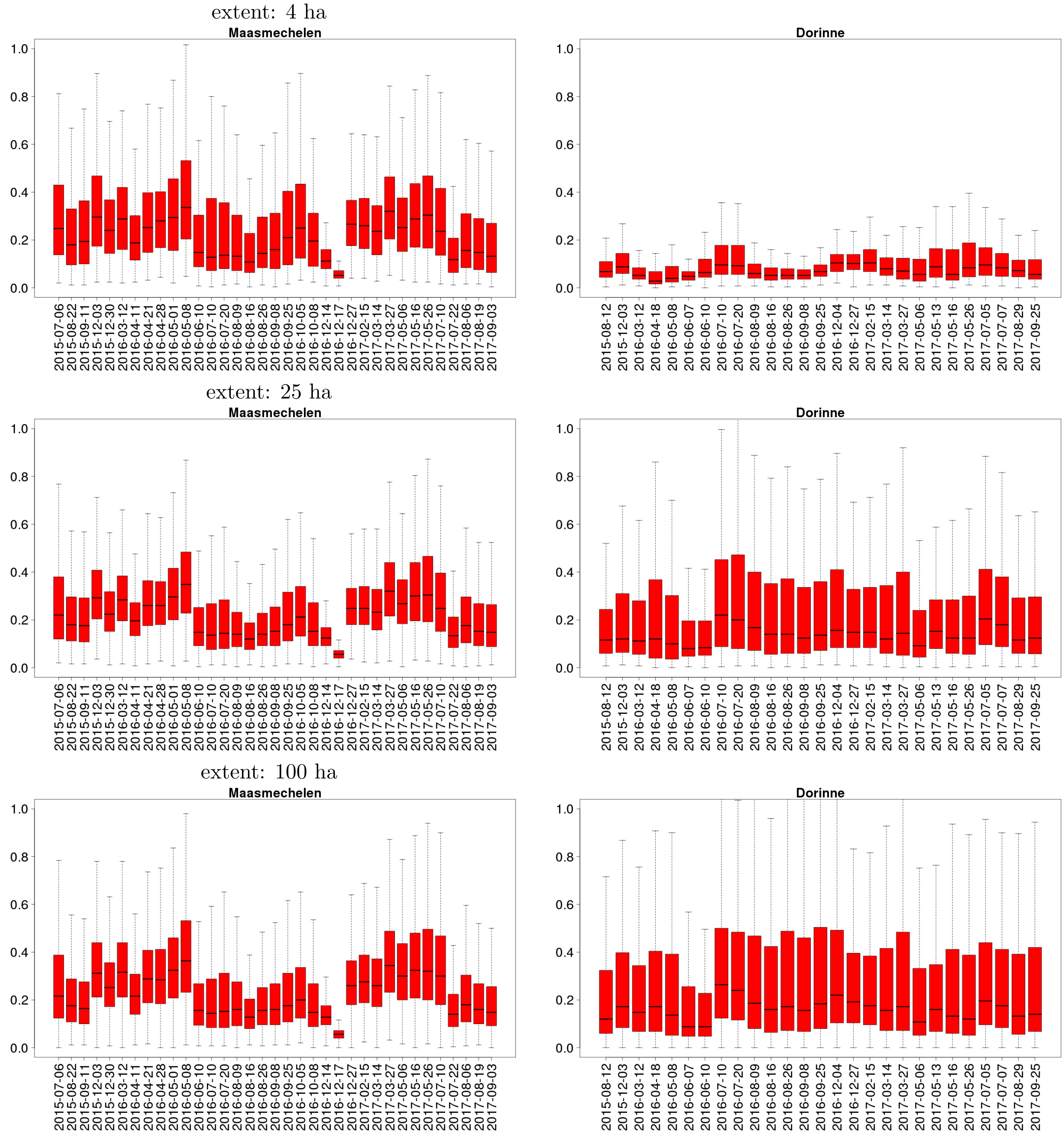

Figure 5. Aggregated value of SHI for different dates in Mechelen and Dorinne

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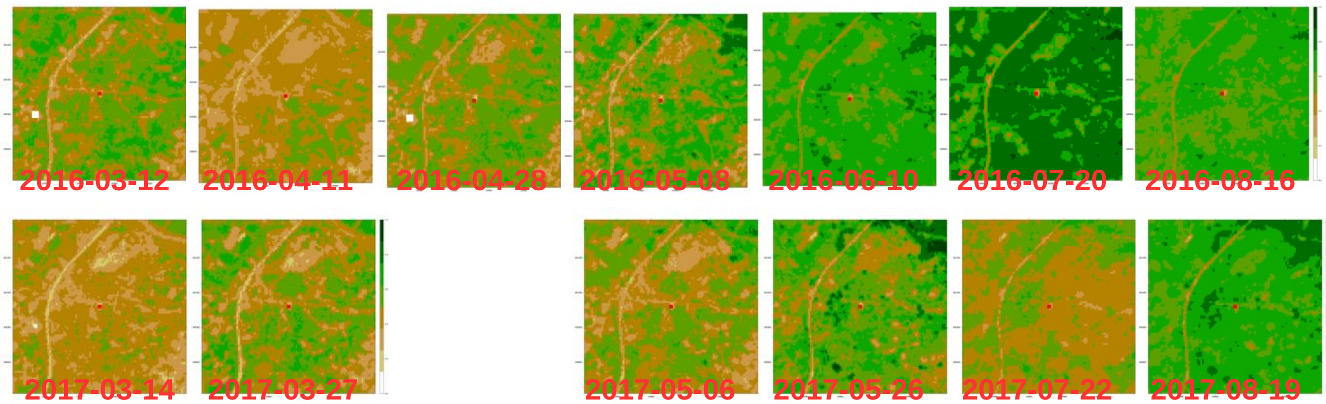

Figure 6. NDVI images for different dates in 2016 and 2017 across an area of 100 hectares around the Maasmechelen EC measurement site

The Figure 7 show fitted omnidirectional semi-variograms for the study sites. These semi-variograms were computed from the NDVI images covering the largest considered extent (100 ha).

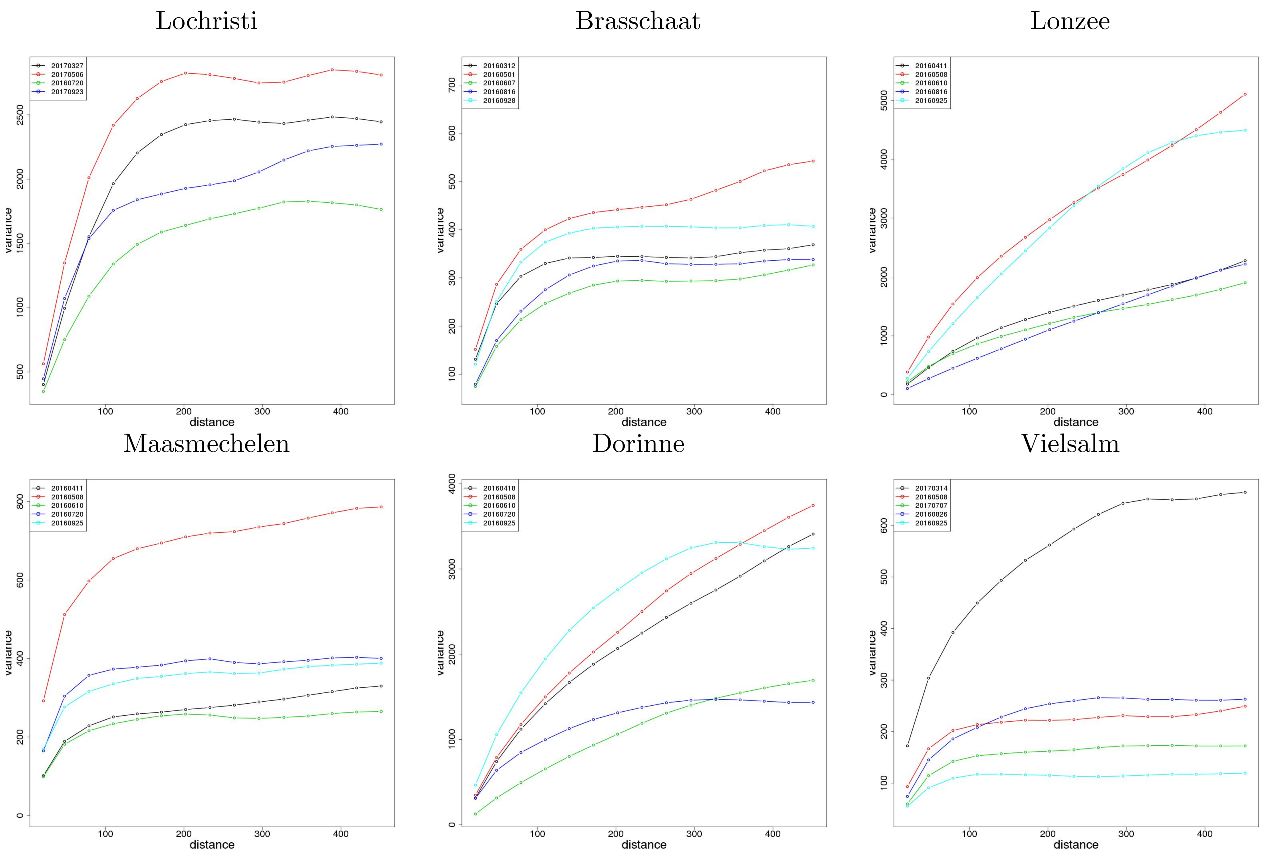

Figure 7. Empirical variograms for different sites over the NDVI images of the study sites

The NDVI semi-variograms give an additional insight in the spatial structure of the studied areas and how it changes in time. The sill of the semi-variogram is of particular interest for the assessment of heterogeneity. The plots in Figure 7, as was the case for the SHI plots of Figure 5, show that the degree of heterogeneity in the site

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changes in time. The clear presence of a sill in the plots in Lochristi, Brasschaat, Maasmechelen (although with a nugget effect), Vielsalm and -to a lower extent- Dorinne is an indicator of spatial autocorrelation. This aspect is not present in Lonzee within the maximum allowed distance for the computation of variance. This result is consistent with the discussion given above about the NDVI histograms.

The results presented so far have confirm the complexity of describing landscape heterogeneity and summarize it in simple indicators. Environmental conditions are variable and so is the response of vegetated areas (as seen in Figure 5). The variability can be reflected as well in indicators of spatial structure (like in Figure 7). The spatial and temporal resolution of S2 allow the implementation of various methods to assess the variability at relatively frequent rate of observation and within typical EC footprint areas, *i.e.* areas where maximum distance between points is in the order of a few hundred meters. The possibilities of resolving smaller objects and assess spatial variability within a short distance is more restricted at the highest spatial resolution of Proba-V: 100 m. The range values (distance at which the sill has been reached) in the semi-variograms of Figure 7 is close to the Proba-V cell size. Therefore, much of the short-distance variability could not be captured by Proba-V. On the other hand, Proba-V offers the possibility of fast data retrieval and processing. Certainly with the tools and archive made available by the Proba-V MEP.

The plots in Figure 8 illustrate mean and IQR values derived from Proba-V and S2 NDVI imagery over 3 of the study sites in 2016 and 2017. The plots include additional spatial extents of aggregation, being one of them the footprint climatology. The visual inspection of these plots suggests great similarity in the mean NDVI values derived from Proba-V and S2 aggregated over the different geographical extents. As for the IQR values, the plots show the ability of S2 to capture bigger contrasts in the lanscape elements. The correspondence between both satellite platforms in the derivation of mean NDVI and IQR is summarized in the plots of Figure 9 where no distinction of sites and geographical extents was made. The values obtained from both satellite platforms correlate well (R^2=0.9016 for mean NDVI; R^2=0.8353 for IQR). The mean NDVI cloud depicts a slope close to 1 whereas the IQR extracted from S2 imagery tends to be higher than Proba-V IQR.

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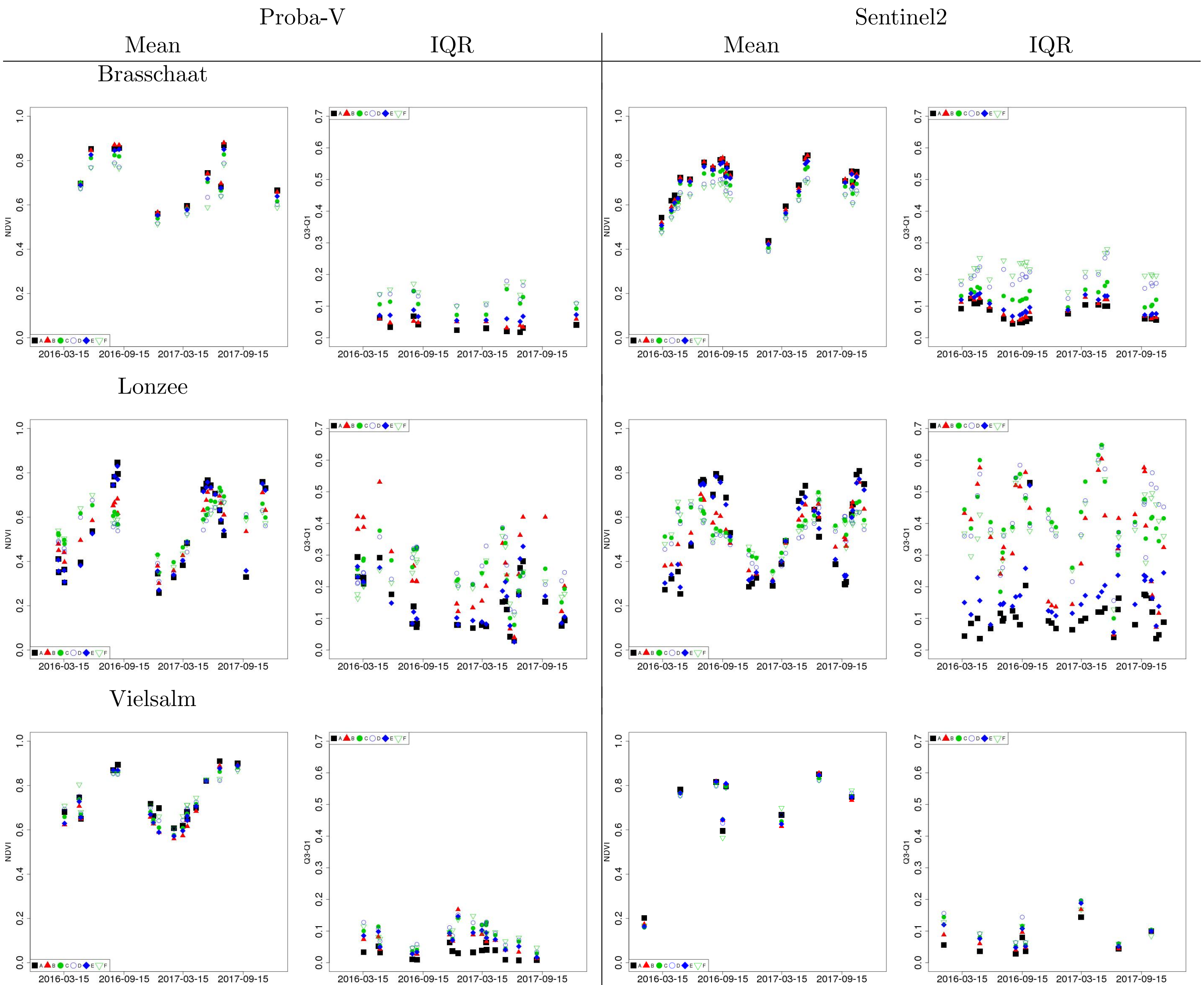

Figure 8. Mean and Interquartile Range (IQR) derived from Proba-V (100 m resolution) and Sentinel2 NDVI images in Brasschaat, Loobos, Lonzee and Vielsalm for different dates in 2016-2017 over different geographical extents: A= 500 x 500 square, B=1000x1000 m square, C= 2000x2000 m square, D=4000x4000 m square, E=Footprint climatology, F=MSG.

The patterns depicted in the plots of Figure 8 are coherent with the findings of other methods presented above. Therefore, it is likely that Proba-V and S2 could work synergetically to investigate the landscape structure around EC towers by using exploiting the former to preliminary screen/explore a large number sites and the latter to perform more detailed analyses. The preliminary step could be based on the aggregation of IQR values derived for different dates. Such an exercise is exemplified in the map of Figure 10. The map shows 122 EC measurement sites classified by the mean NDVI IQR computed from Proba-V 100 m NDVI in 2016 and 2017.

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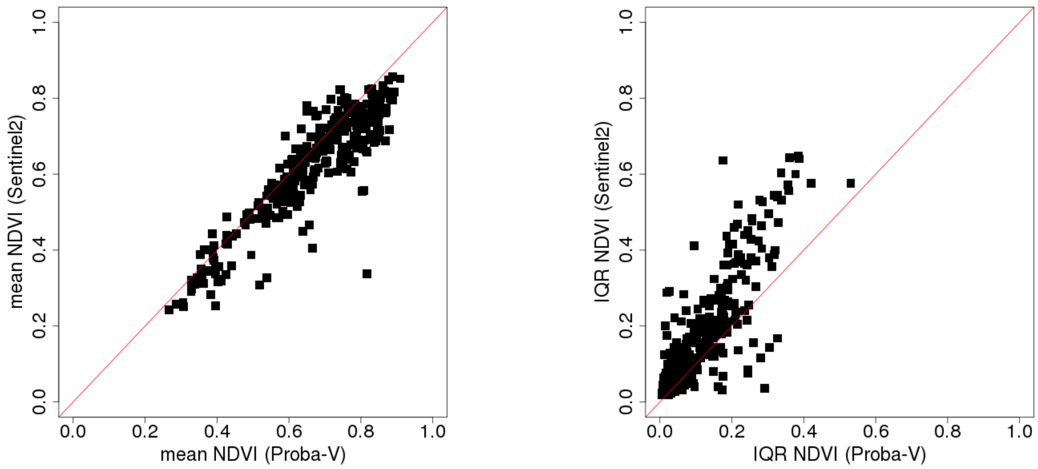

Figure 9. Scatterplot of NDVI mean and Interquartile Range (IQR) as derived from Proba-V and Sentinel2

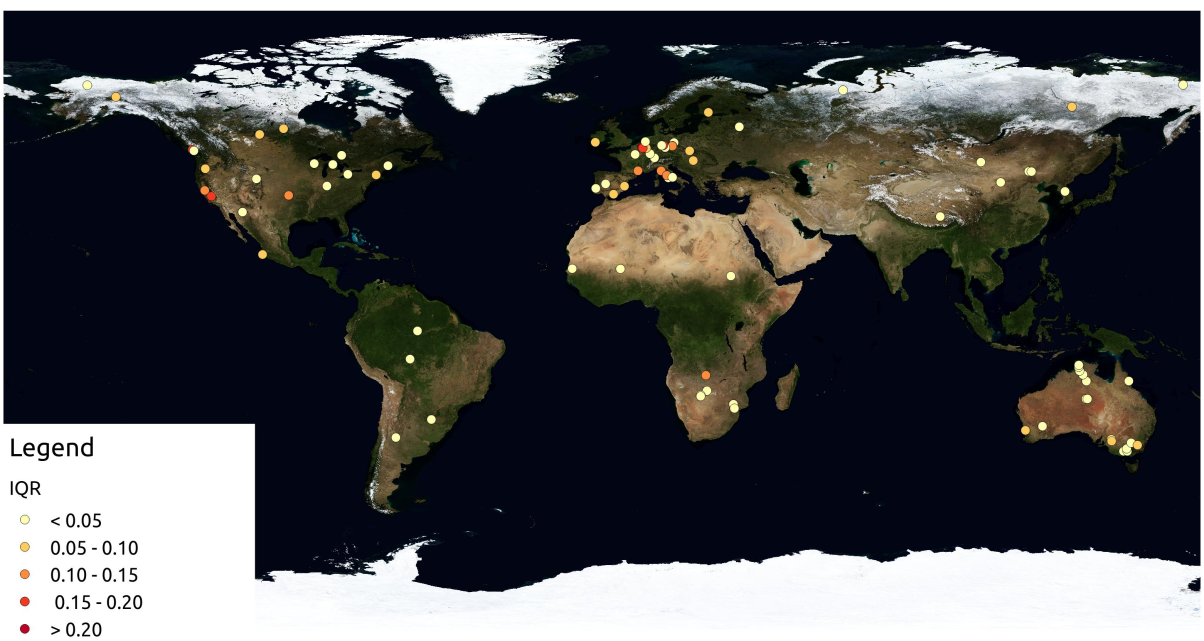

Figure 10. Mean NDVI IQR derived from Proba-V NDVI (100 m resolution) based on the aggregation of values over a square-shaped area centered at the location of EC towers

5. CONCLUSIONS

The main objective of this work was the derivation of heterogeneity indicators from NDVI as derived from observations by Proba-V and S2. The particular focus was the area in the surrounding of EC towers and the

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main motivations was the relevance of landscape characteristics in the definition of energy and water exchange and thus, in the measurements by the tower. In consequence, the actual assessment of the value and usefulness of the methods and datasets presented here will become apparent when interpreting the measurements at EC towers and the output of flux models. Nevertheless, various important conclusions can be extracted from the analyses presented here:

- The temporal and spatial resolution of S2 NDVI enables the implementation of different approaches to investigate the spatial heterogeneity in the vicinity of flux measurement stations.
- The histograms are a basic tool for data analysis but do not reveal the spatial structure of the data.
- The range of SHI values for particular dates and its change in time give a more local view on the spatial heterogeneity. It compares adjacent neighbours only.
- A complementary view can be attained with empirical variograms which allow analyzing different lag-distances.

ACKNOWLEDGMENTS

The research pertaining to these results received financial aid from the Belgian Federal Science Policy according to the agreement of subsidy no. [SR/00/334] under the STEREO III programme.

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