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Quantifying spatial heterogeneity at the landscape scale using variogram models

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Abstract

The monitoring of earth surface dynamic processes at a global scale requires high temporal frequency remote sensing observations which are provided up to now by moderate spatial resolution sensors. However, the spatial heterogeneity within the moderate spatial resolution pixel biases non-linear estimation processes of land surface variables from remote sensing data. To limit its influence on the description of land surface processes, corrections based on the quantification of the intra-pixel heterogeneity may be applied to non-linear estimation processes. A complementary strategy is to define the proper pixel size to capture the spatial variability of the data and minimize the intra-pixel variability.

This work provides a methodology to characterize and quantify the spatial heterogeneity of landscape vegetation cover from the modeling of the variogram of high spatial resolution NDVI data. NDVI variograms for 18 landscapes extracted from the VALERI database show that the land use is the main factor of spatial variability as quantified by the variogram sill. Crop sites are more heterogeneous than natural vegetation and forest sites at the landscape level. The integral range summarizes all structural parameters of the variogram into a single characteristic area. Its square root quantifies the mean length scale (i.e. spatial scale) of the data, which varies between 216 and 1060 m over the 18 landscapes considered. The integral range is also used as a yardstick to judge if the size of an image is large enough to measure properly the length scales of the data with the variogram. We propose that it must be smaller than 5% of the image surface. The theoretical dispersion variance, computed from the variogram model, quantifies the spatial heterogeneity within a moderate resolution pixel. It increases rapidly with pixel size until this size is larger than the mean length scale of the data. Finally based on the analysis of 18 landscapes, the sufficient pixel size to capture the major part of the spatial variability of the vegetation cover at the landscape scale is estimated to be less than 100 m. Since for all the heterogeneous landscapes the loss of NDVI spatial variability was small at this spatial resolution, the bias generated by the intra-pixel spatial heterogeneity on non-linear estimation processes will be reduced.

Keywords: Spatial heterogeneity; Moderate spatial resolution; Variogram model; Landscape; NDVI; Length scale; Data regularization; Optimal spatial resolution

1. Introduction

Remote sensing observations are relevant to describe land surface processes at the global scale, such as primary production, carbon and water fluxes. However, the monitoring of vegetation functioning requires high temporal frequency data which are provided up to now by moderate spatial resolution sensors with a spatial resolution from few hundred meters (MERIS/ENVISAT, MODIS/TERRA) up to one or few kilometers (VEGETATION/SPOT, SEVIRI/MSG, POLDER/ADEOS, POLDER/PARASOL). At such moderate resolution, the surface observed through the instantaneous field of view of these sensors may be very heterogeneous, because the landscape is a mosaic of objects, such as agricultural fields or vegetation patches, that are often smaller than moderate resolution pixels. Since sensors integrate the radiometric signal over the pixels, intra-pixel spatial heterogeneity information is lost at moderate spatial resolution. Intra-pixel spatial heterogeneity biases non-linear estimation processes of land surface variables from moderate spatial resolution sensors (Friedl, 1997; Garrigues, 2004; Hu & Islam, 1997; Raffy, 1994; Tian et al., 2002; Weiss et al., 2000). To limit its influence on the

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description of land surface processes, a first strategy consists in explicitly taking into account the intra-pixel spatial heterogeneity in non-linear estimation processes (Garrigues et al., in press). This strategy requires quantifying the intra-pixel spatial heterogeneity. A complementary strategy is to define the proper pixel size to capture the spatial variability of the data and minimize the intra-pixel variability (Atkinson, 1995; Curran & Atkinson, 2002; Garrigues, 2004; Marceau et al., 1994; Puech, 1994; Rahman et al., 2003). Therefore, characterizing the landscape spatial heterogeneity may help in designing the spatial resolution for future earth observing missions. Regarding validation field campaigns, the landscape spatial heterogeneity is also an essential information to choose a suitable sampling scheme which captures the spatial scale of the surface property and optimizes the field collection resources (Baret et al., in press; Morisette et al., 2002; Morisette et al., in press; Stein & Ettema, 2003).

To properly characterize the spatial heterogeneity, it must be appropriately defined. A surface property is heterogeneous, if its measurements vary in space (Kolasa & Rollo, 1991). In this paper, spatial heterogeneity is described through two components:

- The *spatial variability* of the surface property over the observed scene.
- The *spatial structures*, also called objects or patches. They repeat themselves independently within the observed scene at a characteristic length scale (i.e. spatial scale) which represents the spatial structure extent. They can be viewed as the typical correlation area (i.e. the typical area of influence) of the surface property. Data are often distributed into independent sets of spatial structures, related to different length scales and spatial variability, being overlaid in the same region. A formal definition of the spatial structures is given in Section 4.3.

7. Conclusion

This work showed that modeling the variogram of high spatial resolution NDVI data is a powerful method to characterize and quantify the spatial heterogeneity of vegetation cover at the landscape level. The variogram sill σ^2 measures the landscape spatial variability. The image spatial structures are characterized by both the variogram ranges and the fractions of the total variance associated with each range. In addition, we introduced the concept of integral range which summarizes all structural parameters of the variogram model into a single characteristic area. Its square root is a weighted average of the several range parameters and quantifies the mean length scale of the data, i.e. the mean extent of the image spatial structures. The integral range is used as a yardstick to judge if the size of an image is large enough to measure properly the length scales of the data by the variogram. We propose that it must be smaller than 5% of the image surface. The square root of the integral range must thus be smaller than 671 m for a 3000 by 3000 m image.

The modeling of NDVI variogram for 18 contrasted landscapes highlights the influence of the land use on the spatial heterogeneity of vegetation cover at the landscape level. The most heterogeneous sites (σ^2 between 0.02 and 0.05) are cropland for which the field spatial structure explains the most important part (from 60% to 100%) of the NDVI spatial variability. Natural vegetation and forest sites are more homogeneous at the landscape level (σ^2 between 0.0001 and 0.02). However, their variability may be increased by the presence of singular objects with respect to the type of vegetation. The mean length scale of the landscapes varies between 216 and 1060 m. It results from several processes such as human activity, ecosystem functioning, or climate. Note that on some landscapes, the size of the image was too small to properly quantify its length scales. A 7000 by 7000 m extent would have been more appropriate for these cases.

Variogram modeling is an efficient approach to characterize the loss of spatial variability captured by the sensor as its spatial resolution decreases. A spatial structure cannot be resolved by the sensor when the pixel size is larger than its length scale. The theoretical dispersion variance, computed from the variogram model, quantifies the intra-pixel spatial heterogeneity. It increases rapidly with pixel size until this size is larger than the mean length scale of the data. It then tends asymptotically to the sill of the variogram σ^2. The dispersion variance at the sensor spatial resolution may be used as additional knowledge to correct non-linear estimation processes of land surface variables from remote sensing data. However, ways have to be found to get prior knowledge of this intra-pixel spatial heterogeneity metric without systematic concurrent high spatial resolution images that would make moderate spatial resolution images useless. A possible approach is to retrieve the intra-pixel spatial heterogeneity by using a temporal sampling or a spatial sampling per type of landscape of high spatial resolution data. To test this strategy, variogram modeling should be applied to a broader spatial and temporal database of high spatial resolution remote sensing data.

Finally, an upper limit of the sufficient pixel size to capture the major part of the spatial variability of the landscape vegetation cover is proposed from the mean length scale information provided by the variogram. From the analysis of 18 landscapes of the VALERI database, it is estimated to about 100 m. Since for all the heterogeneous landscapes the loss of NDVI spatial variability was small at this spatial resolution, the bias generated by the intra-pixel spatial heterogeneity on non-linear estimation processes will be reduced. However, this result is limited by the number and the nature of the landscapes analyzed. A more representative sampling of landscape types is required to refine the assessment of the sufficient pixel size. Since the variogram provides the mean characteristics of image spatial heterogeneity, its quantification of length scales can be coarse in some cases. Other tools, such as wavelet analysis, should be used to quantify finer local length scales in the image.

The definition of the optimal pixel size is not a trivial issue. It depends mainly on the objectives pursued, the objects observed and the retrieval techniques used. First, the pixel size must be large enough to be consistent with the object targeted and the retrieval technique considered. If the spatial resolution is too fine, spatial structures at small length scales may hamper the retrieval of the surface property. Further studies are required to estimate the lower limit of the proper pixel size to characterize the vegetation cover at the landscape level. Second, the pixel size must be small enough to capture the spatial variability of the data and minimize the intra-pixel spatial variability. The sufficient pixel size proposed in this study provides an indication of the upper limit of the proper pixel size to characterize the vegetation cover at the landscape level. The optimal pixel size should be chosen in between these two limits but additional factors, including technical and economic constraints, should be considered to define it for incoming earth observing missions.