ANALYSIS OF THE QUALITY OF COLLECTION 4 AND 5 VEGETATION INDEX TIME SERIES FROM MODIS

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ABSTRACT:

Globally acquired data from both MODIS instruments are suitable for science quality time series, because the unique concept of pixel-level quality information of each MODIS land product allows a detailed analysis of the data usability. MODIS datasets are regularly updated and reprocessed to meet present science requirements. This study compares time series of present collection 4 and currently released collection 5 data for the vegetation index product (MOD13). Considerable adjustments were made including changes in cloud and aerosol detection, compositing, and a redesign of the quality information layer. A software package for time series generation of MODIS data (TiSeG) was adjusted to collection 5 products. The quality requirements of collection 5 data are stricter and collection 5 flags are more sensitive to atmospheric disturbances. The newly introduced reliability dataset is important for accurate cloud detection. Compared to the NDVI, the EVI time series has a higher dynamic range for vegetated units and a better inherent temporal consistency also for lower quality composites.

1. INTRODUCTION

Time series provide the possibility to monitor inter-annual and intra-annual processes of the Earth surface. Annual cycles of vegetative activity are used for phenological analysis (Asner et al. 2000), crop monitoring (Tottrup and Rasmussen 2004), or estimating net primary productivity (Running et al. 2000). Changes or modifications of these cycles due to droughts (Tucker et al. 1994), El Niño events (Anyamba et al. 2002), or human impacts (de Beurs and Henebry 2004) are observed with multi-annual time series mostly using vegetation indices (VI; for abbreviations see glossary at the end of the paper) such as NDVI from the AVHRR sensor. Climate modeling, change detection studies, and other applications in the framework of global change require high quality time series with a standardized, consistent, and reliable time series generation process (Sellers et al. 1996, Justice et al. 2002). Therefore the quality of the time series determines its usability for long term analysis.

The level of required data quality is highly dependent on the subsequent analysis. Hereby data quality is related to the level of uncertainty contained in the data and propagated to the results with a high influence on their accuracy (Atkinson and Foody, 2002). With regard to time series, in particular VIs describing the phenological development, the consistency during the year and for multiple years is most important (Roy et al. 2002). Intra-annual variations of a vegetation index profile which cannot be attributed to actual changes on the earth surface are serious quality issues. For example cloud coverage and other atmospheric particles have a substantial influence on the signal and need to be either corrected or at least indicated. Intra-annual comparisons such as trend estimations and mapping of subtle multiyear earth surface processes (e.g. bush encroachment in semi-arid environments) may yield misleading conclusions if either the data are not corrected for sensor degradations or sensors generations are not correctly intercalibrated.

Data from both MODIS instruments are used for a large suite of global, value-added products. The improved sensor design and the standardized radiometric, geometric, and atmospheric calibration are suitable for high quality time series (Justice et al. 1998). The MODIS data production put much emphasis on the data quality starting at raw level 1 data to level 4 modelled products. The innovative concept of a simultaneous generation of remote sensing products and quality assurance indicators facilitates standardized and consistent global products. This is particularly important for high temporal resolution products suitable for time series generation but should also be considered for other satellite datasets.

Several MODIS science teams are concerned with quality assurance and product validation (Roy et al. 2002, Morisette et al. 2002). The LDOPE facility tests the accuracy and consistency of all MODIS land products. Additional quality assurances are computed by SCF for individual products. It is only possible to investigate a selection of all MODIS products for particular areas. Both, LDOPE and SCF ensure high data quality by visual inspections and a number of operational checks, e.g. using time series of summary statistics for globally distributed regions (Roy et al. 2002). General and product-specific quality information is provided for the user as metadata and at the pixel-level. The science quality flag of the metadata describe quality issues for the entire spatial extent and contain the informative quality indicators in seven levels for data ordering. The pixel-level information (QA-SDS), can be used to assess the quality of each grid cell (Roy et al. 2002). This unique concept of product-specific pixel-level quality indicators provides full information, maximum flexibility, and leaves the decision about the sufficiency of data quality by the user.

Multiple versions, also called collections, of MODIS data were released since the launch of MODIS onboard Terra and Aqua in 2000 and 2002, respectively. A new collection of MODIS products incorporates the most recent scientific findings into data processing and requires a complete reprocessing of the current data archive. This study analyzes the quality of time series of the present collection 4 (C4) and the currently released collection 5 (C5) for the vegetation index product MOD13. The Time Series Generator (TiSeG) was used to evaluate the pixel-level QA-SDS and to interpolate invalid data (Colditz et al. 2006a, 2007). The study describes the modifications in quality retrieval and changes in quality settings between both collections and shows the impacts on an annual NDVI and EVI time series for selected natural regions and land cover types of Germany.

2. CHANGES OF THE VEGETATION INDEX PRODUCT IN COLLECTION 5

Two Vis, NDVI and EVI, are included in the MODIS VI product (MOD13). The NDVI, also known as continuity index, matches to long term observations of the AVHRR instruments. The EVI has an improved sensitivity in high biomass areas and decouples the vegetation signal from soil background and atmospheric influences (Huete et al. 2002).

Considerable changes in science and structure were applied to C5 of the MODIS VI product (Didan and Huete 2006). Scientific modifications were made to (1) cloud and aerosol retrieval, (2) a different backup algorithm for EVI computation, and (3) an improved CV-MVC for better spatial consistency. The analysis of cloudy pixels in C4 yielded residual pixels labeled clear and *vice versa*. For example, insufficient cloud masking in C4 data was observed at the margins of clouds and for partly cloudy pixels. Furthermore, the aerosol retrieval was insufficient for heavy aerosols and if climatology parameters had to be used. Changes in C5 occurred in data filtering with emphasis on cloud shadows, pixels adjacent to clouds, and aerosols. The simpler MVC approach (Holben 1986) is used in C5 if all pixels during the compositing period were cloudy, partly cloudy, or adjacent to clouds. Second, in C4 the SAVI (Huete 1988) was used as EVI backup for cloudy pixels, snow and ice covered surfaces, or if the blue band was out of range. C5 uses a newly developed equation, called EVI2 for better continuity with the standard EVI (Huete et al. 2002).

$$EVI2 = 2.5 \frac{\rho_{NIR} - \rho_{RED}}{1 + \rho_{NIR} + \rho_{RED}} \tag{1}$$

The CV-MVC approach (Huete et al. 2002) in C4 processing considers only the two highest VI values with a deviation of less than 30% from the maximum and selects the value with the lowest view zenith angle. Despite the ratio effect the selection of different days for adjacent pixels resulted in a low spatial connectivity in the composite. The approach was modified to a deviation of less than 10% and contextual selection according to the temporal behavior of suitable pixels. This omits a high temporal variability of selected days for compositing, i.e. adjacent pixels are more likely being selected from the same observation or another observation close to the neighbour.

Structural changes comprise (1) additional layers, (2) modifications of the QA-SDS specifications, and (3) phased production between Terra and Aqua data. A layer indicating the day selected for compositing and an indicator for pixel reliability were added. In particular the actual day of each VI value will be helpful to many vegetation studies and will enable a more accurate monitoring and timing of phenological key stages such as beginning of green-up or senescence. In C4 the actual day of image acquisition within the 16-day composite period was unknown. The new reliability SDS includes important pixel-level information on cloud cover, snow and ice surfaces, general usability and fill values for pixels which cannot be retrieved. Second, negligible differences between separate QA-SDS for NDVI and EVI of C4 data lead to a combined VI QA-SDS in C5. In addition to the reliability SDS, structural modifications of the QA-SDS involve a full three bit land and water mask instead of a two bit reduction. In exchange, the bit field of the compositing approach was eliminated because the algorithm does not use the BRDF compositing method. An 8-day phasing in the production of 16-day VI composites between Aqua and Terra allows the generation of a combined 8-day time series. Additional changes in C5 are an effective internal compression and additional metadata parameters.

A merge of C4 and C5 data is not recommended by the MODIS scientists (Didan and Huete 2006). Changes in the generation of the QA-SDS will lead to rather different results, and changes in the algorithm, e.g. EVI2, contributes to a different absolute VI value.

3. TIME SERIES GENERATION

Multiple approaches have been successfully used for time series production mainly focusing on AVHRR datasets (el Saleous et al. 2000, Viovy et al. 1992, Colditz et al. 2006b, Jönsson and Eklundh 2002, Roerink et al. 2000). New sensor developments and dataset production systems e.g. for MERIS and MODIS also create data quality indicators (Brockmann 2004, Roy et al. 2002). These ancillary datasets have been successfully used for data analysis and time series generation (Leptoukh et al. 2005, Lobell and Asner 2004, Landmann et al. 2005, Lunetta et al. 2006). The Time Series Generator (TiSeG; Conrad et al. 2005, Colditz et al. 2006a, Colditz et al. 2007) evaluates the pixel-level QA-SDS available for all value-added MODIS land products and selects suitable pixels according to user-defined settings. The resulting gaps can be masked or interpolated by temporal or spatial functions. The freely available software package generates two indices of data availability for time series quality assessment: the number of invalid pixels and the maximum gap length. While the first indicates the total of useful data for the entire period, the latter is an important indicator for a feasible interpolation. In order to mitigate interpolation problems quality settings can be modified spatially and temporally. A detailed description of TiSeG and examples of time series for various quality settings is described in Colditz et al. (2007). The software package has been extended to C5 data, and adjustments have been made to include the redefined QA-SDS and the additional reliability SDS.

C4 and C5 VI data of Germany with 500m resolution and 16-day compositing period (MOD13A1) were downloaded for one year starting in mid February; day 2000-049 (the earliest available day) to day 2001-033 (the completed period of C5 data production at the point of writing). The tiles h18v03 and h18v04 were mosaiced, reprojected to UTM zone 32N, and subset to the area of Germany using the MODIS Reprojection Tool (MRT). EVI and NDVI time series with three different

Table 1: Quality settings of 16-day 500m VI data (MOD13A1) for collection 4 and 5.

Setting	Usefulness index	Mixed clouds	Snow/ice	Shadow
C-S-S		No	No	No
UI3-C-S-S	Perfect – acceptable	No	No	No
UI5	Perfect – intermediate			

Note: The table only shows the quality settings used in this analysis. For a detailed description on quality settings for MODIS VI products see Huete et al. (1999) and Didan and Huete (2006).

quality settings were generated (Table 1) and interpolated using linear temporal interpolation. Specifics on the MOD13 data generation and quality assessment approach can be obtained from Huete et al. (1999) and Huete et al. (2002). The usefulness index is a weighted score and consists of several other indicators including cloud coverage and shadow, adjacency and BRDF correction during surface reflectance processing, angular information and aerosol quantity (Huete et al. 1999). It ranks from perfect to low quality. C5 data were generated without and with consideration of the newly introduced reliability SDS (indicated by C5+R) selecting good and marginal quality.

4. TIME SERIES ANALYSIS

Temporal plots of the number of invalid pixels and the maximum gap length, indicating data availability for time series generation, are depicted in Figure 1.With regard to the quality settings, UI3-C-S-S was strictest followed by C-S-S and UI5. Considerable differences are shown between C4 and C5 data for the number of invalid pixels with different trends for day 49 to 81, 177 to 209 and day 305 to 1. While the first and last period mark the end and beginning of wintertime and transitional seasons with both, snow and cloud effects, the middle period of lower data quality is related to a typical summer rain period in July. The average and maximum differences in data availability in percent between collections are shown in Table 2. Generally, the quality analysis of C5 data is stricter and therefore omits more pixels. Some reverse patterns are shown for lenient setting UI5, which excludes more data in C4 for days 81, 193, 353, and 17. This effect is due to changes in masking of clouds and shadow as well as aerosol mapping which contribute to a different score of the usefulness index. Furthermore, the additional use of the reliability SDS for C5 excludes more pixels from the analysis (see also Table 2).

The cumulative plot of the maximum gap length (Figure 1) is a suitable indicator how many data can be interpolated with sufficient confidence (Colditz et al. 2007). For example, 95% of C4 data with setting UI5 have a gap shorter or equal three composites. On the other hand, at a gap of five consecutively missing observations 92% of all C4 data with setting UI3-C-S-S are interpolated. Stricter settings cause more invalid pixels which often leads to longer gaps. It depends on the user and the subsequent analysis which maximum gap length is still considered appropriate to interpolate. Although the maximum gap length is mainly used as a feasibility indicator for interpolation, it also shows differences between collections. While the above noted effect of UI5 with slightly more omitted pixels in C4 than C5 also causes a somewhat longer gap length, all other settings show remarkably longer data gaps for C5 data. The additional use of the reliability SDS makes a high difference for lenient setting UI5 and is attributed to the additional cloud and snow/ice masking. The impact of the reliability SDS becomes lower for moderate setting C-S-S and negligible for strict setting UI3-C-S-S. While a strict QA-SDS setting already excludes most of the possible pixels due to reasons such as low angles or other failed corrections which contribute to a high score of the usefulness index, those pixels are still regarded valid by lenient quality settings.

The spatial distribution of data availability is shown in Figure 2 for the number of invalid pixels. Generally, lower data quality is found in upland regions in middle Germany and the alpine region in the South. Considerable differences are apparent among quality settings, where the strictest setting UI3-C-S-S

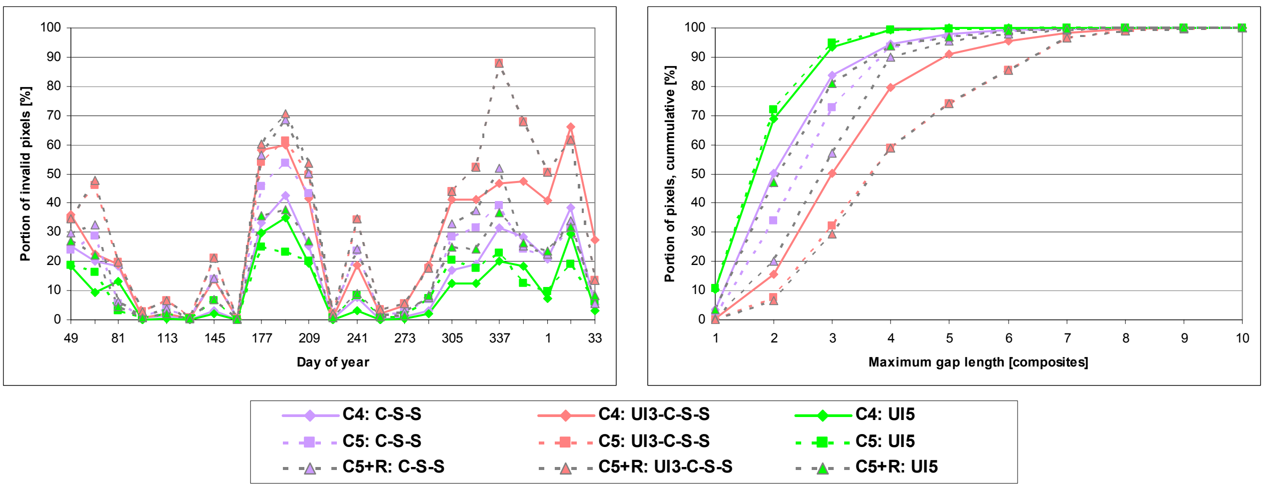

Figure 1: Temporal plot of the number of invalid pixels (left) and maximum gap length (right) for quality settings (see Table 1) of C4, C5, and C5+R data of Germany.

Table 2: Mean and highest differences in the annual course of the number of invalid pixels [%] between C4 – C5 and C4 – C5+R.

Settings	C4 – C5		C4 – C5+R	
	mean	max.	mean	max
C-S-S	6.4	17.9	9.0	25.6
UI3-C-S-S	7.7	41.4	8.3	41.4
UI5	4.0	11.8	6.1	16.4

also indicates less data availability in northern Germany due to frequent cloud coverage. Interestingly, the increasing continental characteristic with less cloud cover during the summer months in southern Germany is clearly revealed by this regional analysis. The comparison of C4 and C5 data visualizes no spatial differences for lenient setting UI5 but decreasing data availability for increasingly stricter settings where substantially more pixels are regarded invalid for upland areas and in the lowland of northern Germany. The difference when using the reliability SDS is also illustrated in Figure 2 and becomes particularly clear for lenient and moderate settings UI5 and C-S-S.

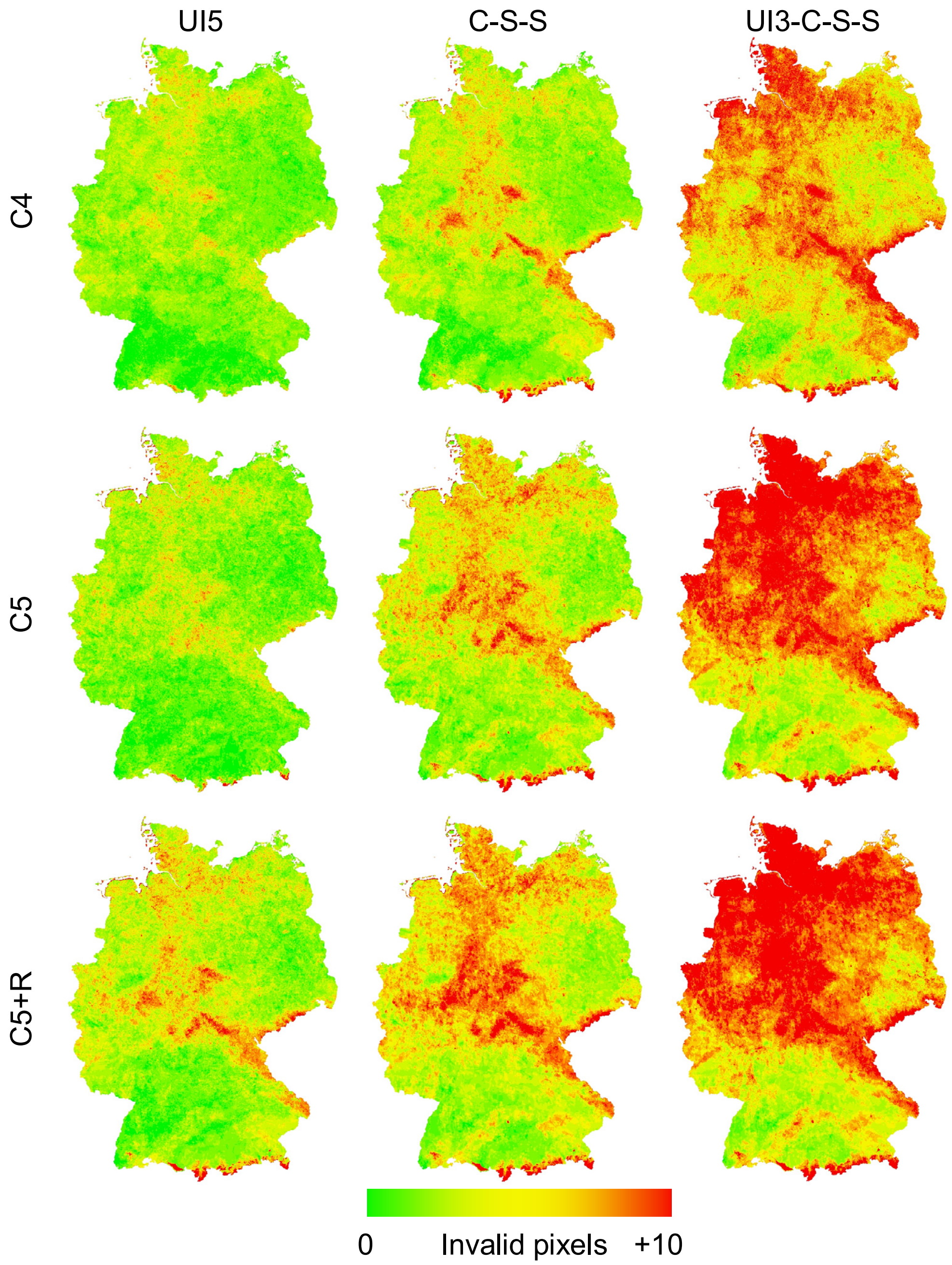

Figure 2: Spatial distribution of the number of invalid pixels for quality settings (Table 1) of C4, C5, and C5+R data of Germany. Note: More than ten out of 23 invalid pixels are depicted in red.

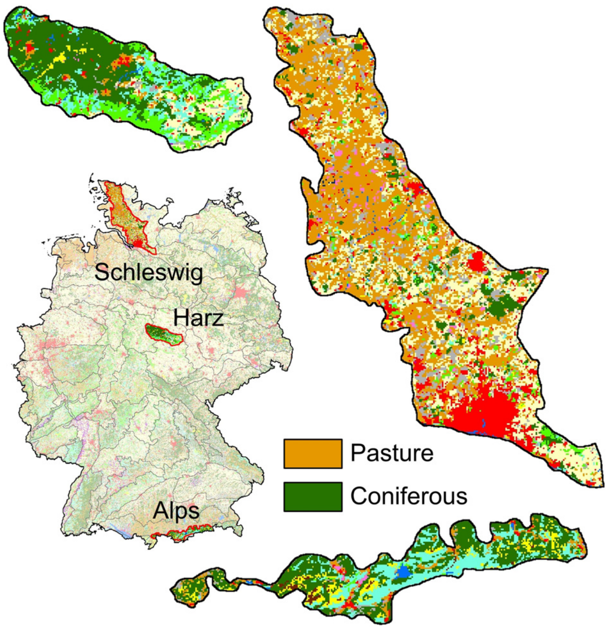

Figure 3: Selected natural regions (Meynen and Schmithüsen 1953) and land cover types (CORINE; Keil et al. 2005) of Germany.
Note: Classes pasture and coniferous are relevant for Figure 4 and Figure 5

A third analysis was made for selected regions of Germany (Figure 3) using the CORINE land cover classification (Keil et al. 2005) and natural regions of Germany (Meynen and Schmithüsen 1953). Schleswig is located in northern Germany and dominated by grazing land for sheep and cattle. The Harz upland is Germany's northernmost upland with peaks above 1000m. In particular its western portion is dominated by dense coniferous forests. These coniferous stands are compared to the Alpine region in southern Germany.

Figure 4 (NDVI) and 5 (EVI) show the average time series plots of C4, C5, and C5+R for the land cover types and regions in Figure 3. The time series correspond with quality settings of Table 1 and also include the original dataset without quality analysis. The original time series shows substantial short term temporal variability, in particular for the NDVI, which is attributed to atmospheric disturbances (clouds, aerosols) and snow/ice cover. It should be noted that the NDVI and EVI SDS itself do not indicate cloud coverage, the major source of remarkably decreasing VI values. Instead they contain a VI value in the valid data range. Only the examination of the additional information, the QA-SDS and the reliability SDS for C5, reveal these influences. This is typical for many MODIS land products where only the additional data quality specifications indicate the data usability (Roy et al. 2002). Lenient setting UI5 often follows the original plot and therefore does not seem to be an improvement. On the other hand, the strict setting UI3-C-S-S eliminates most pixels and requires the interpolation of long periods. This also causes unrealistic VI

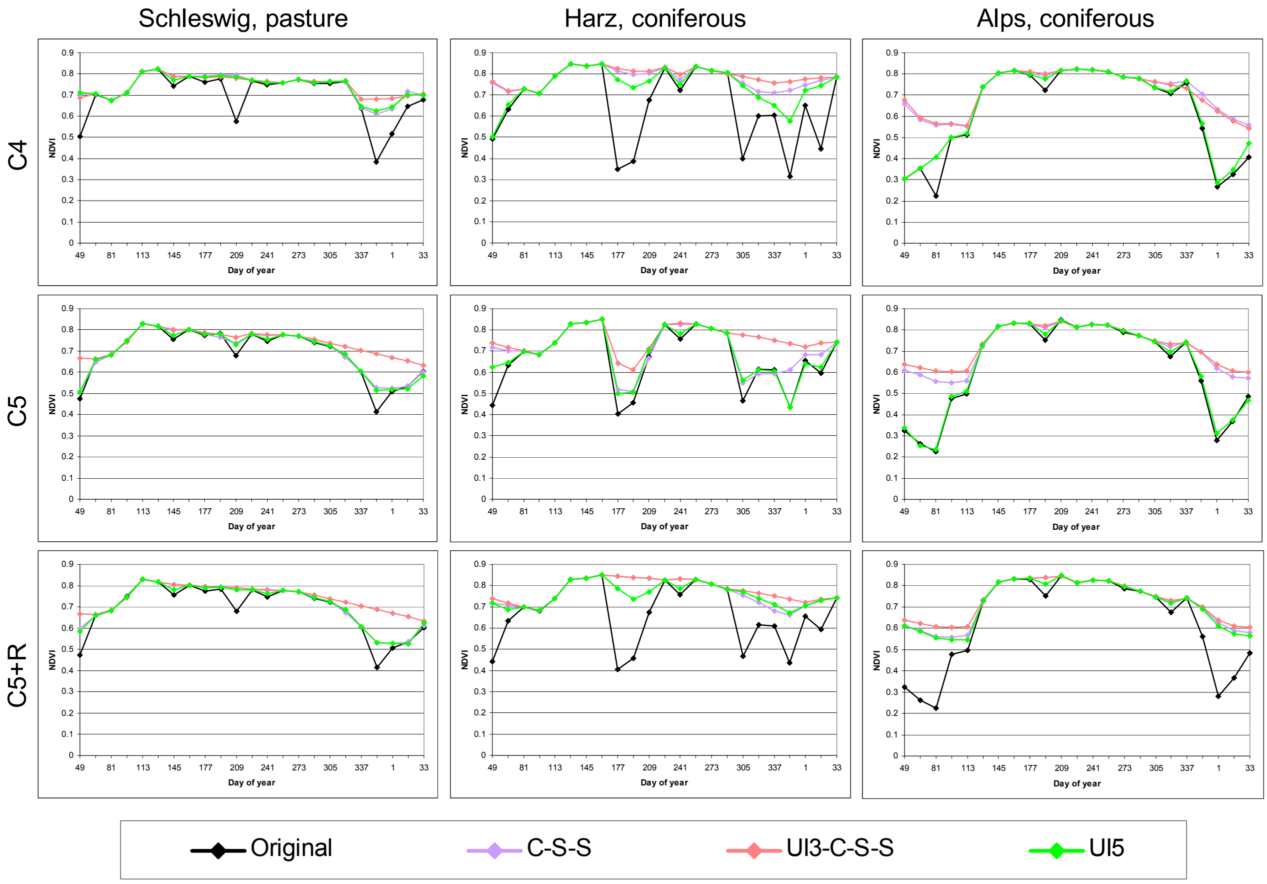

Figure 4: NDVI time series plots of natural regions and land cover types for quality settings (see Table 1) of C4, C5, and C5+R.

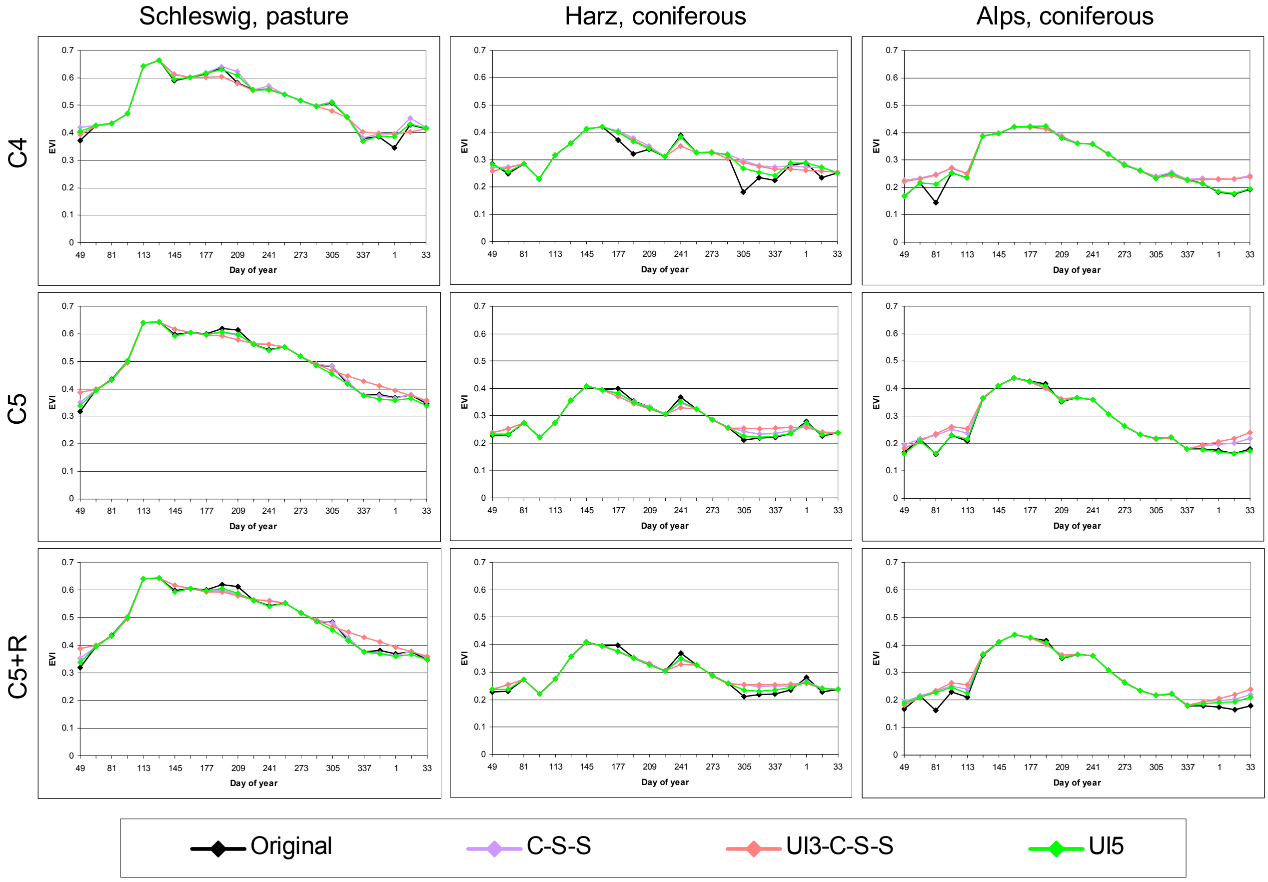

Figure 5: EVI time series plots of natural regions and land cover types for quality settings (see Table 1) of C4, C5, and C5+R.

features and does not resemble expected phenologies, e.g. during the winter season in Schleswig for the NDVI. The time series of this study are best generated with the moderate setting C-S-S, which yields in expected phenological patterns. For an in-depth discussion on quality settings and time series generation see Colditz et al. (2007).

The following discussion will focus on the differences in data collections. The NDVI data of Figure 4 show clear differences for interpolated time series between C4 and C5 products. The stricter characteristics of C5 quality settings are indicated for the winter period of Schleswig. Differences between C5 and C5+R data are well illustrated in Figure 4 for the Harz upland. While the summer cloud period from day 161 to 225 is sufficiently well interpolated by C4 even the strictest quality setting of C5 result in a clear decrease in NDVI if only C5 QA-SDS is considered. The additional use of the reliability SDS, however, interpolates this three composite gap of invalid data successfully and shows expected phenological plots with a pronounced plateau phase during summer. This proves that, in contrast to C4, setting mixed pixels in the QA-SDS of C5 does not necessarily mark all cloudy pixels. In other words, in addition to the QA-SDS the reliability SDS should be considered to exclude all invalid data. For the Harz and the Alps, snow coverage during the winter period is also successfully interpolated with the reliability SDS.

Differences between C4 and C5 are less obvious for EVI data (Figure 5). The temporal dynamic range of meaningfully interpolated EVI data is higher than for NDVI. It seems that the dynamic range slightly increased in C5. EVI values, however, are much less susceptible to atmospheric disturbances and temporary surface changes as indicated by the smoother plot of the original data. This can be attributed to well-working backup algorithms if the EVI cannot be retrieved directly. The changes of the backup approach from SAVI to EVI2 seemed to improve this characteristic, indicated by the original plot for the Harz upland. While C4 data decreased during the summer cloud period and varied in wintertime, the original plot remained close to the interpolated results for C5 data. The changes in quality assessment slightly improved the resulting EVI time series of C5 data, e.g. for the spring in the Alps and during the summer period for Schleswig.

5. CONCLUSIONS

The QA-SDS provides meaningful information for data analysis and time series generation of MODIS data. The Time Series Generator (TiSeG) analyzes the QA-SDS and displays the data availability in time and space according to the user-defined settings. Following, data gaps can be flagged or interpolated with spatial or temporal functions. This software package was adjusted to the modified MOD13 QA-SDS of C5 products and extended to incorporate the newly introduced reliability layer.

The comparison between C4 and C5 quality settings revealed a stricter specification for data quality of C5 data in particular for rigorous quality settings. The quality specifications for cloud and shadow, aerosol, and snow/ice are improved and yield in a more conservative result, i.e. regard more pixels as invalid. This results in less data availability and an increase in the gap length by one composite. The higher sensitivity to atmospheric disturbances yields in a higher quality of the time series, which is measured by better temporal connectivity. Spatial patterns of data availability indicate that higher elevations are frequently flagged as invalid due to both, snow/ice and clouds. Lowlands in northern Germany are marked as invalid by strict settings due to frequent cloud coverage.

The regional time series analysis highlights the necessity of a critical weighting between quality and quantity. Low data quality will include invalid pixels and does not yield improved time series. Highest data quality, on the other hand, will consider most accurate data but often results in too few data for meaningful interpolation. It can be concluded that the reliability SDS should also be analyzed when using the new C5 products. In particular, cloud coverage was better indicated by this new layer. While flag mixed cloud in C4 also indicated full cloudy pixels, the same flag in C5 only labels partly cloudy pixels. Therefore the reliability dataset is the only means to mask cloudy pixels in C5. In comparison with the NDVI, the EVI shows better consistency and a higher temporal dynamic range.

6. GLOSSARY

AVHRR	Advanced very high resolution radiometer
C4	Collection 4 (version 4) of MODIS data
C5	Collection 5 (version 4) of MODIS data
CORINE	Coordination of information on the environment
CV	Constrained view
EVI	Enhanced vegetation index
LDOPE	Land data operational product evaluation
MERIS	Medium resolution imaging spectrometer
MOD13	MODIS vegetation index from Terra platform
MODIS	Moderate resolution imaging spectroradiometer
MRT	MODIS reprojection tool
MVC	Maximum value compositing
NDVI	Normalized difference vegetation index
QA	Quality assurance
SAVI	Soil-adjusted vegetation index
SCF	Science computing facility
SDS	Science data set
TiSeG	Time series generator
UTM	Universal transverse mercator
VI	Vegetation index

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