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Monitoring of vegetation dynamics on the former military training area Königsbrücker Heide using remote sensing time series

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ABSTRACT

In 1989 about 1.5 million soldiers were stationed in Germany. With the political changes in the early 1990s a substantial decline of the staff occurred on currently 200,000 employees in the armed forces and less than 60,000 soldiers of foreign forces. These processes entailed conversions of large areas not longer used for military purposes, especially in the new federal states in the eastern part of Germany. One of these conversion areas is the former military training area Königsbrück in Saxony. For the analysis of vegetation and its development over time, the Normalized Difference Vegetation Index (NDVI) has established as one of the most important indicators. In this context, the questions arise whether MODIS NDVI products are suitable to determine conversion processes on former military territories like military training areas and what development processes occurred in the "Königsbrücker Heide" in the past 15 years. First, a decomposition of each series in its trend component, seasonality and the remaining residuals is performed. For the trend component different regression models are tested. Statistical analysis of these trends can reveal different developments, for example in *nature development zones* (without human impact) and *zones of controlled succession*. The presented workflow is intended to show the opportunity to support a high temporal resolution monitoring of conversion areas such as former military training areas.

Keywords: MODIS NDVI, time series analysis, regression analysis, protected areas, monitoring

1. INTRODUCTION

A protected area is defined by the International Union for Conservation of Nature and Natural Resources (IUCN):

*"A protected area is a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values."*¹

To establish comparability between the different types of protected areas in the national states or regions, the IUCN has published management categories in 1994, which were updated in 2008 (Dudley, 2008). To allow for allocation of these categories to the categories of protected areas in the Federal Republic of Germany EUROPARC Germany (2010) published an edited German version of the document.² The categories of protected areas in Germany are defined in the Federal Nature Conservation Law (BNatschG). Beside nature protection areas the most important categories also include national parks, biosphere reserves and protected landscape areas. According to the Federal Agency for Nature Conservation (BfN), especially in the large protected areas of Germany (national parks, biosphere reserves, nature parks) the object of research and monitoring is an integral part of resources management. The analysis of large areas requires special demands on the monitoring, in which the use of remote sensing methodology and data can make a valuable contribution.

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As no direct interaction for data collection is necessary with using remote sensing for monitoring, the disturbance of ecosystems of protected areas is avoided.^{3,4} Remote sensing data are available in various spatial resolutions ranging from sub-metre to several kilometres and different temporal resolutions up to several observations per day. The selection of appropriate data depends on the particular research question and is often limited by the availability of affordable data in order to minimize costs.⁵ Land Use and Land Cover (LULC) inventories can be used to derive planning measures or to analyze the impact or benefit of applied planning measures.³ Remote sensing plays an important role in monitoring of habitats. For protected areas Nagendra (2013) provide a survey of the use of various remote sensing systems for different monitoring tasks.⁶

Time series analysis is a special form of analyzing remote sensing data and useful for long-term monitoring which is defined by Lindenmayer et. al. (2010) as: "Repeated field-based empirical measurements are collected continuously and then analyzed for at least 10 years." In order to evaluate the phenological status of vegetation high temporal resolution data are required. Therefore MODIS data are highly recommended because they provide a number of products for the description of phenology.³ In particular, the Normalized Difference Vegetation Index (NDVI) is an important parameter for evaluating vegetation status over time.⁷ NDVI times series of different remote sensing systems are available in different temporal and spatial resolutions (e.g. Terra MODIS NDVI, AVHRR GIMMS, SPOT VGT) and were used in numerous studies of vegetation monitoring in various vegetation zones and different scales ranging from global to local.^{8–18} The above mentioned examples show that the use of remote sensing data in conjunction with methods of applied spatial data analysis could make a valuable contribution for monitoring programs in protected areas. Especially high temporal resolution data allow a detailed analysis of short-term phenological processes. In the present study a former military training area is used to be examine whether natural or controlled processes of succession can be detected using high-resolution satellite-based time series. These investigations are carried out for the "Königsbrücker Heide", one of Germany's largest nature reserves.

2. STUDY AREA AND DATA

Of particular interest in the context of monitoring protected areas are those regions that have emerged from redesignation of its use. These include also surfaces that have been previously used as military training areas.

In 1989 about 1.5 million soldiers were stationed in Germany. Beside the Federal Armed Forces (Bundeswehr) and the National People's Army forces (NVA), soldiers of seven other states were stationed. Whereas in the Federal Republic of Germany about 400,000 ha (1.6 %) were used as military areas in the former East Germany with approximately 517,000 ha even 4.4 % of the national territory were used for military purposes. With the political changes in the early 1990s a substantial decline of the staff occurred on currently 200,000 employees in the armed forces and less than 60,000 soldiers of foreign forces. These processes entailed conversions of large areas not longer used for military purposes, especially in the new federal states in the eastern part of Germany.

One of these conversion areas is the former military training area "Königsbrück". This has already been created in 1906 by the Royal Saxon Army and is located about 30 km north of Saxony's capital Dresden. Until 1938 the Wehrmacht expanded the site by depopulating nine villages. After the end of WW2 the Soviet forces occupied the area and used it until their withdrawal in 1992. Since 1996 this territory is declared as the nature reserve (NSG) "Königsbrücker Heide". The fact that large areas are restricted due to the still existing military equipment and weaponry remains enables the opportunity that one of the largest non-fragmented landscapes can develop mostly without human activities. During more than 700 years history as a cultural landscape, the natural forest areas were reduced and used for forestry. In the period of military use large areas were kept free of forest. Since 1990, large areas reforest naturally in order to guarantee a free natural development in about 3/4 of the territory.

At present, the area has the status of a nature reserve and is, with an area of approximately 69.3 km², one of the largest unfragmented nature reserves in Germany. The aim of the reserve is the assurance of large succession areas as retreat for species which have a high area requirement and are particularly sensitive to disturbance.¹⁹ An important prerequisite for achieving the protection aims is the spatial differentiation in protection zones. Therefore the "Königsbrücker Heide" is subdivided into three zones (see figure 1, left).

The **nature development zone** covers an area of about 50 km² and is expected to (largely) develop without the impact of human activities. Basically no engagement, management and maintenance measures are carried out, except from ordnance disposal and maintenance of ways. The goal is the development of a natural forest environment under current conditions. As a result current habitats will gradually disappear.²⁰ In the **zone of controlled succession** (approximately 8 km²) former areas of military use, which are open land habitat for various species, are preserved by selective intervention. In such a case, succession processes are actively disturbed.²⁰ The **buffer zone** serves as a buffer to the surrounding cultural landscape and occupies an area of about 10 km². In the buffer zone on the one hand, existing pine forests are converted to natural forest, on the other hand cultural habitats like fish ponds and meadows are preserved.²⁰

The different objectives in the illustrated zones suggest that different developments in these areas should be recognizable in the observation of long time series, which provide information about the vegetation. Therefore remote sensing provides different methods and data. Based on the data of the MODIS instrument, which is mounted on the Terra satellite as well as on the Aqua satellite, since 2000 the United States Geological Survey (USGS) is able to provide worldwide NDVI time series in a spatial resolution of 250 m and with a repetition rate of 16 days which are capable to characterize vegetation change.^{21,22} The investigation of the used data shows gaps that need to be removed before further processing in a time series analysis can take place. Figure 1 (right) shows the absolute frequency of these data gaps and their spatial distribution over the study area (15 years).

Figure 1. left: Protection zones of the nature reserve "Königsbrücker Heide"; right: Spatial distribution and absolute frequency of data gaps (15 years, 367 observations)

The causes of these data gaps cannot be clarified. However occasional snow cover could be one responsible factor. For further processing of the data, all data gaps in the study area were temporally interpolated using a seasonal Kalman filter.^{23,24}

According to the zoning in the study area, the present 1203 series will be separated according to these categories. For this part, shape-files of the zones as well as an outline polygon of the area boundaries were provided by the administration of the protected area. Due to the geometric resolution of the MODIS data of 250 m, pixels are intersected by the zone boundaries. All pixels that are not covered by the polygon representing the study area or the zoning are excluded.

At the end of preprocessing the data are temporally complete and categorized by zones available for the following time series analysis.

3. METHODOLOGY

The data analysis is organized in a multistage process. The preprocessing of the data as described in the previous section is followed by the decomposition of the time series and a trend analysis. Furthermore residual analyses are an integral part of the quality assessment.

The individual methods required to process this workflow are explained in the following section.

3.1 Methodology of decomposition

Basically it can be said that natural processes in form of a time series, can be represented by a combination of sub-processes, which are also time series. This allows dividing such a signal in a trend component (T), a seasonal part (S) as well as the remaining random residuals (e). The combination of these components can be effected by addition or multiplication. Multiplicative models are especially preferably used when the amplitude of seasonality is not constant over time. The additive model can be described as follows:

$$Y = T + S + e \quad (1)$$

For the present research question determining the components of the additive model has to be done for each MODIS pixel. This process of decomposition of a time series was performed with the function `decompose` implemented in the open source software R.²⁵ The `decompose` function requires a known frequency of seasonality. Since the NDVI data illustrate seasonal recurring phenomena, a frequency of a year or 23/24 measurement times can be assumed for the present time series. Nevertheless, this assumption has been checked and confirmed according to various methods (e.g. autocorrelation function, fast Fourier transformation).²⁶⁻²⁸

For the analysis of trends a moving average approach was selected:

$$T_t = \frac{\sum_{i=t-\frac{n}{2}}^{i=t+\frac{n}{2}} Y_i}{n+1} \quad (2)$$

The size of the moving window is equal to the length of the seasonality plus 1. After the trend is removed from the original series, the seasonal figure S_t can be computed. This is done by calculating the average for each time unit over all periods and centering the resulting figure in a second step. For one period (year), the seasonal part S_t can be expressed by:

$$S_i = \frac{\sum_{j=0}^{m-1} Y_{j \cdot n + i}}{m} \quad (3)$$

where m is the number of years. If the trend as well as the seasonal figure is removed from the input data the error component (random part) remains.

$$e_t = Y_t - (T_t + S_t) \quad (4)$$

After the decomposition of time series the three components of the MODIS NDVI time series are available for each of the 1203 pixel representing the study area. The quality of the decomposition was examined by means of a detailed residual analysis (see Chapter 3.3).

3.2 Methodology of trend analysis

The analysis of trends in the observation period is performed by means of two simple and well established methods. The first is a common ordinary least square regression, in which the time is the independent variable and the NDVI value the dependent variable. The calculation of the regression is carried out based on the method of least squares. In addition, significance was tested on an $\alpha = 0.05$ level. In the simplest form this linear approach is expressed by the equation:

$$NDVI = a + b \cdot t \quad (5)$$

Here, the slope (b) of the function can be considered as an indicator of direction of the development of NDVI over time.²⁹

A second method for the determination of the trends in a time series is the Mann-Kendall monotonic trend test. This non-parametric test is less sensitive to outliers and does not require normal distribution of the data

to be analyzed. The test determines the degree to which a trend is consistently increasing or decreasing (-1 to +1).^{30,31}

An increasing trend is represented by a value of +1 while a decreasing trend is described by a value of -1. Finally a value of 0 is an indication of no trend. The null hypothesis H_0 of this test states that there is no trend in the series, while the alternative hypothesis H_A assumes that there is a trend. H_0 was tested against H_A , two-tailed at $\alpha = 0.05$.

The computational procedure for the Mann-Kendall monotonic trend test considers the time series of n data points and X_j and X_k as two subsets of data where $j = 1, 2, 3, \dots, n-1$ and $k = j+1, j+2, j+3, \dots, n$. For the evaluation, the data values are interpreted as an ordered time series and in pairwise combination each data value is compared with all subsequent data.³²

The result of all increasing and decreasing values leads to the final value of S . The Mann-Kendall S statistic is computed as follows:³³

$$\begin{aligned} \text{sgn}(x_j - x_k) &= 1 \text{ if } x_j - x_k > 0 \\ &= 0 \text{ if } x_j - x_k = 0 \\ &= -1 \text{ if } x_j - x_k < 0 \end{aligned} \quad (6)$$

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (7)$$

where X_j and X_i are the annual values in years j and i , $j > i$, respectively. As part of the data analysis both methods are applied to the entire study area.

3.3 Methodology of quality assessment

Both the quality of decomposition and the modeling of trends require a detailed assessment which was carried out in form of a residual analysis.

For a satisfying quality of the decomposition as well as the modelled trends these residuals should fulfill two main conditions. The first condition demands that the mean value of residuals should be constant over time and the expectation value is 0. The second requirement states, that the variance should be constant over the whole time series. By means of tests of stationarity both conditions can be tested. In this study, three different tests for stationarity were conducted. The first two tests, i.e., the augmented Dickey-Fuller test (ADF) and Philipps-Perron test (PP) are tests on nonstationarity as they were used for testing unit root in time series (H_0). If there is a unit root, the time series is not stationary. If H_0 is rejected and H_A (the time series is stationary) is accepted, the stationarity of the residuals or the random component of the decomposition is confirmed. Because the ADF test tends to reject the null hypothesis too often a further unit root test was performed in addition to the ADF test. It could be happen that the tested random component of the time series will be deemed for nonstationary by the ADF test even through it is not. This limitation of the ADF test can be considered by the PP test.³⁴

In contrast, the third test of Kwiatkowski-Phillips-Schmidt-Shin (KPSS) is a direct test on stationarity as the null hypothesis and alternative hypothesis are changed.³⁴ The KPSS test can be performed with two different options. The first type allows testing the residuals and random component of the time series on stationarity concerning the remaining trend after decomposition (trend stationarity). With second option the KPSS test can be performed in a stricter manner by assuming that there is no further trend signal in the random component. This method is used for the test on level stationarity.³⁵

Many methods of data analyses require normal distributed measurements. Sometimes it is mandatory to test the distribution of the used NDVI time series. These results are the basis for the decision of the chosen analysis method. Therefore, two established tests are performed to confirm or reject the hypothesis of normal distribution (Shapiro-Wilks test, Kolmogorow-Smirnov test). The test value W of the Shapiro-Wilks test is the ratio between the variance of an assumed normal distribution and the variance of the real distribution of measurements.³⁶

The null hypothesis of the Shapiro-Wilks test is that the measurements are normally distributed. The Kolmogorow-Smirnov test can either be used to compare the distribution of two samples or to test one sample on specific distribution.³⁷ Here the Kolmogorow-Smirnov test was performed for normal distribution and therefore serves as a confirmation of the Shapiro-Wilk test.

4. RESULTS

4.1 Results of decomposition of time series

The decomposition of the time series was carried out according to the explanations in chapter 3.1 using the additive approach. Exemplary of a total of more than 1200 performed decompositions, figure 2 shows a results for the *nature development zone* and a second example for the *zone of the controlled succession*.

Figure 2. Examples for the decomposition of the time series containing the original series and the three resulting components (trend, seasonal, random residuals); top: Nature development zone; down: Zone of controlled succession

The figures show that in principle a different development can be observed in different parts of the protected area. A first visual analysis also suggests that the boundaries of the zones partly reflect this different development. The quality of the decomposition was confirmed by a detailed residual analysis as described in Chapter 3.3. It was found that for the processed KPSS test, the maximum test values for level stationary (0.028) and trend stationary (0.014) for the whole study are below the corresponding critical values ($L_{crit} = 0.463$; $T_{crit} = 0.146$). Thus, the null hypothesis of stationarity is proved for each single time series.³⁵ The results of the KPSS tests are confirmed by the ADF test and the PP test. It was shown for both methods that no unit root is present and

therefore the null hypothesis of non-stationarity is rejected for each time series in the study area. As a result can be assumed that decomposition of the time series was successful and the trend component is available for further analysis.

4.2 Results of time series analysis

4.2.1 Linear Ordinary Least Square Modeling

Based on the trend components of the decomposition, linear trend models have been developed for all the pixels in the study area. With respect to the aims of this study, the analysis of the slopes of these trend models is of particular interest. Figure 3 shows the slope and the corresponding R^2 values for the study area within the boundaries of the protection zones:

Figure 3. Results of the linear ordinary least square modeling; left: slopes; right: Adjusted R^2

The first impression of the analysis of decompositions, as explained in chapter 4.1, can be confirmed. For the trend modeling, the residual analysis also serves as a step for quality assessment. For this reason both, the KPSS test and the ADF test, has been applied to the residuals of the linear modeling. For the KPSS test, the results indicate that not for all pixels a stationarity can be confirmed. The critical value is significantly exceeded for some pixel (critical value: 0.146; maximum test value: 0.831). The results of the ADF test confirm this statement (critical value: -3.42; maximum test value: -2.14). In summary, it is obvious that the use of a linear model over the entire observation period is not possible. Clear structural breaks in the trend, as can be seen in figure 2 (e.g. decomposition), are expected to be the cause of non-stationarity, as these breaks cannot be displayed appropriate by a linear model. Both examples in figure 2 show one narrow break in 2010 and a longer period of lower values between 2013 and 2014. In the plot for the *zone of controlled succession* an additional breakpoint followed by a period of lower NDVI values occurs in 2005.

Since the objective of the study is not the linear modeling of NDVI itself but the investigation on trends in NDVI signal, in the following a non-parametric trend test was used to confirm the results of the simple linear regression with respect to the increasing signal.

4.2.2 Mann-Kendall monotonic trend analysis - zonal analysis

Due to the fact that the Mann-Kendall monotonic trend test is less sensitive to structural changes in a time series, it can provide evidence to what extent a trend can be detected in each of the study area. Figure 4 shows the results of this analysis.

Also in this case the results show different trends in the study area. The values reach amounts of up to 0.7, which corresponds to a clear positive trend in the development of vegetation in particular in the *nature development zone*. Even compared to the results of the Ordinary Least Square Modelling differences can be

Figure 4. Results of the Mann-Kendall monotonic trend analysis; left: Kendall's tau; right: p value

recognized. Qualitatively, the appearance is quite comparable. However in some areas of the study area, using the Mann-Kendall monotonic trend test a larger development could be detected.

In addition to the evaluation of the whole study area further analyses should show, whether different developments can be detected in the individual zones of the study area. Figure 5 shows the distribution of Kendall's tau-values as box plots.

Figure 5. Zonal statistical analysis of Mann-Kendall tau

It is clear that in the *nature development zone*, but also in the *buffer zone*, the average value of Kendall's tau is higher than in the *zone of the controlled succession*. Based on these results it could be assumed that in the *nature*

development zone the mean slope is higher. But it can also be seen in the box plot, that the distributions overlap in large parts. So the question arises, whether the means are actually a good indicator of different development. In order to answer this question different methods of inductive statistics were used. To check whether the mean values are significantly different the Wilcoxon-Mann-Whitney test^{38,39} was used. This test was preferred because the results of Shapiro-Wilks test³⁶ and Kolmogorow-Smirnov³⁷ test indicate non-normal distributed data. The results of Wilcoxon-Mann-Whitney test clearly show that it cannot be assumed that different processes appear in the protected zones, although it may be considered by the mere inspection of the medians values.

The causes can be manifold. On the one hand it could indeed be assumed, that there are no different developments in the protection zones, on the other hand it can be possible, that the analysis based on the boundaries of the protection zones is not suitable to verify and quantify the different developments, which can be recognized in figure 4.

5. DISCUSSION

Basically it can be said that a positive ($slope > 0$) development of the NDVI in the nature reserve "Königsbrücker Heide" can be shown. It could be shown, that a simple linear modeling is not sufficient to reflect the positive trend entirely. The lack of linearity can be partly explained by the nature of the data basis. The NDVI as an indicator of the status of vegetation can reach a maximum value of 1 due to its calculation. Therefore by using an exponential model better results could be expected.

In addition, the visual analysis of the trend curves of decomposition already show that structural breaks in the time series can have a significant impact on the modeling. A qualitatively better modeling can be expected, if the time of such structural break is considered as a discontinuity in the development and trend modeling before and behind this point is done separately. Osunmadewa et al. (2015) have shown that in consideration of these breaks improvements in linear modeling is possible for a GIMMS NDVI time series.⁴⁰ In the case for the standard deviation a relative improvement of more than 1/3 was detected.

However the aim of the present investigation was to analyze the principle development. This was successfully done by using the Mann-Kendall monotonic trend test. But also the nature of the used data has to be considered. The MODIS data have a geometric resolution of only 250 m. Changes on a larger scale will have only attenuated influence on the NDVI value of the larger grid cell. Therefore it can be assumed that in partial areas of such grid cell the development differs significantly from that of the whole pixel. Such differing development can appear in both directions (greening, browning). Increasing the resolution, by using higher resolution satellite imagery (e.g. Landsat, ASTER, Sentinel), could remove this barrier to some extent, however, then it has to be mentioned that the temporal resolution of the data is significantly reduced. But high temporal resolution is of paramount importance to evaluate the data in terms of time series analysis. In this conflict of interest a decision must be made according to the respective research question.

Based on the results it can be said that there is no clear statement possible about the development in the individual zones. But it can be shown, that certain developments appear more frequent in certain protection zones. So it cannot be said that the *nature development zone* generally show very strong trends. But it is obvious that for areas where high trends occur, mainly the protection status of a *nature development zone* is present. This is because in the *nature development zone* areas can be found which were already covered by dense vegetation during the military use. In such areas a further increase, also reasoned by the above mentioned restrictions of the NDVI signal, is not expected. Such possible explanation can be impressively confirmed by a simple visual comparison of high resolution Landsat imagery from 1992 (end of military use), 2000 (start of MODIS time series) and 2015 (end of MODIS time series).

At the same time the evaluation of NDVI trends in the *zone of controlled succession* cannot be done without the ecological objectives in such a zone. On the contrary; the low slopes in NDVI trend show that the process of controlled succession, in the sense of open landscapes is detectable in the present time series.

Figure 6. Visual comparison of high resolution imagery; left: 1992 (end of military use; Landsat 7), middle: 2000 (start of MODIS time series; Landsat 7), right 2015 (end of MODIS time series, ASTER); Data Source: United States Geological Survey

6. SUMMARY

With the foundation of the nature reserve "Königsbrücker Heide" in 1992 an about 7,000 hectare landscape has changed significantly in some areas. The results of this analysis show, that these developments occur differently in different parts of the reserve, and that these developments are not necessarily based on the zoning. The selected data base will allow a high temporal resolution monitoring, indicating fast possible deviations from the long-term behavior in the past. To such events belongs, for example, the significant deviation of the NDVI values from the trend and the cyclical behavior in 2005, which again can be found in many decompositions of the time series data. Future research will increasingly focus on artifacts of this type. This includes in particular the aforementioned detection of structural breaks in the time series, the discussion of underlying causes and the evaluation of these breaks. In addition, the synergetic use of different data sources will become increasingly important. The advantage of spatially higher resolution data sources at irregular times within a less spatially resolved time series with high temporal resolution promises the possibility of more detailed analyses. The transformation of data with coarse spatial resolution to higher resolution datasets can be done by transformation rules, which take place on the basis of observation times at which datasets of both spatial resolutions are available. The benefit of these methods for the analysis of NDVI time series is open and the subject of recent scientific research.

The "Königsbrücker Heide" as former military training area faced major changes in the past two decades. Thus, from an ecological point of view but also from the perspective of the remote sensing and applied geoinformatics it represents an interesting study area in the future.

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