PFG 2/2015, 0117–0127
Stuttgart, April 2015

Article

Multi-temporal Analysis of RapidEye Data to Detect Natural Vegetation Phenology During Two Growing Seasons in the Northern Negev, Israel

Stefanie Elste, Cornelia Glässer, Ivo Walther & Christian Götze, Halle (Saale)

Keywords: RapidEye, phenology, natural vegetation, semi-arid, multi-temporal analysis

Summary: This study focused on the analysis of semi-arid natural vegetation phenology in the Northern Negev in Israel during the two growing seasons in 2010/2011 and 2012/2013 with different precipitation patterns. The objective was to develop a methodology based on vegetation indices to detect the characteristic phenological cycles of three types of vegetation, annual grasses, perennial shrubs and biological soil crusts, with multi-temporal RapidEye data. For the first time the usage of RapidEye's high temporal resolution as well as its red edge band enabled a detailed detection of this phenology in semi-arid environments. In doing so, the vegetation indices differed in their suitability for the different vegetation types. One could benefit from the Normalized Difference Vegetation Index (NDVI) for annual plants, the Normalized Difference Red Edge Index (NDRE) for perennial plants and the Modified Normalized Difference Vegetation Index (MNDVI) for biological soil crusts. The spatial distribution of the vegetation is illustrated by combining the three indices during their maximal photosynthetic activity.

Zusammenfassung: *Multitemporale Analyse von RapidEye-Daten zur Untersuchung der phänologischen Entwicklung natürlicher Vegetation zweier Vegetationsperioden in der nördlichen Negev, Israel*. In vorliegender Studie wurde die phänologische Entwicklung semiarider, natürlicher Vegetation im Norden der Wüste Negev während zwei Vegetationsperioden mit sehr unterschiedlichen Niederschlagsverhältnissen anhand von RapidEye-Daten untersucht. Ziel ist die Entwicklung einer Methode auf der Basis von Vegetationsindizes wie dem NDVI, welche die charakteristischen phänologischen Zyklen der Vegetation ermittelt: einjährige Gräser, mehrjährige Büsche sowie biologische Krusten. Die hohe temporale Auflösung der RapidEye-Daten sowie der RedEdge Kanal ermöglichten zum ersten Mal eine detaillierte Erfassung der Phänologie in diesem Gebiet. Die Indizes eignen sich dabei für die Vegetationstypen unterschiedlich gut. So konnten für mehrjährige Pflanzen der NDRE sowie der MNDVI für biologische Krusten Informationsgewinne liefern. Die räumliche Verbreitung der Vegetation wird durch die Kombination jener Indizes, die die maximale photosynthetische Aktivität der Vegetationstypen widerspiegeln, dargestellt.

1 Introduction

The characteristic feature of arid and semi-arid ecosystems is their high temporal and spatial variability regarding precipitation (Blümel 2013). Therefore, they are very vulnerable to additional climate extremes in terms of climate change (Schlesinger et al. 1990). Hence it is important to monitor this vegetation in relation to climate to notice changes in their development for the management and protection of these ecosystems. Phenology has proven to be a very suitable tool for this because it comprises "the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species" (Lieth 1974). Due to the spatial coverage as well as financial and time related savings, remote sensing techniques proved to be very suitable for these kinds of analyses. For example until now especially dense

www.schweizerbart.de
DOI: 10.1127/pfg/2015/0258
1432-8364/15/0258 $ 2.75

time series of NOAA AVHRR data were used in semi-arid environments like the Northern Negev because of its very high temporal resolution (Schmidt & Karnieli 2000, Wang & Tenhunen 2004). Contrarily, Landsat data would provide more spatial details due to its better spatial resolution but is limited concerning phenological analyses in very sensitive ecosystems in arid regions because of its coarser temporal resolution (Elmore et al. 2000). Consequently, a combination of high temporal and spatial resolution data is needed to detect important phenological events as well as changes in the spatial distribution of vegetation especially in heterogeneous landscapes like the Northern Negev. With the development of multi-sensor satellite systems such as RapidEye, the temporal resolution of high spatial resolution optical sensors has increased remarkably. Therefore, multi-temporal RapidEye data has been successfully applied to classify vegetation units or different plant parameter (Schuster et al. 2012).

The Northern Negev is characterized by sparse natural vegetation cover that consists of annual grasses, perennial shrubs and biological soil crusts (Karnieli 2003). Karnieli (2003) described that each of these vegetation types exhibit their own typical phenology in relation to precipitation (Fig. 1). In the following these different phenologies are referred to as phenological cycles. In contrast to shrubs and grasses, biological soil crusts consist of cyanobacteria, algae, mosses, fungi and lichens (Danin 1996). These microphytes are typically representative in arid and semi-arid areas (Danin 1996). Dry conditions force these organisms into a latent state; only when they have some water they become physiologically active and turn green due to their photosynthetic activity (Danin 1996). Because of this very sensitive response to moisture, Karnieli (2003) found that they are the first to become physiologically active at the beginning of the growing season when the first rainfall occurred (Fig. 1). At this point annuals and perennials are still dormant, because water is only available at the soil surface. The seeds of annual vegetation in the deeper soil layers require water to germinate, so they will not become active until more precipitation is available, which occurs in the middle of the rainy season. After the annuals fulfilled their development and become dry organic matter, perennial plants start to become active at the end of the growing season, when water is available for their deeper roots.

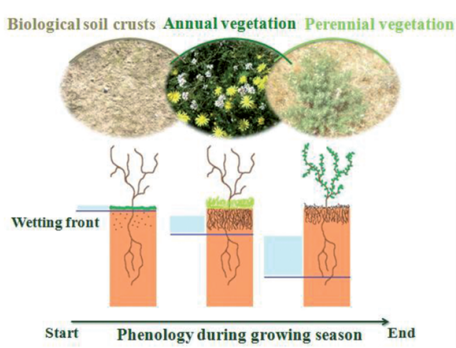

Fig. 1: Phenology of different vegetation types during the growing season in the Negev, Israel (after Karnieli 2003).

From the remote sensing point of view it is very difficult to discriminate photosynthetically active biological soil crusts from vital grasses and shrubs because their spectral signatures resemble each other (Weber et al. 2008). Karnieli et al. (1999) discovered that phycobilin pigments in the crusts cause a stronger reflection in the blue region of the electromagnetic spectrum which facilitates the discrimination. When dry, their spectral signature resembles soil (Karnieli et al. 1999).

The objective of this study was to develop a methodology to detect this characteristic natural vegetation phenology based on vegetation indices due to the different spectral characteristics of the vegetation types. Time series of RapidEye datasets with a high temporal resolution were analyzed for two seasons. 2010/2011 was a relatively dry season and 2012/2013 reached nearly the annual average for the study area. The comparison of the phenology of these seasons should reveal the sensitive reaction of the vegetation to different precipitation patterns.

2 Study Area

Sayaret Shaked Park, a heterogeneous landscape formed by loessial soils, is an area of one km² located in the Northern Negev with center coordinates of 31°16’11’’ N and 34°39’10’’ E in Israel. The annual mean precipitation is 200 mm and mainly concentrates between November and April and constitutes semi-arid climatic conditions (Karnieli et al. 2002). During this rainy period, later referred to as growing season, vegetation get photosynthetically active due to better moisture conditions (Climate Service Center 2.0 2014). The climatic and topographic conditions lead to a heterogeneous mosaic of perennial shrubs (e.g. *Noaea mucronata*, *Thymelea hirsute*), annual grasses (e.g. *Stipa capensis*, *Avena barbata*) and biological soil crusts which consist mostly of cyanobacteria (Burgheimer et al. 2006). While shrubs and grasses settle predominantly on sinks and slopes, the crusts cover the whole soil surface (Burgheimer et al. 2006), which leads to a lot of transition zones. One part of the park is closed off to livestock grazing since 1987 (Karnieli et al. 2002) and represents a research area of the Long Term Ecological Research Programme (LTER) and the Experimentation in Ecosystem Research Programme (ExpeER). Therefore, it is possible to study the natural vegetation in a small undisturbed ecosystem. Nevertheless, very dry consecutive years led to the death of numerous perennial shrubs recently, which partly destabilizes the ecosystem (Sher et al. 2012).

3 Data and Methodology

To cope with the sparseness and heterogeneity of the vegetation cover in Shaked Park, RapidEye data was chosen for the multi-temporal analysis because it combines high temporal with high spatial resolution. The five identical earth observation satellites located in a sun-synchronous orbit in approx. 630 km height record information in five multispectral bands with a temporal resolution of 1 to 5.5 days and a spatial resolution of 6.5 m (BlackBridge 2013). Designed predominantly for agriculture and forestry, RapidEye provides additional information for vegetation applications by the red edge channel from 690 nm – 730 nm (BlackBridge 2013) (Tab. 1).

Tab. 1: Spectral band widths of the RapidEye sensor.

Multispectral bands	Band widths
Blue	440 nm – 510 nm
Green	520 nm – 590 nm
Red	630 nm – 685 nm
Red Edge	690 nm – 730 nm
NIR	760 nm – 850 nm

To characterize the seasonal phenology of the three vegetation types, temporal dense time series of RapidEye data were required. Hence, images were ordered every 10 days, but due to meteorological and technical conditions the scenes were sometimes limited. Finally, as shown in Fig. 2, for the season 2010/2011 nine and for 2012/2013 thirteen cloud-free images were used.

Preprocessing of the data included orthorectification of Level 1B data and an atmospheric correction with ATCOR® 2 of every image (Richter & Schläpfer 2012). Furthermore, the geometric correction of the data was improved by additional co-registration because the spatial location of the scenes was partly inaccurate. This is caused by the small number of ground control points which varies from region to region and influences the spatial accuracy (BlackBridge 2013). In addition to the satellite images, daily precipitation data for the two seasons was available from the Ben-Gurion University weather station. During a field campaign in spring 2013 different kinds of reference data were gathered from various test sites, which were selected separately for areas with predominantly coverage of annual grasses, perennial bushes and biological soil crusts. The data contained photos of vegetation coverage during the growing season, field mapping for the vegetation index (VI) analysis and GPS data, which served as reference pixel for each type of vegetation.

Due to their simple and robust application, vegetation indices, which proved to be very suitable for remote sensing of vegetation, were chosen for the multi-temporal analysis (Chu-

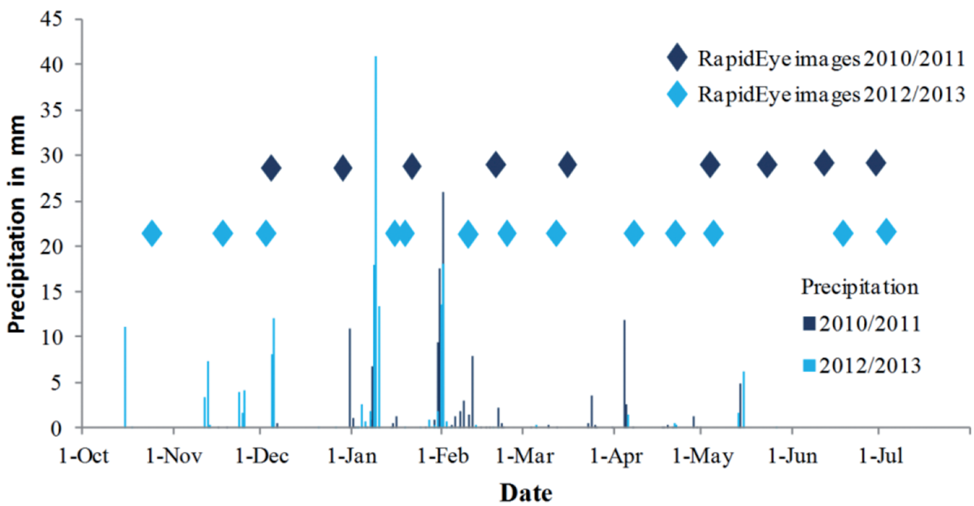

Fig. 2: Acquisition dates of RapidEye data in relation to precipitation.

vieco & Huete 2010). The NDVI (1) (Rouse et al. 1974) was selected as the basic VI since up to now it is proved as suitable tool for vegetation analysis in numerous studies (Pettorelli 2013). To test whether the red edge band provides additional information for this study, the NDRE was used (2), where the NIR band of the NDVI formula is replaced by the red edge band (Barnes et al. 2000). The red edge spectral region is also very sensitive for mapping stressed vegetation (Eitel et al. 2011). Furthermore, the specific spectral features of biological soil crusts lead to the application of the MNDVI (3), where the blue band is integrated in the original NDVI formula (Sims & Gamon 2002).

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

$$NDRE = \frac{Red\ Edge\ - \ RED}{Red\ Edge + RED} \quad (2)$$

$$MNDVI = \frac{NIR - RED}{NIR + RED - 2BLUE} \quad (3)$$

After preprocessing, each VI was calculated for every reference pixel of the test sites. For each vegetation type the values of the reference pixels were averaged and visualized as VI curves and analyzed in relation to precipitation. These temporal profiles proved to be a very useful tool in phenological research with remote sensing data (Förster et al. 2012, Rasmussen 1997, Odenweller & Johnson 1984, Justice et al. 1985). Knowledge-based, accordingly to Fig. 1, the slopes and local maxima – as indicators of photosynthetic activity – in the graphs were assigned to the phenological cycles of the vegetation types. During this process it was investigated which VI shows the best result to characterize the phenology of each vegetation type. Finally, the index images with the maximal photosynthetic activity for each type of vegetation were chosen and combined in a false colour composite to illustrate their spatial distribution.

4 Results

This section shows the results of the multi-temporal analyses. We determined the typical phenological cycles for the two growing seasons 2010/2011 and 2012/2013 with multi-temporal remote sensing data as a function of time and precipitation. A dotted line between each index value shall help to interpret the graphs in Figs. 3 and 4.

4.1 *Vegetation Period 2010/2011*

Multi-temporal index profiles for the growing season 2010/2011 are illustrated in Fig. 3. Based on our research it is observed that crusts got photosynthetically active relatively late, because significant rainfall did not occur until the end of December. Therefore, the growing season started in late December and ended in July. The NDVI of annual plants stayed constant from December until the middle of January although considerably rainfall occurred during December and the beginning of January. Subsequently it increases rapidly to its peak from February until March because the red portion of the electromagnetic spectrum declines and the NIR increases due to the photosynthetic activity. Afterwards, the NDVI declines to the level at the beginning in May and June as a result of reduction of photosynthetic activity which leads to a relatively stronger reflectance in the red spectral region. Based on the explanations to Fig. 1 a peak of photosynthetic activity in the middle of the growing season suggests the phenological cycle of annual vegetation.

At the beginning of the growing season the MNDVI shows a different behaviour in comparison to the NDVI of the annuals, because it increases to the middle of January when the NDVI stood constant. This is an important indication of the photosynthetic activity of the crusts, because the RapidEye image of the 19th January was acquired briefly after rainfall occurred (Fig. 2). Consequently, this scene is very suitable to discriminate the phenological cycle of the crusts from the annual vegetation phenological cycle which starts about one month later than the cycle of the soil crusts. Since this increase cannot be found in the NDVI curve, it indicates a benefit of the additional blue spectral band of the MNDVI to detect the physiological activity of the soil crusts. After this increase it also reaches its maximum in March and declines until May, similar to the NDVI of the annuals. This supports the assumption of the peak of the phenological cycle of the annuals during March 2011, because annuals appear on these sites too and cover the spectral signal of the crusts due to their more intensive coverage at this time.

Noticeably there is no further increase of these two indices at the end of the growing season and therefore no sign of the activity of perennial plants. In contrast to that, there is a slight increase in the curve of the NDRE for areas with predominantly perennial vegetation cover from the beginning until the middle of May with a clearer decrease at the end of July. Unfortunately there is no RapidEye image in June which could confirm this assumption. Even though this is just a slight indication of the phenological cycle of the perennials it is an important sign of their activity in regards to this very dry year and the plant's

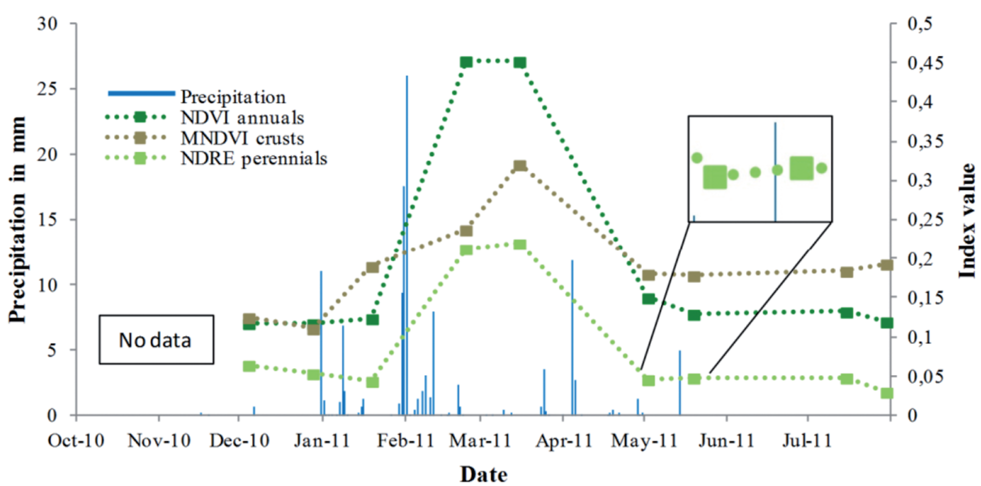

Fig. 3: Multi-temporal index profiles of the growing season 2010/2011.

partly critical health status due to the drought from 2008 until 2010 (Sher et al. 2012). Furthermore, the fact that only the NDRE shows the indication of this cycle it can be reasoned that the red edge channel contributes to an improved detection of their photosynthetic activity in Shaked Park.

In summary the phenological cycles for biological soil crusts and annuals of the growing season 2010/2011 could be detected completely with the datasets. The phenological cycle of the annuals from the middle of January until May with a peak from February until March could be determined completely while the crust cycle started at the end of December, due to the precipitation, with a peak in the middle of January. Contrarily to the annuals, a clear end of the cycle of crusts could not be determined because the MNDVI does not decline before the annuals started to germinate. The start and end of the phenological cycle of the perennials was more complicated to determine because their scarce distribution and critical health status led to a very low signal of photosynthetic activity in this very dry year.

4.2 *Vegetation Period 2012/2013*

The phenological cycles for natural vegetation during the growing season 2012/2013 differ in the timing as well as in the duration of the cycles and the growing season in general in comparison to 2010/2011. Accordingly to the previous period, the multi-temporal profiles of the three VI are illustrated in relation to precipitation in Fig. 4. As consequence of the different precipitation pattern the vegetation types are active from November until May. In this figure relatively similar courses of the index profiles with slight differences can be recognized.

As seen in the previous season 2010/2011, the different behaviour of the NDVI of the annuals and the MNDVI of the crusts at the beginning of the growing season is repeating but occurs earlier. The NDVI stays constant from the middle of October until the middle of November although significant rainfall occurred just two days before the RapidEye image in November was recorded. In the meantime the MNDVI of the crusts increases due to the sensitive reaction of these organisms to moisture. Again the combined analysis of these two indices proved to be suitable to discriminate the beginning of the phenological cycle of the biological soil crusts from the annual grasses. The MNDVI further increases from that point until the 17th January. Three days after this RapidEye image was taken, the MNDVI declines due to the missing precipitation which leads to a decline of the photosynthetic activity of the crusts. This would not be the case if the annuals were already active so that this

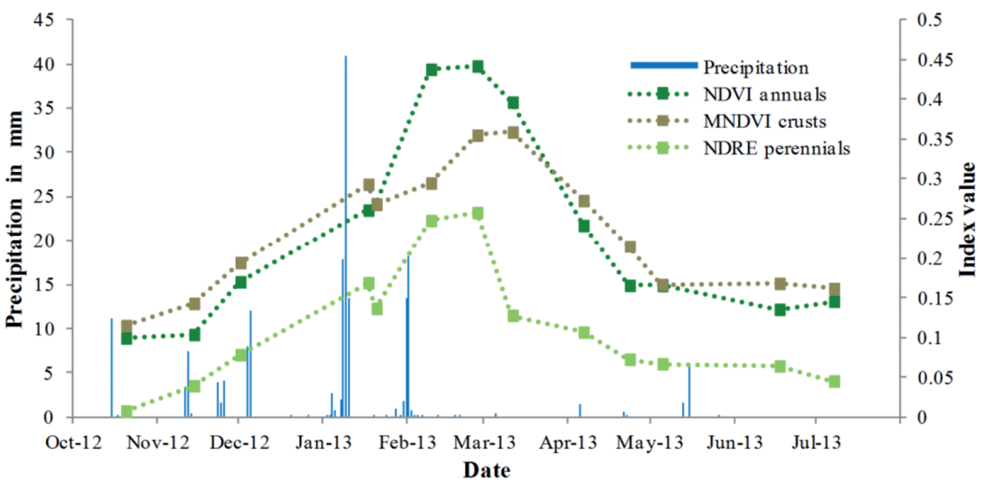

Fig. 4: Multi-temporal index profiles of the growing season 2012/2013.

point of time represents the end of the phenological cycle of the crusts. After this decline the MNDVI reaches its peak in March before it declines until May due to the photosynthetic activity of the annuals which superimpose the signal of the crusts because of their dense coverage at this point of time.

In contrast to that, the NDVI of the annuals starts to increase continuously from the middle of November to February where it reaches its maximum until March before it declines at the end of April almost to the base level. Consequently, it does not decline in January like the MNDVI. This is a clear sign of the photosynthetic activity of the annuals at that time. However, it is not definitely clear when the phenological cycle of the annuals starts because the NDVI increases already from the beginning of the growing season 2010/2011 which is unusual for these plants. A potential explanation for that is the early beginning of the precipitation season that leads to a stronger signal of the photosynthetic activity of the biological soil crusts which superimposed that of the annuals so that the NDVI increases at that early stage of this season.

Similar to the previous season (2010/2011) the phenological cycle of perennial vegetation cannot be extracted from the multi-temporal profiles of the NDVI and MNDVI but is shown more clearly in the NDRE profile. At the end of the growing season the NDRE falls not directly after the decline since the peak of the annuals in March. From the end of March until the beginning of April it stays almost constant before it declines until May which is again an indication of the activity of perennial plants.

All in all the existent RapidEye images allowed the complete detection of the pheno-

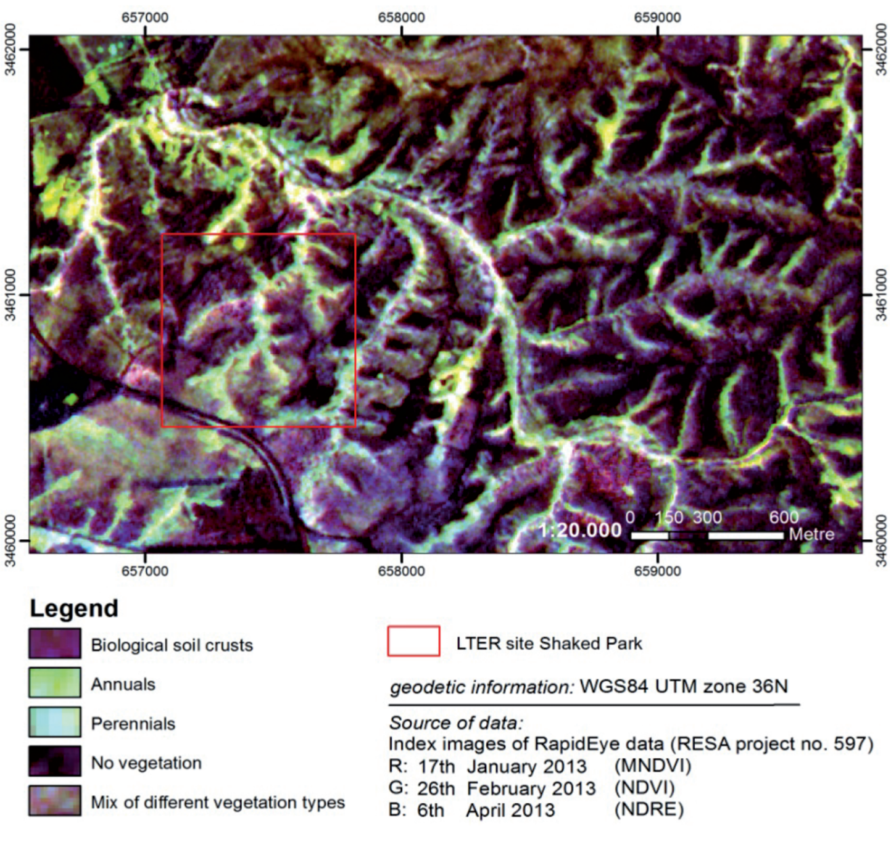

Fig. 5: False colour composite of index images of RapidEye data which show the maximal photosynthetic activity of each vegetation type in Shaked Park.

logical cycle of the crusts which lasts from November until January except of their maximum because no RapidEye images were available in December. The peak and end of the cycle of the annuals could be determined, too. In contrast to that, uncertainty exists for its beginning. The perennials were active from March until April.

For the season 2012/2013, the spatial distribution of natural vegetation in Shaked Park is illustrated with a false colour composite (Fig. 5). For this composite the three indices which show the maximal photosynthetic activity of the different vegetation types were combined. The red channel represents the MNDVI for crusts at the middle of January, the green represents the NDVI for annuals at the end of February and the blue represents the NDRE for perennials at the beginning of April (Fig. 5). Because there are predominantly areas with different portions of annuals, perennials and crusts, the colours in this image represent a mixture of red, green and blue. Obviously, annuals (green colours) and perennials (cyan-green colours) concentrate on sinks and slopes due to the better water availability. In contrast, biological soil crusts (dark purple-brown colours) are broadly distributed in the park due to their excellent adaptation to semiarid conditions.

5 Discussion

For the first time the typical natural vegetation phenology in the Northern Negev could be detected by high resolution RapidEye datasets. RapidEye images proved to be very suitable for the multi-temporal analysis because its high temporal resolution was helpful to determine the phenological cycles in detail. A robust methodology based on a combination of different vegetation indices could be developed which was applied successfully to two seasons with different precipitation patterns. The results correspond very well with those of other studies of this region (Karnieli 2003, Karnieli et al. 2002) and could be verified by field data.

Nevertheless, the results depend strongly on the availability of satellite data. So missing scenes in time periods of one month in June 2011 and December 2012 led to incomplete phenological cycles without maxima. Also every other index feature just shows the photosynthetic activity of the vegetation types at a specific point of time. For example, the start of the phenological cycle of the biological soil crusts in November 2012 cannot be fixed to that point because significant rainfall events were recorded in the middle of October which would cause the crusts to become active. So probably the MNDVI would be lower than in the end of October, but there was no scene available that was acquired earlier. Consequently, the time lag between rainfall events and the acquisition dates of the satellite images are also essential to describe the phenological cycles in detail especially for the sensitive reaction to moisture of the biological soil crusts.

The comparison of temporal profiles of the different vegetation indices demonstrated the NDVI as the most suitable index for detecting the phenological cycle of annual vegetation because it presented the maximum photosynthetic activity most clearly. Every investigated VI, i.e. NDRE, MNDVI, and NDVI, shows this maximum because all computation methods are an enhancement of the NDVI. Furthermore the MNDVI proved to be most suitable to determine the physiological activity of the biological soil crusts because it experienced the fastest reaction to precipitation at the beginning of the growing season. This is probably due to the phycobilin pigments whose stronger reflection in the blue spectral region could be registered much better by incorporating the blue band. The phenological cycle of perennial vegetation could only be detected by using the NDRE which confirms the generation of additional information through the red edge band. Other studies which evaluated the benefit of the red edge channel discovered an improvement of classification accuracies by using the NDRE, too (Schuster et al. 2012). Schuster et al. (2012) stated the higher sensitivity of the red edge band for vegetation adapted to dry climate conditions. One reason could also be the higher sensitivity of this spectral region for stressed vegetation, which could also be confirmed with RapidEye data for woody vegetation (Eitel et al. 2011). All in all one single index could not always represent the whole natural vegetation phenology. In this study the NDRE in 2012/2013 was the only situation where this VI shows all phenological cycles together. Probably high precipitation during this season led to a strong growth of the plants and therefore a strong spectral signal, but to be sure further analyses are required. Hence a combined analysis with the three proposed VI is recommended.

Furthermore, the sensitive reaction of the natural vegetation to different precipitation patterns could be revealed by comparing the timing and duration of the cycles for each season. The variations of the durations of the cycles were less compared to variations in timing. Due to the earlier onset of precipitation in the growing season 2012/2013, the phenological cycles in this season started about one month prior to the average. For instance, the cycle of biological soil crusts started in the 2012/2013 season in the middle of November, while in the previous season the start was dated in the middle of January 2011. In general, the complete phenological development pattern is shifted to earlier dates by one month. This clearly demonstrates the good adaption of desert plants to the highly temporal variable moisture conditions.

6 Conclusion and Outlook

For the first time high resolution RapidEye images allowed a detailed multi-temporal analysis concerning phenological events in a semi-arid region in Israel with high variability in precipitation. To detect the characteristic natural vegetation phenology a robust methodology based on a combination of the vegetation indices NDVI, MNDVI and NDRE was developed, which can be applied independently to the distribution and quantity of precipitation. Each of these three indices turned out to be suitable for one particular type of vegetation: the MNDVI for biological soil crusts, the NDVI for annual grasses and the NDRE for perennial vegetation. Furthermore, the methodology allows analyses of the spatial distribution of this natural vegetation by combining the index images of the scene of the respective maximal activity of each component in a false colour composite. The comparison of two growing seasons showed the shifting of phenological events due to the different precipitation patterns which emphasizes their role as important indicators of climate change and ecosystem stability in a very vulnerable semi-arid environment. RapidEye datasets proved to be very suitable for the multi-temporal analysis of phenological analyses in semi-arid environments especially with regards to its high temporal resolution and the gain of additional information with the NDRE provided by the red edge band. The time-series allowed the detection of natural vegetation phenology after the scheme of (Fig. 1) in both seasons, but uncertainties exist for perennial shrubs due to their scattered distribution and critical health status. Also the transition between the start and end of the phenological cycles is highly variable because of their spatial overlap. Future work will aim on the adaption of the approach to other sensors like WorldView-2 with a better spatial resolution of 2 m which can improve the detection of the perennial shrubs.

Acknowledgements

We thank the DLR for providing data from the RapidEye Science Archive (RESA project no. 597). Financial support by the Transnational Access to Research Infrastructures activity in the 7th Framework Programme of the EC under the ExpeER project for conducting the research is gratefully acknowledged. We also want to thank Prof. Arnon Karnieli, Alexander Goldberg and Natalia Panov of the Remote Sensing Laboratory of the Ben-Gurion University of the Negev for the very good cooperation. Furthermore we are grateful for the support of a research stay in Israel in the framework of the PROMOS programme of the DAAD.

References

Barnes, E.M., Clarke, T.R., Richards, S.E., Colaizzi, P.D., Haberland, J., Kostrzewski, M., Waller, P., Choi, C., Riley, E., Thompson, T., Lascano, R.J., Li, H. & Moran, M.S., 2000: Coincident detection of crop water stress, nitrogen status and canopy density using ground-based multispectral data. – Robert, P.C., Rust, R.H. &

Larson, W.E. (eds.): Fifth International Conference on Precision Agriculture: 1–15, Bloomington, IL, USA.

BlackBridge, 2013: Satellite Imagery Product Specifications. –http://www.blackbridge.com/rapideye/upload/RE_Product_Specifications_ENG.pdf (3.2.2014).

Blümel, W.D., 2013: Wüsten – Entstehung, Kennzeichen, Lebensraum. – First Edition, 327 p., Ulmer, Stuttgart.

Burgheimer, J., Wilske, B., Maseyk, K., Karnieli, A., Zaady, E., Yakir, D. & Kesselmeier, J., 2006: Ground and space spectral measurements for assessing the semi-arid ecosystem phenology related to CO_2 fluxes of biological soil crusts. – Remote Sensing of Environment **101** (1): 1–12.

Chuvieco, E. & Huete, A., 2010: Fundamentals of Satellite Remote Sensing. – 436 p., CRC Press, Boca Raton, FL, USA.

Climate Service Center 2.0, 2014: http://www.climate-service-center.de/033626/index_0033626.html.de (17.12.2014).

Danin, A., 1996: Plants of desert dunes. – Adaptation of desert organisms, 177 p., Springer, Berlin.

Eitel, J.U.H., Vierling, L.A., Litvak, M.E., Long, D.S., Schulthess, U., Ager, A.A., Krofcheck, D.J. & Stoscheck, L., 2011: Broadband, red-edge information from satellites improves early stress detection in a New Mexico conifer woodland. – Remote Sensing of Environment **115** (12): 3640–3646.

Elmore, A.J., Mustard, J.F., Manning, S.J. & Lobell, D.B., 2000: Quantifying Vegetation Change in Semiarid Environments: Precision and Accuracy of Spectral Mixture Analysis and the Normalized Difference Vegetation Index. – Remote Sensing of Environment **73** (1): 87–102.

Förster, S., Kaden, K., Förster, M. & Itzerott, S., 2012: Crop type mapping using spectral-temporal profiles and phenological information. – Computers and Electronics in Agriculture **89:** 30–40.

Justice, C.O., Townshend, J.R.G., Holben, B.N. & Tucker, C.J., 1985: Analysis of the phenology of global vegetation using meteorological satellite data. – International Journal of Remote Sensing **6** (8): 1271–1318.

Karnieli, A., Kidron, G.J., Glässer, C. & Ben-Dor, E., 1999: Spectral Characteristics of Cyanobacteria Soil Crust in Semiarid Environments. – Remote Sensing of Environment **69** (1): 67–75.

Karnieli, A., Gabai, A., Ichoku, C., Zaady, E. & Shachak, M., 2002: Temporal dynamics of soil and vegetation spectral responses in a semi-arid environment. – International Journal of Remote Sensing **23** (19): 4073–4087.

Karnieli, A., 2003: Natural vegetation phenology assessment by ground spectral measurements in two semi-arid environments. – International Journal of Biometeorology **47** (4): 179–187.

Lieth, H., 1974: Phenology and seasonality modeling. – Ecological Studies **8**, Springer, New York, NY, USA.

Odenweller, J.B. & Johnson, K.I., 1984: Crop Identification Using Landsat Temporal-Spectral Profiles. – Remote Sensing of Environment **14** (1–3): 39–54.

Pettorelli, N., 2013: The Normalized Difference Vegetation Index. – First Edition, 208 p., Oxford University Press, New York, NY, USA.

Rasmussen, M.S., 1997: Operational yield forecast using AVHRR NDVI data: Reduction of environmental and inter-annual variability. – International Journal of Remote Sensing **18** (5): 1059–1077.

Richter, R. & Schläpfer, D., 2012: Atmospheric/Topographic Correction for Satellite Imagery (ATCOR-2/3 User Guide). – http://www.dlr.de/eoc/Portaldata/60/Resources/dokumente/5_tech_mod/atcor3_manual_2012.pdf (13.5.2014).

Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W. & Harlan, J.C., 1974: Monitoring the vernal advancement and retrogradiation (greenwave effect) of natural vegetation. – NASA/GFSC Type III, Final Report, Greenbelt, MD, USA.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A. & Whitford, W.G., 1990: Biological Feedbacks in Global Desertification. – Science **247** (4946): 1043–1048.

Schmidt, H. & Karnieli, A., 2000: Remote Sensing of the seasonal variability of vegetation in a semi-arid environment. – Journal of Arid Environments **45:** 43–59.

Schuster, C., Förster, M. & Kleinschmit, B., 2012: Testing the red edge channel for improving land-use classifications based on high-resolution multi-spectral satellite data. – International Journal of Remote Sensing **33** (17): 5583–5599.

Sher, Y., Zaady, E., Roonen, Z. & Nejidat, A., 2012: Nitrification activity and levels of inorganic nitrogen in soils of a semi-arid ecosystem following a drought-induced shrub death. – European Journal of Soil Biology **53:** 86–93.

Sims, D.A. & Gamon, J.A., 2002: Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. – Remote Sensing of Environment **81** (2–3): 337–354.

Wang, Q. & Tenhunen, J.D., 2004: Vegetation mapping with multitemporal NDVI in North Eastern China Transect (NECT). – International Journal of Applied Earth Observation and Geoinformation **6** (1): 17–31.

Weber, B., Olehowski, C., Knerr, T., Hill, J., Deutschewitz, K., Wessels, D.C.J., Eitel, B. & Büdel, B., 2008: A new approach for mapping of Biological Soil Crusts in semi-desert areas with hyperspectral imagery. – Remote Sensing of Environment **112** (5): 2187–2201.

Address of the Authors:

Stefanie Elste, B.Sc., Prof. Dr. Cornelia Glässer, Ivo Walther, B.Sc. & Dr. Christian Götze, Martin-Luther-University Halle-Wittenberg, Institute of Geosciences and Geography, Department of Remote Sensing and Cartography, Von-Seckendorff-Platz 4, D-06120 Halle (Saale), Tel.: +49-0345-55-26020, e-mail: stefanie.elste@student.uni-halle.de, cornelia.glaesser@geo.uni-halle.de, ivo.walther@student.uni-halle.de, christian.goetze@geo.uni-halle.de.

Manuskript eingereicht: Juni 2014
Angenommen: Dezember 2014