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Article

Analysing Phenological Characteristics Extracted from Landsat NDVI Time Series to Identify Suitable Image Acquisition Dates for Cannabis Mapping in Afghanistan

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Summary: Since 2009, the United Nations Office on Drugs and Crime (UNODC) has carried out various annual surveys of cannabis cultivation in Afghanistan. The mapping of cannabis fields is based on very high resolution satellite imagery. The image acquisition dates have a strong influence on whether cannabis can be visually differentiated from other crops. Expert knowledge shows that the ideal acquisition dates are at the end of the growing period (senescence) of cannabis. For future surveys a method was developed to predict the optimum observation dates independent of temporal differences of the phenology. The study includes an analysis of Landsat-based NDVI time series and the calculation of information about the senescence stages of cannabis and other vegetation. The approach was applied to four test sites in Afghanistan.

Zusammenfassung: *Analyse phänologischer Eigenschaften basierend auf Landsat NDVI Zeitreihen für die Bestimmung geeigneter Zeitpunkte für die Aufnahme von Satellitenbildern für die Kartierung von Cannabis in Afghanistan.* Das Büro für Drogen- und Verbrechensbekämpfung der Vereinten Nationen (UNODC) führt seit 2009 jährlich eine Auswertung der Anbaufläche von Cannabis in Afghanistan durch. Die Kartierung von Cannabisfeldern erfolgt mit Hilfe von sehr hochauflösenden Fernerkundungsdaten. Der Aufnahmezeitpunkt der Daten ist sehr bedeutend dafür, ob Cannabis von anderen Feldfrüchten visuell eindeutig unterschieden werden kann. Nach Expertenansicht liegt dieser Zeitpunkt am Ende der Wachstumsperiode (Seneszenz) von Cannabis. Für zukünftige Auswertungen wurde eine Methode entwickelt, den idealen Aufnahmezeitpunkt unabhängig von zeitlichen Unterschieden der Phänologie im Voraus zu bestimmen. Der Ansatz umfasst eine Analyse von NDVI Zeitreihen basierend auf Landsat-Daten und die Ableitung von Informationen über die Seneszenz-Phasen von Cannabis und anderen Pflanzen. Die Methode wurde in vier Testgebieten in Afghanistan angewandt.

1 Introduction

Illicit crops like cannabis, opium poppy and coca bush form the basis for highly lucrative narcotic drug production. Illicit crop cultivation (cannabis and opium poppy) in Afghanistan takes place in areas where insecurity and insurgencies are prevalent and is strongly linked with organized criminal networks (Unodc 2013a). Policy measures to tackle the problem require an integrated approach of stabilization measures, creating opportunities for alternative development and law enforcement. In order to ascertain the impact of these measures, the United Nations Office on Drugs and Crime monitors illicit crop production, providing technical assistance to its member states on methodology. One of the key components to estimate plant-based drug production is the area under cultivation, which is mostly done with the help of satellite images and appropriate statistical techniques. These estimations face various challenges and in particular the optimum timing of the satellite imagery.

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This is especially difficult for monitoring cannabis in Afghanistan due to the possible confusion with other crops.

Up until now UNODC has conducted four annual cannabis surveys in Afghanistan to determine the area under cultivation (2009 – 2012). In addition UNODC has been conducting annual opium poppy surveys in Afghanistan since 1994 and since 1999 with satellite imagery. For estimating the area, UNODC used satellite imagery that were acquired for locations based on a spatial sampling approach. The very high resolution satellite images (VHR) obtained on a single acquisition date were used to identify cannabis fields (Fig. 1) and to calculate the area under cultivation, which was extrapolated to a larger cannabis risk area (Unodc 2013b). Reliable information on the growing cycle of cannabis plants (phenology) is essential for the selection of the ideal acquisition time of the VHR images. Within the growing cycle that is subject to seasonal and regional variations, an attempt is made to try and find the most appropriate time for the acquisition of the satellite images where the illicit crop can best be identified and distinguished from other vegetation by means of a visual interpretation. According to local UNODC experts in Afghanistan cannabis is harvested later than most other crops.

Studies on the mapping of cannabis are often directed towards the early detection of plants in order to guide eradication campaigns, e.g. by mapping of potential high-risk areas to reduce the search area (Lisita et al. 2013). There are various unpublished studies but only a few scientific publications on detection through remote sensing using spectral differences detected from aerial platforms or hyperspectral images. Daughtry & Walthall (1998) and Azaria et al. (2012) identified specific spectral ranges that are optimum for differentiating cannabis from other crops that are at their best when the cannabis fields have dense canopies. Although there is a lot of informal knowledge on the behaviour of cannabis plants and how they are affected by the environment and cultivation practices, as far as the authors could verify, there is no scientific literature on monitoring the phenology of cannabis with remote sensing time series.

Phenology is defined as the study of the timing of recurring plant life cycle events that are driven by environmental factors (Morisette et al. 2009). The documentation of the timing of phenological events often relies on visual observations in the field. In order to collect data on phenology over large geographic areas, measurements of reflected electromagnetic radiation from the land surface can be used. The timing of recurring changes in reflectance is defined as land surface phenology (Hanes et al. 2014). In this paper "phenology" refers to this term. Information on phenology as derived from remotely sensed images differ from conventional phenology data in that the information relates to the aggregated characteristics of the vegetation within the areal unit measured by satellite sensors. Phenological changes can be monitored by means of remote sensing as plants change in appearance and structure during their growth cycle.

The analysis as described in this paper is based on the normalized difference vegetation

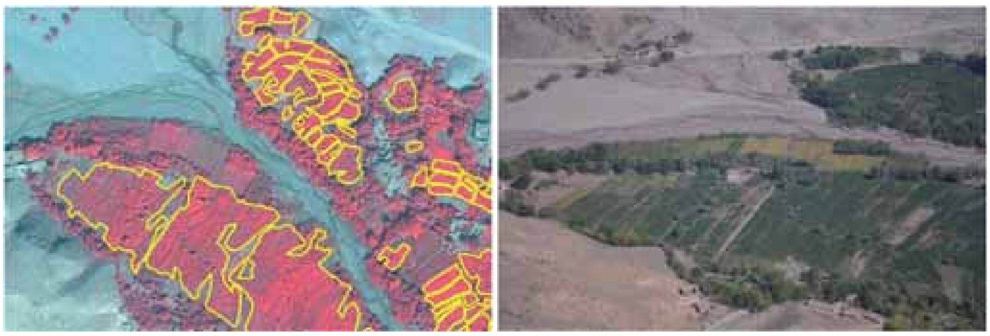

Fig. 1: Left: cannabis fields at flowering stage, as seen on a colour infra-red (CIR) satellite image, right: as seen from helicopter in Nangarhar province in 2012 (Unodc 2013).

index (NDVI). The NDVI is a mathematical combination of the Red and the NIR (near-infrared) band. Annual time series of satellite-derived vegetation indices and biophysical metrics that incorporate the reflectance of the NIR and the red wavelengths generally capture the spectral changes associated with leaf growth and senescence in the large areal units monitored by the sensor (Hanes et al. 2014). In order to better distinguish cannabis from other plants and to determine the ideal acquisition dates for VHR images, focus is laid on a more detailed analysis of the senescence. During the onset of senescence, deterioration of cell walls in the mesophyll tissue produces a distinctive decline in infrared reflectance; an accompanying increase in visible brightness may be the result of decline in the abundance and effectiveness of chlorophyll as an absorber of visible radiation (Campbell & Wynne 2006). This leads to a significant decrease of NDVI values.

While many studies have analysed phenological trends in general (e.g. Morisette et al. 2009), only a few studies have focussed on information on senescence derived from remotely sensed images. Jönsson & Eklundh (2004) for example developed a method to determine the number of seasons or seasonal parameters, e.g., the beginning or the end of the season. Zhang et al. (2003) used MODIS and AVHRR data for modelling the key phenological phases: green up, maturity, senescence and dormancy. A software tool developed by Lange & Doktor (2013) can also be used to determine such parameters.

The objective of this paper is to test whether the cannabis phenology in different regions in Afghanistan is different from the general vegetation at the end of the growing season, when cannabis can best be identified on VHR satellite imagery. In addition, the research looks at whether the development of cannabis in comparison to the general vegetation provides a basis for the development of a forecasting tool to determine the best dates for VHR image acquisition. This is done by analysing two parameters: i) the time span between the dates when the differences of the NDVI values of cannabis and non-cannabis vegetation reach a maximum; and ii) the maximum number of occurrences of senescence within each test site. The maximum difference of NDVI between cannabis and non-cannabis is expected to be the date where cannabis is most easily distinguishable. The maximum number of

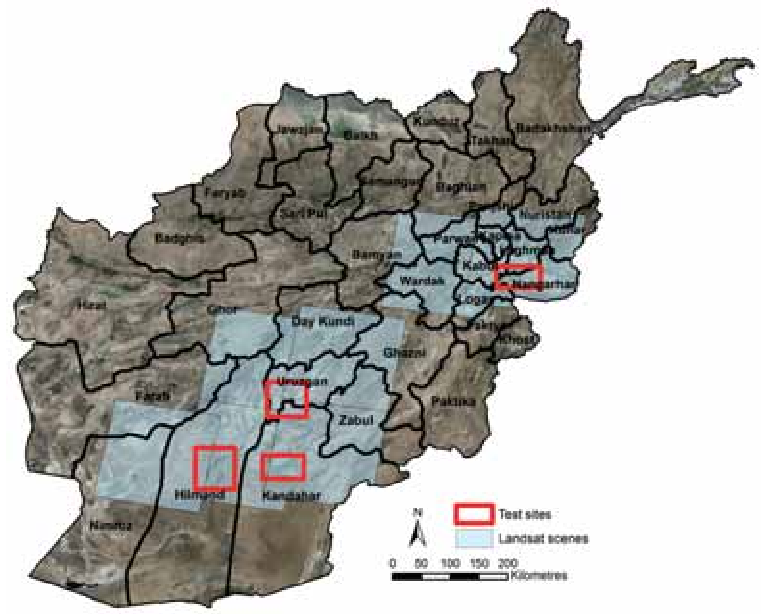

Fig. 2: Test sites in Afghanistan and Landsat scenes necessary to cover the areas.

occurrences of senescence is used to define a comparable phenological stage sensitive to seasonal changes between the years.

2 Study Area

Cannabis in Afghanistan is mostly (almost 90%) grown as an irrigated, annual monocrop, whereas the remaining 10% of the cannabis growing farmers cultivate cannabis in combination with other crops or on bunds (UNODC 2011). Cannabis flowers have the highest concentration of the active chemical drug components (cannabinoids like tetrahydrocannabinol) and the time of flowering is dependent on the age and variety of the plant, change in the photosynthetic period and environmental conditions. Cannabis plants usually start flowering after two months of growth but the abundant flowering starts when darkness (night length) exceeds approximately 11 hours per day. The flowering stage lasts between 4 and 12 weeks, depending on environmental conditions (CLARKE 1993). Outdoor cannabis cultivation in temperate zones like Afghanistan takes place in the summer season (March – September) and the life cycle of cannabis in Afghanistan is 5 – 6 months. From interviews with Afghan farmers, it is known that the planting season for cannabis starts between March and May/June. The plants are harvested from September/October to November/December depending on the region (UNODC 2013b). Cannabis is harvested when parts of the plants have already started deteriorating. Four test sites were selected in the provinces of Hilmand, Kandahar, Nangarhar and Uruzgan that represent the major cannabis growing areas in Afghanistan (Fig. 2). The northern growing provinces were not included since this region is a mountainous area where the matching of the reference dataset with the Landsat time series is highly challenging. The test sites are mainly flat, irrigated areas surrounded by desert.

3 Methodology

3.1 *Data*

The analysis was carried out using a time series of archived medium resolution satellite images. In this case all available data of the Landsat series (Landsat 5 TM and Landsat 7 ETM+) are acquired for the period between September 2008 and July 2012. Landsat was chosen as it offers free available data with a relatively high spatial resolution, and the continuity of acquisition is guaranteed for the coming years with the new Landsat 8 data. The time series are based on Landsat 5 TM and Landsat 7 ETM+ (SLC-off) and were downloaded from the USGS Earth Explorer (EARTH EXPLORER 2014). Fig. 2 shows the Landsat scenes necessary to cover the test sites. In total 7 different scene locations were needed. Landsat 5 TM could only be used until November 2011. The temporal resolution of each Landsat is 16 days resulting in a revisiting time of 8 days with both sensors. Additionally, in Afghanistan the overlapping areas from images of neighbouring Landsat orbits are covering more than 50 % of each scene (approximately 30 % on each side) leading to data for additional dates (LANDSAT 7 2012). For the period approximately 230 Landsat scenes per test site were downloaded and processed.

Landsat 7 ETM+ and Landsat 5 TM have very similar spectral bands. To produce a NDVI the Red (band 3) and the NIR (band 4) are required. The Red bands of both sensors have the identical spectral wavelength, the NIR is in Landsat 7 ETM+ with 0.77 µm to 0.90 µm slightly narrower compared to 0.76 µm to 0.90 µm in Landsat 5 TM. Since the difference is small it can be assumed that the impact can be neglected.

As reference data polygon data representing the cannabis fields (as shown in Fig. 1) were made available by UNODC. The polygons were delineated by UNODC staff based on VHR satellite images taken during the growing seasons of 2009, 2010 and 2011. Therefore, no geometric adjustment of the Landsat data was necessary as Landsat images fit with the reference data.

3.2 *Data Pre-Processing*

In order to process accurate NDVI values, spectral data were transformed from digital numbers which is basically top-of-atmosphere radiance with bias and gain introduced for storage optimisation to top-of-atmosphere reflectance using the R package "Remote Sensing" (R Core Team 2012, Mattiuzzi et al. 2012a). In a second step the data has been cropped and mosaicked to the extent of the test sites (Fig. 2). This was done using utilities of the geospatial data abstraction library (Gdal 2012). The NDVI values were filtered to reduce the impact of noise, cloud cover, missing data (Landsat 7 ETM+ SLC-off) and to derive smooth curves at regular temporal intervals. For filtering the „Modified Whittaker Smoother" (Atzberger & Eilers 2011) was chosen as the method allows filtering data without information on pixel quality. This method is based on two assumptions (Chen et al. 2004): i) that the NDVI time-series follows an annual cycle of growth and decline as the index is primarily related to vegetation density and plant vigour; and ii) that clouds and poor atmospheric conditions depress NDVI values, requiring that sudden drops in NDVI, which are not compatible with the gradual process of vegetation change, are regarded as noise and will be removed. Filtering was carried out with the MODIS package available in R (Mattiuzzi et al. 2012b).

3.3 *Analysis of the Phenology and the Senescence*

The result of the pre-processing is a yearly stack of layers of which NDVI graphs can be derived highly reflecting phenological stages at certain locations (Fig. 3 right).

Fig. 3 left shows the locations of cannabis fields in Kandahar. A VHR satellite image (colour infrared) acquired on November 15 in 2010 is used as a background image. The yellow polygons indicate cannabis fields as visually interpreted by UNODC experts. At the highlighted green marker the NDVI values are read out of the NDVI layer stack based on Landsat data and displayed as a graph (Fig. 3 right). The example clearly shows two peaks within a year. In most locations, where cannabis was identified, two crops occur within a year. On those fields the first peak can be identified at the end of March/beginning of April (winter crop) and in August/September (summer crop) a second peak occurs. The second peak represents cannabis while the first peak relates to other crops. The yellow points mark the main phenological stages: start of the season (local minimum NDVI at the beginning

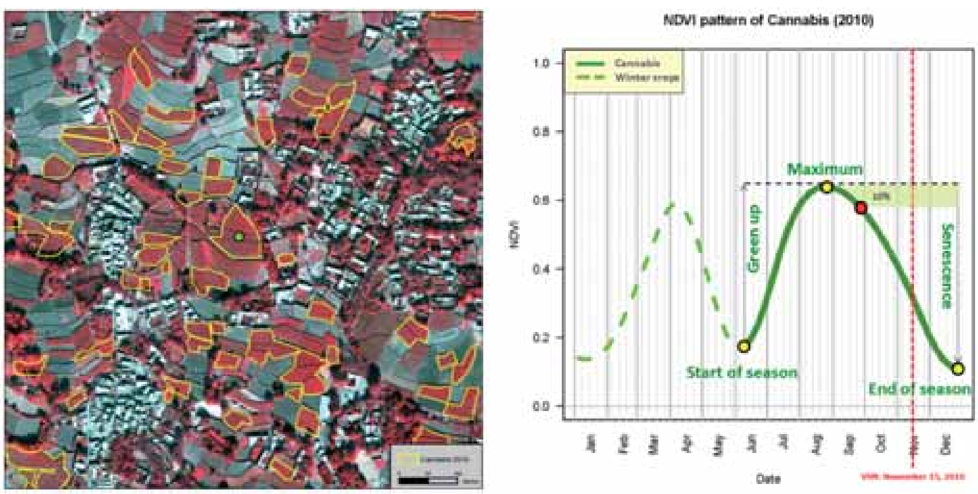

Fig. 3: Left: WorldView-2 satellite image (CIR; © DigitalGlobe Inc., all rights reserved) and cannabis polygons, right: NDVI curve with phenological indicators at one pixel location for 2010.

of green up), maximum (highest NDVI value) and end of season (local minimum NDVI at the end of senescence). A senescence of 10% is the point where the NDVI decreases by 10% of the cycle amplitude. The threshold was set to 10% in order to ensure an early detection of the declining phase of the NDVI values. This value is used for the subsequent analysis. The dashed red line represents the acquisition date of the VHR satellite image as used for the visual interpretation in 2010.

The best acquisition date of VHR satellite images when cannabis can be distinguished from other crops is expected to be at the date when the maximum difference in the NDVI occurs. Theoretically this can be at any time within the growing cycle but the aim is to determine the best date at the end of the growing season when cannabis can best be differentiated through visual interpretation. In order to forecast this optimal date without knowing the location of cannabis, the phenology of all active summer vegetation at the test sites is further investigated. The basic idea is to focus on the timing of senescence of all active summer vegetation pixels including cannabis in the test regions and to draw conclusions on the timing of NDVI differences.

The usage of the senescence for the prediction has been selected as it is expected that the senescence stage is closely related to the NDVI differences at the end of the growing cycle. The period between the maximum number of occurrences of early senescence (active summer vegetation, which can include cannabis sites) and maximum difference in NDVI (between cannabis and non-cannabis) is estimated based on two of the three available years, e.g. 2009 and 2010, using the average number of days of these years. This time period is then added to the date of the maximum number of occurrences of early senescence (active summer vegetation) in the year of the forecast, in this case 2011. The maximum number of occurrences of senescence is used to determine the general land surface phenology and training years are used to determine how the NDVI of cannabis behaves compared to the rest of the vegetation.

The time of the maximum NDVI was calculated for the summer period only. Within each geographic region 5000 random points were selected which have a NDVI maximum of at least +0.3 in the period of 40 days before and after the day where cannabis (mean) reaches its maximum. A NDVI value between 0.0 and +0.2 indicates a very low or no photosynthetic activity. The underlying assumption is to select those pixels with consistent active vegetation within the cannabis growing period. It is assumed that within a region the composition of planted crops is relatively stable in the years. The selected points can by chance also include cannabis pixels. This is because for the prediction of the senescence of cannabis in the following year no information about cannabis will be given. Therefore, two out of the three years were used to learn how the phenology of cannabis behaves in comparison to the general senescence of all crops in the region. For the remaining year the phenological stage of cannabis was predicted using the knowledge derived from the other years.

Based on the NDVI curves of the summer period the senescence was derived using the R package "phenex" (Lange & Doktor 2013). The date of the senescence was determined in the following way: In a first step the amplitude of the vegetation period was calculated using the minimum and maximum NDVI values found in the green up phase of the summer crop. The date of senescence refers to the point where the NDVI values decrease after the maximum by a given threshold of the NDVI amplitude (see Fig. 3 right), in this case 10% as mentioned before.

The distance between the date of the maximum senescence intensity of active summer vegetation (see red dashed line in Fig. 4) and the date of the maximum NDVI difference (black solid line) was calculated. The mean difference of the chosen reference years was then added to the maximum senescence intensity of active summer vegetation in the prediction. The number of occurrences of senescence is used as an indicator if the phenology in the test regions has changed from one year to another. For the subsequent analysis only reliable cannabis pixels were taken into account, the selection was done by using only those pixels that are fully contained by a cannabis reference polygon.

4 Results

The main outcome of this study is shown by region in the following figures. In the lower part of each graph the intensity of senescence is shown over time for active summer vegeta-

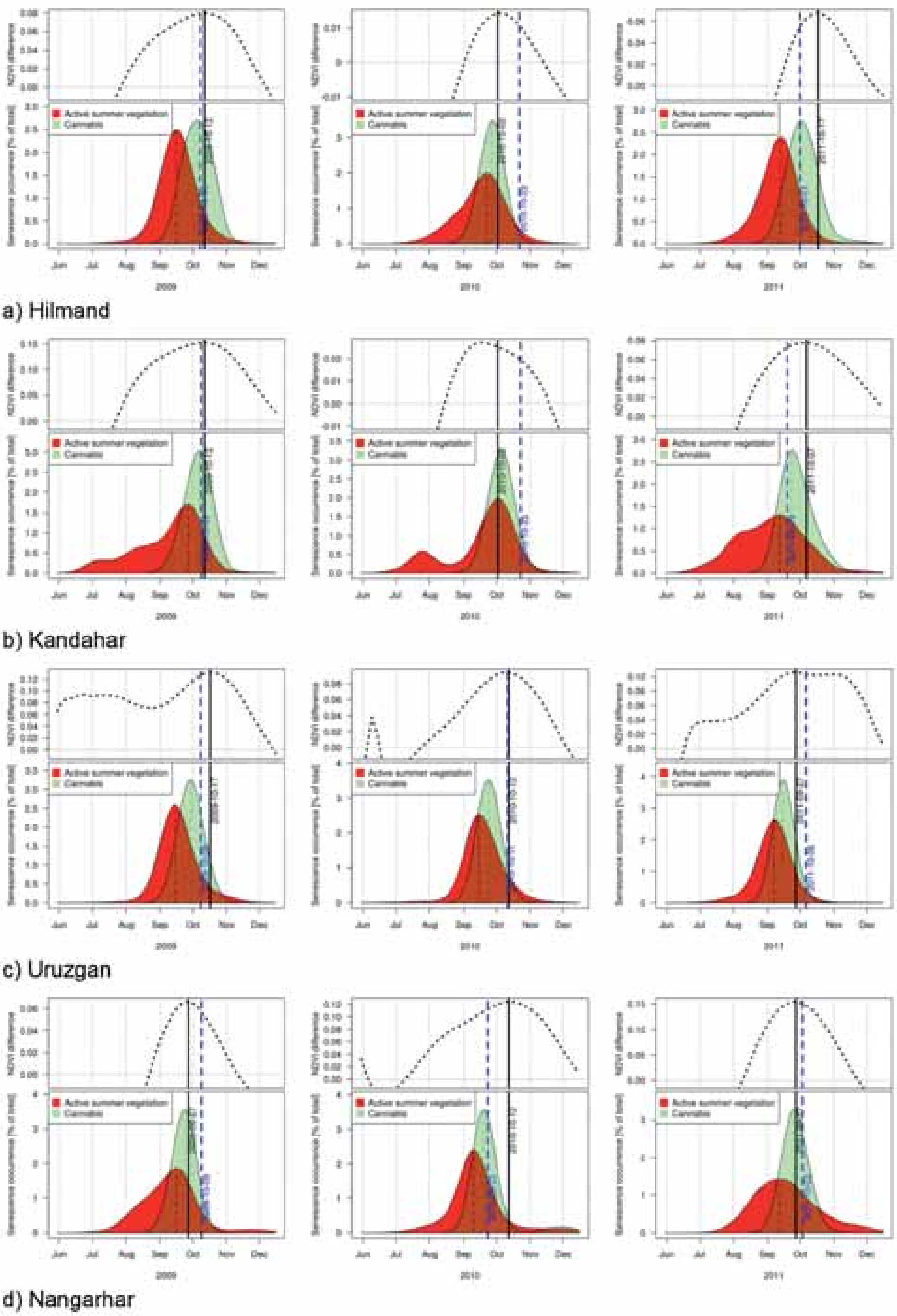

Fig. 4: Differences in NDVI and timing of senescence by region for 2009, 2010 and 2011 (lines: black solid = date of maximum NDVI difference, blue dashed = predicted maximum NDVI difference).

tion (red) and cannabis (green). In most cases it can be seen that cannabis reaches its maximum number of senescence occurrences later than the active summer vegetation. This confirms the experience of UNODC interpreters that cannabis is harvested later than other crops. The upper part shows the difference in NDVI (subtraction of non-cannabis from cannabis) and the bold black vertical line indicates the date of the maximum difference. The NDVI difference in Kandahar 2010 reaches its maximum earlier than the maximum number of occurrences of senescence. Therefore, the optimum date has been shifted to the maximum number of occurrences of senescence of the active summer vegetation.

The dashed blue lines in the graphs represent the predicted maximum NDVI difference (predicted ideal acquisition date). The calculation is based on the two other years. Comparing this with the date of the actual maximum NDVI difference (black line) gives information about the validity of the assumption for this study. The differences between the two dates in 2011 is 18 days for Hilmand, 17 days for Kandahar, 7 days for Uruzgan and 9 days for Nangarhar. A time range can be derived, taking into account the difference of the previous years. For Hilmand this time range can then be defined between 4 to 20 days, for Kandahar between 3 to 21 days, for Uruzgan between 1 to 10 days and for Nangarhar between 7 to 13 days.

5 Conclusions and Discussion

This research shows the usefulness of using Landsat time series to determine differences in crop phenology for the monitoring of cannabis in Afghanistan. The graphs depicting the development of the vegetation consistently show that cannabis tends to reach the stage of senescence later than other active summer vegetation. It is not known whether this depends on the type of vegetation, e.g. crop types, management of the crops or the eco-physiological circumstances in Afghanistan. The identified pattern supports the perception of the experts that undertake the identification of cannabis fields in the VHR satellite images, however it should be systematically monitored by the survey team if the date of maximum difference in NDVI corresponds with the date when cannabis can be best interpreted in the VHR satellite images. This information will be essential for optimising the programming of the VHR satellite images.

The method presented here to find the optimum acquisition date shows that in most cases the predictions based on the timing of senescence of the active summer vegetation strongly correspond with the optimum dates calculated from the actual NDVI values. Differences between predicted and actual dates range from 1 to 21 days. Although for operational purposes these time ranges are acceptable, it should be looked at more closely whether this method of prediction yields better results than other methods, e.g. using the start of the vegetation activity (green up) or simply using the mean date of maximum NDVI difference.

A limitation is the lack of an independent dataset to verify if the number of maximum occurrences of senescence reliably reflects the shifts in the timing of phenology. A deeper investigation, for example on test sites with ground based weather stations, could explain factors that influence phenological stages.

A strong limitation for developing and testing the method was that the predictions are based on two observations only. It would require longer time series to obtain more robust results, e.g. by including subsequent cannabis surveys. When this research was conducted another cannabis survey was finalised, which can give additional data to enhance the analysis.

Attention should be paid to the selection of cannabis pixels, as the median cannabis field size is only slightly larger than a Landsat pixel thereby reducing the number of usable cannabis reference pixel drastically. For this reason, many pixels had to be left out from the analysis because of probable mixed signatures. In the near future, images from Sentinel-2 (launch planned in 2015) could be used for this purpose offering a spatial resolution of 10 m. Another benefit of Sentinel-2 is the very high temporal resolution (5 days) which would lead to a more accurate computation of phenological phases.

One problem that this study faced was also the lack of information on the cultivation of other crops. Information on crops growing in the same season would help to understand the difference between cannabis and crops with similar growing cycles. A crop by crop analysis could also help to detect which crops are causing problems in the prediction.

Future research can focus on what can be learned from the NDVI difference plots (Fig. 4, upper parts). The dates derived from this graph should be interpreted as an optimum within a time range and not as a single date. Experts with better knowledge of the crop types in the regions could interpret graphs from previous years. Similar NDVI difference patterns between the years could indicate that similar crops were grown and therefore represent a better prediction. Another aspect is to focus on a more detailed analysis of the regional senescence patterns in order to determine the point in time within the year when a reliable prediction of the ideal acquisition date is feasible.

Disclaimer

The views expressed herein are those of the authors and do not necessarily reflect the views of the United Nations.

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