MONITORING VEGETATION PHENOLOGY USING MODIS NDVI 250M IN THE CITY OF TSHWANE, SOUTH AFRICA

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Abstract

The unprecedented influx of people into urban areas has led to the horizontal and vertical growth of urban environments. One of the notable impacts of urbanisation is the encroachment of urban-like environments into non-urban areas. This is common in both developed and developing countries, and South Africa's City of Tshwane, the administrative capital of the country, has been affected by urbanisation because of migration. One of the parameters or proxies used to quantify urban growth is vegetation cover. There is a consensus that with the increase in the population of urban dwellers, vegetation cover will decrease. To assess and monitor vegetation cover, the Normalised Difference Vegetation Index (NDVI) is commonly used. In this study, MODIS NDVI data with a 250m spatial resolution was used to assess the impact of urban growth on vegetation. A time series analysis of the MODIS NDVI with a spatial resolution of 250m was used to establish the patterns of vegetation cover. Trends in vegetation change were determined in newly developed residential areas, informal settlements, and various vegetated areas. Sen's slope estimator and Mann-Kendall's statisticwere used to analyse the spatial trends and variations in trends among different land cover classes. The slope of the trends differs significantly but there is a general decline in vegetation cover. The temporal profiles revealed the high and low NDVI values, respectively showing greening (high vegetation) and browning (low vegetation) trends from 2000 to 2016. It is concluded that urban growth has an impact on vegetation cover. However, this does not disturb the seasonal changes in vegetation where high NDVI values prevail in summer and low values in winter.

Keywords: *Urban areas, Remote sensing, MODIS, Phenology, Time Series, Mann-Kendall, NDVI*

1. Introduction

The influx of people into urban areas has led to urban sprawl, which is the encroachment of urban-like environments into non-urban environments (Cobbinah and Amoako, 2012; Turok and Borel-Saladin, 2016). It has been estimated that there will be an increase of about 3 billion in the global urban population by the year 2050 (United Nations, 2014). This increase in urban dwellers has led to both uncontrolled and controlled urban sprawl (Magidi and Ahmed, 2018). Urban sprawl entails the transformation of natural areas and agricultural areas into urban environments which has a negative impact on natural ecosystems (Grobler et al., 2006; Zeng et al., 2015). The establishment of houses, industries, and shopping malls has its own unique impact on the environment (Grobler et al., 2006). Urban dwellers, local authorities, land developers and residents plant their own trees and grass (lawns), thereby establishing their own urban ecosystems (Jombo et al., 2020). Both the construction and extension of road networks have accelerated the conversion of non-urban-like environments into urban areas (Walters, 2013; Wood, 2014). The construction of the Gautrain infrastructure, the widening of roads, and the construction of the bus transit system in the City of Tshwane (CoT), are some of the examples reflecting this trend (Walters, 2013; Wood, 2014). With the rapid urban population growth, which is posing housing challenges, the local government is struggling to provide decent housing. The result is that people are resorting to makeshift houses (shacks) and those in formal houses in the suburbs are establishing back-yard dwellings (Munyati and Motholo, 2014; Tiwari et al., 2016; Turok and Borel-Saladin, 2016), leading to densification of housing structures.

There are many informal settlements situated in different locations in the CoT - in low, medium, and high population density areas (Munyati and Motholo, 2014; THDA, 2012). On the other hand, there are well-managed open areas such as nature reserves, stadiums, and some riparian areas which are well maintained. As urban areas develop, portions of them are left undeveloped, thereby leading to habitat fragmentation (Grobler et al., 2006). Nature Reserves and Parks in the CoT are the only places with a high density of natural tree species, while some of the areas, mainly the unconserved areas, have suffered from massive deforestation for firewood (Chishaleshale et al., 2015). Some of the natural areas still maintain thick bushes but they are in sharp contrast to the natural areas in close proximity to the residential areas, especially the informal settlements, where the source of energy is firewood (Grobler et al., 2006; NPC, 2011).

Some urban renewal projects shopping malls, and quarries mining have been established in the city and have, as such, brought about an increase in the built up areas (Wen et al., 2017). Therefore, the establishment of such facilities, .including roads, malls, residential suburbs, etc., are accompanied by the growth of indigenous and exotic vegetation species introduced by the residents, local government or developers, thereby establishing an urban ecosystem (Cobbinah and Amoako, 2012; Turok and Borel-Saladin, 2016). Some of the vegetation will grow to cover the established structures (roads, houses, offices, industries) (Chishaleshale et al., 2015). In the CoT, most of the roads are lined with Jacaranda trees and other invasive and non-invasive species which are of high social, cultural economic, landscape and ecological value to the city (Dickie et al., 2014; Little, 2014).

The advent of remote sensing and geographical information systems has provided a cost-effective and unique tool to assess and monitor qualitative and quantitative urban land use change (Bhatta et al., 2010; El Garouani et al.; Espindola et al., 2017; Jat et al., 2008). With observational and repetitive capability, remote sensing and GIS are used in quantifying, monitoring, and predicting urban land use changes, the information is beneficial to decision-makers, resource managers, researchers and planners (El Garouani et al.; Jat et al., 2008; Magidi and Ahmed, 2018; Wen et al., 2017). Many parameters are employed to quantify and monitor urban sprawl and one of them even determines the greenness of the environment (El Garouani et al.; Wen et al., 2017). The phenological aspect, e.g. the temporal variation in vegetation as influenced by changes in the weather and climate, is yet another suitable indicator that can be investigated to assess land use change (Matongera et al., 2021). To assess vegetation phenology there is a need for certain statistical tests, such as the Mann-Kendall statistical test (Kendall, 1938; Mann, 1945) and Sen's slope (Sen, 1968), which can be used to assess the trends in vegetation change over time.

There are transformational indices that can be used to measure the vegetation vigour, with the most popular being the Normalised Difference Vegetation Index (NDVI) (Eckert et al., 2015). The NDVI is a slope-based vegetation index, derived from the reflectance values of near-infrared and red portions of the electromagnetic spectrum, and is used to quantify photosynthetic capacity, moisture stress, and vegetation productivity (Eckert et al., 2015). Chlorophyll, which is the primary photosynthetic pigment in the plant absorbs visible light bands but reflects infrared light wavelengths (Eckert et al., 2015; Gamon et al., 1995). Contrary to sparse vegetation in arid areas and in the dry season, vegetated areas reflect more infrared light and thus absorb more red light (Eckert et al., 2015). NDVI values range from -1 to +1, with 0 standing for no vegetation, less than 0 standing for non-vegetated surfaces (e.g. water bodies and glaciers) and above zero (0) representing vegetated areas (Eckert et al., 2015). .

There are many remote sensing algorithms that are used to detect changes using multi-temporal satellite images, and these include time series analysis. Many satellite platforms (e.g. Landsat, IKONOS, QUICKBIRD) are used extensively in different studies (Bhatta et al., 2010; El Garouani et al., 2017). Because of its low spatial resolution, MODIS is rarely used to assess change in urban areas . However, its high temporal resolution allows for the assessment of temporal variations over larger areas. Using a software called TIMESAT, a 250-metre spatial resolution, MODIS NDVI was ued in Wuhan City to profile changes in vegetation cover(Tao et al., 2016; Wen et al., 2017). These data have also been used in Limpopo (Mpandeli et al., 2019). MODIS NDVI data is used to compile temporal profiles, mainly because of its capability to continuously monitor vegetation as compared to some medium, high, and very high spatial resolution satellite sensors (Gu and Wylie, 2015). For continuous monitoring, MODIS 250 is better than the Landsat and Sentinel sensors, which are affected by cloud cover (Gu and Wylie, 2015). The objective of this study is to monitor and assess spatio-temporal dynamics in vegetation cover in the CoT using MODIS NDVI data.

2. Study Areas

The CoT (Figure 1), popularly known as the City of Pretoria, located in the North of the Gauteng Province, was founded in 1855 by Marthinus Pretorius and renamed, Tshwane, in 2000 and it was merged with the Metsweding District following the Gauteng Global City Region Strategy. It is regarded as the single largest metropolitan municipality in the country with seven regions, 105 wards, and 210 councillors. The CoT lies between latitudes 25°6'34.60" S and 26°4'41.12" S, and longitudes

27°53’24.26” E and 29°5’54.31” E. It has a land area of 629 618 ha, and a population of 2 921 490. The population of the CoT was 1 770 330 in 1996, 2,142,322 in 2001 and 2,921,488 in 2011 (STATSSA, 2012).

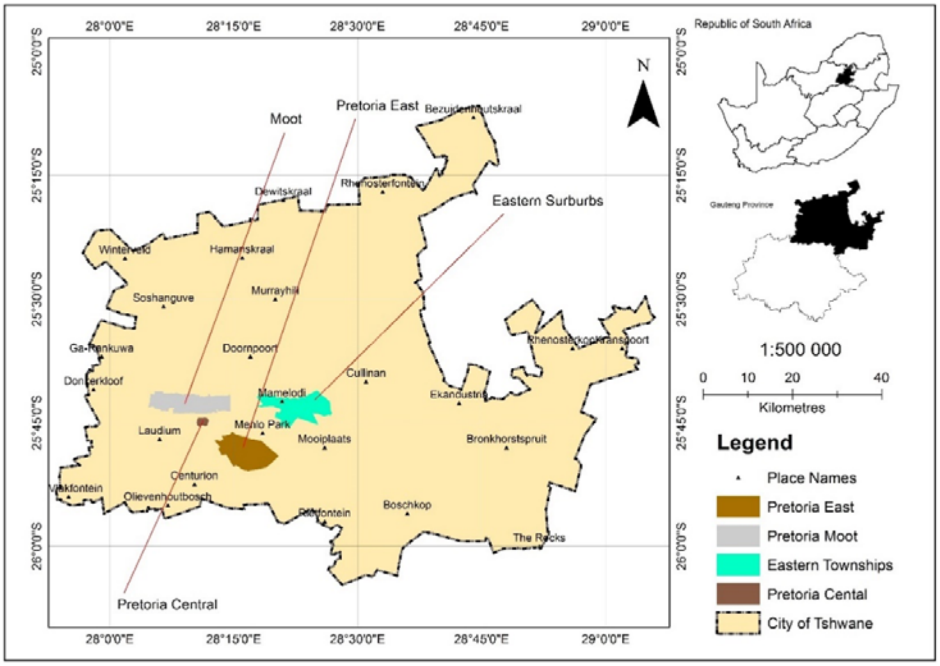

Figure 1: Map of the study area

3. Methods

The remote sensing data used in this study is the MOD13Q1 v005 product recorded by NASA’s Terra satellite and downloaded from the USGS data portal to cover the period from February 2000 to December 2016. Some of the products in the MOD13Q1 include the 250 m EVI and NDVI data, reflectance data derived from the maximum value composite (MVC), which has a temporal resolution of 16 days. After downloading, the projection of the data was reprojected to UTM Zone 35 s using the MODIS Projection Tool. MODIS temporal data from 2000 to 2016 were layer-stacked into a single file and thereafter clipped into the study area (Figure 1) using ERDAS Imagine. For each year, the phenology of the vegetation of the area was determined using MODIS NDVI images and a compound of 388 images was used to run a time series analysis in ENVI. Spatio-temporal profiling (times series analysis) to assess the phenology of the vegetation was run using ENVI across the entire study area and across different land cover classes in the study area. Mann Kendall statistical analysis tool and Sen’s estimator were run on the NDVI datasets using XLSTAT to determine the trend in vegetation according to the different land uses (Kendall, 1938; Mann, 1945). These were the main land cover classes:

i. the CoT as a whole,

ii. newly developed areas, natural vegetation, and already developed areas,

iii. high, medium, and low population density areas,

iv. different informal settlements,

v. Natural vegetation areas in low, medium, and high population density areas.

4. Results and Discussion

4.1. NDVI variations for the whole of CoT

Temporal variations in NDVI in the CoT and the temporal profile show a sinusoidal curve with a peak in summer and low values in winter, which is generally characteristic of the variation in vegetation in the tropical regions (Figure 2). The minimum NDVI is 0.228, the maximum NDVI is 0.629 and the mean is 0.405, with the standard deviation being 0.114 (Table 1). The S-statistic is -232, Kendall’s tau is -0.039, the p-value (two-tailed) is 0.497, variance is 115781, and the Sen’s slope is 0.

Table 1: The statistics of the change in NDVI in the CoT derived from the Mann Kendall statistical analysis using XLSTAT

Variable	Minimum	Maximum	Mean	Std Deviation	Kendall's tau	S'	Var(S')	p-value (two-tailed)	Sen's slope
CoT	0.228	0.629	0.405	0.114	-0.039	-232	115781	0.497	0.000

4.1.1. NDVI variations in the high, medium, and low population density suburbs

All these areas used for the analysis of the high population density areas (Eastern Townships, Northern Townships), medium population density (Pretoria Moot) and low population density areas (Pretoria East) have a sinusoidal curve with high values in summer and low values in winter (Figure 3). As depicted on Figure 3, the values of NDVI in the low population density areas are higher than those for the medium and high density areas, with the values for the high density areas being the lowest . The highest mean NDVI is 0.425, and in Pretoria East, it is 0.425 (a low population density area), with 0.415 in Pretoria Moot (a medium population density area), 0.366 in the Eastern Townships (a high population density area) and the lowest (0.353) in the Northern Townships (a high population density area). The S-statistic is -232, Kendall’s tau is -0.039 and the p-value (two-tailed) is 0.497 (

Table 2).

Table 2: The statistics of the change in NDVI in the low, medium and high population density areas in the CoT. as derived from the Mann Kendall statistical analysis using XLSTAT

Variable	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	S'	Var(S')	p-value (two-tailed)	Sen's slope
Eastern Townships	0.211	0.554	0.366	0.096	-0.095	-568	110981	0.089	-0.001
Northern Townships	0.196	0.573	0.353	0.106	-0.052	-310	117210	0.367	-0.001
Pretoria Moot	0.249	0.587	0.415	0.091	-0.075	-444	106880	0.175	-0.001
Pretoria East	0.274	0.567	0.425	0.074	-0.052	-308	106541	0.347	-0.001

4.2. NDVI variations in the undisturbed areas (natural vegetation), developed and newly developed suburbs

The NDVI variations in natural vegetation (undisturbed) for developed (by 2000 the place was already urban) and newly developed areas are shown in Figure 4 and they are still showing the sinusoidal variation with vegetation vigour high in summer and low in winter. These NDVI values for the natural vegetation (untransformed or undisturbed) are very high as opposed to the developed areas (Pretoria CBD). Even though the Pretoria CBD (a developed area) shows high NDVI values in summer and low NDVI values in winter, the values are generally very low as opposed to the untransformed areas. In the newly developed areas, the variations in the NDVI values appear to be uniform, but there has been a significant decline in the summer values. The time factor that coincides with these declines is the time when development was initiated in the areas. The highest mean NDVI of 0.384 is in the undisturbed areas (natural vegetation), followed by 0.298 in the newly developed areas, and 0.242 in Pretoria Central (an already established area). The standard deviations differs for the respective areas, with 0.110 in the undisturbed areas, 0.095 in the newly developed areas, and 0.46 in the already developed areas (Pretoria Central) (Table 3). Kendall's tau is -0.08 in the undisturbed areas, -0.154 in the already developed areas (Pretoria Central), and -0.223 in the newly developed areas (Table 3). The variance is high in newly developed areas (140735), followed by Pretoria central (117093), and low in the undisturbed areas (113187) (Table 3).

Table 3: The statistics of the change in NDVI in the undisturbed areas, newly developed areas, and in the Pretoria CBD, as derived from the Mann Kendall statistical analysis using XLSTAT

Variable	**Minimum**	**Maximum**	**Mean**	**Std Deviation**	**Kendall's tau**	**S'**	**Var(S')**	**p-value (two-tailed)**	**Sen's slope**
Undisturbed	0.212	0.581	0.384	0.110	-0.008	-46	113187	0.894	0.000
New Development	0.154	0.527	0.298	0.095	-0.223	-1328	140735	0.000	-0.003
Pretoria Central	0.151	0.349	0.242	0.046	-0.154	-914	117093	0.008	-0.001

4.3. NDVI variations in the informal settlements

No apparent difference could be detected among the informal settlements that were used in the analysis. They are all showing the high summer and low winter variations which are characteristic of vegetation in the tropical regions. The mean NDVI values for informal settlements are quite close to one another and the values are 0.345, 0.343, 0.369, and 0.328 for Mooiplaas, Mahube, Gomora, and Saulsville, respectively (Table 4). There is a high standard deviation of 0.116 in Mooiplaas, followed by one of 0.093 in Mahube, 0.091 in Saulsville, and the lowest, 0.088, in Gomora. Kendall's tau was found to differ between the four places with the highest value of -0.046 in Saulsville, -0.119 in Gomora, -0.182 in Mooiplaas, and lastly -0.199 in Mahube (Table 4). P-values are 0.001, 0.02, 0.025 and 0.415 for Mahube, Mooiplaas, Gomora, and Saulsville, respectively. There are variance values of 1306641 in Mahube, 123117 in Mooiplaas, 114011 in Saulsville, and 99369 in Gomora (Table 4). Sen's slope is -00.003 for Mooiplaas and Mahube, and -0.001 for Gomora and Saulsville.

Table 4: The statistics of the change in NDVI in informal settlements in the CoT, as derived from the Mann Kendall statistical analysis using XLSTAT

Variable	Minimum	Maximum	Mean	Std deviation	Kendall's tau	S	Var(S')	p-value (two-tailed)	Sen's slope
Mooiplaas	0.185	0.655	0.345	0.116	-0.182	-1084	123117	‘0.002	-0.003
Mahube	0.193	0.543	0.343	0.093	-0.199	-1182	130641	0.001	-0.003
Gomora	0.213	0.588	0.369	0.088	-0.119	-706	99369	0.025	-0.001
Saulsville	0.188	0.540	0.328	0.091	-0.046	-276	114011	0.415	-0.001

4.4. NDVI variations in natural vegetation in high and low population density areas

Figure 6 shows the variation in NDVI values among areas adjacent to high, medium and low population density areas, and vegetation in protected areas. Besides the normal variation in all of the areas (low winter and high summer), according to Figure 6, there are low NDVI values in areas that are situated in high population density areas as opposed to those situated in low population density areas. The highest mean NDVI value of 0.515 is found on the mountain close to Marabastad, followed by 0.456 in Magaliesburg, 0.412 in Soshanguve, with the lowest value of 0.378 in Mamelodi (Table 5). Kendall's tau varies in all four of the areas, with values of -0.11, 0.048, -0.047 and -0.013 in Mamelodi, Soshanguve, Magaliesburg and Marabastad, respectively (Table 5). The variance is high in Soshanguve (115186), followed by Mamelodi 112929, then Marabastad (108317), and lowest in Magaliesburg (104806) (Table 5). There is a negative trend in vegetation in all the areas with natural vegetation, except for the vegetation areas close to Marabastad where there is a zero gradient slope.

Table 5: The statistics of the change in NDVI in the natural vegetation in high, medium, and low population density areas,,as derived from the Mann Kendall statistical analysis using XLStat

Variable	Minimum	Maximum	Mean	Std deviation	Kendall's tau	S’	Var(S')	p-value (two-tailed)	Sen's slope
Magalisburg	0.277	0.672	0.456	0.102	-0.047	-282	104806	0.385	-0.001
Marabastad	0.275	0.736	0.515	0.116	0.013	-80	108317	0.810	0.000
Mamelodi	0.216	0.586	0.378	0.105	-0.110	-652	112929	0.053	-0.001
Soshanguve	0.213	0.693	0.412	0.134	-0.048	-288	115186	0.398	-0.001

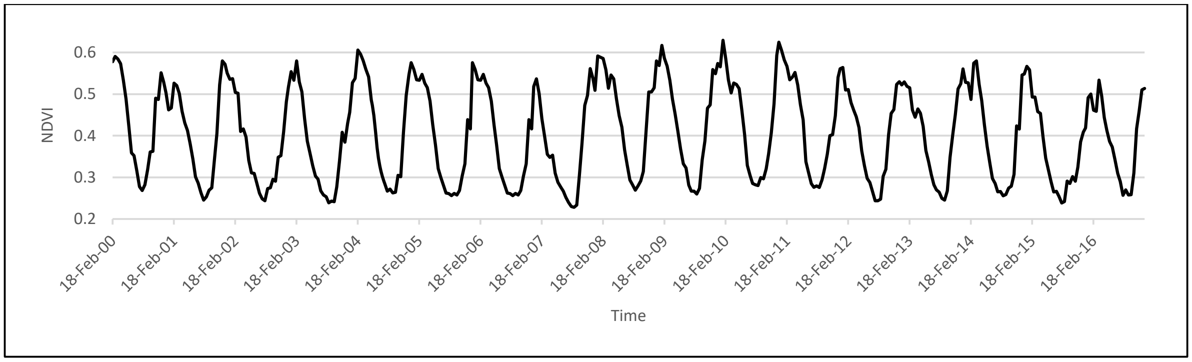

Figure 2: Vegetation Phenology in the whole of CoT, based on the MODIS 250m NDVI data from February 2000 to December 2016

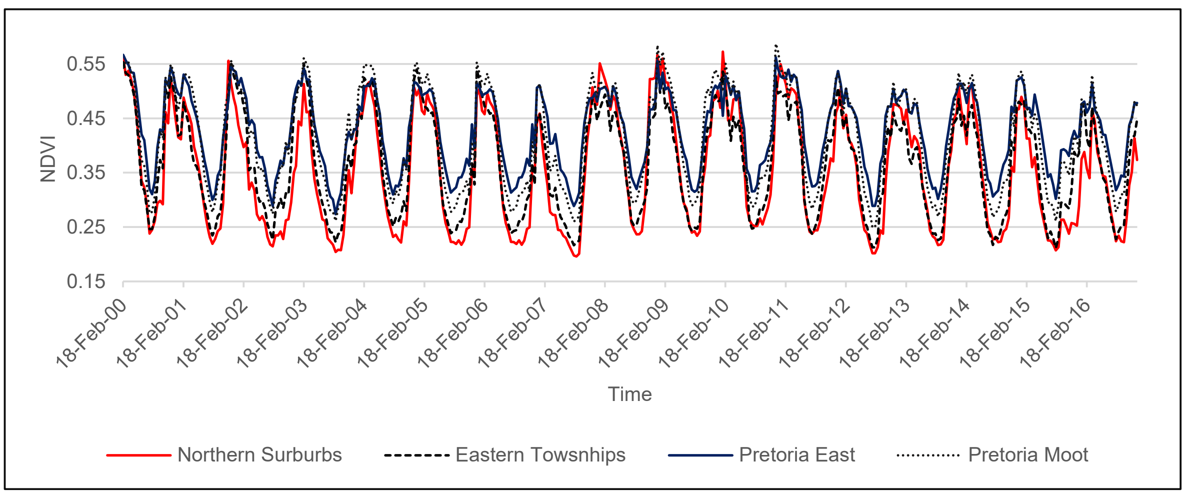

Figure 3: Vegetation phenology in the four areas (low, medium, and high population density areas) in the CoT, based on the MODIS 250m NDVI data from February 2000 to December 2016

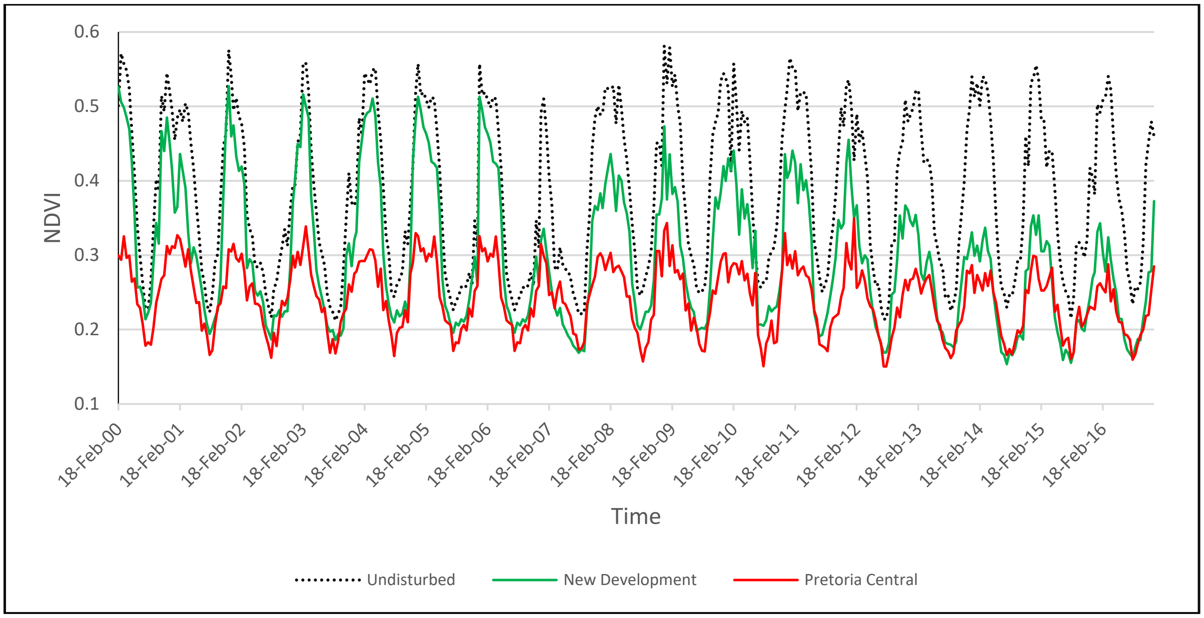

Figure 4: Variations in vegetation in the already developed area (Pretoria Central (CBD)), newly developed suburbs, and the vegetated area (undisturbed), based on the MODIS NDVI data from February 2000 to December 2016

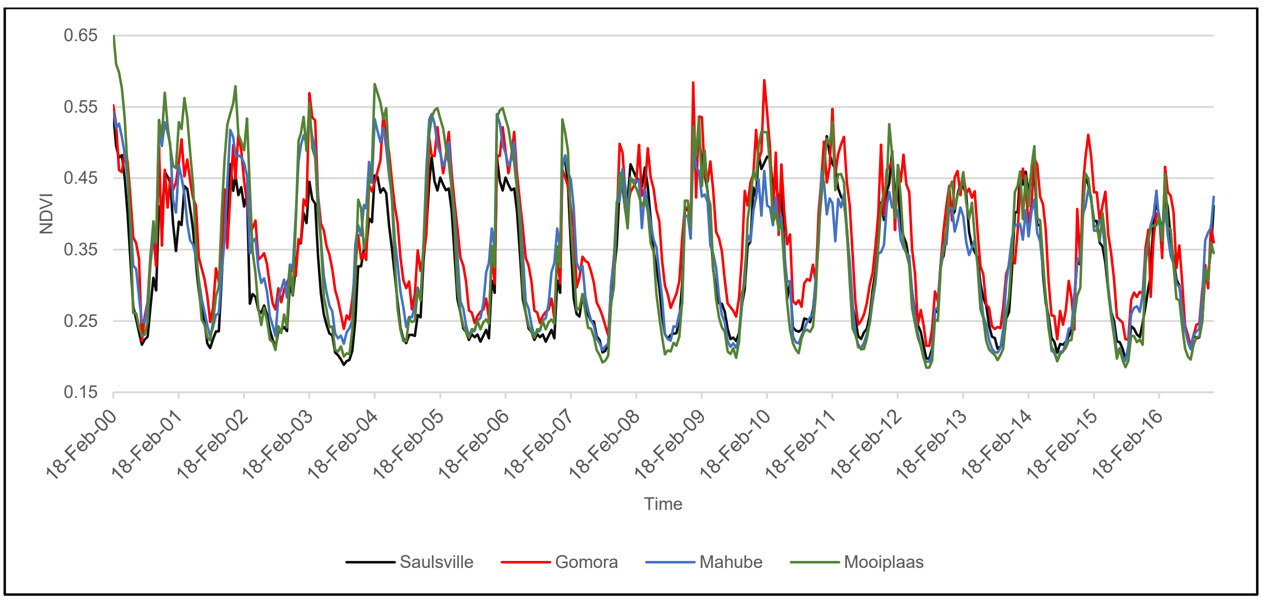

Figure 5: The variations of vegetation in different informal settlements in the CoT, based on the MODIS NDVI data from February 2000 to December 2016

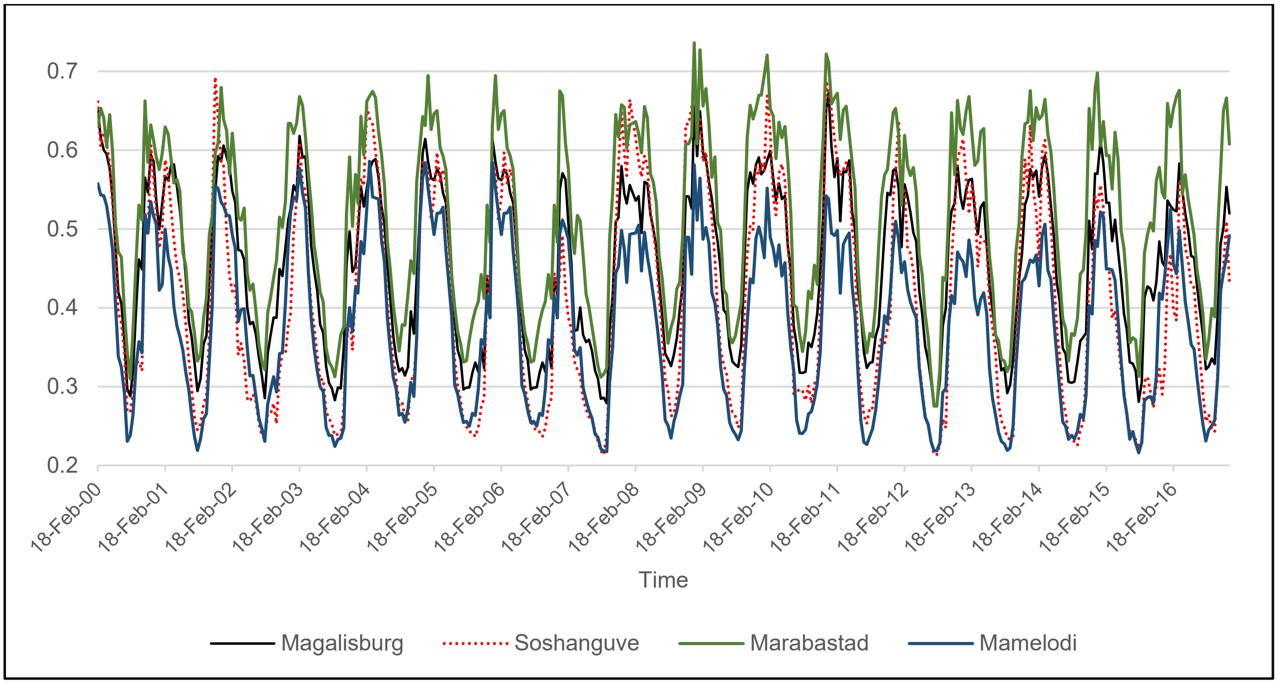

Figure 6: The variation in vegetation between open areas adjacent to residential areas and one protected area, based on the MODIS 250m NDVI data from February 2000 to December 2016.

In the temporal profiles, the greenings and brownings are quite evident with high NDVI (greening) in summer and low NDVI (browning) in winter. Just as de Jong et al. (2011) revealed, some temporal changes in vegetation cover, with high (greening) and low (browning) levels, are difficult to quantify; hence, the use of the seasonal Mann–Kendall model to properly illuminate seasonality (de Jong et al., 2011), According to de Jong et al. (2011), the Kendall findings are lower than 0.25, which indicates a weak trend; hence, the need to make use of maps.

There is a negative trend in the vegetation cover in the informal settlements and this is because in informal settlements, people depend on both firewood and electricity for their energy and there is no space to plant new trees. This agrees with a research study conducted in the Cui Cuiabá informal settlements in Brazil where there is serious environmental degradation in both the terrestrial and aquatic ecosystems as a result of informal settlements (Zeilhofer and Topanotti, 2008).

Vegetation is quite crucial in preventing environmental degradation in urban areas. Urbanisation has proved to be the main contributor of urban dynamics and has caused a global decline in vegetation cover (Odindi and Mhangara, 2012). In Port Elizabeth, based on the research by Odindi and Mhangara (2012), there was a general decline in green vegetation cover between 1990 and 2000 and this was attributed to urban expansion as a very low vegetation density was found in the built-up areas (Odindi and Mhangara, 2012). This is also evident in some of the South African cities, such as eThekwini (Otunga et al., 2014). It was found that urbanisation leads to an excessive decline in the extent and density of vegetated areas (Odindi and Mhangara, 2012; Otunga et al., 2014).

5. Conclusion

The unprecedented growth in the urban population has put pressure on terrestrial ecosystems and has led to the depletion of vegetation. Vegetation is needed in urban areas to reduce environmental degradation, for carbon sequestration, and for providing shade. Urbanisation has proved to be the main contributor to vegetation loss, and in fact a global decline in the vegetation cover. To examine the spatio-temporal changes in vegetation in the CoT, MODIS NDVI 250m was layer-stacked and used in the profiling of variations in NDVI in different landscapes. Seasonal time series analysis and the Mann-Kendall test were conducted to show the overall trend in vegetation phenology from 2000 to 2016, and it was found that under different land covers, there has been a decrease in vegetation cover from 2000 to 2016. One of the characteristics of the study area, as depicted in the temporal profiles, is that the vegetation cover shows a seasonal pattern. When a settlement is established, the community and local government will start growing trees on their properties and their streets. This is the main reason why even the urban environments are following the seasonal patterns of high density vegetation levels in summer and low levels in winter. The same applies in both formal and informal settlements. NDVI variations can show the dates when the development in the areas started. Subsequent to these developments, there have been notable reductions in the NDVI values, and this is evident from the NDVI profile. The vegetation cover in high population density areas is low as compared to those variables in other areas. This is mainly because in the high population density areas people invade the natural vegetation to cut wood for their fires. The natural areas are cleared of trees and left with only grass, thereby causing a reduction in the NDVI values. Most of the people staying in the highdensity suburbs are low-income earners or the jobless, so they are inclined to depend on firewood as an energy source. Natural vegetation in the low population density areas has a high NDVI value because there are few people and most of the people in those areas are high-income earners, who can afford electricity and if need be, buy firewood, without chopping down the nearby bush to destroy the veld. Some of these areas are protected and inaccessible and, as such, show high NDVI values.

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