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Desertification of forest, range and desert in Tehran province, affected by climate change

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Abstract. Climate change has been identified as a leading human and environmental crisis of the twenty-first century. Drylands throughout the world have always undergone periods of degradation due to naturally occurring fluctuation in climate. Persistence of widespread degradation in arid and semiarid regions of Iran necessitates monitoring and evaluation. This paper aims to monitor the desertification trend in three types of land use, including range, forest and desert, affected by climate change in Tehran province for the 2000s and 2030s. For assessing climate change at Mehrabad synoptic station, the data of two emission scenarios, including A2 and B2, were used, utilizing statistical downscaling techniques and data generated by the Statistical DownScaling Model (SDSM). The index of net primary production (NPP) resulting from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images was employed as an indicator of destruction from 2001 to 2010. The results showed that temperature is the most significant driving force which alters the net primary production in rangeland, forest and desert land use in Tehran province. On the basis of monitoring findings under real conditions, in the 2000s, over 60 % of rangelands and 80 % of the forest were below the average production in the province. On the other hand, the long-term average changes of NPP in the rangeland and forests indicated the presence of relatively large areas of these land uses with a production rate lower than the desert. The results also showed that, assuming the existence of circumstances of each emission scenarios, the desertification status will not improve significantly in the rangelands and forests of Tehran province.

1 Introduction

Soil loss is highly dependent on soil formation and degradation processes, and desertification plays a key role in this issue (Xie et al., 2015; Xu et al., 2014). Land degradation and its manifestation in drylands, desertification, are still widespread, jeopardizing livelihoods and sustainable development (Fleskens and Stringer, 2014; Reynolds and Stafford, 2002). Drylands (arid, semiarid and dry subhumid areas) cover approximately 41 % of the Earth's surface and approximately 10 to 20 % of these regions are experiencing degradation and desertification processes, resulting in a decline in agricultural productivity, loss of biodiversity and the breakdown of ecosystems (Keesstra, 2007). Considering the widespread and threatening aspects of desertification in locations all around the world, many researchers have tried to analyze it by means of experimental models and methods (Prince et al., 1988; Ladisa et al., 2011; Liu and Yang, 2003), remote sensing methods (Symeonakis et al., 2014; Helldén and Tottrup, 2008; Hill et al., 2008; Rasmussen et al., 2001) and modeling (Nicholson et al., 1998; Salvati and Zitti, 2009; Santini et al., 2010).

Vegetation is an effective way to prevent soil erosion and plays an important role in soil and water conservation (Gabarrón-Galeote et al., 2013; Lieskovský and Kenderessy, 2014). The vegetation on the slopes increases hydraulic roughness and vegetation, and creates the most resistance compared to other surface roughness (Zhao et al., 2015). Vegetation decreases wind erosion in arid and semiarid areas in three ways: (a) by reducing the corrosive power of winds near the earth's surface through breaking wind direction at several angles; (b) by creating a protective layer against corrosive air forces; (c) by trapping sediments (Hong et al., 2016). In many studies conducted on land degradation and desertification, vegetation cover was used as an important criterion (Helldén and Tottrup, 2008; Hill et al., 2008). Even in some research, the vegetation cover has been used as the only criterion for assessing desertification and destruction of land (Wessels et al., 2008; Rasmussen and Madsen, 2001).

Recently, the net primary production (NPP) index, derived from remote sensing data, is used to assess the relationship between production and land degradation (Wessels et al., 2008; Prince et al., 2009). Net primary production is one of the main components of the carbon cycle and it represents an increase in plant biomass after deducting the amount used by autotrophs. NPP or the absorption rate of CO_2 through photosynthesis is the basic link between the atmosphere and biosphere. Human activities release a lot of CO_2 into the atmosphere and have direct effects on NPP, evident in changing weather patterns (Greer et al., 1995; Nakićenović et al., 2000). Furthermore, humans currently consume almost a quarter of potential NPP (Haberl et al., 2007). Awareness of the global carbon emissions is necessary for the development of global policies on climate change (Wofsy, 2002; Piao et al., 2008; Schulze et al., 2000). It should be noted that changes in environmental factors are different in areas of natural resources. According to a report presented by FAO in the 1990s, the main factors of forest changes in different continents of the world are mainly land use changes (Jafari, 2013). In Asia, about 23 % of changes in forest areas depend on other factors, such as climate change. Climate change such as changes in temperature and rainfall affect phonology and plant growth timing (Jafari, 2007). Climate change has been observed in different parts of Iran and it is also predicted that the changes will also occur in the future. Climate change causes a biomass production change in natural ecosystems (Jafari, 2013). Therefore, prediction of NPP in natural areas, and the understanding of the effect of climate change on global ecosystems, products and the sustainability of services are fundamental issues that many researchers have addressed (Fang et al., 2003; Ei-Masri et al., 2013; Hemming et al., 2013; Piao et al., 2005; Zhao et al., 2010).

Liang et al. (2015) investigated the spatial and temporal patterns of annual, seasonal and monthly changes of the NPP index. They also studied the climatic factors controlling it at the national biome level from 1982 to 2010 in China. The results showed that the NPP increased under the influence of precipitation from the north to the south of China; and temperature was introduced as a control factor of NPP in all biomes except the dry biome. Raich et al. (1991) monitored the potential of NPP in relation to climatic variables for different land uses in South America. Their results showed that seasonal NPP has a positive correlation with the amount of available moisture in most vegetation cover, but seasonal difference in cloudiness strongly affects the NPP in tropical evergreen forest. Li et al. (2015) used NPP, Normalized Difference Vegetation Index (NDVI) and rain use efficiency (RUE) in order to investigate the dynamics of land degradation in the Beijing–Tianjin area in the first decade of the twenty-first century. Their results showed that according to the NPP index, from 2000 to 2010, the Beijing-Tianjin area was extensively degraded at a rate of 52.7 %, while the reported destruction based on RUE was 65.2 %.

Choosing the appropriate tools that are able to predict the impact of climate change on NPP has always been a challenge. The most reliable tools for evaluating the effects of this phenomenon on different systems are climate variables which are simulated by coupled atmosphere–ocean general circulation models (GCMs) of the atmosphere (Haghtalab et al., 2013). Along with the emissions scenarios of greenhouse gas which were codified by the Intergovernmental Panel on Climate Change (IPCC), the atmospheric general circulation models have been developed by different emissions assumptions such as B2, B1, A2 and A1 to determine the climatic conditions in the next decades (IPCC, 2000). Each of these different scenarios presents a future climate condition. For example, the A2 scenario is characterized heterogeneously by the continued growth of population and regional economic growth (Nakićenović et al., 2000). B2 scenario shows a separate, but more ecologically friendly, world. It considered an average economic development and a steady increase of population which emphasizes regional solutions for sustainable development and slower and dissimilar growth of technologies than A1 and B1 scenarios (Rahmani, 2011). One of the main problems of current evaluation studies at a regional level is the prediction extent of variables in these models (the study of areas around 5000 km^2). Due to the topography and climate change in this area, the results cannot be used directly at the station scale. In other words, the model considers similar conditions such as surface cover, topography and climate for a grid with dimensions of several hundred kilometers, while real situations of surface area can be completely different in the study area. To address this shortcoming, various methods have been created to generate climate scenarios at a regional scale, named downscaling (IPCC-TGCIA, 1999).

Various downscaling models and software have been developed. One popularly used model is the Statistical DownScaling Model (SDSM; Wilby et al., 2002). For example, Wilby and Perry (2006) combined SDSM with a conceptual water-balance model and a mass-balance water quality model to investigate climate change impact assessment and uncertainty in river flow and water quality.

Reeves et al. (2014) investigate the effects of potential climate change on NPP by predicting the climate regime under global change scenarios A1, B1, A2 and B2 in the grassland of America, from 2001 to 2100. The results showed across all three scenarios, that rangeland NPP increased by 0.26 % yr^{-1} (7 kg C ha^{-1} yr^{-1}) but increases were not apparent until after 2030, and significant regional variation in NPP was revealed.

Bachelet et al. (2001) tried to model the relationship of vegetation changes under the influence of temperature and precipitation in the United States, and then the future vegetation cover of the United States was illustrated by using emission scenarios.

The methods used for monitoring land degradation and desertification in Iran have been on the basis of expertise and field measurements such as MEDALUS, IMDPA, FAO-UNEP and ICD methods (Khosravi and Zehtabian, 2012), which can be used to evaluate the progress of land degradation (Oldeman et al., 1991; Stocking, 1995). Although these studies are accurate and appropriate to determine initial destruction features, some challenges, such as being not simple for users, high volume data entry and low repetitions in different area and a loss of accuracy in region with a large surface area, cause a lot of problems (Omuto, 2008). The aim of this study is to monitor degradation and desertification in three types of land use, including pasture, forest and desert, affected by climate change. For this purpose, the data of two scenarios, A2, B2, provided by the US National Center for Environmental Prediction (NCEP), have been utilized (Rahmani et al., 2011).

2 Material and methods

2.1 Study area

Tehran province is located between 35°14′ and 36°17′ N latitude and 50°14′ and 53°6′ E longitude. It covers an area of 18 909 km^2 and is located to the north of the central plateau of Iran (Fig. 1). The province of Tehran has over 12 million inhabitants and is Iran's most densely populated region. Approximately 86.5 % reside in urban areas and 13.5 % in rural areas of the province. Environmentally, the climate of Tehran province in the southern areas is warm and dry, but in the mountain areas, it is cold and semi-humid, and in the higher regions, it is cold with long winters. The hottest months of the year are from mid-July to mid-September, when temperatures range from 28 to 30 °C and the coldest months reach 1 °C around December–January, but at certain times in winter, it can reach −15 °C. The city of Tehran has moderate winters and hot summers. Average annual rainfall is approximately 200 mm, the maximum being during the winter season. On the whole, the province has a semiarid, steppe climate in the south and an alpine climate in the north.

2.2 Climate data and SDSM

The data that have been used in this study include the average, minimum and maximum of rainfall, and temperatures at the Mehrabad synoptic station, from 1961 to 2005. The Hadcm3 model, under emission scenarios A2 and B2, was used to determine GCMs and appropriate scenarios according to the region. In the study area the scenario which had the highest accuracy under the Hadcm3 model was selected as a scenario that has more similarities with the basin. Finally, downscaled model data and observational data were analyzed in order to select the suitable general circulation climate models and scenarios. R^2 (correlation coefficient), root mean square error (RMSE) and percent bias (PBIAS) criteria were used to evaluate the model. Equations (1) to (4) show how these criteria were calculated.

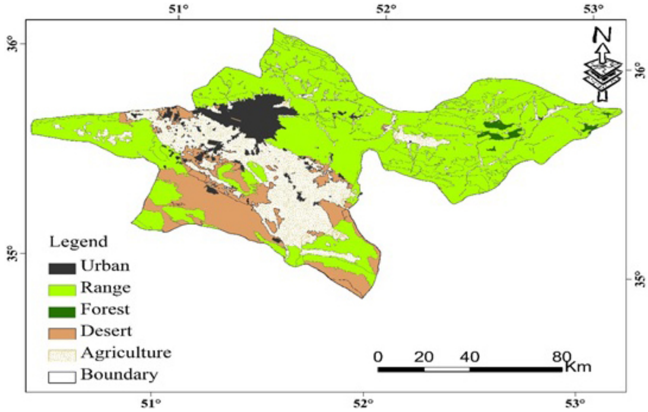

Figure 1. Location of Tehran and its different land uses.

The correlation coefficient (R^2) is calculated as follows:

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2}, \tag{1}$$

where y_i is the observed value and $\hat{y}$ is the estimated value.

The root mean square error (RMSE) is calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\mathrm{SSE}}{N}}, \tag{2}$$

where SSE is the sum of squared errors and N is the number of samples used.

The SSE is calculated as follows:

$$\mathrm{SSE} = \sum_{i=1}^{N}(y_i - \hat{y}_i)^2, \tag{3}$$

where y_i is the observed value and $\hat{y}$ is the estimated value.

2.3 Bias

$$\mathrm{Bias} = E(H) - \theta \tag{4}$$

The bias of an estimator H is the expected value of the estimator less the estimated value of θ.

NCEP and GCM predictive variables are calibrated and analyzed by the SDSM. SDSM is a two-phase sampling and conditional method. In this method, at the first predicator variables of temperature and precipitation are downscaled by using regression methods and by generating a random meteorological method. Precipitation was therefore produced at the station again. The SDSM is a combination of a statistical weather generating method and composed functions (Taei Semiromi et al., 2014). The statistical downscaling processes of the climate variables are done by SDSM Software as follows:

1. quality control and transformation of data,
2. selection of the best predictor variables,
3. calibration of the model,
4. analysis of climate models,
5. statistical analysis,
6. selection of graphical output model,
7. production of climate scenarios (by using the predictor model).

2.4 The climate change trend

A Mann–Kendall test and Sen's estimator slope method were used to assess the climate change trend under emissions scenarios. This test was presented firstly by Mann in 1945 and then developed by Kendall in 1975. One of the advantages of this method is the suitability of its application for time series that do not follow a specific statistical distribution. This method is less affected by the limit values observed in some time series (Salmi et al., 2002).

The Sen's slope estimator method is a nonparametric technique for estimating a linear trend. The procedure was computed in MAKESENS1.0 macros (Salmi et al., 2002).

2.5 Net primary production (NPP)

Satellite images used in this study are from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra satellite. This sensor has been receiving and sending images to the terrestrial receivers every day since 2000. In all Earth observing system satellites, the MODIS radiometer is a key tool. This sensor has continuous and broad spectral and spatial coverage. Two bands have a resolution of 250 m, five bands have a resolution of 500 m and 29 other bands have a spatial resolution of 1000 m. Therefore, studying and evaluating short-term and long-term changes in the sea, land and atmosphere is possible by MODIS. The spectral range of these 36 bands is between 0.4 and 14.4 µm. Mod17A3 is a set of net land data and net primary production with a resolution of 1 km obtained from Terra spacecraft and MODIS. Net photosynthesis is defined in Eq. (5):

$$\mathrm{PsnNet} = \mathrm{GPP} - R_{\mathrm{ml}} - R_{\mathrm{mr}}, \tag{5}$$

where R_{ml} is respiring leaves and R_{mr} is respiring roots. The annual NPP is calculated by Eq. (6):

$$\mathrm{NPP} = \sum_{i=1}^{365} \mathrm{PsnNet} - (R_{\mathrm{mo}} + R_{\mathrm{g}}), \tag{6}$$

where R_{mo} is respiration by other organisms except leaves and R_{g} is breath growth.

Gross primary production (GPP) is the storage capacity and carbon and energy absorption during photosynthesis (Heinsch et al., 2003; Running et al., 2004). GPP is derived from the estimation of net ecosystem exchange (NEED) and ecosystem respiration (R_{eco}). NPP is the net stored carbon after subtraction plant respiration of autotrophs from GPP. A part of the annual NPP in ecosystems may be lost by events such as strong winds and fire. There is a need for ecosystem services such as fuel, food, feed, fiber and materials for the purposes of metabolism.

In this study, annual NPP was acquired from global MODIS data (MOD17A3) with a resolution of 1 km in the period of 2001–2010. NPP obtained from MODIS (MOD17A3) based on the light useable model and annual NPP provides the evaluation of the temporal and spatial variations in production and land behavior in annual scale. For obtaining the NPP and determining land use in the study area, the ENVI 4.9 software was used.

In order to evaluate the effect of climatic factors on NPP in Tehran province, first, a logical relationship was calculated between the decrease and increase of NPP and both variations of temperature and precipitation in 2001–2010. Then, the decreasing or increasing changes of NPP were calculated in the 2030s per unit changes in rainfall and temperature portrayed by emission scenarios in the Hadcm3 model (A2 and B2).

3 Result and discussion

3.1 Prediction of climate trends

Table 1 shows the results of the annual temperature variations in both emission scenarios A2 and B2 for Tehran synoptic station. The results of temperature average using the Mann–Kendall and Sen's slope estimator methods showed a significant increasing trend in both scenarios. Emission scenario A2 showed 0.004 % reduction, and 0.05 and 0.15 % increase for the decades of 2030, 2060 and 2090 respectively (Fig. 2). These values for emission scenarios B2 were 0.02, 0.001 and 0.1 % increase respectively. The temperature reduction in the A2 scenario happened in the 2030s; the rate of change in the increasing temperature was greater than B2 scenario in 2060. The maximum temperature rise was in A2 emission scenario, which will happen in early 2090. To evaluate the significant difference between the results of two scenarios for imaging the average temperature, a t test of two samples was used. According to the significance of 0.02 in the test which was lower than the intended significance (0.05), it is concluded that there is a significant difference between the results of the two emission scenarios. The results of the trend test for the imagined amount of the rainfall average by two emission scenarios, A2 and B2, are shown in Table 2.

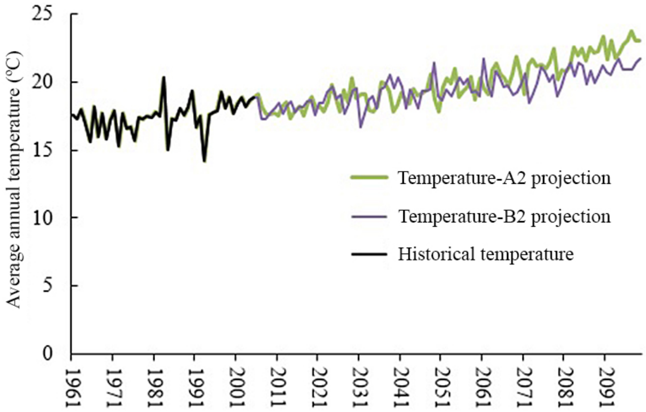

Figure 2. The average temperature in A2 and B2 scenarios for the synoptic station in Tehran.

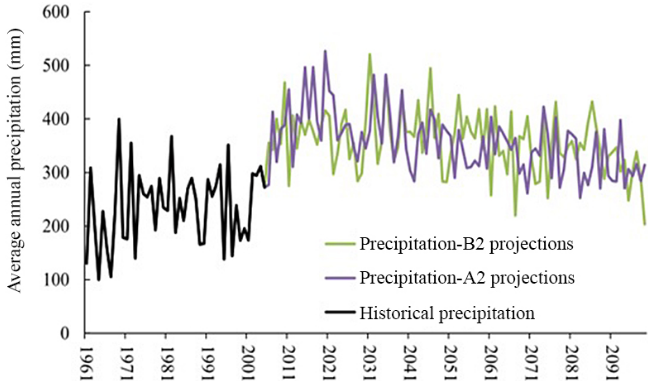

Figure 3. The average precipitation in A2 and B2 scenarios for the synoptic station in Tehran.

The results of both the Mann–Kendall and Sen's slope estimator represent a significant decreasing trend in rainfall amounts between 2006 and 2099. Additionally, the percentage of rainfall change was studied for 3 decades of 2030, 2060 and 2090 compared to the base decade of 2000 based on two scenarios, A2 and B2. The results showed that the rainfall average in A2 scenario increased 0.27 and 0.32 % in the decades of 2030 and 2060, respectively. However, in the 2090s, the rate of rainfall average decreased by 0.15 %, but in general, from 2006 onwards, average annual rainfall had a decreasing slope of -1.12. Under this scenario, the rainfall annual average will vary between 362.4 and 412 mm in the coming 8 decades. These amounts in scenarios B2 have increased 0.16, 0.07 and 0.09 for the 3 decades of 2030, 2060 and 2090, respectively. Additionally, based on the results of this scenario, the trend line slope of -0.06 has been seen from 2006. The rainfall annual average will vary between 423.9 and 382.4 mm at Tehran synoptic station in the next 8 decades (Fig. 3). Using two sample t tests showed that there were no significant differences between the results of two time series of rainfall obtained by Hadcm3 model (A2 and B2). The results showed that in both scenarios, the rainfall annual average will decrease from the 2030s, while the results of temperature changes are in contrast and incremental changes in temperature will happen from the 2030s.

3.2 NPP trend

Given that the Mann–Kendall test and Sen's slope estimator are not suitable to determine the trend of short time series (Sheng and Pilon, 2004), in this study the map of the deviation from the average of NPP was used to evaluate the changes in NPP. In other words, the 10-year average of NPP for three types of land use, forest, grassland and desert, was estimated separately and then the annual changes of every pixel to the 10-year average of that pixel were evaluated. For this aim, changes were classified into eight classes: 0–0.04 C, 0.04–0.08 D, 0.08–0.12 E, 0.12–0.16 F and 0.16 < (kg cm^2 yr^{-1}). These refer to positive amount and increase of NPP related to the long-term average. Classes of -0.04–0 B and < -0.04 A are in relation to the amounts of decrease to the long-term average. Figure 3 shows the percentage of each class area in the three mentioned land use types for the period 2001–2010. The results of NPP changes from annual long-term average for rangeland showed that in 2007, over 60 % of rangeland area was in the C class (0 to -0.04). This means that production had declined in these years. However, from 2008, these changes were more balanced, and the percentage of area with production more than 0 to 0.04 has become equal with the B class (-0.04 to 0). It is necessary to note that in 2008, the whole areas of Tehran rangeland had 0 to 0.04 NPP growth compared to the annual long-term average.

In forest land use, the percentage of changes of NPP area compared to long-term average was variable in each year (Fig. 4); in 2001, more than 90 % of forest land had a production rate in the B class (-0.04 to 0). In other words, a decline in the production of most forestland occurred. However, in 2002, the percentage of land in this class was 0. Instead, the percentage of the classes that had a greater rate of production than the average increased. After that, more than 35 % of forests were less productive than the average by 2005; and in areas where production increased, the production amount was in the class of 0.00–0.04. However, in 2006, approximately 80 % of the forest area had a greater production rate than the long-term NPP. There was a dramatic change in these fluctuations in 2007 and 2008 and over 80 % of forest land had a decline in NPP. In 2009 and 2010 the forest production increased compared to the average.

The trend of net primary production changes in deserts in Tehran province is quite different to forests and rangelands; in the 10-year studied period, except in 2003, the production changes compared to long-term average decreased. In the 2000s, more than 80 % of desert area had a reduction in the production to -0.04 (kg cm^2 yr^{-1}) compared to the

Table 1. The amount of Z test and trend slope of the temperature average at Tehran synoptic stations during 2006–2099.

				Mann–Kendall trend		Sen's slope estimate
Time series	First year	Last year	n	Test Z	Significant level	Slope trend
Temperature A2 projection	2006	2099	94	10.23	0.01	0.05
Temperature B2 projection	2006	2099	94	8.61	0.01	0.03

Table 2. The amount of Z and trend slope of the rainfall average at Tehran synoptic stations during 2006–2099.

				Mann–Kendall trend		Sen's slope estimate
Time series	First year	Last year	n	Test Z	Significant level	Slope trend
Precipitation A2 projections	2006	2099	94	−5.23	0.01	−1.12
Precipitation B2 projections	2006	2099	94	−3.11	0.01	−0.67

Figure 4. Percentage of changes in rangeland area or the deviation from the long-term average of NPP. 0–40 C, 40–80 D, 80–120 E, 120–160 F and 160 <are related to a positive amount; classes of −40–0 B and < −40 A are related to the amounts of decrease compared to the long-term average.

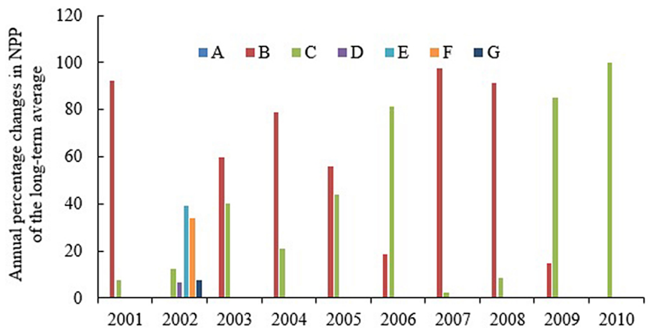

Figure 5. Percentage of changes in forest area or the deviation from the long-term average of NPP.

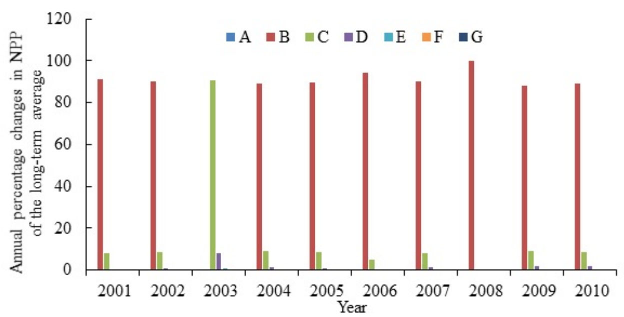

Figure 6. Percentage of changes in pasture land area or the deviation from the long-term average of NPP.

long-term average (Figs. 5 and 6). Although, the net primary production is low in areas with rainfall less than 100 mm per year, in many semiarid ecosystems, net production on land may also reach approximately the same production of temperate forests (Whitford, 2002). Therefore, a decrease of change in initial production of the desert areas in Tehran province cannot just be related to the land use type and the reasons for this reduction should be determined.

Figure 7 shows the average of NPP changes in the range, forests and deserts land in Tehran province. The variation range of average NPP in rangeland is variable from 0 to 0.37 ($kg\,cm^2\,yr^{-1}$) This range for forest and desert changed between 0 and 0.21 and 0 and 0.39 ($kg\,cm^2\,yr^{-1}$), respectively. However, it should be noted that except for some microclimate zone considering as spots, production of forest land use was higher than range and desert land use because of the vegetation amount (Barnes et al., 1998). On the other hand, given the definition of land degradation include reduction of productivity and ecosystem functioning in a long-term period (Bai et al., 2008), this is often related to the reduction in plant cover and biomass (Wessels et al., 2007; Salvati and

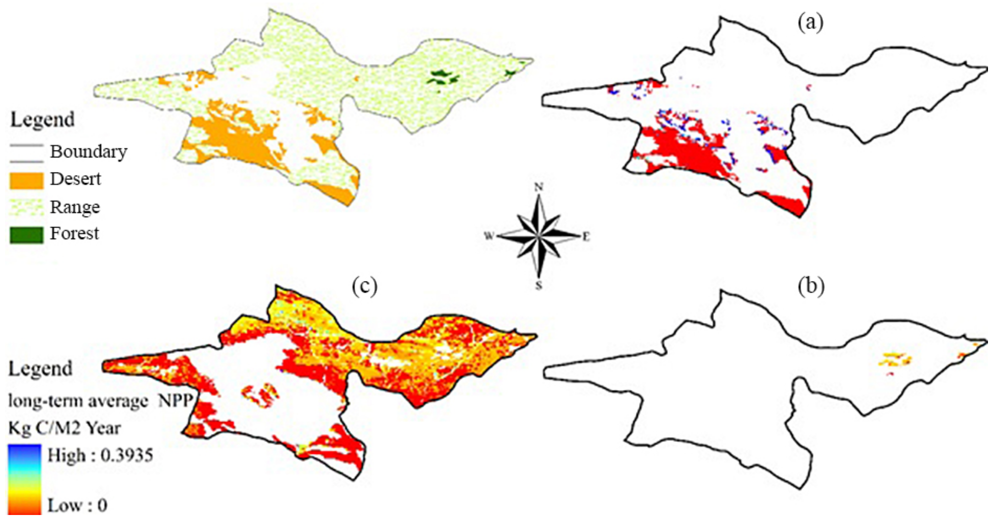

Figure 7. The long-term average of NPP in deserts **(a)**, forests **(b)** and ranges **(c)**.

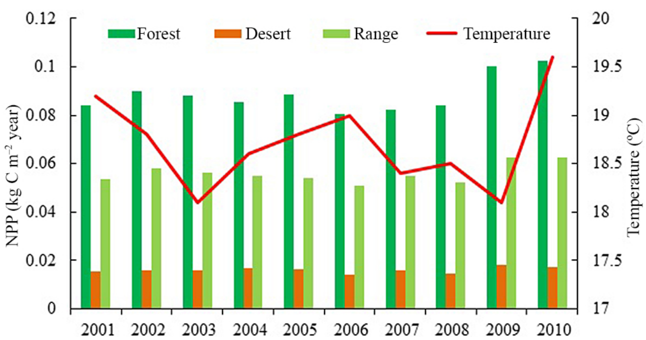

Figure 8. Average NPP changes of each type of land use regarding the annual average temperature changes.

Zitti, 2009). With these descriptions and based on the map of the different land uses average NPP (Fig. 7), the fact that the process of desertification is undeniable for forest and less intense for the rangeland is undeniable in the 2000s; more than 50 % of rangeland has 0 production (kg cm^2 yr^{-1}) in Tehran province (Fig. 7). Despite the small forest area, some areas of forest have 0 production, and also the maximum amount of NPP average of forest is 0.21 (kg cm^2 yr^{-1}). This maximum production is around that of the desert NPP (Fig. 7).

3.3 The relationship between climate change and NPP

One of the important impacts of climate change on forest ecosystems, rangelands and desert is the effects of changes in temperature and precipitation on the NPP of vegetation. The impacts of changes in precipitation (per mm decreasing or increasing) or temperature (for each degree of increase or decrease) on NPP were separately determined in rangeland, forest and desert ecosystems in Tehran province.

The results showed that the range of temperature changes varied between 18.1 and 19.6 °C in the 2000s at Tehran synoptic station. Figure 8 shows the relationship between NPP and the average annual temperature for range, forest and desert land uses. In rangeland use in most years, every time the temperature has increased or decreased, the NPP decreased or increased, respectively (Figs. 8 and 9). Only in 2002–2003, while the temperature decreased 0.7 °C, the NPP amount decreased 0.0026 (kg cm^2 yr^{-1}) per unit decrease in temperature. However, in other years, per unit reduction in temperature (1 °C) net rangeland production increased 0.0118 (kg cm^2 yr^{-1}). Per unit increase in average temperatures in rangelands and the NPP of the rangelands declined 0.0015 (kg cm^2 yr^{-1}). Therefore, based on this relationship and the portrayed values of emission scenarios A2 and B2, changes in NPP in the 2030s were estimated based on the annual average temperature variable. The rainfall range also varied between 174 and 311.7 mm in the 2000s. NPP changes were aligned with rainfall changes unlike temperature. In other words, whenever precipitation increased or decreased, the amount of NPP increased or decreased, respectively. Obtained patterns showed that with a one unit increase or decrease in rainfall (1 mm), the NPP increases or decreases 0.00016 (kg cm^2 yr^{-1}) in rangelands. Such as temperature, based on the relationship between changes in precipitation and NPP in the 2000s, NPP changes in the 2030s were estimated in different emission scenarios, A2 and B2.

The projected results of the NPP of the range ecosystem, under the A2 emission scenario, showed that the highest amount will be reached in the 2030s (Fig. 10a). Under this scenario, changes in precipitation and temperature will increase the NPP in the 2030s to the 2000s. However, assuming the existence of the B2 scenario, production changes of rangelands will decline in the 2030s (Fig. 10a). The changes occur in such a way that the production average of rangelands

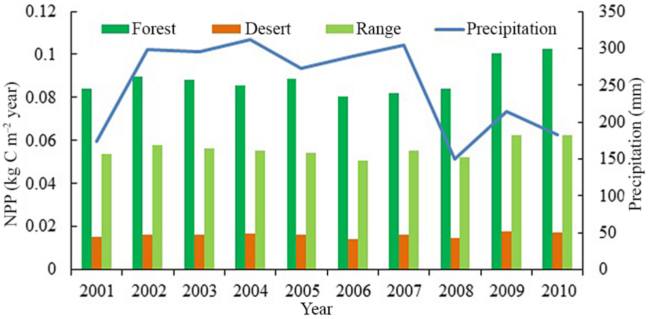

Figure 9. Average NPP changes of each type of land use regarding the annual average rainfall changes.

(in both precipitation and temperature patterns) will decrease under B2 scenario in 2038 and 2039 compared to 2000s. It should be noted that based on the rainfall in scenarios B2, the lowest NPP will occur in rangelands in Tehran province. Under these conditions, the average annual of NPP in 2030s will reach the same production rate in the desert as during the 2000s.

The results of NPP in forest had significant changes in temperature patterns of two emission scenarios, A2 and B2, while the NPP amount showed no significant changes in rainfall patterns of two scenarios, and the results were very similar (Fig. 10b). In scenario A2 and under the temperature changes, the production amount will increase from 0.118 (kg $\mathrm{cm}^2\ \mathrm{yr}^{-1}$) in 2030 to 0.191 (kg $\mathrm{cm}^2\ \mathrm{yr}^{-1}$) in 2039, and the average of production will have a rising trend in the entire decade (Fig. 10b). However, projected results of the NPP under temperature change of scenario B2 show the relative decreasing trend for NPP amount in forest land use (Fig. 10b). It is important to note that if there are conditions of scenario B2 and even under rainfall pattern of the A2 scenario, the annual average of NPP for forest land use in the 2030s will be in the range of the lowest levels of production (desert production in the 2000s).

The forecasting results of production changes in the desert land use showed assumptions of the temperature conditions of the B2 scenario, NPP amount decreased sharply and it will decrease from 0.014 (kg $\mathrm{cm}^2\ \mathrm{yr}^{-1}$) in 2031 to 0 in 2033 (Fig. 10c). However, due to the amount of average annual rainfall generated in this scenario (between 316 and 520 mm), occurrence of such a mode of production is not reasonable in desert land use and it would be more correct to consider production changes under precipitation conditions of this scenario. The study of Seely (1987) on Namib Desert production indicated that the annual rainfall changes between 12.5 and 95 mm caused the production to increase from 0.00075 to 0.50 (kg $\mathrm{cm}^2\ \mathrm{yr}^{-1}$). He attributed this amount of production in the driest desert of the world to the perennial grasses with developing root systems that allow them to respond quickly to soil moisture, and thus they are better able to take advantage of rainfall. Therefore, judgment about

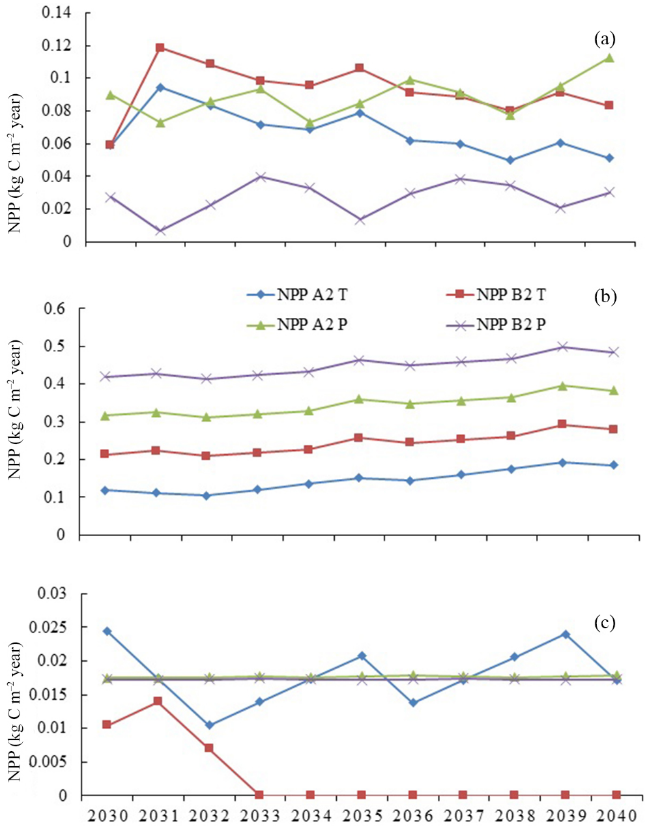

Figure 10. The NPP annual average in range lands **(a)**, forests **(b)** and deserts **(c)** in 2030. NPP B2T is the NPP under the thermal pattern on B2 emission scenario, NPP A2T is the NPP of thermal under A2 emissions scenario, NPP A2P is the NPP of thermal under A2 emissions scenario and NPP B2P is the NPP model under thermal emission B2 scenario.

the occurrence of such cases depends on precise knowledge about the desert flora. Production changes fluctuated between 0.01 and 0.025 (kg $\mathrm{cm}^2\ \mathrm{yr}^{-1}$) under the temperature of A2 scenario. In terms of rainfall under both scenarios, the desert production was 0.017 (kg $\mathrm{cm}^2\ \mathrm{yr}^{-1}$), which is less than the average annual production of the 2000s (Fig. 10c).

4 Discussion

Understanding the complex relationships between the effects of environmental factors on NPP and recoverable biomass is essential to avoid overharvesting (leading to desertification) (Whitford, 2002). In this study, the effects of climate change on NPP of range, forest and desert in Tehran province, Iran, were studied. For this purpose, the NPP index derived from MODIS satellite images was used to monitor degradation over the period of 2001 to 2010 for each land use. The scenarios of Hadcm3 model were also used to investigate the climate scenarios. Climate assessment results showed that both A2 and B2 scenarios have the most similarity to the actual amount of climate parameters. The changes in trends of temperature and precipitation variables were evaluated under each scenario by using the Mann–Kendall and Sen's slope estimator methods. The results showed that the rising trend of temperature and reducing trend of rainfall were significant for both emission scenarios in the period of 2006 to 2099. The results are consistent with the findings of Haghtalab et al. (2013) in Tehran and Mazandaran province in Iran. The annual production deviation compared to the long-term average was used to study the NPP changes trend for each type of land use. The results showed that more than 60 % of range lands in Tehran province had a production rate less than average by 2007. More than 80 % of the forests had a production rate less than the long-term average in half of the 2000s. More than 80 % of desert lands had an NPP less than the average amount in the 2000s except in 2003. The results showed that NPP values in some areas of forest are equal or even less than the production in desert regions in this decade. In some desert areas, there are some microclimate that cause an increase in the NPP, but certainly in most desert areas, the production is at the lowest level in comparison with other land uses (Tietjen et al., 2010). According to the desertification definition (desertification is defined as the impairment or destruction of the biological potential of land) by Whitford (2002) and by comparing the results of the long-term average NPP in three types of land use, range, forest and desert (Fig. 7), the desertification trend of forest and range can be studied in the 2000s in Tehran province. This result is consistent with the results of Haghtalab et al. (2013).

In this study, the average annual rainfall and temperature variables were used as the most effective factors on NPP to find a suitable relation between climate change and production in different types of land use. The projection of NPP was done in range, forest and desert land uses in Tehran province for the 2030s. The results showed that the amount of production increased in the range lands under the rainfall and temperature pattern in the A2 scenario that is consistent with the results of Reeves et al. (2014). However, under the B2 scenario, the production level of rangelands declined. The temperature pattern in the A2 emission scenario has the greatest influence on the variability of NPP of forest land use. The NPP changes in the desert are pretty low under the rainfall pattern in both scenarios, and under the temperature pattern in the A2 scenario also change sinuously in the range of 0.01–0.025 ($\mathrm{kg\,cm^2\,yr^{-1}}$). The notable point will happen for desert NPP in the 2030s; the NPP level will reach 0 from 2033 onwards. This situation would be logical only if there were no vegetation in desert areas and it had also been completely destroyed in previous years for some reason. It is recommended that NPP projection should not be done by only considering the influence of one climate pattern such as temperature.

This paper explored the relative contributions of climate change to NPP variations. However, this study only addresses the IPCC SRES (Special Report on Emissions Scenarios) B2 and A2 emission scenarios concerning climate change. Future work will involve extending the study to a wide range of emission scenarios, while representing the probable climate change in future decades. This includes some other scenarios investigated in IPCC AR4 (e.g., SRES A1, A2, B1 and B2).

5 Conclusions

In this paper, the probable impacts of climate change on NPP in future decades were explored by using a combination of downscaled GCMs and remote-sensing-based carbon models. For modeling future forest, range and desert land NPP, an NPP proportion method was proposed, assuming the ratio of real NPP in this areas to their potential NPP will be constant in future decades. The relative contributions of climate change to the NPP were investigated by using scenario analysis.

The results showed that the rising trend of temperature and reducing trend of rainfall were significant for both emission scenarios in the period of 2006–2099. In this study, temperature was detected as the most significant driving force of change in NPP in range, forest and desert ecosystems. The rainfall variable demonstrated fewer changes than temperature in these ecosystems.

The results indicate that the NPP index can be used as the key criterion for monitoring the environmental features. This index shows the stress magnitude logged to the environmental characteristics, the degree of stress to which an ecosystem can be exposed or the degree of ecological response to the stress. The index of NPP has reduced in all natural areas in Tehran province. In addition, an increasing trend in production and a reduction in land degradation cannot be imagined under the terms of the climate emissions scenarios, A2 and B2, in the region.

It is worth noting that all models are a simplified form of reality and the interpretation of the results depends on uncertainty, inputs and model assumptions. In this study, the issues related to climate scenarios were verified properly on the basis of actual data. However, due to a lack of field measurement of NPP in Iran, the validation of NPP amounts has not been done for the base period (2001–2010). Given the continuing destruction in arid and semiarid areas of Iran, determination of the destruction process and early warning systems is very important. This purpose can be obtained by monitoring and evaluating the systems with reasonable accuracy. Given that the monitoring function is a time-consuming process, it is recommended that terrestrial sampling of NPP must be done in different types of land use in Tehran province and generally in the whole country, and adequate data should be provided for the status of each ecosystem in its geographical scope. Therefore, in the future, they can be used to check the accuracy of satellite images results. This will cause costs to be reduced and time to be saved in the monitoring of the desertification trend in ecosystems through remote sensing methods.

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