ORIGINAL ARTICLE

Dynamic trend of land degradation/restoration along Indira Gandhi Canal command area in Jaisalmer District, Rajasthan, India: a case study

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Abstract

Land cover is a crucial component in assessment of biodiversity and ecosystem services. In arid regions, land cover is mostly composed of aeolian structures which exhibit fragile environmental scenario. The major challenge in this highly dynamic landscape was conversion of desertic land to intensive land use such as agricultural farmlands. To overcome this challenge Indira Gandhi Canal (IGC) and its branches were extended over this district. The main interest of this research was to investigate net primary productivity (NPP) changes using multi-temporal satellite imagery and meteorological datasets within the timeframe of 30 years from 1982 to 2012 over this region. This study was taken up to assess the impact of canal in and around IGC command area in Jaisalmer District to understand the consequence on desertic environment. Analysis of three decades terrestrial NPP over IGC command area in Jaisalmer District, India, shows significant increase in NPP. The satellite data-based analysis of NPP as well as validation with the optical data in the study region revealed that this increasing trend in NPP is basically associated to increase in canal networks. The water supply from the canal gradually led to expansion of irrigation in the agricultural fields leading to change in dynamics of the area. This systematic and long-term NPP analysis will be useful to strengthen our understanding for the role of regional land cover types and impact of their change in the national and global carbon cycle for understanding land degradation and desertification scenario in the study area.

Keywords Land Degradation · Desertification, · Change · IGC · NPP

Introduction

The United Nations Convention to Combat Desertification (UNCCD) recognizes land degradation and desertification as one of the most noticeable environmental concerns of recent times (UNCCD 1994, 2002). Land degradation is often described as a substantial decrease in the biological productivity of the land system, due to natural events exaggerated by anthropogenic activities (Johnson and Lewis 2007). Land degradation in the dry lands is often termed as desertification (Dregne 2002). The interrelationship between land degradation and socio-economic activities is multilayered and complex, several multi-disciplinary approaches, integrated with multiple data sources and methodologies to study the

implications of land degradation is the need of the hour. Assessment and monitoring of regional land degradation or restoration of land are very important so as to understand the dynamic trend of land degradation or restoration, allowing better scientific prevention and control (Sun et al. 2017). To address the issue of gaining a systematic understanding of the magnitude of changes in land degradation at the regional scale over a period of time, remote sensing and geographical information system (GIS) has been chosen as the best means.

Land degradation is an important issue of the Indian subcontinent, since 29.32% (according to 2011–2012) of Indian land mass is under threat of land degradation (SAC 2016). Inter-Governmental Panel on Climate Change (IPCC, Solomon 2007) reported that climate change at the end of 21 century was more likely on the arid ecosystem than in semiarid or sub-humid regions of India. Therefore, Thar Desert region of India provides a classic example of linkages among the climatic dimension, biophysical dimensions and socioeconomic dimension of land degradation or restoration in a developing country (Ravi and Huxman 2009). Agriculture

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land-use pattern in western Rajasthan has a long history dating back to the pre-Harappan and Harappan era (Whyte. 1961). In recent decades land-use pattern in this region has undergone major changes (Kar 2014). Low-value crops and single cropping season since years resulted in poor yield with high dependence on livestock and traditional agroforestry over this region but Green Revolution have made drastic changes in agricultural land use in the post-independence era, and have improved the farmers' economy introducing irrigation facility, new technologies, better infrastructures, etc. Since lots of changes have taken over time in this region it can be considered as a hotspot point for understanding land degradation/regeneration changes over time.

To our knowledge, this is the first study that has tried to explore the recent historical and current extent of land degradation or restoration using remote sensing datasets, over a 30-year period from 1982 to 2012 around IGC command area of Jaisalmer District which forms the core part of the Thar Desert. The main goal of this study is to investigate the dynamics of land degradation or restoration either of which has taken place over the time frame (1982–2012), with a major focus on the change in net primary productivity (NPP) over the region. NPP is the organic matter produced by the green vegetation per unit area and per unit time (Peng et al. 2000). Direct measurement of NPP is a time taking process and is insufficient to determine the spatio temporal variability of NPP at a larger scale (Parihar et al. 2014). Decrease or increase of NPP clearly indicates whether land degradation or restoration is propagating, as well as it will help in quantitative assessments. The specific scope of this paper is embedded in the dimension of land degradation and restoration. We specifically addressed: (1) change rate; (2) spatial distribution of changes; (3) driving forces of changes and (4) validation and accuracy assessment of change detection. The information generated in this study will be a useful basis, for analyzing the underlying causes of change and designing management strategies. The spatiotemporal pattern analysis associated with landscape processes might affect policy making, conservation and restoration programs stronger.

Study area

The Thar Desert is one of the most highly inhabited deserts in the world, located in the extreme western part of the Indian subcontinent. The desert extends over 446,000 km^2, of which 208,110 km^2 lies in India and the rest in Pakistan (Idris et al. 2009). Around 61% of the Indian Thar Desert lies in Rajasthan State. Jaisalmer District of Rajasthan has a total geographical area of 38,400 km^2 and the entire area is covered under the desertic environment (Chouhan and Sharma 2009). Jaisalmer District is located between 26°4′ and 28°23′N, and 69°20′ and 72°42′E in the Great Indian

Thar Desert (Fig. 1). About 34% of the geographical area in the district is covered by rocky surface often known as desert pavement. There is no perennial stream in the area. The district is extended by 270 km in east–west and 186 km in the north–south direction and is bounded by Bikaner district on the north, Indo-Pakistan border on the west and south–west, Barmer and Jodhpur districts in the south, and Jodhpur and Bikaner districts in the east. Annual average rainfall of Jaisalmer District is about 196 mm, with less than 10 mm rainfall events per annum. Critically it has been observed that the annual rainfall variation follows a cycle of 4–5 years (Santra and Chkraborty 2011). Mean maximum and minimum temperatures vary from 40 to 42 °C (Santra et al. 2014). The topography of the region is characterized by the extensive alluvial plain of the Pleistocene period and creeping sand dunes formed in the early Holocene period on the alluvial surface (Kumar et al. 1993).This region is mainly covered by sandy plain and dune structures of several sizes. The dune soils are slight to moderately calcareous, uniformly structure less sandy mass with color at different locations ranging from pale brown to light yellowish brown and devoid of any pedogenic features (Sharma et al. 2006), Most of the Thar Desert area is occupied either by dry open grassland or trees and thorny bushes (Gupta and Prakash 1975).

In mid-1980s IGC was introduced to rejuvenate the Thar region using water from three eastern rivers of the Indus system: Ravi, Beas and Sutlej. It was constructed with the aim to reduce desert and transform the desert wasteland into the agriculturally productive area over the timescale, ensuring positive socio-economic effects over the region. As this area has a unique geographical location, and it is important ecologically, it has become the focus of the study on land degradation/restoration in recent years. Thus an attempt is made to study the long-term change along the IGC command area over the Jaisalmer District.

Data acquisition and processing

Data used

Remote sensing datasets

Sequential datasets of Normalized Difference Vegetative Index (NDVI) from (1982 to 2012) years was obtained from advanced very high resolution radiometer (AVHRR) sensors onboard series of National Oceanic and Atmospheric Administration (NOAA) satellites. The data are gridded with a spatial resolution of 8 km, generated by removing cloud contamination and performing atmospheric calibration at the earth resources observation system (EROS) (Tucker et al. 2005). Land-use land cover information was extracted for the study area based on the land cover map of Southeast
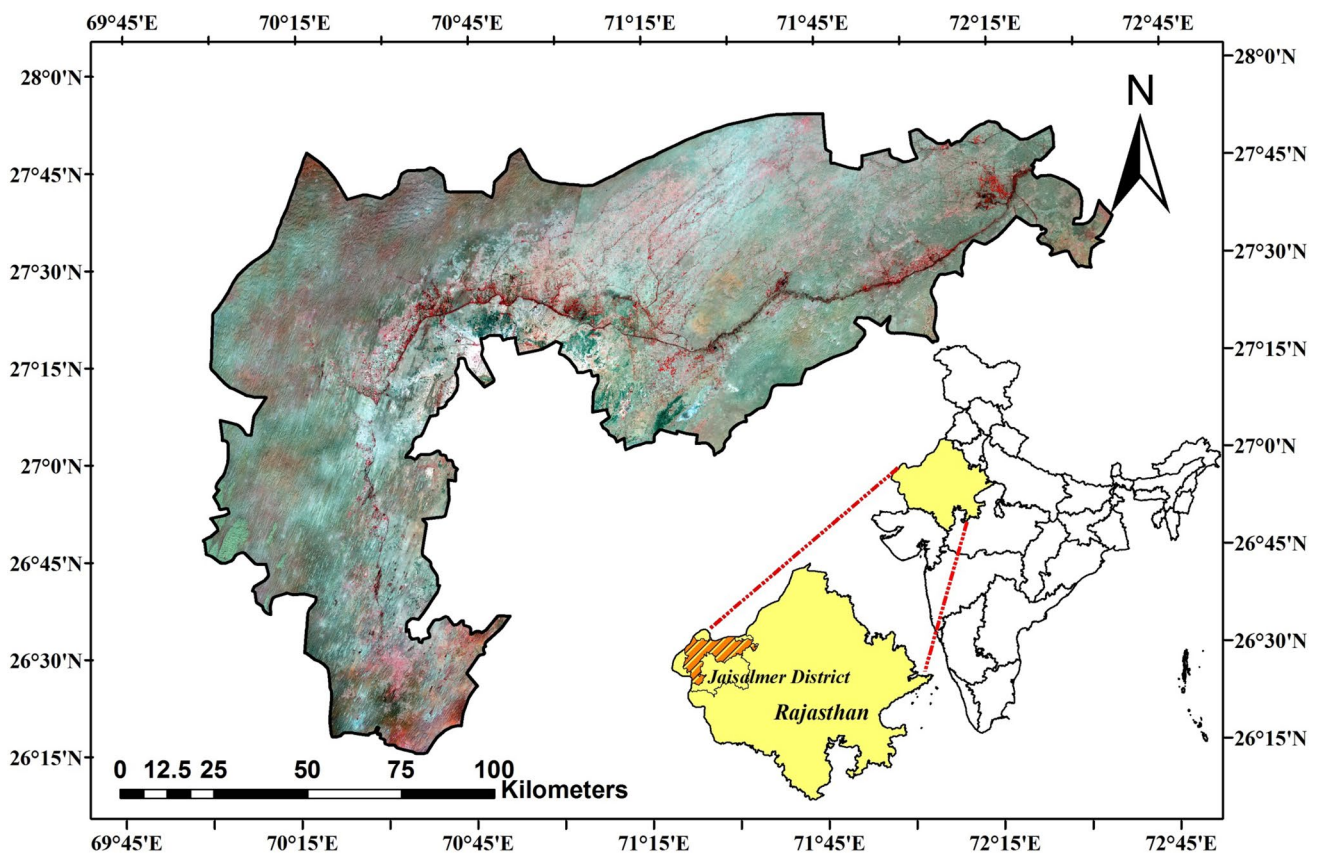
Fig. 1 Location map of Indira Gandhi Canal command area in Jaisalmer District Rajasthan using landsat image of Oct 2016

Asia derived at 1-km spatial resolution by using time series SPOT-NDVI datasets (Agrawal et al. 2003). Time-series datasets from digital globe and landsat were also used for validation purpose. Digital elevation model (DEM) of GEO-TOPO at a spatial resolution of 30 m was used in conjunction for analysis of slope in the study area.

Meteorological dataset

Meteorological parameters like air temperature and precipitation at spatial resolution $0.5°$ were used in this study from Climate Research Unit (CRU) at the University of East Anglia (UEA) http://www.cru.uea.ac.uk/. Shortwave radiation with $1/2 \times 2/3°$ spatial resolution was obtained from Modern-Era Retrospective Analysis for Research and Applications (MERRA) https://earthdata.nasa.gov/community/community-data-system-programs/reason-projects/merra. Finally, air temperature, precipitation and incident solar radiation was used to compute the moisture stress coefficient.

Methodology

Spatial and temporal variability over the time period through a major challenge to land degradation/desertification assessment efforts in dryland management (Sur and Chauhan 2019). Thus, analysis of the various data in one platform is the basic requirement. The different methodological working steps for NPP estimation from 1982 to 2012 are illustrated in Fig. 2. The entire work was carried out using Matlab 2014 software package in conjunction with ARC GIS 10.3.

Improved CASA model

A simple terrestrial process-based model, named improved CASA (Carnegie–Ames–Stanford) ecosystem model was used for NPP estimation over the study area as it is appropriate for regional and global scale (Yu et al. 2009). This model is based on the product of absorbed photosynthetically active radiation (APAR) and LUE (light use efficiency). The model can be expressed as in equation below elucidated by Potter et al. (1993):

$$NPP = APAR \times \varepsilon_{max}. \tag{1}$$

Fig. 2 Flow chart showing improved CASA model framework for NPP calculation and change detection over a long time period 1982–2012
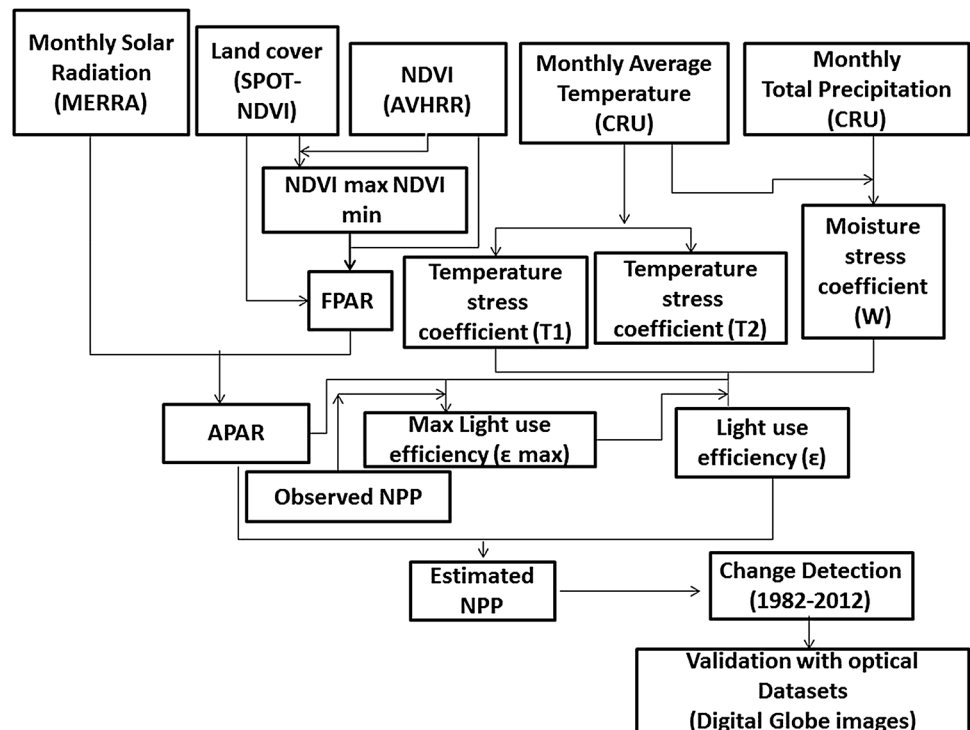
The model includes three key components: (a) remote sensing datasets (land cover, NDVI), (b) meteorological inputs [monthly solar radiation (SOL), which are used to estimate APAR; monthly average temperature and monthly total precipitation, which are used to estimate temperature stress coefficients ($T1$, $T2$) and moisture stress coefficient (W)], and (c) biome-specific observed NPP based on NPP Distribution map of East Asia, 1999. Further using the land cover map, observed NPP, temperature stress coefficients and moisture stress coefficient, a characteristic radiation conversion efficiency parameter (ε_{max}) is extracted to produce ε, which is then used with APAR to predict the monthly NPP. The final estimation of the annual NPP is obtained by adding the 12-month NPP in a year.

APAR estimation

APAR can be estimated by the equation below, where S is the monthly total solar radiation, F is the fraction of photosynthetically active radiation (FPAR) (FPAR is mainly determined by vegetation type and its canopy) and r is the ratio of the solar radiation that can be used by the vegetation (Piao et al. 2001):

$$APAR = S \times F \times r. \tag{2}$$

Estimation of LUE

LUE can be estimated by the equation below:

$$LUE = T1 \times T2 \times W \times \varepsilon_{max}, \tag{3}$$

where $T1$ and $T2$ are temperature stress coefficients ($T1$ indicates the restricted extent of extreme low and high temperature conditions to vegetation photosynthesis and $T2$ expresses the decreasing trend of LUE of the vegetation when the environment conditions change from the optimal temperature to a lower or higher temperature (Potter et al. 1993; Field et al. 1998). W is the moisture stress coefficient calculated from the equation:

$$W = 0.5 + 0.5 \times \left[\frac{E}{P}\right], \tag{4}$$

where E is evapotranspiration and P is potential evapotranspiration (Piao et al. 2001) and ε_{max} is the maximal LUE of the vegetation in ideal conditions.

Decadal change detection

The NPP datasets obtained from the improved CASA model was subjected to statistical change analysis. Firstly mean NPP of each year was computed individually from 1982 to 2012. Then mean was computed for each decade 1982–1992, 1992–2002, 2002–2012 further standard deviation of NPP over the three decades was computed to understand the deviation over each decade. To understand the relative change in

NPP over the canal command area grid level relative deviation (RD) of NPP over canal command area for the period 1982–2012 was calculated using the equation below:

$$RD(\%) = 100 \times \frac{(C2 - C1)}{C1}, \tag{5}$$

where $C1$ indicates mean NPP for the study area from 1982 to 1992 and $C2$ is mean NPP of the study area from 2002 to 2012.

Analysis of NPP is followed by accuracy assessment which involved a set of sample locations to be verified by the lower resolution imagery like digital globe images which will give us vivid clarity about the change over the time period.

Results and discussion

Anthropogenic interactions within any ecosystems are inherently dynamic and complex, any categorization of these is quite complicated (Ellis and Ramankutty 2008). Thus,

working at a broad scale over this theme has the advantage of providing general trends of land degradation/restoration at the regional scale. These analyses are also useful for landscape planning and management, as they serves as a basis for analyzing drivers of land cover change taking place over the area. Results are discussed based on the scale of 8 × 8 km spatial datasets because long-term datasets over the entire study area across the years are only available at this spatial resolution. Validation of the data was done at selected points with higher resolution images. Higher resolutions and lower resolution datasets were accurately geocoded in GIS environment giving prior importance to the precision level that was maximum possible.

Spatial variability of NPP around IGC command area

The study area shows change in elevation from east to west and north to south. This also indicates the slope of land, since slope is function of change in elevation. The north eastern part of the region has a general elevation of about 335 m, but towards the south it has about 34 m. Figure 3 shows the general elevation of the land around the area of

Fig. 3 Elevation of the region and graphical representation of elevation along the canal
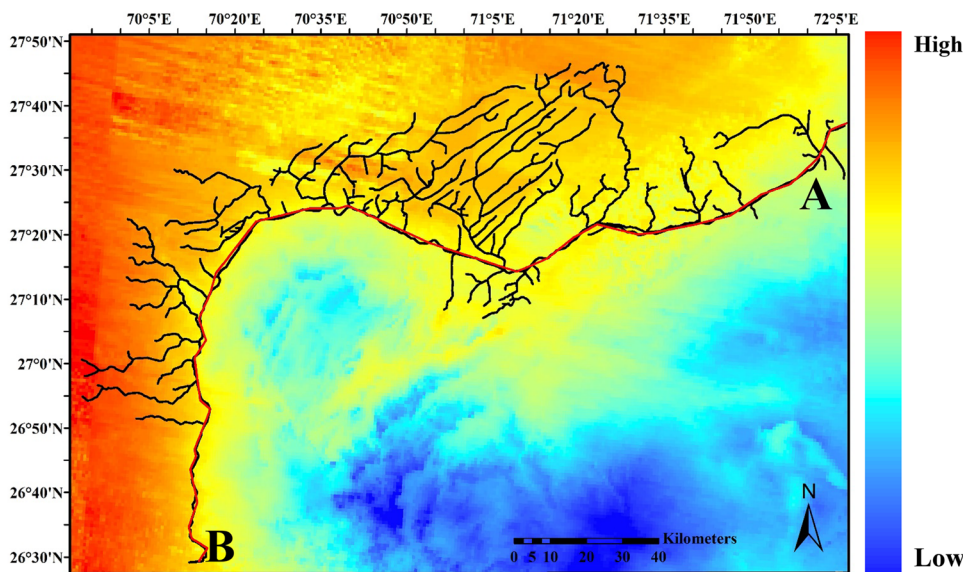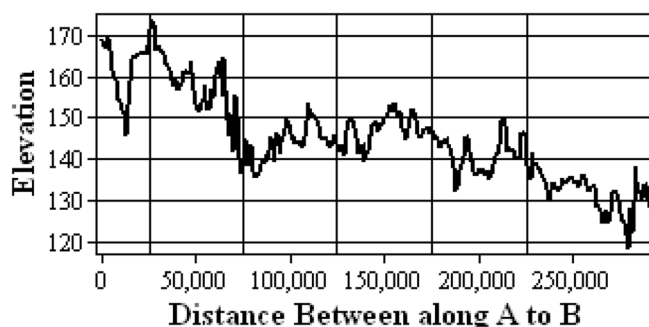
interest and the graph below shows the elevation of the region along the canal in Jaisalmer District from point A to point B. The elevation along the canal also clearly depicts a sharp fall from high to low. The western half is covered with dunes, which are mostly stabilized. IGC across Jaisalmer District is part of the lower reaches of the entire canal, which includes a long distribution system with intensity of irrigation in flow ranging up to 80% and 60% intensity flow under lift system (Kumar 2013). Initially the groundwater level around this region ranged between 20 and 100 m below the surface, but with the advent of IGC the water level has risen up to 40–50 m at the level of upstream region (Roy et al. 2016). However, due to the sharp elevation change of the landscape the water has a tendency to flow in the lower catchment of the study area. The upper stream literally cannot hold the water in its regime. Thus, the spatial distribution of NPP is also higher in the downstream of the region due to high availability of water resource. Figure 4 illustrates the spatial variability of decadal mean NPP and standard deviation of NPP over the period 1982–2012 around IGC command area in Jaisalmer District. Figure 4a shows mean NPP in this region varied from 1 to 15 gC m^{-2} year^{-1} between 1982 and 2012. Specifically mean NPP in the last three decades varied from 1 to 11 gC m^{-2} year^{-1}, 1–13 gC m^{-2} year^{-1}, 1–15 gC m^{-2} year^{-1}. It is clearly seen that along the canal NPP is comparatively higher, ranging between 10 and 15 gC m^{-2} year^{-1}, whereas the NPP decreases as we go away from the main and the feeder canals. Similarly, we see that in Fig. 4b the standard deviation for each decadal time period is quite high as it deviates in a positive direction from 0 to 10 gC m^{-2} year^{-1} along the three decades, precisely it deviates from 1 to 7 gC m^{-2} year^{-1} in 1982–1992, 1–9.2 gC m^{-2} year^{-1} in 1992–2002, 1–10 gC m^{-2} year^{-1} in 2002–2012. This increment in NPP in the region over the time is due to the increase in agricultural activity in the desertic environment after the introduction of the canal networks in the study area over the time period.
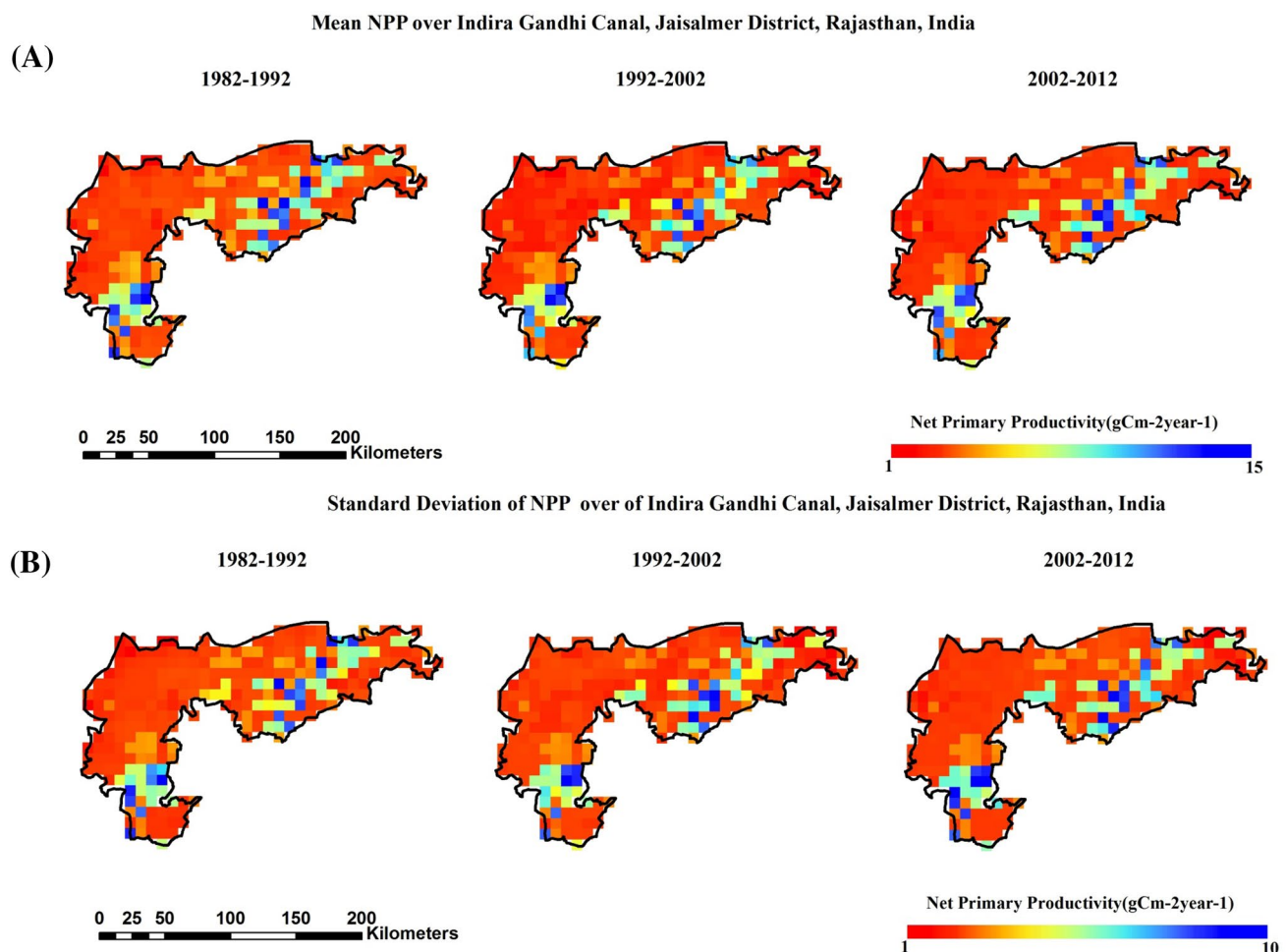

Fig. 4 **a** Mean NPP and **b** standard deviation of NPP over 3 decades 1982–1992, 1992–2002, 2002–2012
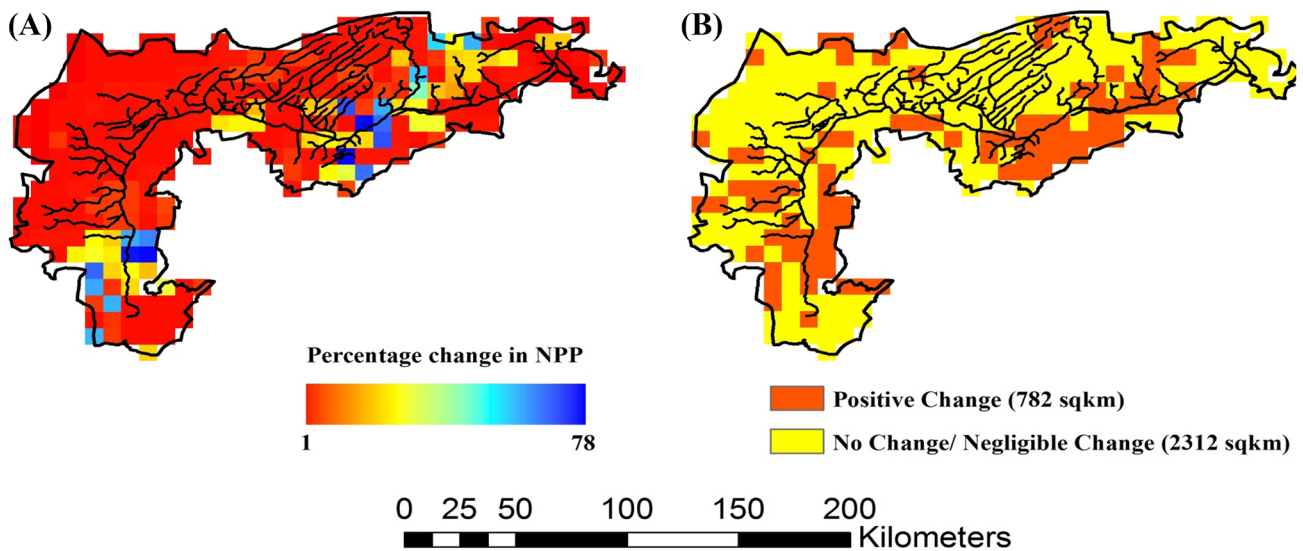
Fig. 5 **a** Percentage change in NPP over Indira Gandhi Canal command area in Jaisalmer District Rajasthan during 1982–2012. **b** Area undergoing positive change over 1982–2012

Percentage change in NPP around IGC command area

Percentage change in NPP over IGC command area in Jaisalmer District Rajasthan for the study period 1982–2012 is depicted in Fig. 5a. Overall, an increasing trend is observed. Some places exhibit quite high changes around 78%. This large-scale change may be due to a proportionate increase in large area under irrigation within the time scale, as a result of the increase in canal networks over the time. Initially, Jaisalmer District had an almost negligible area under irrigation farming but now, with coverage of canal networks some parts of the district by IGC, its irrigated farming scenario is changing with a greater pace (Pathak 2015). Before the canal approached in the study area, this area was sandy which was highly vulnerable to wind erosion. However, with increase in water resource agriculture activity started to spread. Cultivation increased over the time and the cropping seasons also increased, currently this area takes up more than one crop and it is observed that the fallow land has decreased over the time. 728 km^2 areas are observed with positive changes over 1982–2012 constantly in the canal command area (Fig. 5b). Further to validate the above statement of positive changes of NPP standalone NDVI datasets over the time series 1982–2012 (for the month of October was presented because it showed maximum vigor of vegetation growth) was plotted to understand the change in dynamics of the vegetation trend. Figure 6a shows a positive trend with a positive correlation of 0.056 over the years 1980–2015. Next, in Fig. 6b with respect to 1982 the anomaly in vegetation vigor over the area is accounted to see the positive and negative change within the canal command area. This also shows clearly, that other than the drought years in the country the growth is positive throughout 1982–2012.

Consequences of changes around IGC command area

Achievements of landscape planning and management are the main goals of any kind of project. IGC Project is the largest irrigation project of the world it aimed to provide irrigation to semi-arid and arid areas and tried to lift its economy and economic development. This canal has influenced vegetation growth which definitely reduced land degradation. Increment in infiltration rate and runoff regulation promotes control of soil erosion and has a positive impact on groundwater recharge and agricultural growth. Vegetation cover is highly correlated with water balance and regional climate regulation (Feddema et al. 2005; Foley et al. 2007; Pielke 2005) and thereby effect is clearly observed. Land-use pattern change for the structure and functioning of ecosystems and effect of environmental goods and services; effect of humans in a number of ways that go beyond the immediate land-use situation (Turner et al. 1993).The continuous increment of the vegetation cover, have a strong impact on the human livelihood of this region. Environmental problems like degradation, loss of biodiversity and decreases in productivity, decreased over the long term and effected in regional, economic and social upliftment. However, in conjunction to the above positive factors the matter which worries is the presence of shale/clay, hard compact friable carbonate nodules, and lime coated gravel with clay at varying depths with poor infiltration rate and behaving as an impervious barrier in certain parts and leading to water
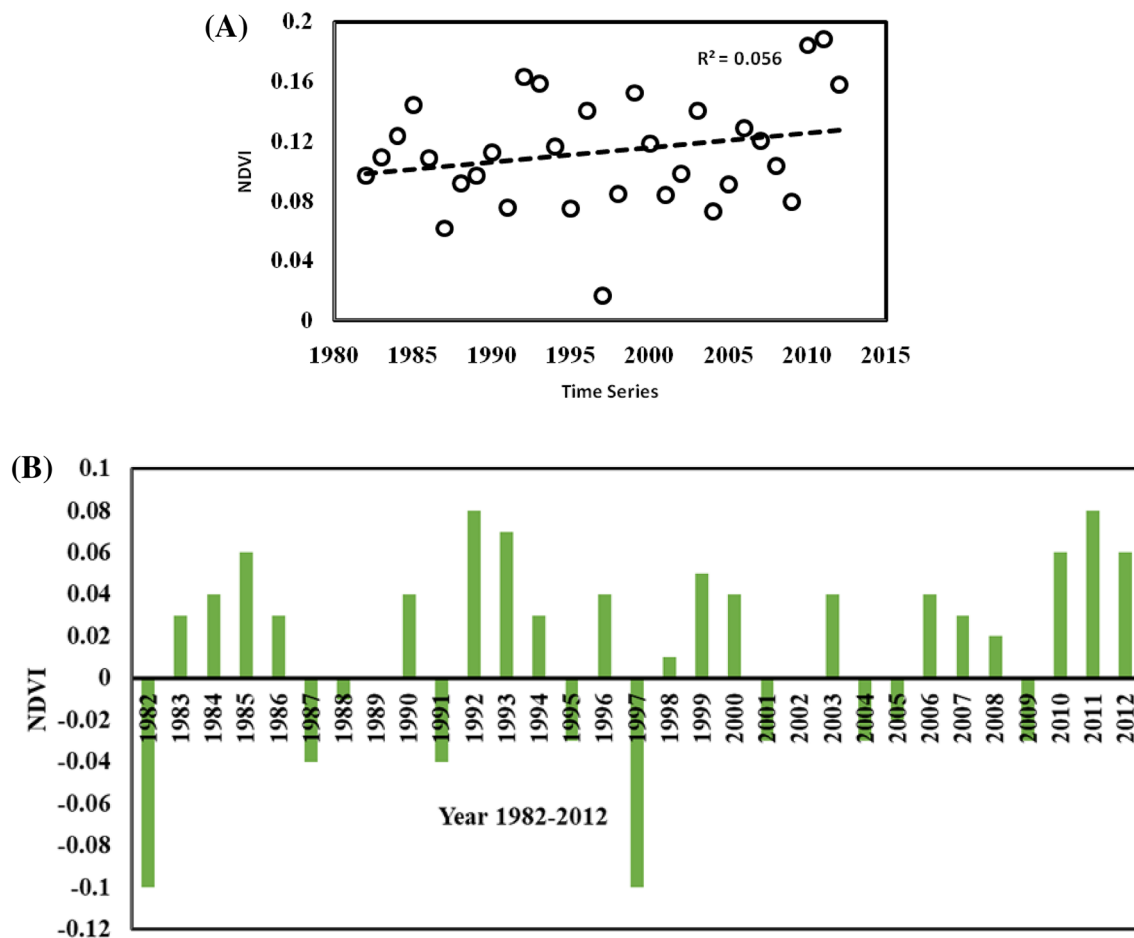
Fig. 6 a Correlation between NDVI and time period 1982–2012. b Trend analysis of NDVI over the period 1982–2012

logging in the lower catchment of the canal (Sharma et al. 2009). This in long-term may lead to waterlogging of large areas along the canal and has probably started but not identifiable at this scale of study.

Validation of changes over IGC command area

The spatial extent of the study area has multi-temporal nature of land degradation and regeneration processes, as well as many interrelated natural and human influences on land degradation and regeneration over the region makes validating the NPP time series trend map a challenging task. Computation of NPP in IGC command area revealed that, a large area of

change is undergoing constantly over the time due to increment in agriculture practices during recent decades. However, the positive change in the region is only due to the introduction of the canal which is constantly affecting the surrounding regions. Places which exhibited more than 50% change were observed in lower resolution datasets from digital globe over the time period of the study. Two validation examples are presented in Figs. 7 and 8. The figures illustrate the introduction of network canal over the time scale in the area which has brought about irrigation for the sustainable agricultural management measures, this have led to an increase in vegetation cover and the recovery of a degraded patch of sandy area. However, the
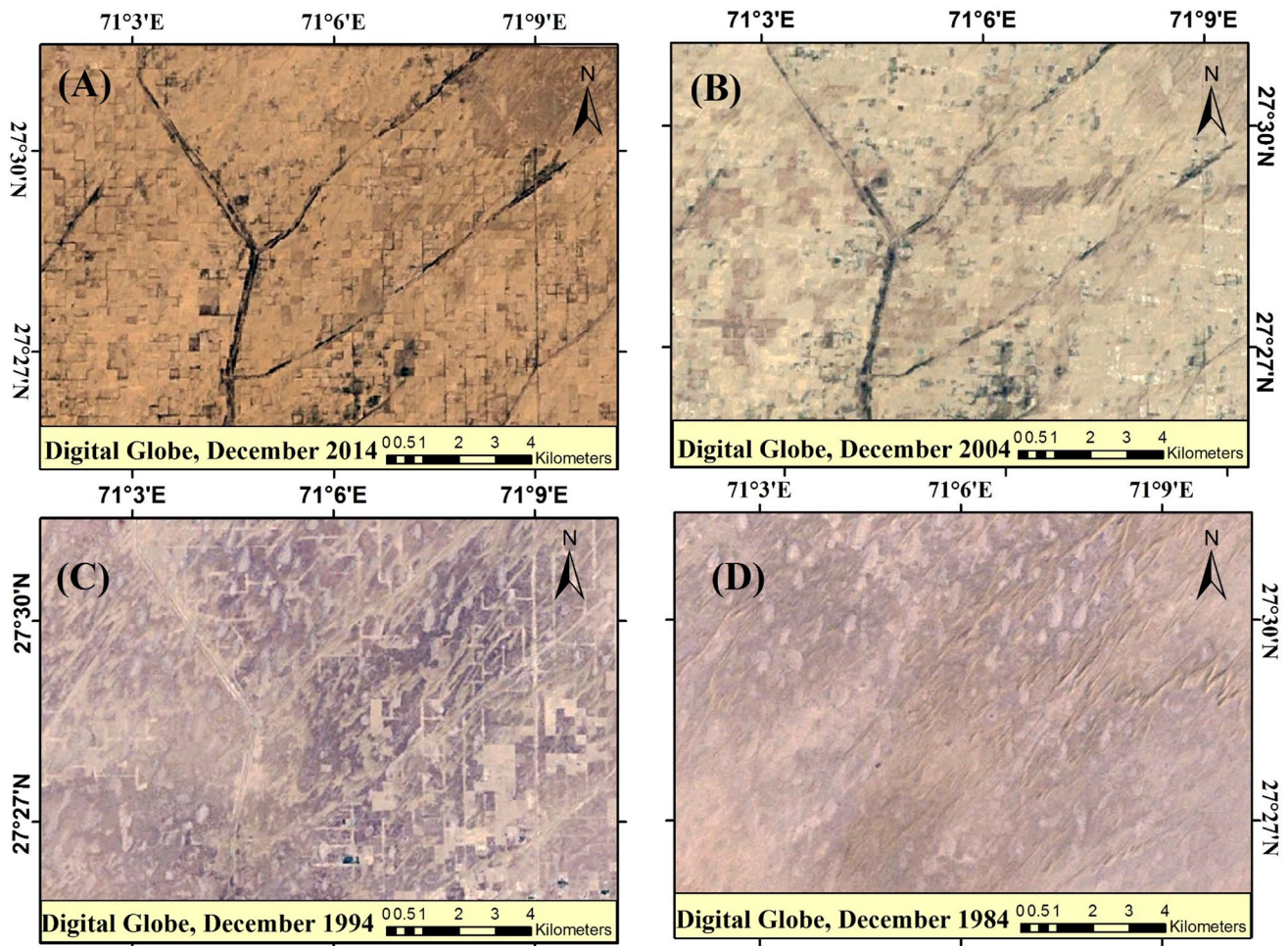
Fig. 7 Showing gradual increase in vegetation with increase in canal network

gradual increase in vegetation represents gradual, changes over a fairly long period of time.

Conclusion

This study explored 30 years of NPP time-series datasets generated from satellite images and meteorological data-sets over Indira Gandhi Canal command area in Jaisalmer District Rajasthan. The present analysis was carried out to assess decadal change in net primary productivity (NPP) over IGC command area using multi-sensor satellite data in improved CASA ecosystem model. Significant change in NPP was observed during the study period from 1982 to 2012. The change analysis shows, 1–78% changes over the entire region. IGC has brought large parts of the driest and the dune-covered western-most districts of Rajasthan Jaisalmer under irrigated agriculture with many new
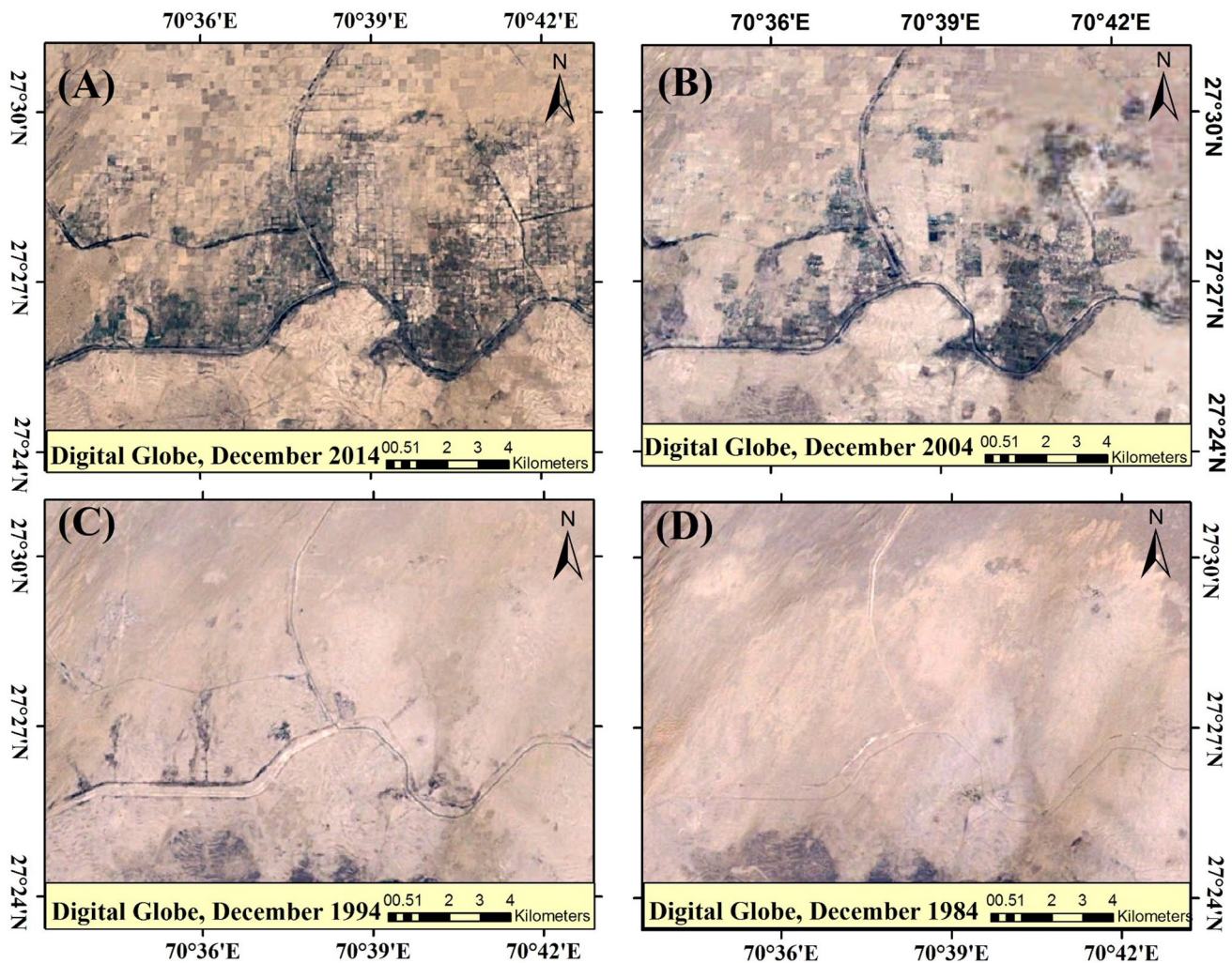
Fig. 8 Showing increase in canal network and increase in agricultural crop area

and high-value crops. More than 51% of the livestock of Rajasthan is concentrated in the arid areas, but their productivity is low primarily due to scarcity of good quality fodder and critical nutrients, which are required for maintenance of normal physiological functions, production and reproduction of the animals. These kinds of problems are being solved gradually over the time scale due to land restoration over the study area. However, our next research would be focused on changes occurring gradually over a fairly long period of time or changes that occur for short period of time. For these reasons, focus will be on implementing the improved methodology that can characterize iteratively estimates of the time and number of changes. Furthermore, its applicability would be tested in different areas where irrigational facilities have come up in recent times.

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