Science of the Total Environment 658 (2019) 922–935

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Spatiotemporal transition of institutional and socioeconomic impacts on vegetation productivity in Central Asia over last three decades

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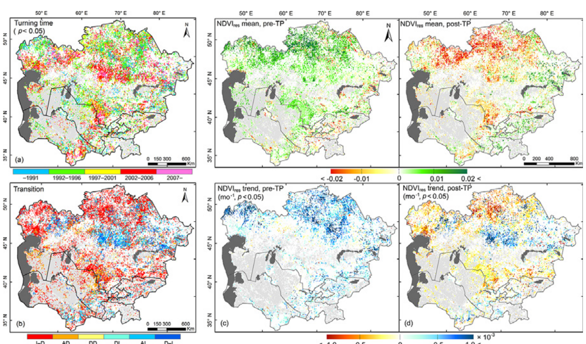
HIGHLIGHTS

- Transition of human impacts on CA drylands mostly occurred after 1991.
- Institutional and socioeconomic changes largely suppressed vegetation productivity.
- Negative impacts mostly resulted from land abandonment and water shortage.
- Agricultural changes and decrease in grazing would promote positive transitions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 September 2018
Received in revised form 18 November 2018
Accepted 10 December 2018
Available online 11 December 2018

Editor: Deyi Hou

Keywords:
Dryland
NDVI residual
Land abandonment
Grazing
Agriculture
Water resource

ABSTRACT

Central Asia experienced substantial institutional and socioeconomic changes during the last few decades, especially the Soviet Union collapse in 1991. It remains unclear how these profound changes impacted vegetation productivity across space and time. This study used the satellite-derived normalized difference vegetation index (NDVI) and gridded climate data to examine the institutional and socioeconomic impacts on vegetation productivity in Central Asia in 1982–2015. The improved Residual Trend (ResTREND) algorithm was used to calculate NDVI residuals ($NDVI_{res}$) that reflect the impacts of human factors by excluding the influences of multiple climate factors. Our results showed that 45.7% of the vegetated areas experienced significant transitions ($p < 0.05$) in $NDVI_{res}$ with turning point (TP), of which 83.8% occurred after 1992 except for the Aral Sea Basin. During the pre-TP period, positive $NDVI_{res}$ (i.e., positive impact) and increasing trends (i.e., positive tendency) were predominant, accounting for 31.6% and 16.5% of the vegetated land, respectively. This was attribute to the expanded cultivation due to Virgin Lands Campaign in North Kazakhstan region and the Amu Darya and Syr Darya Basins. However, the institutional and socioeconomic changes largely suppressed vegetation productivity. In the post-TP period, only 7.0% of the vegetated lands experienced an increasing trend in $NDVI_{res}$, while $NDVI_{res}$ decline accounted for 20.1% of the vegetated areas ($p < 0.05$), mainly distributed in northern Kazakhstan and large areas in the Amu Darya and Syr Darya Basins. Positive transitions resulted from the changes in crop types, decreases in grazing pressure, and increases in water resources, whereas negative transitions were coincident with areas that saw land abandonment, water resource shortages, and soil salinization due to former intensive

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https://doi.org/10.1016/j.scitotenv.2018.12.155

cultivation. These findings highlight the spatiotemporal changes of institutional and socioeconomic impacts on vegetation productivity in Central Asian dryland and provide implications for future dryland management and restoration efforts.

1. Introduction

Natural (e.g., temperature, precipitation, and atmospheric carbon dioxide concentrations) and human (e.g., policies, socioeconomic changes, management practices) factors can substantially affect vegetation productivity at annual to decadal scales (Vitousek, 1997; Alexander et al., 2013; Krausmann et al., 2013; Xiao et al., 2015). Terrestrial ecosystems in Central Asia are dominated by drylands and climate change could significantly affect the productivity of these sensitive dryland ecosystems (Propastin, 2008; Sommer et al., 2013; Eisfelder et al., 2014). On the other hand, Central Asia experienced profound institutional and socioeconomic changes during the last few decades, the most significant of which was perhaps the collapse of the Soviet Union in 1991. However, it remains unclear how these institutional and socioeconomic changes impacted vegetation productivity in this region across time and space.

To alleviate food shortage in the Soviet Union, the Virgin Land Campaign was initiated in 1954 and approximately 45 million ha (Mha) of steppe grasslands were converted to croplands, approximately half of which were located in Russia and Kazakhstan (McCauley, 2016). In 1987, the total area of croplands in Kazakhstan reached 36.5 Mha (World Bank, 2016). In particular, the North Kazakhstan region, known as "the major granary" of the former Soviet Union and characterized by intensive rain-fed farmlands (Lerman et al., 2004), possessed 94% of the croplands in Kazakhstan in 1991–1993 (World Resources Institute, 1996). In addition to the expansion of rainfed croplands, the Virgin Land Campaign converted vast land to irrigated cropland in the midstream and downstream areas of the Amu Darya, Syr Darya and the Ili River, which mainly pass through Uzbekistan, Turkmenistan, and southern Kazakhstan. The territory of these countries in the downstream areas is dominated by deserts and is partly covered by mountains (<10%). Back in the 1960s, policymakers and managers in the Soviet government recognized significant potential for developing agriculture in these regions albeit with commensurate demands on water resources for irrigation. To the contrary, abundant water resources are available in the upstream areas of the Amu Darya and Syr Darya (nowadays Kyrgyzstan and Tajikistan) basins, but the mountainous topography in these areas presents limits to cultivation. Considering this disparity of water and arable land, the Soviet government decided to regulate water resources through constructing dams and reservoirs for the development of irrigated agriculture in the midstream and downstream regions. The irrigated farmlands (9.4×10^6 ha in 1988) expanded with a 70% increase in Central Asia from 1976 to 1988 (Saiko and Zonn, 2000). Irrigation became the dominant agriculture practice in Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan, accounting for 92%, 91%, 75%, and 67% of the croplands in 1991–1993 for these four countries, respectively (World Resources Institute, 1996).

In the past two decades since 1991, countries in Central Asia have also experienced varying degrees of socioeconomic and political reforms and notable land conversions. With the drastically reduced profitability of farming and insecure land tenure after the Soviet Union collapse, approximately 1.6 million people migrated outside of Kazakhstan in 1991–2000 (World Bank, 2016), and vast areas of ploughed land in northern Kazakhstan were abandoned and reverted to grassland (Kraemer et al., 2015). Additionally, the Kazakhstan government withdrew its regulation and support for agricultural and animal husbandry industries, which caused a subsequent transition from a state-commanded to a market-driven economy (Lioubimtseva and Henebry, 2009; Prishchepov et al., 2012). Consequently, grain production dropped from 23.4 to 10.7 million tons, and livestock numbers declined from 48.6 to 14.5 million heads in Kazakhstan from 1990 to 2000 (ARKS, 2016; World Bank, 2016). Kraemer et al. (2015) reported the cropland abandonment in Kostanay Province of Kazakhstan and suggested the low potential of previously abandoned lands for cropland re-cultivation after 2000, but the effectiveness of current land management practices and their consequent impacts on vegetation productivity across northern Kazakhstan is still unknown. The Soviet collapse also influenced irrigation systems established in the Soviet era, and the increasing water withdrawal for the gradual expansion of irrigated land and the construction of hydroelectric energy became a source of conflicts among countries in Central Asia (Bernauer and Siegfried, 2012). The negative impacts were evident with the degradation of the Aral Sea Basin, such as desertification due to severe soil salinization (Saiko and Zonn, 2000) and significant shifts in discharge and runoff patterns (Bernauer and Siegfried, 2012; Schlüter et al., 2013). In the meanwhile, the increasing temperature led to a large amount of evapotranspiration and thus aggravated the land degradation in this area (Small et al., 2001; Shibuo et al., 2007). However, the respective impact of climate change and human activates on the degradation is remains unclear.

The climatic variation and the institutional and socioeconomic changes jointly contribute to the changes in vegetation productivity in Central Asia. Most previous studies on the drivers of vegetation dynamics in Central Asia has been focused on climate change (e.g., Propastin, 2008; Sommer et al., 2013; Li et al., 2015; Zhou et al., 2015; Xu et al., 2017) and vegetation response to climatic variations (e.g., Kariyeva et al., 2012; Lu et al., 2014; Dubovyk et al., 2016). Many studies showed that the productivity of dryland ecosystems was sensitive to water availability and its change can be largely attributed to the climatic variations (Gessner et al., 2013; Zhou et al., 2015; Zhang and Ren, 2017; Lamchin et al., 2018), whereas climate warming could intensify water shortage and aridity in Central Asia (Lioubimtseva and Cole, 2006; Hu et al., 2014) and could in turn suppress plant growth (Zhou et al., 2015). The land degradation is expected to be much severer under future climatic scenarios (Miao et al., 2015). By contrast, only a limited number of studies tried to explain the impacts of socioeconomic activities on vegetation productivity for this region (e.g., Jiang et al., 2017), which could partly attribute to the lack of long-term records of socioeconomic indicators (e.g., gross domestic product (GDP), house income, occupational class) at national, state and county levels. Two previous studies indicated opposite trends in vegetation greenness (Piao et al., 2011; Xu et al., 2017) and phenology (Kariyeva and van Leeuwen, 2012) for large areas in Central Asia before and after the collapse of the Soviet Union. Both of these studies set year 1991 as a turning point when the Soviet Union collapsed. However, human impacts may have lag effects or last for a longer time than expected. To our knowledge, no study has examined the spatiotemporal transition of the profound institutional and socioeconomic impacts on vegetation productivity in Central Asia during the last three decades.

In contrast to the socioeconomic records in Central Asia, satellite-derived imageries are able to provide continuous trajectories and patterns of vegetation variations with >30-yr records. The objective of this study is to explore the effects of institutional changes and socioeconomic activities on the spatiotemporal variations of vegetation productivity in Central Asia from 1982 to 2015 using satellite-derived normalized difference vegetation index (NDVI) and gridded climate data. In this study, an improved Residual Trend (ResTREND) algorithm was used to obtain $NDVI_{res}$ that can reflect the impacts of human activities by excluding climate influences. We first assessed the contribution of socioeconomic activities to NDVI variations using NDVI residuals ($NDVI_{res}$). We then detected the time of change in the $NDVI_{res}$ trend and assessed the transitions in vegetation productivity induced by institutional and socioeconomic changes at the pixel and regional levels, respectively. Our results were also compared with statistical data from multiple sources, such as the Food and Agriculture Organization (FAO), World Resources Institute, and World Bank. Our findings will enhance understanding of the relative contributions of various socioeconomic developments responsible for vegetation change in Central Asia and similar dryland areas characterized by analogous management activities to inform future dryland management and restoration.

2. Data and methods

2.1. Study area

Central Asia constitutes the core region of the Asian continent, spanning from the Caspian Sea in the west to China in the east and from Afghanistan in the south to Siberia in the north (Fig. 1(b)). In this paper, we focus on five countries in Central Asia: Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan. Kazakhstan is the largest country (2,724,902 km^2) and Tajikistan is the smallest (141,376 km^2) in terms of the land area (World Bank, 2016). Elevation is the highest in the eastern mountainous region of Altai, Tien Shan, and Pamir in eastern Kazakhstan, Kyrgyzstan, and Tajikistan, exceeding 3000 m above sea level, and gradually decreases to the Caspian Sea in the western Kazakhstan and Turkmenistan. Mean summer temperatures of Central Asia range from 20 °C in the north to above 30 °C in the south, while the temperature during winter is below zero, with extremes below −20 °C in the northern and mountain areas. The mean annual precipitation in the lowlands ranges between <100 mm in some areas of Uzbekistan and Turkmenistan and ~400 mm in the north of Kazakhstan (Lioubimtseva and Henebry, 2009).

We used the land cover map generated by Klein et al. (2012) in this study (Fig. 1(a)). We combined evergreen needleleaf forest and deciduous broadleaf forest to forests, sparse shrubs and herbaceous vegetation and grassland to grassland, and closed shrubland and open shrubland to shrublands. Grasslands account for 59.0% of the vegetated area in Central Asia, occupying considerable areas of Kazakhstan, Tajikistan, and Kyrgyzstan. The main socioeconomic activity on grasslands is grazing. Croplands account for 22.2% of the vegetated area in Central Asia, mainly located in Kazakhstan. The dominant crop types (wheat, oats, and barley) are rain-fed in North Kazakhstan region that includes North Kazakhstan (north), Kostanay (southwest), and Akmola (southeast) (Fig. 1(c)), accounting for 19.5% of the vegetated area in Kazakhstan, while vast areas in the Amu Darya Basin, Syr Darya Basin and Ili-Balkhash Basin (mainly in Turkmenistan, Uzbekistan, and southern Kazakhstan) are irrigated croplands (e.g., cotton and rice).

The two important rivers for irrigation in Central Asia are the Amu Darya and the Syr Darya, which originate from snowmelt in mountainous regions, travel through Kyrgyzstan, Tajikistan, Kazakhstan, and Uzbekistan, and eventually converge in the Aral Sea. Nearly 56.2% of

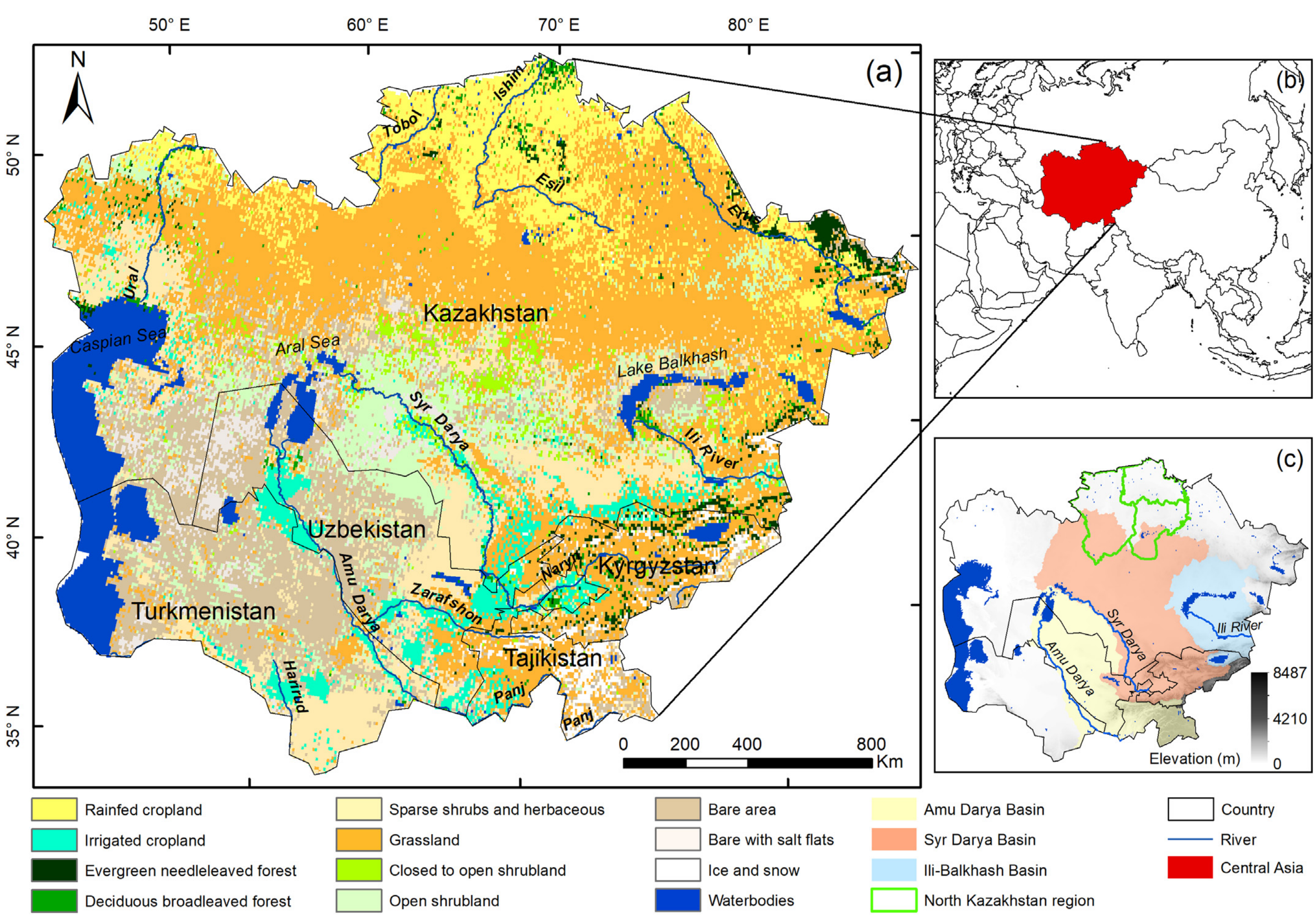

Fig. 1. Land cover map of Central Asia modified from Klein et al. (2012). Source of rivers and country boundaries: Natural Earth (www.naturalearthdata.com). Source of basin boundaries: HydroSHEDS (Lehner and Grill, 2013). Source of elevation: Shuttle Radar Topography Mission (SRTM, https://lta.cr.usgs.gov/SRTM1Arc).

water volume was annually withdrawn from the Amu Darya for irrigation, and 15.9% was for hydroelectric energy (Abdullaev et al., 2007).

2.2. Data

The GIMMS3g NDVI dataset, available from July 1981 to December 2015 for the version 1 (v1), is a long-term NDVI dataset developed by the Global Inventory Monitoring and Modeling System (GIMMS) project at NASA Goddard Space Flight Center. The dataset was derived from the Advanced Very High Resolution Radiometer (AVHRR) onboard a series of National Oceanic and Atmospheric Administration (NOAA)'s polar-orbiting satellites (NOAA 7, 9, 11, 14, 16, 17, and 18). To avoid the effects caused by sensor changes and orbital decay on the quality of the AVHRR data, several procedures were performed to minimize the deviation among satellites. A satellite orbital drift correction was performed using the empirical mode decomposition (EMD)/reconstruction method, which minimizes the effects of orbital drift by removing the common trends between the time series for the solar zenith angle (SZA) and NDVI (Pizon, 2005; Fensholt et al., 2013). Corrections were also applied for volcanic stratospheric aerosol effects from the El Chichon (1982–1984) and Mt. Pinatubo (1991–1993) volcanic eruptions (Fensholt et al., 2013). Calibration was performed using SeaWiFS data, which were based on inter-calibration with the SPOT sensor (Zhu et al., 2013). The GIMMS3g NDVI dataset is at a spatial resolution of 0.083° and an interval of 15 days from 1982 to 2015. To further reduce cloud effects, this study adopted the maximum value compositing (MVC) method to generate monthly maximum NDVI from 1982 to 2015.

NDVI is one of the most widely used vegetation indices derived from satellite observations. NDVI captures the contrast in the reflectance of vegetation canopies between red and near-infrared wavelengths. It is strongly related to the fraction of absorbed photosynthetically active radiation absorbed by vegetation canopies. NDVI has been widely used to approximate vegetation productivity at various spatial and temporal scales (Paruelo et al., 1997; Xiao and Moody, 2004; de Jong et al., 2011). In this study, we used NDVI as a proxy for vegetation productivity in Central Asia over the period 1982–2015. Analyses were restricted to the growing season period, defined in this study as the period from April to October.

Potential factors that affect plant photosynthesis and evapotranspiration include precipitation (*precip*), air temperature (T_{air}), surface pressure (P_s), photosynthetically absorbed radiation (*PAR*), surface net longwave radiation (L_{net}), and air specific humidity (H_{air}) (Bonan, 2015). These factors were derived from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis dataset. The MERRA reanalysis dataset was developed by NASA's global modeling and assimilation office (GMAO), with a spatial resolution of 0.5° × 0.667° and temporal duration from 1979 to present. These variables were aggregated to the monthly time step to match the interval of the NDVI data. This study used the monthly data of abovementioned climatic variables from 1982 to 2015, with additional precipitation data from 1981 for lag analysis. The climate data were resampled to 1/12° spatial resolution to match the resolution of the GIMMS3g NDVI data.

2.3. Data analysis

We first used the ResTREND method to calculate the NDVI residuals ($NDVI_{res}$). The ResTREND method is commonly used to evaluate human-induced impacts on vegetation change for various ecosystem types by detecting the trends of residuals based on NDVI–climate regression (e.g., Evans and Geerken, 2004; Wessels et al., 2007; Li et al., 2012). The basic assumption of the ResTREND method is the variation of remotely sensed NDVI time series can be attributed to climatic factors, human activities, and random noises/errors that may come from sensor calibration and NDVI-climate regression. In ResTREND, the observed NDVI values are regressed against climatic factors to generate a statistical NDVI–climate model, and the $NDVI_{res}$ is then calculated as the differences between observed and predicted NDVI values. The variations of the $NDVI_{res}$ time series are considered to be caused by human activities. A decreasing trend in $NDVI_{res}$ indicates vegetation degradation presumably induced by human activities (e.g., grazing and urbanization); an increasing trend in $NDVI_{res}$ implies improved vegetation conditions that may be attributed to restoration efforts (e.g., afforestation and improved agricultural practices); no trend in $NDVI_{res}$ suggests that the NDVI changes are purely attributed to climatic factors. This study advances the ResTREND approach for separating socioeconomic impacts from climatic contributions on NDVI variations by accounting for lagged and multivariate climate effects. This involves four steps as follows (Fig. 2).

Step 1: Determine the lag of the NDVI response to precipitation (*lag-cul precip*) for each month within the growing season. Vegetation in Central Asia exhibits lagged response to precipitation (Gessner et al., 2013; Zhou et al., 2015), and therefore we considered five types of lag (lag 0–4 months) with three types of accumulated (1–3 months) precipitation for each month. Through comparing the R^2 in all 15 regressions in one month, precipitation with the highest R^2 (*lag-cul precip*) was selected to represent the response of NDVI to precipitation in this month.

Step 2: Conduct principal component analysis (PCA) for multiple climate factors for each month separately. To derive $NDVI_{res}$, we generated multivariate regression models through regressing NDVI values against *lag-cul precip*, T_{air}, *PAR*, P_s, H_{air}, and L_{net} at the pixel level for each month. Most ResTREND studies used climatic factors directly in multivariate regression (e.g., Li et al., 2012), while the possible high auto-correlations among climatic factors, i.e. multicollinearity, would confound model analysis and substantially limit insights. To ensure the independence of all input variables, PCA was applied to generate orthogonal, composite climate components before multivariate regression was conducted. This step transferred the abovementioned climatic factors into six climatic principal components (CPCs).

Step 3: Derive $NDVI_{res}$ by a bidirectional variable selection regression. One fundamental assumption of ResTREND is the strong relationship between climate factors and vegetation greenness or productivity. In order to remove the effects of CPCs that are significantly related to NDVI and exclude noises in the original GIMMS 3 g NDVI dataset, we used a bidirectional variable selection (MASS::stepAIC in *R* software; Ripley, 2002) in the regression procedure to identify the best subset (CPC_j, $j \leq 6$) from CPCs. The resulting $NDVI_{res}$ did not include the effects of climatic factors, and the variations of $NDVI_{res}$ were considered to be primarily caused by human factors.

Step 4: Conduct transition analysis of the $NDVI_{res}$ time series using the Break For Additive Season and Trend (BFAST) method. A turning point of $NDVI_{res}$ marks the time when the impact of socioeconomic factors on vegetation changed, with either monotonic or reversed transition. The turning points (TPs) were detected from monthly $NDVI_{res}$ from April to October (seven months as the frequency in BFAST) from 1982 to 2015 using BFAST (Verbesselt et al., 2010). BFAST integrates the decomposition of growing season $NDVI_{res}$ into trend, seasonal, and remainder components with methods for detecting change within the time series, and iteratively estimates the time and number of changes. In this study, BFAST was used to detect a major turning point in the $NDVI_{res}$ time series, which is also called BFAST01. The major turning point represents the predominant transition of socioeconomic impact of the terrestrial surface. We set the minimum window size as consecutive 21 months, i.e., three years in BFAST months for the testing of a candidate $NDVI_{res}$ trend. The significance level (*p*-value) for turning point detection was set to 0.05 in this study. BFAST outputs were further analyzed to characterize the transition by its magnitude ($NDVI_{res}$ mean) and direction ($NDVI_{res}$ trend). A *t*-test was adopted to test the significance of spatially averaged $NDVI_{res}$ mean/trend difference between pre- and post-TP periods. Comparing the $NDVI_{res}$ trends between pre- and post-TP periods ($trend_{post}$ and $trend_{pre}$, respectively) quantitatively

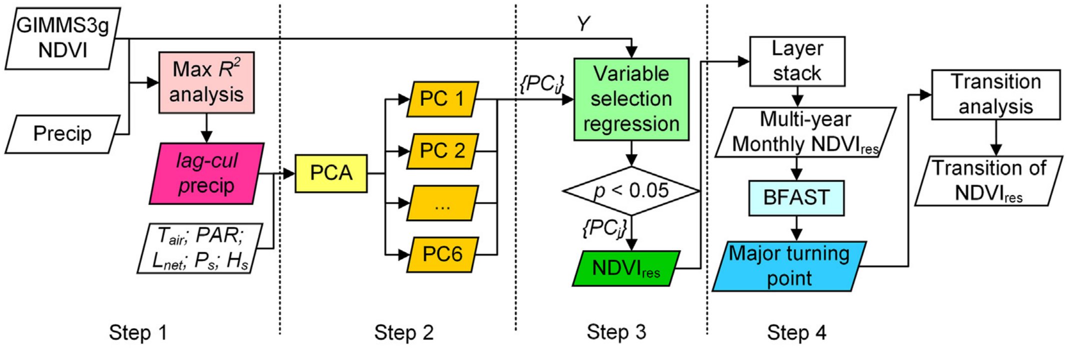

Fig. 2. Flowchart of the improved ResTREND algorithm with a PCA-transformed and variable-selected regression.

and qualitatively, we defined six types of human-induced transition of $NDVI_{res}$ trends: increase to decrease (I-D, $trend_{post} < 0 < trend_{pre}$), accelerated decline (AD, $trend_{post} < trend_{pre} < 0$), diminished decline (DD, $trend_{pre} < trend_{post} < 0$), diminished increase (DI, $0 < trend_{post} < trend_{pre}$), accelerated increase (AI, $0 < trend_{pre} < trend_{post}$), and decrease to increase (D-I, $trend_{pre} < 0 < trend_{post}$).

To examine the effects of institutional and socioeconomic changes on vegetation productivity in Central Asia, we first calculated $NDVI_{res}$ for each month within the growing season (i.e. April–October) from 1982 to 2015. Based on the residual time series, we detected the major turning time, if any, and corresponding transition of growing season $NDVI_{res}$ at the pixel level in 1982–2015 (Section 3.1). We analyzed the transition by comparing $NDVI_{res}$ before and after turning points, specifically studying the shifts in the $NDVI_{res}$ mean and trend. The regional-level TP was also detected using the BFAST01 algorithm based on time series of spatially averaged $NDVI_{res}$ within a given region (Section 3.2). We analyzed the $NDVI_{res}$ tendencies before and after the regional-level TP to explore how each region responded to the dominant socioeconomic activates that occurred, if any, and if they agree with pixel-level results. We further compared the $NDVI_{res}$ variations in two cultivated regions in Kazakhstan and examined the spatial relationships of watershed-level $NDVI_{res}$ within the Amu Darya and the Syr Darya Basins, separately.

3. Results

3.1. Major transitions of $NDVI_{res}$ in 1982–2015

In Central Asia, 45.7% of the vegetated areas experienced significant transitions in $NDVI_{res}$ ($p < 0.05$), of which 83.8% occurred after 1992 when the Soviet Union collapsed (Fig. 3(a–b)). The $NDVI_{res}$ firstly showed turning points before 1991 mainly around the Aral Sea, and turning points of 1992–1996 were mostly located in the northern Kazakhstan (Fig. 3(a)). Grasslands in central Kazakhstan and the midstream of the Amu Darya and Syr Darya Basins (mixed irrigated cropland, shrubland, and grassland) experienced later turning points mainly after 2002 (Fig. 3(a)).

The transition in $NDVI_{res}$ exhibited a clear spatial pattern associated with vegetation type and ecoregion domain (Fig. 3(c)). 71.8% of the transitioned lands had a significant negative trend in $NDVI_{res}$ after the turning point (reddish color in Fig. 3(c–d), $p < 0.05$), mostly located in western and central Kazakhstan, the Amu Darya Basin, and southern Turkmenistan and dominated by grassland (59.8%) and partly covered by shrubland (18.1%), rainfed cropland (14.6%), irrigated cropland (5.0%), and forest (2.5%) (Table 1). The positive trends in $NDVI_{res}$ (blueish color in Fig. 3(c–d), $p < 0.05$) during the post-TP were detected in eastern and central Kazakhstan, the mountainous region in southern Central Asia, accounting for 28.2% of the total transitioned areas dominated by grassland (71.3%) and partly covered by rainfed cropland (11.6%), shrubland (9.1%), irrigated cropland (5.0%), and forest (2.3%).

Overall, the $NDVI_{res}$ mean tended to be higher during the pre-TP periods compared to the post-TP periods. Positive $NDVI_{res}$ mean was found for a large proportion of the vegetated land in the pre-TP period (31.1%, Fig. 4(a)), mostly located in grassland of central Kazakhstan, rainfed cropland areas in northern Kazakhstan, Kyrgyzstan, and downstream areas of the Amu Darya Basin. The transition from positive to negative $NDVI_{res}$ mean during the post-TP period was most pronounced in northern Kazakhstan, grasslands in central Kazakhstan, and the Syr Darya Basin. Transitions toward positive $NDVI_{res}$ mean from negative values were found around the Balkhash Lake, Kyrgyzstan, grasslands in southern Kazakhstan, and upstream regions of the Amu Darya Basin (Fig. 4(b)). Residuals during the pre-TP period ($NDVI_{res}$ mean $= 2.80 \times 10^{-3}$) was also statistically higher than residuals during the post-TP period ($NDVI_{res}$ mean $= -4.50 \times 10^{-3}$) (Fig. 4(c)).

During the pre-TP period, $NDVI_{res}$ tended to increase in most areas. During the post-TP period, however, $NDVI_{res}$ exhibited increasing trends in some areas and decreasing trends in other areas. Trends also tended to be stronger after turning points. During the pre-TP period, 16.5% of the vegetated areas experienced an increasing trend in $NDVI_{res}$ ($p < 0.05$), mainly located in northern Kazakhstan and eastern Central Asia, while a significant decreasing trend only accounted for 1.7% of the vegetated areas ($p < 0.05$), mainly in central Kazakhstan grasslands (Fig. 4(d)). In the post-TP period, the areas exhibiting a significant decline in $NDVI_{res}$ accounted for 20.1% of the vegetated areas ($p < 0.05$), distributed in the northern Kazakhstan and the Amu Darya and Syr Darya Basins. Comparing to the pre-TP period, the post-TP period had less area exhibiting increasing $NDVI_{res}$ (7.0% of the vegetated lands), mainly located in the central Kazakhstan, the Ili-Balkhash Basin, most upstream areas of the Amu Darya and Syr Darya Basins, and some downstream areas of the Amu Darya Basin (Fig. 4(e)). This transition is consistent with the frequency distributions that the average $NDVI_{res}$ trends decreased from 5.00×10^{-4} mo^{-1} to -8.59×10^{-5} mo^{-1} (Fig. 4(f)). Taken together, our results indicate noteworthy transitions not only in $NDVI_{res}$ mean but also in $NDVI_{res}$ trend in Central Asia over the last three decades.

3.2. Assessment of $NDVI_{res}$ transitions at regional level

At the regional scale, similar significant positive-to-negative transitions in $NDVI_{res}$ mean and trend could be found in the three regions, the North Kazakhstan, the Syr Darya Basin, and the Amu Darya Basin (Fig. 5). Among these three regions, the North Kazakhstan experience the largest transition in both $NDVI_{res}$ mean (from 8.30×10^{-3} to -1.12×10^{-2}) and trend (from 6.51×10^{-4} mo^{-1} to -2.62×10^{-4} mo^{-1}), followed by the Syr Darya Basin (mean: from 2.40×10^{-3} to -4.00×10^{-3}; trend: from 4.57×10^{-4} mo^{-1} to 3.71×10^{-5} mo^{-1}), and Amu Darya Basin (mean: from 1.30×10^{-3} to -2.80×10^{-3}; trend: from 2.60×10^{-4} mo^{-1} to -1.38×10^{-5} mo^{-1}). The Ili-Balkhash Basin presented an insignificant transition.

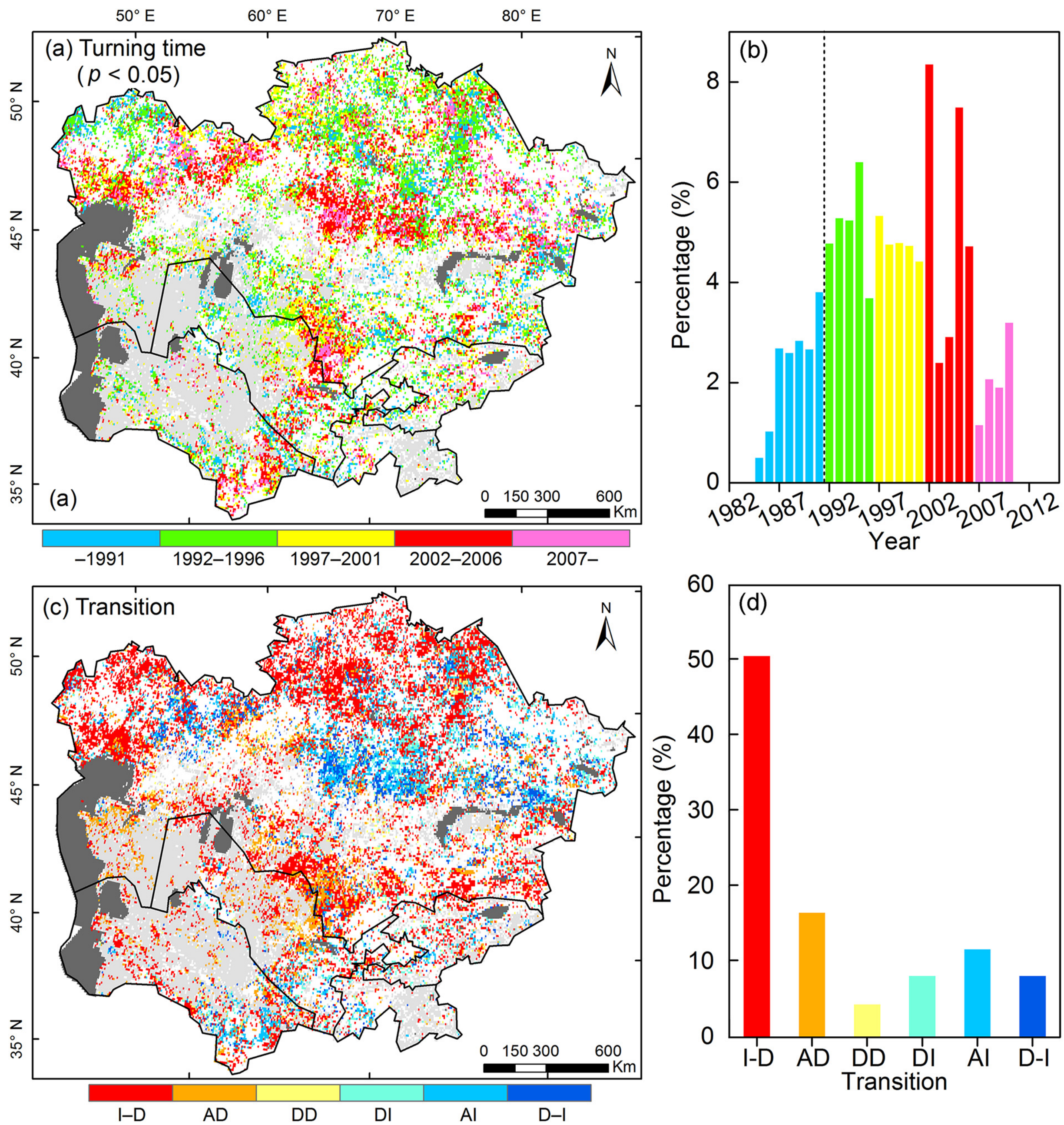

Fig. 3. Transitions of $NDVI_{res}$ detected by the improved ResTREND algorithm. (a) Map of major turning time of $NDVI_{res}$ time series from 1982 to 2015 ($p < 0.05$) and (b) the histogram of turning time (black dash line is the time of the Soviet collapse). (c) Map of transitions pre- and post-TP and (d) the histogram of six transition classes. White represents no significant turning point. Light grey is non-vegetated cover. Dark grey indicates water bodies.

To assess the regional transition, we detected the major turning point for each region using the spatially averaged $NDVI_{res}$. In the North Kazakhstan region, the dominant land cover types are rainfed croplands and grasslands. In this region, the major turning year occurred in 1995. The North Kazakhstan region presented a significant increasing trend prior to 1995 (1.44×10^{-3} mo^{-1}, $p < 0.01$; Fig. 6(a)), corresponding to the major turning point around 1992–1995 found in Section 3.1 that has an increasing-to-decreasing transition of $NDVI_{res}$ trend (I-D, Fig. 3). After 1995, this region presented a rapidly decreasing trend in $NDVI_{res}$ (-6.92×10^{-4} mo^{-1}, $p < 0.05$). However, this trend slightly changed around 2008 by a transition to increasing trend during 2008–2015 (1.74×10^{-3} mo^{-1}, $p < 0.05$) although the $NDVI_{res}$ was still mostly negative.

Table 1
Statistics of $NDVI_{res}$ transition by land cover type.

Land cover type	Percentage of vegetated area (%)	Percentage of $NDVI_{res}$ transited area (%)	
		Positive	Negative
Grassland	62.8	71.3	59.8
Rainfed cropland	12.7	11.6	14.6
Irrigated cropland	5.9	5.6	5.0
Shrubland	14.7	9.1	18.1
Forest	3.9	2.3	2.5

Similarly, the major turning year was also detected in 1995 in the Ili-Balkhash Basin. $NDVI_{res}$ significantly increased at a rate of 1.17×10^{-3} mo^{-1} ($p < 0.05$) before 1995 but insignificantly decreased at a rate of -1.81×10^{-4} mo^{-1} ($p = 0.47$) in 1995–2015 (Fig. 6(b)). Comparing to the North Kazakhstan region during 1995–2015, the

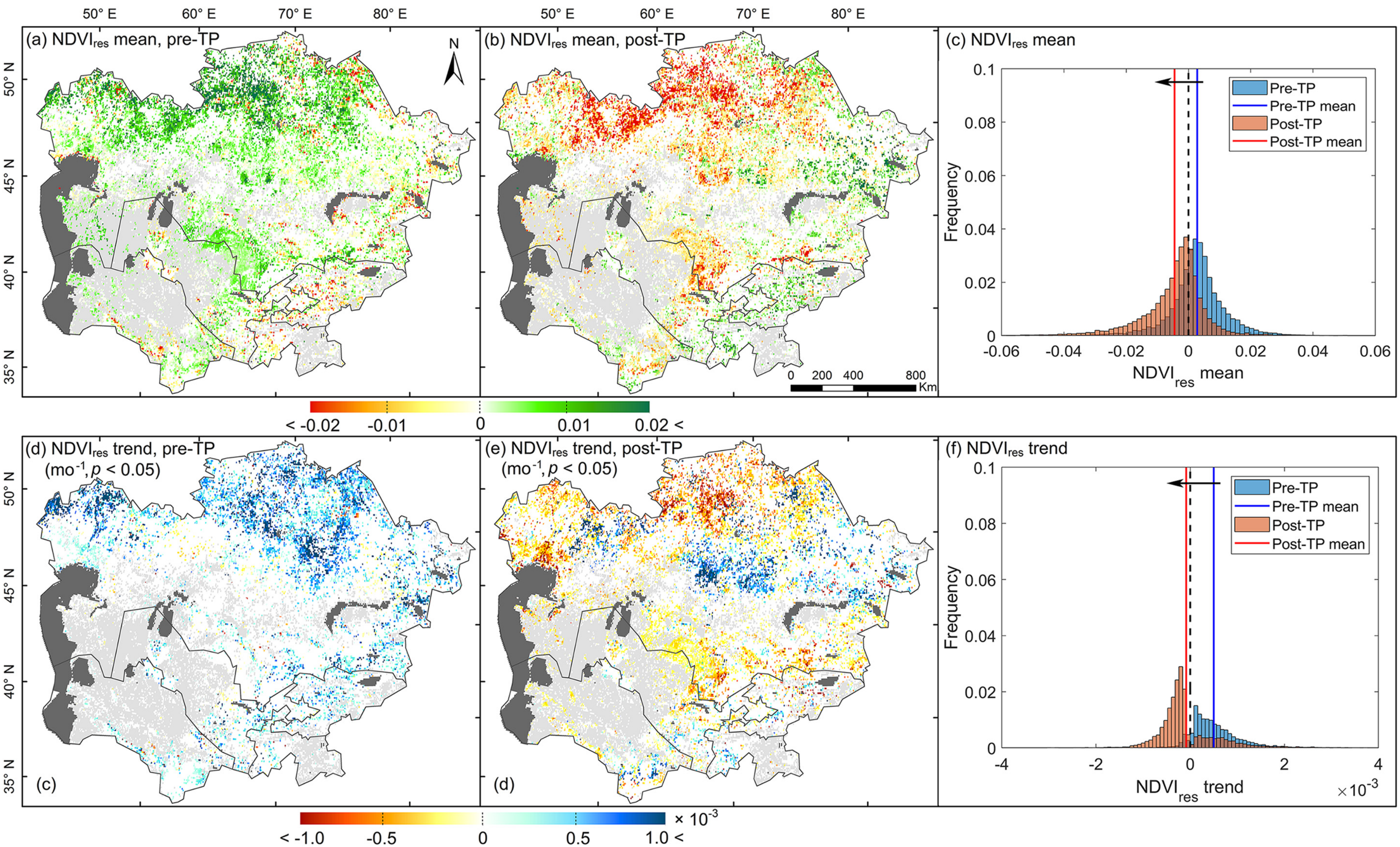

Fig. 4. Mean $NDVI_{res}$ over the growing averaged over the pre- and post-TP and the corresponding $NDVI_{res}$ trend for each period. (a) and (b) are the mean $NDVI_{res}$ for the pre- and post-TP periods, respectively; (d) and (e) are the trends in $NDVI_{res}$ for the pre- and post-TP periods, respectively. White represents no significant turning point. Light grey stands for non-vegetated cover. Dark grey indicates water bodies; (c) and (f) are histograms of $NDVI_{res}$ mean and trend ($p < 0.05$) in the growing season over the pre- and post-TP periods in Central Asia, respectively. Black arrows indicate transition direction or magnitude with 95% significance.

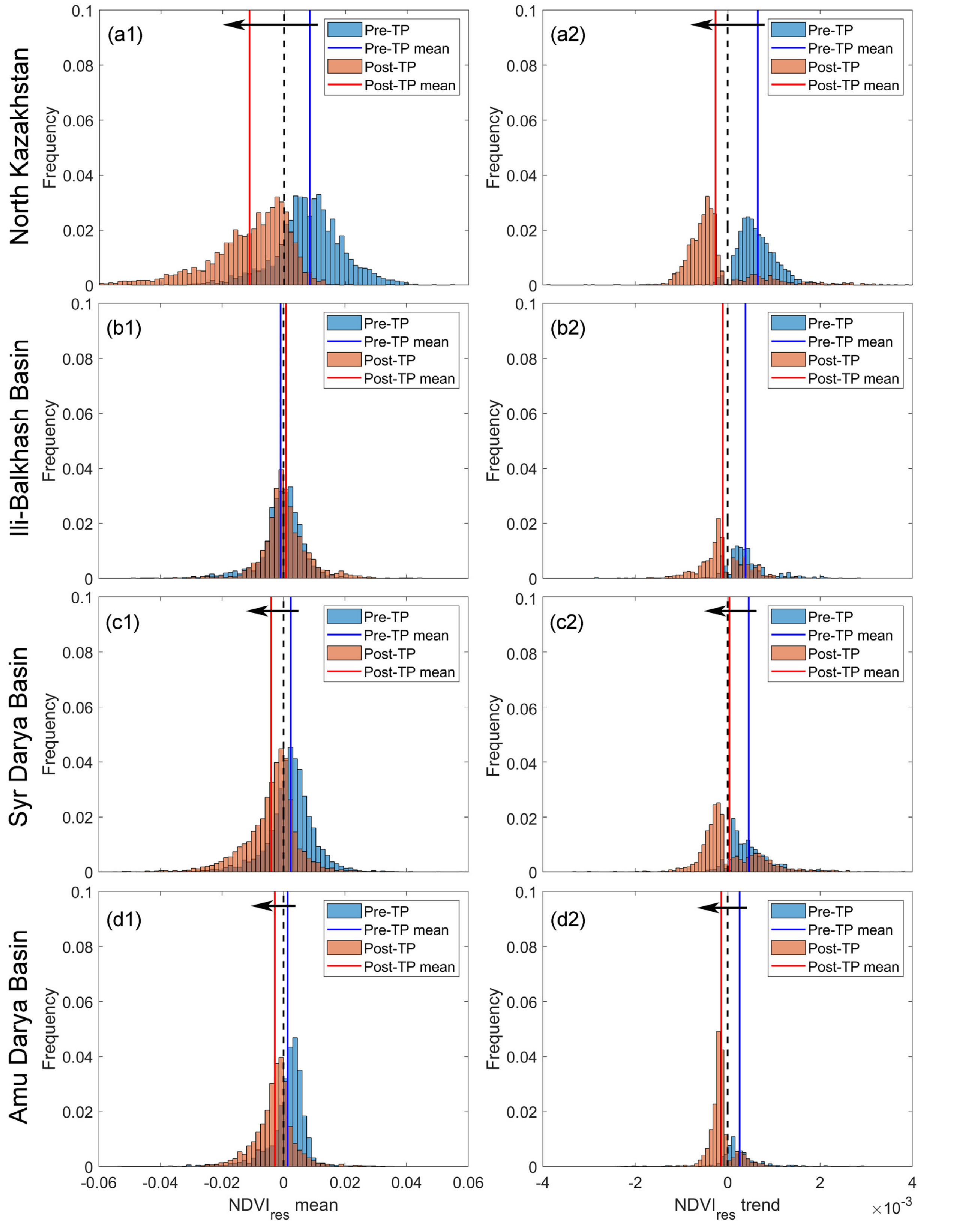

Fig. 5. Histograms of $NDVI_{res}$ mean (left column) and trend (right column) ($p < 0.05$) in the growing season over the pre- and post-TP periods in four regions: (a) the North Kazakhstan, (b) the Ili-Balkhash Basin, (c) the Syr Darya Basin, and (d) the Amu Darya Basin, respectively. Black arrows indicate transition direction or magnitude with 95% significance.

decreasing trend was less severe, and the $NDVI_{res}$ mean was less negative in the Ili-Balkhash Basin. Similar to the North Kazakhstan region, the decreasing trend of $NDVI_{res}$ has a tendency to change to a rapidly increasing trend (2.09×10^{-3} mo^{-1}, $p < 0.05$) in the late post-TP period from 2006 to 2014. The $NDVI_{res}$ was more positive in the Ili-Balkhash Basin than that in the North Kazakhstan region, especially during 2010–2014. The overall similarity in the transition pattern of $NDVI_{res}$ trends between the North Kazakhstan region and the Ili-Balkhash

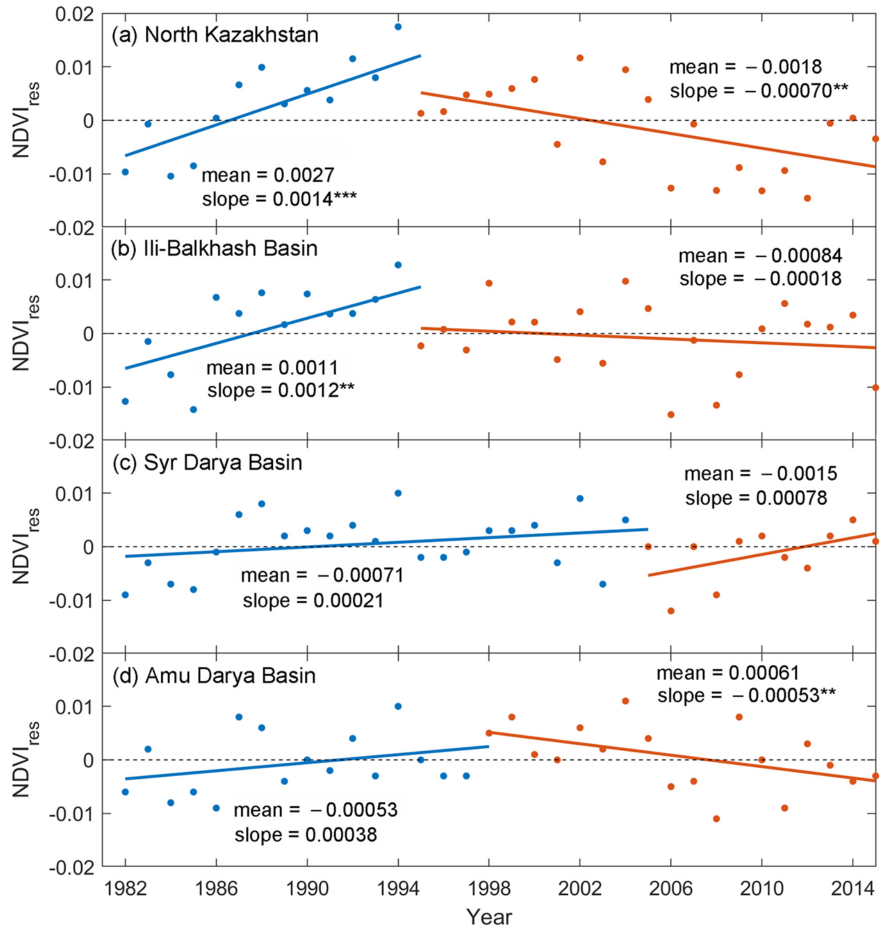

Fig. 6. The annual variation of growing-season averaged $NDVI_{res}$ over the period from 1982 to 2015 in (a) the North Kazakhstan region and (b) the Ili-Balkhash Basin. The superscripted star indicates the significance level of the annual trend of $NDVI_{res}$: *** is $p < 0.01$, ** is $p < 0.05$, and * is $p < 0.1$.

Basin indicates nearly coincidental socioeconomic changes in these two regions over the period from 1982 to 2015 (further discussed in Section 4.2).

The Syr and Amu Darya Basins presented the major TP in 2005 and 1998, respectively. During the pre-TP periods, these two regions experience insignificant increasing trends at rates of 2.20×10^{-4} mo^{-1} ($p = 0.16$) and 3.77×10^{-4} mo^{-1} ($p = 0.18$), respectively, and the $NDVI_{res}$ means were both negatives (Fig. 6(c–d)). During the post-TP period, the $NDVI_{res}$ of Amu Darya Basin significantly decreased at a rate of -5.34×10^{-4} mo^{-1} ($p < 0.05$), and the $NDVI_{res}$ mean was slightly positive (6.11×10^{-4}). In contrast, the $NDVI_{res}$ trend of the Syr Darya Basin was insignificant (3.77×10^{-4} mo^{-1}, $p = 0.11$), and its mean was still negative during the post-TP period.

The spatial pattern of the $NDVI_{res}$ transition was highly variable in the Amu Darya and Syr Darya Basins with turning points widely ranging from 1992 to 2006 (Fig. 3), and the regional transition is less significant compared to the North Kazakhstan region and the Ili-Balkhash Basin (Fig. 6). To investigate the trends for each basin, we performed an additional statistical analysis at the watershed level. In the Syr Darya upstream area, forest and grassland are the dominant vegetation types in the Naryn watershed (Fig. 7(a1)). During 1982–1993, the spatially averaged $NDVI_{res}$ mean was mostly negative (Fig. 7(a2)), indicating that socioeconomic activities generally had negative impacts in this period. However, $NDVI_{res}$ presented a drastic increase from 1994 to 2002, and NDVIres was mostly positive after that. In contrast, the Turgay watershed, where is dominant by grassland, experienced a decrease in $NDVI_{res}$ from 1987 to 2006, and it was mostly negative during this period. Irrigated lands are mostly located in the midstream areas, including the Main Stream and Chu-Talas watersheds. The Sarysu-Tengiz watershed is dominated by grassland and rainfed cropland. $NDVI_{res}$ in the three midstream watersheds fluctuated around zero from 1982 to 2002 but presented more negative values after 2002. Over the three decades, the only watershed showing a significant increase in $NDVI_{res}$ was the Naryn watershed (5.95×10^{-4} mo^{-1}, $p < 0.01$; Fig. 7(a3)). Other watersheds experienced insignificant decreases in $NDVI_{res}$, except the Sarysu-Tengiz watershed. The temporal variation of $NDVI_{res}$ in the Naryn watershed was positively correlated with that in the Main Stream ($r = 0.35$, $p < 0.05$) and Chu-Talas ($r = 0.30$, $p < 0.05$) watersheds but negatively correlated with that in the Turgay watershed ($r = -0.34$, $p < 0.1$) which is located in the most downstream area. The $NDVI_{res}$ of Turgay watershed was also negatively correlated with the two adjacent watersheds, the Main Stream ($r = -0.33$, $p < 0.1$) and the Chu-Talas watershed ($r = -0.32$, $p < 0.1$). The correlations among the three midstream watersheds were significantly positive (Fig. 7(a3)).

The vegetated areas in the Amu Darya upstream regions dominated by grassland and irrigated cropland exhibited a significant increasing trend in 1982–2015 (3.42×10^{-4} mo^{-1}, $p < 0.01$; Fig. 7(b2)). The midstream vegetation (mainly irrigated and grassland) had a similar increasing but insignificant trend in 1982–2015. However, the downstream lands that were intensively developed to irrigated croplands experienced a strong decreasing trend of $NDVI_{res}$ (-3.89×10^{-4} mo^{-1}, $p < 0.01$), especially over the period 2002–2015 (-9.58×10^{-3} mo^{-1}, $p < 0.01$). The upstream $NDVI_{res}$ was only positively correlated with the midstream ($r = 0.58$, $p < 0.01$), and downstream $NDVI_{res}$ was also positively correlated with the midstream ($r = 0.43$, $p < 0.05$). Overall, the upstream regions in both the Amu Darya Basin and the Syr Darya Basin experienced significant increases in $NDVI_{res}$ in 1982–2015, while the downstream regions of these two basins showed

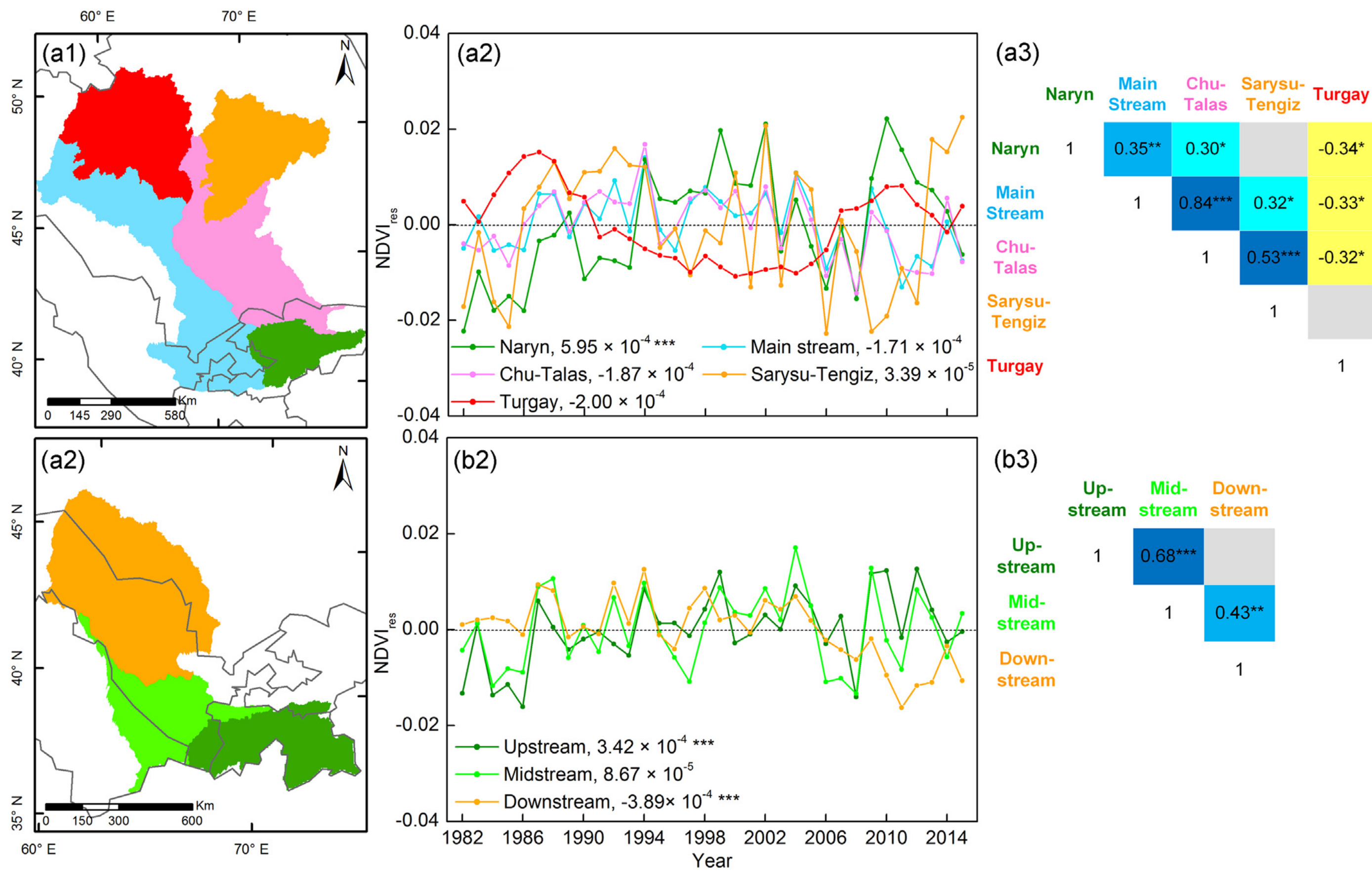

Fig. 7. Watersheds within the Syr Darya Basin and the Amu Darya Basin and the spatially-averaged $NDVI_{res}$ for each watershed. Watersheds within (a1) the Syr Darya Basin including the main stream (blue), Naryn (dark green), Chu-Talas (magenta), Sarysu-Tengiz (orange), and Turgay (red), and (b1) the Amu Darya Basin that is divided into the upstream watershed (dark green), the midstream watershed (green) and the downstream watershed (orange). The annual variation of growing-season averaged $NDVI_{res}$ over the period 1982 to 2015 is presented using the corresponding color of each watershed in (a2) the Syr Darya Basin and (b2) the Amu Darya Basin. (a3) and (b3) are the temporal correlations among watersheds in these two basins, separately. Grey indicates insignificant correlation. The superscripted star indicates significance level of $NDVI_{res}$ trends and correlations: *** is $p < 0.01$, ** is $p < 0.05$, and * is $p < 0.1$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

either negative correlations with other watersheds or significant declines in $NDVI_{res}$ during this period.

4. Discussion

4.1. Socioeconomic impacts on vegetation productivity during the Soviet period

We found that the socioeconomic impacts on vegetation productivity in Central Asia showed large fluctuations from 1982 to 2015 and a great proportion of the vegetated land experienced significant transition over this 34-yr period. Since the former Soviet Union initiated the Virgin Lands Campaign (1953–1964) to alleviate food shortage, considerable grasslands in northern Kazakhstan had been converted to cropland and had been heavily cultivated. Cropped area accounted for 36.5 million ha in Kazakhstan in 1984 (Fig. 8(a)), and agricultural income accounted for 26.7% of the country's total Gross Domestic Product (GDP) in 1992 (World Bank, 2016). Although the cropland area reached its peak in 1984, the yield of the dominant rainfed crops in the North Kazakhstan region (wheat, barley, and oat) increased from 5930 Hg/ha in 1984 to 11,412 Hg/ha in 1993 (FAO, 2017). This is consistent with the positive $NDVI_{res}$ trend and relatively high mean $NDVI_{res}$ in the North Kazakhstan region during the pre-TP period. Under the state regulation in Kazakhstan, the state-owned farmland always had a steady land for agricultural activities, ranging from 35.1 to 36.5 million ha from 1984 to 1992, which was much higher than that of other countries in Central Asia (Fig. 8(a)). In addition to agricultural activities, the animal husbandry industry also rapidly developed in Kazakhstan during the Soviet period. Rather than continuing traditional pastoral movement following seasonal pastures, pastoralists were sedentarized into a collective system of state-run farms. Policymakers encouraged reducing pastoral movements and supported livestock industry with subsidy, fodder, and maintenance of local wells, and therefore livestock production system was intensified (averaged 81.2 million head in 1982–1992; FAO, 2017).

The other part of the Virgin Lands Campaign was the expansion of irrigated lands in the southern Kazakhstan and other countries. The most abundant water resources are located in the upstream regions of the Amu Darya and Syr Darya Basins, but these areas have less favorable land for agriculture due to mountainous topography. Through constructing dam and reservoir, Soviet decision-makers tried to regulate regional water resources and relocate water resources from upstream to the midstream and downstream reaches of the Syr Darya (nowadays Uzbekistan, Turkmenistan, and southern Kazakhstan) where they could be utilized for irrigated agriculture, particularly for cotton production (Dukhovny and Sokolov, 2003). The irrigated farmlands accounted for 9.4×10^6 ha in Central Asia in 1988, with a 70% increase from 1976 to 1988 (Saiko and Zonn, 2000). These irrigation expansions corresponded to positive $NDVI_{res}$ values found in our study during the pre-TP period, demonstrating a positive impact on local vegetation. However, this agricultural activity directly led to the rapid decrease of water volume and level in the Aral Sea. In 1960, the water volume of the Aral Sea was 1083.0 km^3, and its water level was 53.4 m (CAWATERinfo, 2014). In 1985, the water volume of the Aral Sea drastically decreased to 444.6 km^3 and the water level declined to 41.9 m; meanwhile, the Aral Sea was separated into the Small Aral Sea in the north (filled by

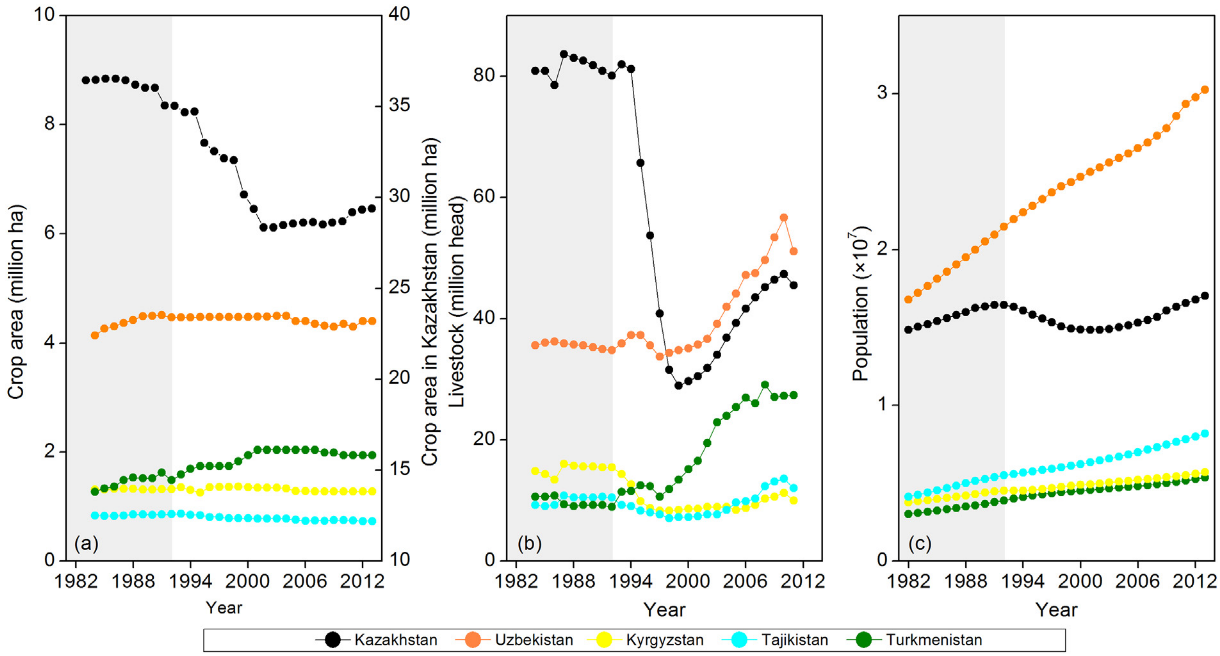

Fig. 8. Statistical time series of (a) crop area (million hectares), (b) livestock (million head) and (c) total population ($\times10^7$) in five countries of Central Asia. The data for crop area and total population were acquired from World Bank (2016). The data for livestock number were obtained from FAO (2017).

the Syr river) and the Big Aral Sea in the south (filled by the Amu river). The water volume of the Small Aral Sea was much less (<20km^3) than that of Big Aral Sea (about 400.0 km^3) (CAWATERinfo, 2014). Our study also revealed the early turning point of $NDVI_{res}$ occurred in 1980s in the Aral Sea Basin. The shrinking of the Aral Sea led to highly adverse social, economic and environmental consequences in the region, which will be further discussed in Section 4.2.

4.2. Socioeconomic impacts on vegetation productivity after the Soviet Union collapse

There were several major changes in socioeconomic activity between the Soviet period and the post-Soviet period. Land conversion was the most notable activity after the Soviet collapse, including the abandonment of croplands in northern Kazakhstan, irrigated land abandonment in eastern Kazakhstan, and irrigation expansion in major basins. The collapse of the Soviet Union in 1992 had enormous consequences for the agriculture sector, notably with the drastic decrease or termination of subsidies to the farmers that resulted in large-scale cropland abandonment especially in regions with low productivity, and a subsequent transition of agricultural management from a state-commanded to a market-driven economy (Lioubimtseva and Henebry, 2009; Prishchepov et al., 2012). About 1.6 million people emigrated outside of Kazakhstan in 1991–2000 because of reduced profitability of farming and insecure land tenure, and consequently, vast areas of ploughed land in Kazakhstan were abandoned. We found that there were significant turning points around 1992–1996 in rainfed croplands of northern Kazakhstan and irrigated cropland of the Ili-Balkhash basin, most of which transitioned from positive to negative impacts due to the cropland abandonments. Similarly, several studies also found significant changes in vegetation productivity (Zhou et al., 2015) and phenology (de Beurs and Henebry, 2004; Kariyeva and van Leeuwen, 2012) after the collapse of the Soviet Union. As a result of this transition, the crop area in Kazakhstan decreased from 36.0 million ha to 30.1 million ha from 1990 to 2000, grain production dropped from 23.4 to 10.7 million tons, and the number of livestock declined from 48.6 to 14.5 million heads (ARKS, 2016; World Bank, 2016). Local people tended to gain lower agricultural income than before, and the contribution of agriculture to the nation's total GDP decreased from 26.7% in 1992 to only 8.7% in 2000 in Kazakhstan (World Bank, 2016). Overall, our results revealed the spatiotemporal pattern of reduced vegetation productivity due to the land abandonment and population migration along with the institutional change. We also found a significant increasing trend in $NDVI_{res}$ but mostly $NDVI_{res}$ was still negative during 2008–2015 for the entire North Kazakhstan region, which was associated with population resurgence and a return to cultivation of the land (cropland increased 3763.9 thousand hectares from 2003 to 2010; ARKS, 2016). Although the potential of re-cultivation of abandoned croplands remains controversial (Lambin et al., 2013 vs. Kraemer et al., 2015), our study proved that current land management can potentially improve vegetation productivity in this area. Farmland abandonment in global dryland regions not only results from socioeconomic factors such as policy change and population migration, but also lies in the change of environmental factors such as water availability and soil quality (Benayas et al., 2007). The farmland abandonment in Central Asia led to significant negative transitions in vegetation productivity in both former rainfed and irrigated lands, but these lands still have a chance to restore with adequate and sustainable investments in land management (e.g., re-cultivation in the North Kazakhstan region).

The other notable land conversion during the post-Soviet period was the expansion of irrigated croplands. In the Amu Darya and Syr Darya Basins, the Soviet Union government installed vast irrigation schemes to support state-run Soviet collective farms by withdrawing water from upstream rivers. With the collapse of the Soviet Union, however, these integrated systems had to be shared among the resulting independent countries. The drastic increase of population in countries of Central Asia (except for Kazakhstan; Fig. 8(c)) substantially increased the demand for crop areas and yield, leading to the increase in crop area from 1.48 million ha in 1992 to 2.04 million ha in 2002 in Turkmenistan (World Bank, 2016). The consequential mismatch between water supply and crop patterns in the downstream countries caused an increasing number of water-related disputes. We found that socioeconomic activities had more positive impacts on vegetation productivity in the post-transition period than in the pre-transition period in the upstream areas, while the opposite pattern was observed for the downstream areas. There are over 20 major dams in the upstream countries, i.e. Kyrgyzstan and Tajikistan, and these dams and reservoirs were switched from balancing water usage between agriculture and energy sectors to favoring exclusive usage for energy generation after the Soviet collapse (Severskiy, 2004). The shift led to reduced river flows downstream in the summer and increased flows in the winter (CAWATERinfo, 2014), significantly altering the downstream runoff regime. Moreover, the irrigation system was often poorly maintained but had to serve thousands of individual farms downstream. This likely led to the negative $NDVI_{res}$ values for irrigated croplands in the downstream regions in the post-TP period. Moreover, the irrigation legacy from the Soviet period also contributed to the negative impacts after the turning points. For example, the water flows that intensively interacted with irrigated lands return to the main river by carrying salt and agricultural chemicals. The expanded and exacerbated salinization in the Amu Darya and Syr Darya Basin were irreversible and led to negative impacts on vegetation productivity (Funakawa et al., 1998; Toderich et al., 2004; Alibekov and Alibekov, 2008; Lioubimtseva and Henebry, 2009). The increase of water usage for socioeconomic activity, exacerbated salinization and aggravated aridity resulted in the break-up of the Big Aral Sea into Eastern Sea and Western Sea in 2006, and the Eastern Sea almost disappeared (<1 km^3) in 2014 (CAWATERinfo, 2014). As the continuous rise in temperature increases evapotranspiration in Central Asia, the shortage of water resources and aridity is expected to be intensified (IPCC, 2007; Mannig et al., 2013). Several studies also proved that the expansion of global dryland accelerated under climate change (Feng and Fu, 2013; Huang et al., 2016), and the climatic warming would be more intense in the future drylands (Hulme, 1996; Huang et al., 2017). Sustainable development and management of water network are suggested for future dryland restoration. Additionally, countries that share water resources from transboundary rivers should seek opportunities to collaborate in water management. Our study pointed out the importance of collaboration among upstream, midstream, and downstream regions.

Aside from significant negative impacts on most downstream areas after the turning point, we found positive $NDVI_{res}$ in some downstream areas in Uzbekistan. de Beurs et al. (2015) reported changes in crop patterns in formerly irrigated regions of Uzbekistan and Turkmenistan in the south of the Aral Sea. Over the last two decades, winter wheat production has significantly increased to alleviate food security and has partially displaced cotton (Dukhovny and Sokolov, 2003). The area harvested for wheat in Uzbekistan was only 38% of the area harvested for cotton in 1992 but exceeded 100% in 2013 (FAO, 2016). Wheat production first exceeded cotton production in 1998 and has since varied between 100% and 204% with a distinct increasing trend (FAO, 2016). Winter wheat is typically planted in the fall and harvested in early spring, while cotton primarily grows in the hot summer season when water resource is less abundant compared to other seasons in the downstream areas. Moreover, water demand is significantly lower for winter wheat than for cotton. Therefore, FAO (2016) records show a decrease in agricultural water withdrawal in Uzbekistan from 54.37×10^9 m^3 in 1994 and 54.78×10^9 m^3 in 2001 to 50.4×10^9 m^3 in 2005. To alleviate the water shortage impact on vegetation productivity in dryland regions, Burton and Lim (2005) suggested a change in cropping pattern (e.g., planting of drought-resistant or fast-maturing crops) could be a future management direction to make local farming adapted to climate change. Our results further proved that a change in cropping types can not only increase vegetation productivity but also alleviate local water shortage in the Central Asia dryland.

Similarly, irrigated cropland had shrunk in the Ili-Balkhash Basin in the post-Soviet period compared to that in the Soviet period. Agricultural water withdrawal in Kazakhstan decreased from 27.4×10^9 m^3 (27.4% of total water withdrawal) in 1995 to 14.0×10^9 m^3 (14.0% of total water withdrawal) in 2010 (FAO, 2016); meanwhile, the crop area equipped for irrigation decreased from 3.56×10^6 ha in 1993 to 2.07×10^6 ha in 2010 (World Bank, 2016). The decreasing agricultural water withdrawal would potentially alleviate water shortage, and the resulting increase in water availability likely led to the positive transition in $NDVI_{res}$ mean in the southern basin. Unlike most regions in Kazakhstan, East Kazakhstan experienced a steady population decrease from 1.53 million in 1999 to 1.39 million in 2013 (ARKS, 2016). Our results also indicated the positive transition in $NDVI_{res}$ mean and trend in the northern basin. The pastures of the mountain steppes and meadows in the northern basin (Altai and Tien Shan mountains) were used for transhumance of cattle in summer. The main pastures are located mainly in the steppes of high mountains and to a lesser extent in low and medium-high mountains (Rachkovskaya and Bragina, 2012). Kazakhstan pastoralists formerly followed short-distance migration with stipend supported by the Soviet government (Coughenour et al., 2008). However, almost all livestock in Kazakhstan was owned privately by rural people after the Soviet disintegration. Most pastoralists could not afford seasonal migrations, and these small-scale livestock owners were forced to graze their animals within a 5-km radius from their villages (Coughenour et al., 2008). The restricted grazing and decreased population led to a decrease in grazing pressure on rangeland, providing the opportunity of pasture regrowth and the increase of soil C and N sequestration (Bi et al., 2018), which is consistent with our results. However, moderate to extensive pastoralism accounts for 51% of global dryland areas (Koohafkan, 2012) and overgrazing is one of the most important factors contributing to land desertification (Darkoh, 1998). The reduction of grazing pressure, for example, by fencing and supplemental feeding, is an important component of future dryland management.

4.3. Challenges and limitations

Remotely sensed data are able to provide invaluable resources for long-term analysis of vegetation dynamics, especially for areas such as Central Asia with difficulty in getting continuous and reliable long-term statistical data. Advances to the ResTREND approach presented here sought to isolate impacts of human factors on vegetation from climate impacts and generally captured the transitions of socioeconomic impacts on vegetation productivity at both pixel and regional scales. However, human activities have the potential in impacting the regional climate in Central Asia (Lioubimtseva and Cole, 2006), and it is impossible to perfectly disentangle the human factors from climate variations. The method proposed in this paper is expected to remove the general climatic impact on vegetation productivity. However, this ResTREND method has limitations. Firstly, impacts of natural disturbances such as wildfire and insect outbreak are difficult to be separated from land use effects. Climate extremes, such as drought, present another challenge by falling outside the range of normal climate controls and thus at risk of failing to be fully removed by this method. In fact, de Beurs et al. (2015) reported that an intensive drought occurred in the region during 2001–2013 particularly to the north of the Caspian Sea and the Aral Sea. The rapidly decreasing trend of $NDVI_{res}$ in these regions likely resulted from a combination of intensive drought and agricultural abandonment. Secondly, most mountainous regions in Central Asia experienced increases in $NDVI_{res}$ in both pre- and post-TP periods. In addition to water management and less grazing pressure, the increased $NDVI_{res}$ could also be attributed to the degradation and melting of glaciers in mountainous areas in Altai and Tien Shan (Sorg et al., 2012). The steady increase in atmospheric CO_2 concentration (Lioubimtseva and Cole, 2006; Cao et al., 2017) and water discharge from glacial runoff (Sorg et al., 2012) in mountainous regions jointly contributed to the positive trend in $NDVI_{res}$, but they were not included in our climatic factors because the long-term and spatially explicit datasets are unavailable.

5. Conclusions

Our study used the modified ResTREND algorithm to evaluate vegetation responses to institutional and socioeconomic changes in Central Asia in 1982–2015. We found that 45.7% of the vegetated areas experienced significant transitions in $NDVI_{res}$ ($p < 0.05$) using turning point detection based on BFAST. Most transitions occurred after 1992 when the Soviet Union collapsed, whereas the transitioning time of the Aral Sea Basin was before 1992. Pre-TP periods tended to present positive $NDVI_{res}$ (31.6% of the vegetated land) which indicates generally positive socioeconomic impacts, and 16.5% of vegetated areas experienced significant increasing trends ($p < 0.05$) in $NDVI_{res}$, potentially attributed to the Virgin Lands Campaign, such as the expansions of cultivation in the northern Kazakhstan and irrigated croplands in the Amu Darya and Syr Darya Basins, and governmental regulation of grazing and water usage. However, many areas experienced a transition to lower mean $NDVI_{res}$ with decreasing trends during post-TP periods, which indicates that institutional and socioeconomic changes suppressed vegetation productivity. Similar positive-to-negative transitions in $NDVI_{res}$ were also evident in the North Kazakhstan region due to farmland abandonment and in the downstream areas of the Amu Darya and Syr Darya Basins due to water shortage and salinization.

As the imbalanced distribution of water resources in Central Asia affected the pattern of vegetation productivity, unsustainable water regulation aggravated water shortage and endangers local food security. Our results also indicated that changes in crop types on previously irrigated lands (e.g., some downstream areas in the Amu Darya Basin) and decreases in grazing intensity (e.g., the north of the Ili-Balkhash Basin) facilitated regional ecosystem restoration. Our study revealed the spatiotemporal dynamics of the profound institutional and socioeconomic impacts on vegetation productivity in Central Asia during the recent three decades. Our findings improve the current understanding of the long-term vegetation dynamics of dryland ecosystems in Central Asia, and those positive transitions in vegetation productivity caused by human activities in the Central Asian dryland can inform future management and restoration efforts of similar dryland ecosystems.

Acknowledgments

This research was funded by the Strategic Priority Research Program of the Chinese Academy of Sciences, China [Grant No. XDA19030302], the International Partnership Program of Chinese Academy of Sciences, China [Grant No. 131C11KYSB20160061], and Major Project to Promote Development of Big Data from National Development and Reform Commission, China [Grant No. 2016-999999-65-01-000696-01]. J. X. was supported by the National Aeronautics and Space Administration (NASA) through the Carbon Cycle Science Program, United States [Grant No. NNX14AJ18G]. The authors thank the NASA Global Inventory Modeling and Mapping Studies (GIMMS) group for producing and sharing the GIMMS3g NDVI dataset. We thank the NASA for making the MERRA-2 data freely available. We thank the anonymous reviewers and the associate editor for the constructive comments on the manuscript.

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