Changes in alpine water storages in central Asia and land surface degradation in Amu Dar'ya River basin

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Preamble

This research focuses on modeling and predicting environmental, social, and economic consequences of snow/glacier water resources loss on land degradation and agricultural resources in Amu Dar'ya River (Aral Sea Basin) by integrating NASA Remote Sensing products and in situ long-term terrestrial data.

Amu Dar'ya River originates in the Pamir mountains (Tajikistan) (**Fig. 1**), providing 65% of inflow to the Aral Sea supporting agriculture in dry land areas populated by over 60 million people (Tajikistan, Uzbekistan and Afghanistan. Amu Dar'ya R. Basin is characterized by complex social and economic problems ensuing from extensive resource consumption and natural responses to global climate change.

However, snow cover and glaciers are shrinking in Pamir. In some Amu Dar'ya alpine basins glaciers have lost more than 14% their area during the last 30 years and glaciers with area less than 2 km^2 have disappeared entirely (*Aizen et al, 2011a,b,c*). In the last two decades Amu Dar'ya R. lover reaches oases began suffering from serious multi-year droughts while river runoff increased at upper and middle river reaches due to intensive glacier melt and spring-summer increase of precipitation. Current glacial recession in mountainous regions, while initially is considered as a positive factor that increases the rivers flow, further it will cause runoff to decrease which may create serious economical and transboundary water problems in Central Asia.

Data, Methods, and Products

http://www.asiacryoweb.org/wiki/bin/view/Home/WebHome (**Fig. 2**)

***AsiaCryoWeb Data Base* – is an open source science project devoted to international collaborative studies of snow and ice in mid- low- latitude mountains of Asia created and launched on a Twiki Web 2.0 platform in December 2010**.

AsiaCryoWEb enables flexible storage and search of information in different file formats without a preexisting database scheme as in typical Relational Database Management System (RDBMS**).** Data and products that has been collected and developed during NASA and NSF sponsored projects downloaded and in process of download into the AsiaCryoWeb.

To evaluate ***climatic changes*** in Pamir and Amu Darya R. Basin, we decided to analyzed climate over the entire territory of central Asia to understand the regional scale climate impact. We used meteorological data from 252 stations spanning 35.28°-50.25° N and 50.4°-91.98°E and from -134 m. b.s.l. to 4,169 m. a.s.l. (**Fig. 1, 3**) (*Aizen et al., 2011a,b,c*). The longest period of observation was from 1885 to the present, but the number of stations with these long-term data was limited therefore, we used only those stations with homogeneous data for two basic periods: before and after 1972, e.g., 1942-1972 and 1973-2008, the year after which abrupt climatic changes and the acceleration of central Asia glacier recession were observed. To generate continuous spatial fields for the calculated climatic characteristics, we evaluated two commonly used methods for spatial interpolation of precipitation and temperature: GWR and Spline with Tension (ST) (*Hofierka et al., 2002*). GWR is a spatial extension of a classical regression model of the dependence of climatic characteristics on altitude. The GWR model assumes non-stationary conditions by varying the intercept and lapse over space.

Two ***glacier area change (Fig. 4a)*** inventories for the 1960s and 2000s were developed for Altai-Sayan, Tien Shan and Pamir mountain systems using declassified high resolution Corona/Hexagon KH-9 photographs and Landsat ETM+/ASTER images. All images were co-registered using GCPs collected in field and from Quickbird (Google Earth™) high resolution imagery and orthorectified using the DEMs of the Altai, Pamir, and Tien Shan mountain area at 100 m resolution was developed using SRTM, Corona, ASTER and ALOS Prism data (*Aizen et al., 2006a,b; Surazakov et al., 2006; Surazakov & Aizen, 2010; Aizen et al., 2011a,b,c*). The ***glacier ice volume change*** between 1973 and 2009 was calculated for the Fedchenko Glacier in Pamir (the World's largest alpine glacier, 649 km^2, 77 km long), central Altai glaciers, and Inylchek Glacier in Tien Shan (the second large CA alpine glacier, 567 km^2, 59 km long) using two DEMs computed from KH-9 (1973) and ALOS Prism (2009) (**Fig.4b,c,d**).

Snow cover data (*Zhou and Aizen, 2011; Aizen et al., 2011d*) over all central Asia territory were generated from AVHRR (1978-2009) and MODIS (2000-2009). A new 8-day dataset from AVHRR LAC and HRPT images was developed using the SAPS software, which was originally developed at Canadian Centre for Remote Sensing (*Khlopenkov and Trischenko, 2007; Latifovic, et al. 2005*). The SAPS system imported the AVHRR data, calibrated each band using most up to date methods, and performed geometric correction and georeference with subpixel accuracy. A pixel scene identification procedure is implemented in SAPS to provide mask of cloud, clear sky, cloud shadow, snow, and ice. Daily clear-sky composite AVHRR images were generated using SAPS. Daily AVHRR snow cover maps in 1km resolution were compared with 30m resolution LANDSAT imageries, which serve as the 'ad-hoc ground truth' in the comparison. The results suggest that the daily AVHRR snow cover maps show good overall correspondence with snow cover maps derived from same day LANDSAT images, with an overall accuracy of

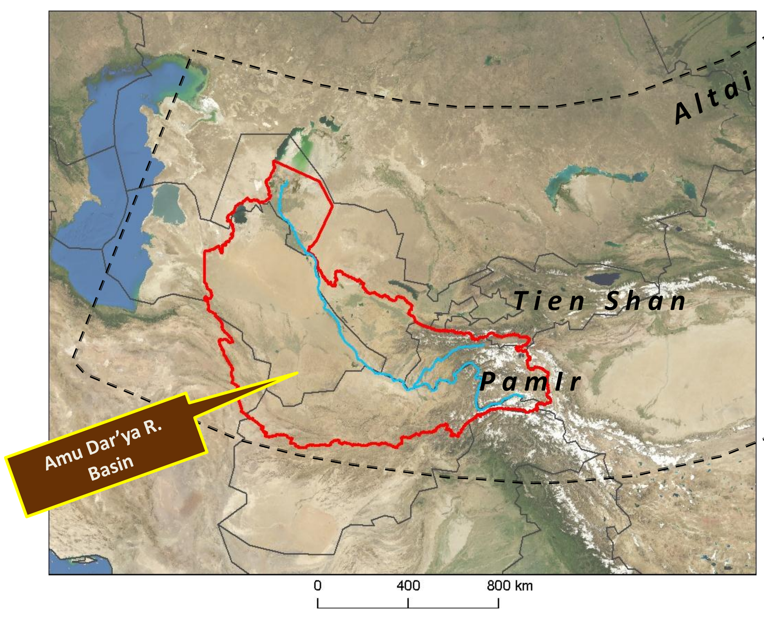

Fig. 1. Central Asia map. Area of interest and research countered by dotted line and the Amu Dar'ya R. basin by solid red line.

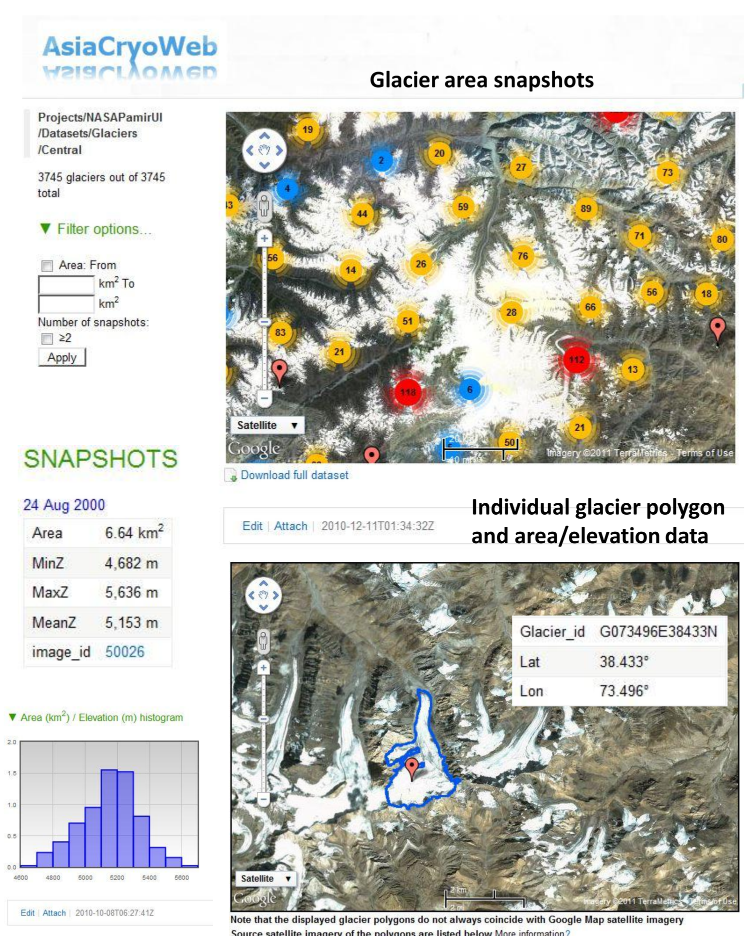

Fig. 2. Online glacier data base at AsiaCryoWeb, is developing at the University of Idaho on a Twiki 2.0 Platform.

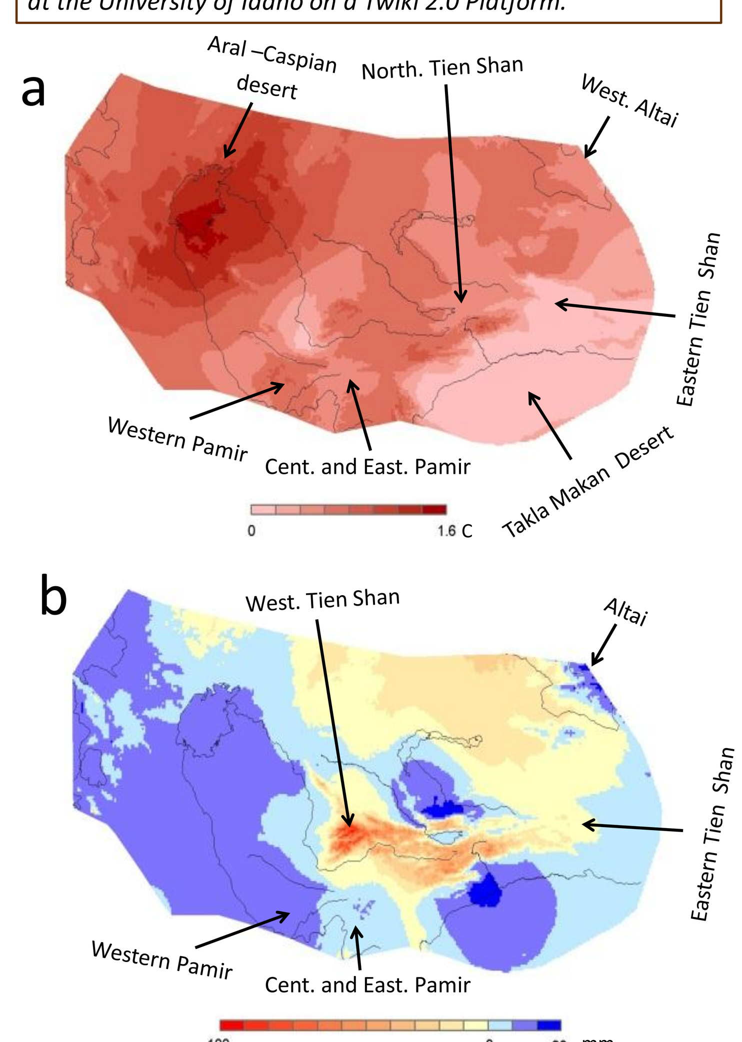

Fig. 3: (a) Differences in 30-year averages (1942-1972 and 1973-2008) of summer mean air temperatures ($dT_s = aveT_{s1973\text{-}2008} - aveT_{s1942\text{-}1972}$) over central Asia; (b) Differences in 30-year averages of annual precipitation ($dP_{an} = aveP_{an1973\text{-}2008} - aveP_{an1942\text{-}1972}$) over central Asia in mm computed using observational data from 252 meteorological stations.

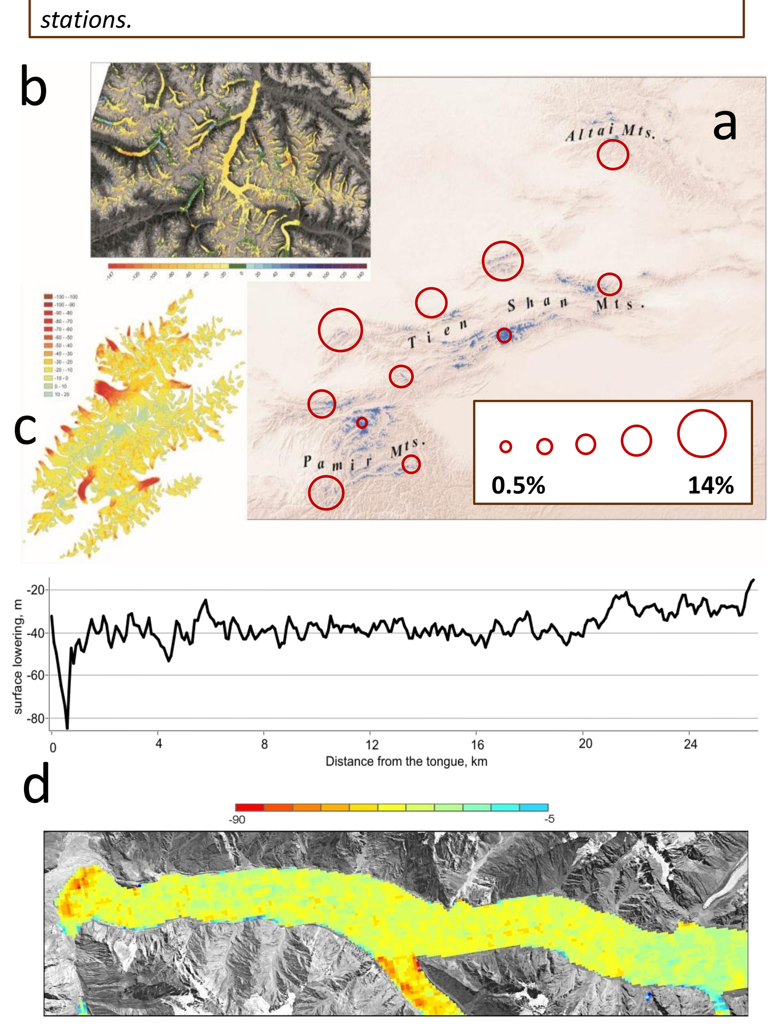

Fig. 4. (a) Glacier area changes in Altai, Pamir and Tien Shan mountains during last 30 years in % determined by KH-9, Landsat, and Aster data and, c) glacier surface (ice-thickness) reduction for the same period in central Pamir (b), and (c) central Tien Shan determined by KH-9 (1973) and ALOS Prism (2009), (d) the Fedchenko Glacier surface lowered up to 90 m.

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0.92. Another comparison has been done between daily AVHRR snow cover and daily MODIS snow cover maps in 500m over Amu Darya R. basin (**Fig. 5 b**). The overall accuracy is 0.98, with an omission error for snow at 0.19 and a commission error for snow at 0.11.

Vegetation index/NDVI: (*Aizen et al., 2011e*) developed using AVHRR images and SAPS extending the existing 2000-2009 MODIS NDVI time series (MOD13A2 V005) back to 1980 and a new NDVI developed dataset for central Asia from 1 km AVHRR LAC and HRPT images. The accuracy of AVHRR derived NDVI values was compared with concurrent MODIS NDVI products. In addition, the MODIS 16 day NDVI series in 500m resolution and 16 day NDVI composite series with 1km resolution were developed from AVHRR using SAPS. Comparison of MODIS and AVHRR datasets for the same day confirmed high accuracy (r=0.93) of the AVHRR NDVI composites. Compared with SRTM water bodies data (downloaded from USGS EROS Data Center), both datasets were spatially consistent. Using MODIS NDVI and AVHRR NDVI time series, we classified ***land cover/land use*** in Amu Dar'ya R. basin according to the shape of their phenological cycle (NDVI cycle) (**Fig. 6,7,8).** The NDVI time series for each pixel were analyzed using harmonic analysis of time series (*Roerink et al., 2000*).

Results

Climate (*Aizen et al.,2006a; 2007a; 2011b,c*). Central Asia has experienced an accelerated increase in air temperatures with maximum in the Aral Caspian deserts and Kazakhstan steppes (up to 1°C) for the last three decades. The most significant increase of air temperature occurred in summer in all central Asia regions (**Fig. 3a**).

The average annual precipitation did not change significantly throughout central Asia, increasing only 0.9% but its spatial distribution has changed (**Fig. 3b**). Increase of summer precipitation occurred at the northern and eastern Tien Shan, western Altai foothills, and Eastern Pamir alpine area. Significant deficit in winter precipitation occurred all over central Asian alpine areas, which reduce amount of snow accumulation, accelerate seasonal snow melt and intensify glacier degradation. Tien Shan alpine areas particularly undergone deficit in precipitation through all seasons during the last three decades. Excess of annual precipitation (20-30 mm) in Takla Makan and Aral Caspian deserts do not contribute to regional hydrology. Thus, current climatic conditions are not favorable for central Asian alpine cryosphere and future water resources projection.

Glacier covered area. During the last three decade the rate of glacier covered area loss almost doubled (*Aizen et al., 2006; 2007a,b; 2009; 2011b; Surazakov and Aizen, 2006; 2010a, 2011a,b)* (**Fig. 4a**): Altai -85 km^2 (6.2%); Tien Shan -709 km^2 (8.5%); and Pamir -615 km^2 (5%), which is twice the loss that occurred between 1940s and 1970s (*Aizen et al., 2007*). However, the rate of glacier recession is varying. Maximum recession occurred in the northern and western Tien Shan, and in south-western Pamir (up to 14.3%). Over 20% of small glaciers (<2 km^2) disappeared between 1970s and 2000s. The number of medium (2.1 – 10.0 km^2) and large glaciers (over 100 km^2) remained stable. At the same time glaciers in Tien Shan and Pamir loss 15 to 27% of their volume that increasingly defines the problem of water resources of Central Asia (**Fig.4b,c,d**).

Seasonal snow covered area. For the last three decade, total sum of daily snow covered areas has a negative trend of -1.7% yr^{-1} in central Asia mountains. Maximum snow covered area reduction observed at the end of May and beginning of June at elevations over 3000 m a.s.l. in Tien Shan and Pamir. There was a decrease in annual maximum Snow Covered Area (SCAmax) with a trend of -2.7% yr^{-1}. Snow cover appearance 9 days later at the end of November in Amu Dar'ya R. basin and disappeared in early June (**Fig. 5a,b**) . The duration of snowmelt has been reduced by 18 days in Pamir and 30 days in Tien Shan mountains. A negative trend was observed in the autumn and in the middle of March (*Aizen et. al, 2011c; Hang and Aizen, 2011*) .

Vegetation (*Aizen et al., 2011c*). The 1980s – 2000s AVHRR/MODIS NDVI time series analysis (**Fig. 6**) present significant changes in the area of irrigated lands and intensity of agriculture in Amu Darya R. middle and low reaches. The total area of irrigated lands has decreased by 18%, mostly due to the progressive droughts and desertification. However, there is a positive trend in NDVImax in the last decades, correlated with small increase of spring-summer precipitation at the Amu Darya R. basin lower reaches. Another explanation of the increase in NDVI in Amu Dar'ya low reaches during the last decades is the accelerated growth of biogenic crusts (*microphytic* communities formed by desiccation-tolerant mosses, fungi, algae, and cyanobacteria) in deserts and semi-desert landscapes (*Lioubimtseva, 2007).* In the upper and middle reaches of Amu Dar'ya R. basin, where water is abundant all summer, switch to double cropping occurred in most existing agricultural areas since 1991, which maybe explained by rural restructurization during the civil war in 1990s and afterward when local agriculture became more vital for small mountain communities. Consequently, water use at foothills and middle river reaches increased and compensated by intensive glacier melt runoff.

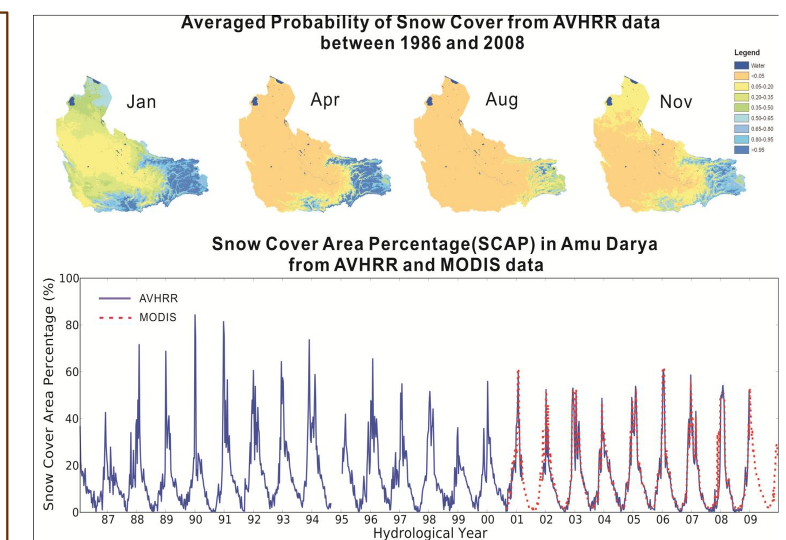

Fig. 5. a) averaged monthly probability of snow derived from AVHRR data (1986-2008), Amu Darya R. basin, Pamir, b) snow covered area annual variability computed from the MODIS 8-day cloud free data and AVHRR 8-day cloud free data using AVTREE and SAFNWC algorithms.

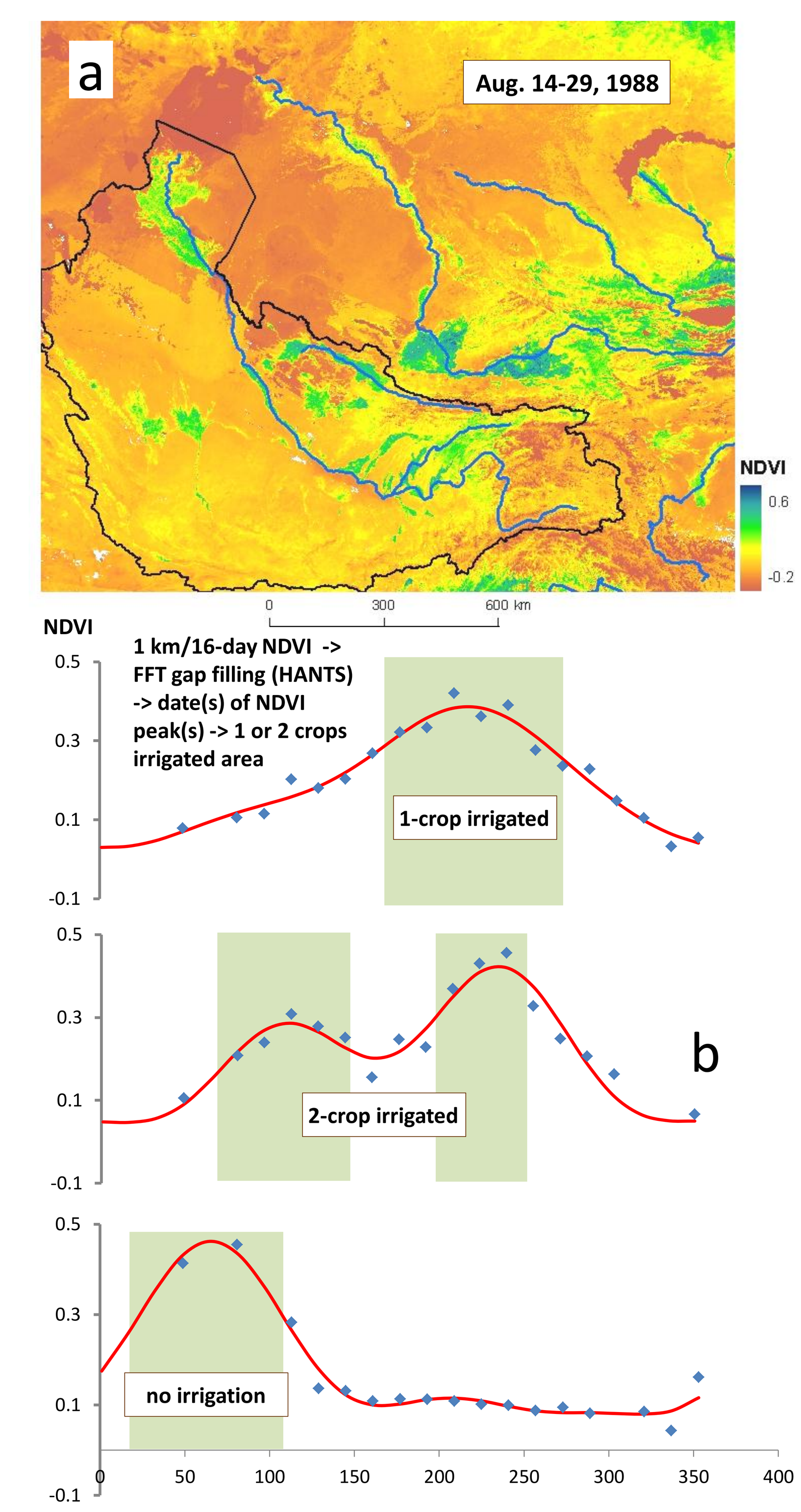

Fig. 6. Land surface phenology analysis: (a) NDVI on irrigated lands in late summer in central Asia, (b) original 16-day NDVI filtered values (blue dots) using Fourier Fast Transform (HANTS approach) (red line) and extracted the dates of NDVI peaks (green bars). Timing and number of NDVI peaks provide crucial link for identification of irrigated lands, because in the semi-arid and arid climate of central Asia non-irrigated vegetation rapidly decline after short spring greening.

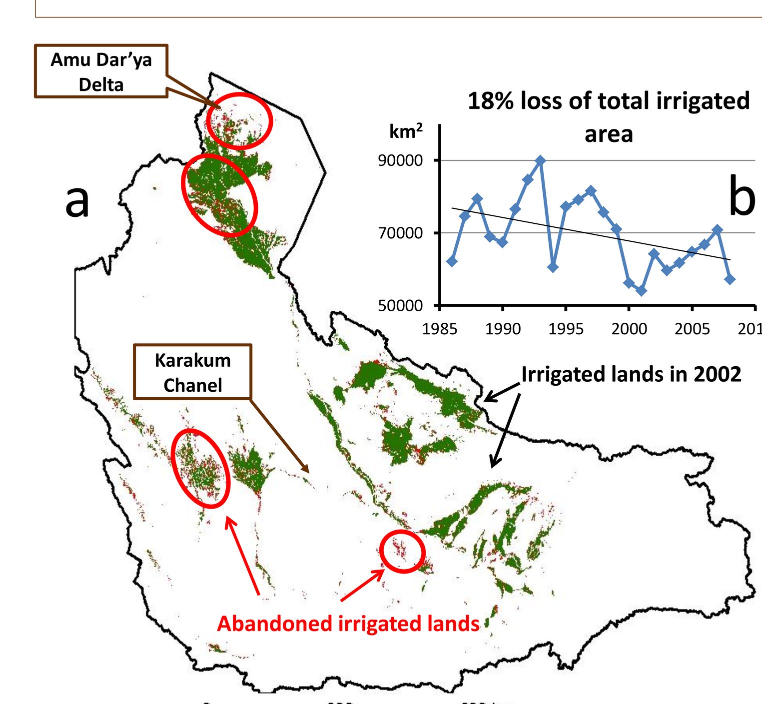

Fig. 7. Loss irrigated lands in 1986-2009: (a) an example of derived irrigated lands extent (green color) for 2002, (b) strong intra-annual variations due to droughts or availability of water for irrigation (long-term trend of land degradation).

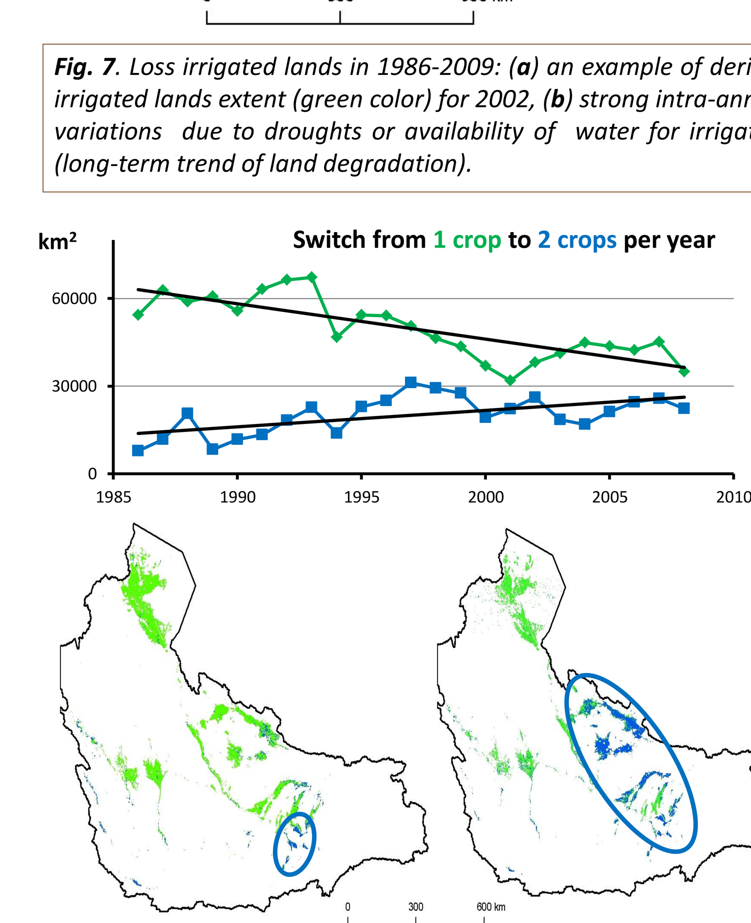

Fig. 8. Switch from one crop to two crops per year with significant increase irrigation intensity at mountain foothills in middle river reaches where water is abundant due to increasing glacier melt and spring summer precipitation.