Alarming rise in aridity in the Ganga river basin, India, in past 3.5 decades

The Indian Ganga river basin (IGRB) is one of the most fertile and densely populated river basins in the world. Spread over 844,247 sq. km, the IGRB is mostly covered by agricultural land and deciduous vegetation. The basin is experiencing the cascading effects of human interference and climate change, leading to vegetation loss, soil degradation and expansion in mining and industrial activities. Aridity, as measured by the aridity index (AI), is projected to increase over land under climate change[1]. There is a great interest among researchers and land managers in understanding how climate change would impact aridity through the interaction of precipitation changes with rising temperatures[2]. The growing impact of aridity in IGRB is one of the most important consequences of climate change for which we are not ready yet! Most of the aridity maps available for the region are either too coarse[3] or prepared using inappropriate climatic variables[4].

The precipitation and temperature data at a resolution of 0.5° × 0.5° grids were utilized from CRU repository (www.cru.uea.ac.uk), to calculate the AI[5,6]

$$AI = 100 \times T/P,$$

where T stands for annual mean temperature in °C and P is the annual sum of rainfall in millimeter. Here AI < 2 corresponds to dry sub-humid, AI 2–3 characterizes a semi-arid area, AI 3–6 characterizes an arid area and AI > 6 refers to extremely arid or desert land. A simple rationing of rainfall and temperature was done using the averaged value for the years 1940–1975 and 1975–2010. Both the AI maps are shown as colour-filled and isohyets corresponding to the period of 1975 and 2010 respectively (Figure 1 *a*). Further, 35-years aridity anomaly was calculated by utilizing the 1975 and 2010 AI maps on the basis of 'pixel to pixel deviation' (Figure 1 *b*). We linked Landsat images of the year 1975 (MSS sensor) and 2010 (ETM+ sensor) period and trawled to visualize the long-term changes in vegetation loss, soil degradation and expansion in mining and industrial activities in the region, and generated image chips of the areas corresponding to very high aridity anomaly (Figure 2).

We observed decreasing pattern of AI from southwest to northeast in IGRB (Figure 1 *a*). Further, the range changes during the past 35 years are alarming, i.e. dry sub-humid to semi-arid, semi-arid to arid and arid to hyper-arid. We observed a maximum anomaly of 2.8 in aridity with epicentre in three pockets (i.e. western Great Indian desert, northern Aravalli range and western Chota Nagpur plateau), whereas 36 districts were possessing above 2 AI anomaly over the past 3.5 decades (Figure 1 *b*). The northern and the eastern tips showed minimal shift in aridity.

In the western Great Indian desert, many natural land covers have been vanished leading to regime shift. For example, in 1975, *Anogeissus pendula* forest was reported in Jaipur and adjoining upland areas[7], whereas in 2010, only a few sparsely distributed *A. pendula* trees were found. While in the lowlands, dense *A. pendula* forest was entirely replaced by agricultural crops. Similarly, a dense forest of tall *A. pendula* tree was observed in 1975 in the Alwar district of Rajasthan, has been reduced to scrubs in 2010 (Figure 2 *a*).

Long-term change in inherent and dynamic qualities of soil has accelerated the land degradation in many regions throughout the IGRB[8]. Construction of

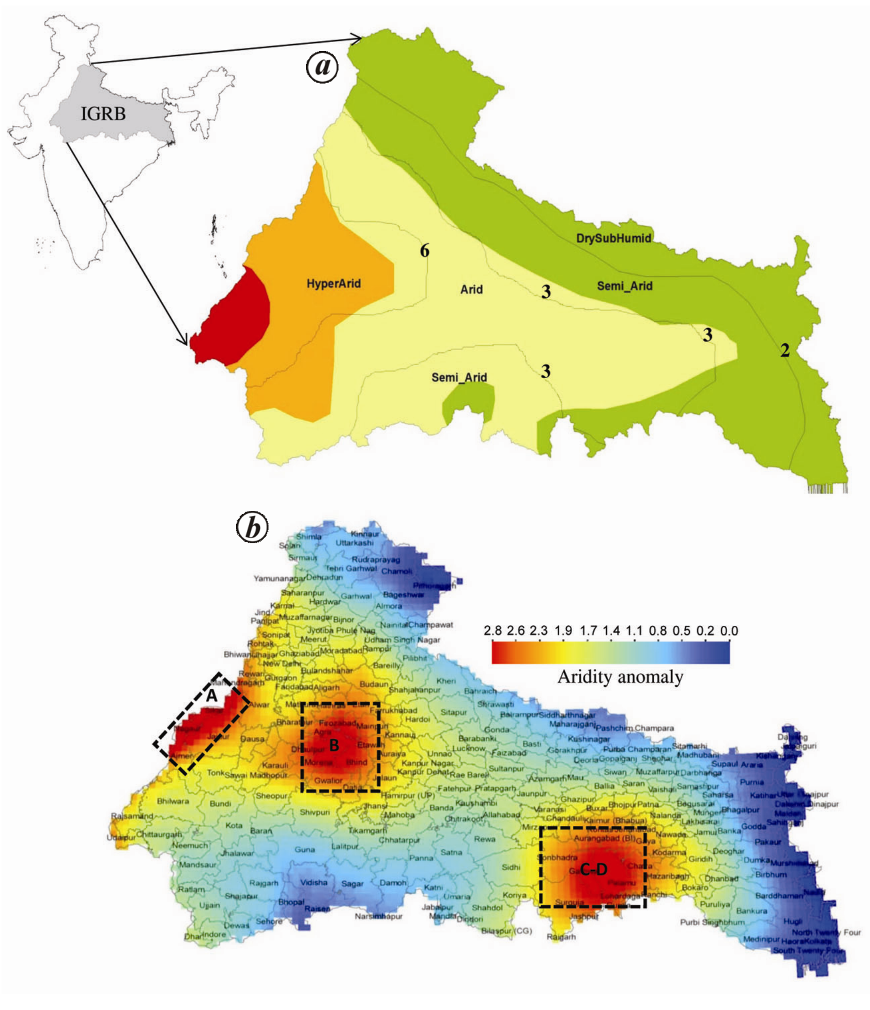

Figure 1. ***a***, Aridity index maps of 1975 and 2010 are shown as colour-filled and isohyets (shown) respectively. ***b***, Aridity anomaly during 1975 and 2010 in Ganga River Basin, India; District boundaries and names overlaid for reference. Maximum aridity anomaly of 2.8 is seen in 3-pockets (i.e. western Great Indian desert, northern Aravalli range and western Chota Nagpur plateau). Image chips for the corresponding boxes can be seen in Figure 2.

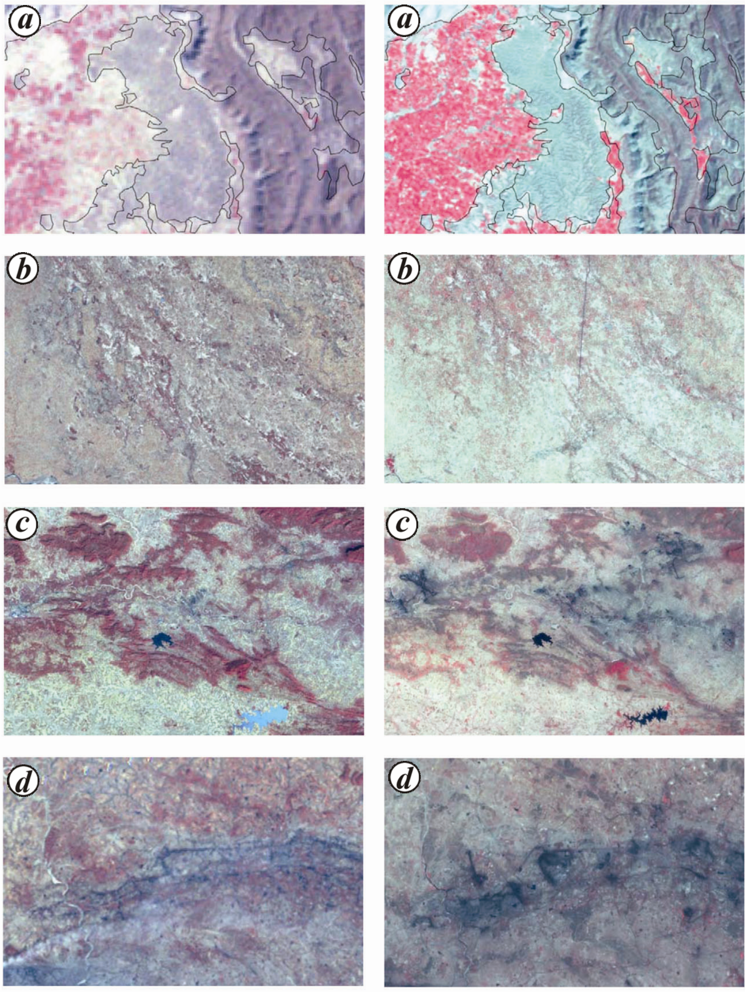

Figure 2. Satellite images showing long-term changes observed during 1975 (left panel) to 2010 (right panel). ***a***, Large scale deforestation for agricultural expansion around Alwar; ***b***, Increase in soil salinity leading to formation of Usar lands around Firozabad; ***c***, Large scale open-cast mining activities around Chatra; ***d***, Expansion of mining and industrial activities around Bokaro.

dams and canals to provide agricultural infrastructure to farmers under Green Revolution initiatives (1967–1978) and later over-exploitation of these resources along with poor land management practices have resulted in diminishing of soil fertility in IGRB. Concurrently, soil salinity and sodicity have also increased rapidly in the region[9]. On comparing the satellite images of 1975 and 2010 using visual interpretation technique, we observed that canal network has increased in the region, leading to formation of sodic soil. This is evident in Figure 2 *b*, where agricultural and fallow land were converted into a white sheath of sodic land.

Expansion of open-cast mining for coal and other minerals was observed in many parts of Jharkhand, West Bengal and Bihar (Figure 2 *c*, *d*). Land resource extraction, such as mining in natural land cover or near to the forest has resulted in a loss of about 0.3 million ha of forest cover in Jharkhand alone between the year 1977 and 2015 (ref. 10). Deforestation, land degradation and industrial emission could have contributed to the alarming rise in aridity in the region. Chatra and Dhanbad districts in Jharkhand are well-known for coal mining, and the extraction has tremendously increased over the past few decades (Figure 2 *c*). Heavy-steel and iron industries of Durgapur and Bokaro in the western Chota Nagpur plateau have contributed to the alarming increase in aridity in these regions (Figure 2 *d*).

Using temperature and precipitation data of 1950–2006, Behera *et al.*[11] calculated one-time period aridity map of India along a 3° longitudinal stretch across the 'tropic of cancer'. However, they could not bring out the anomaly of aridity change. The present analysis clearly elucidated the emergence of 3-pockets of the alarming increase in aridity that could cause other cascading impacts in future, including encroachment of more lands under 'desert', thereby making nearly unfit for human use. Satellite-based images provide vital visual evidence, and thus useful for long-term change detection studies.

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