

Surface albedo decreases from anthropogenic impacts over High Mountain Asia with implications of positive radiative forcing feedbacks

Fadji Zaoua Maina (✉ fadjizaoua.maina@nasa.gov)

Goddard Space Flight Center

Sujay V. Kumar

Goddard Space Flight Center

Chandana Gangodagamage

Goddard Space Flight Center

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1 **Surface albedo decreases from anthropogenic impacts over High Mountain**

2 **Asia with implications of positive radiative forcing feedbacks**

3 Fadji Z. Maina^{1,2*}, Sujay V. Kumar¹, Chandana Gangodagamage¹

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5 ¹ NASA Goddard Space Flight Center, Hydrological Sciences Laboratory, Greenbelt, Maryland,
6 USA

7 ² University of Maryland, Baltimore County, Goddard Earth Sciences Technology and Research
8 Studies and Investigations, Baltimore, Maryland, USA

9

10 *Corresponding Author: fadjizaouna.maina@nasa.gov

11 **Abstract**

12 Human and climate induced land surface changes resulting from irrigation, snow cover
13 decreases, and greening impact the radiative forcing by changing the surface albedo. Here we use
14 a partial information decomposition approach and remote sensing data to quantify the effects of
15 the changes in leaf area index, soil moisture, and snow cover on the surface albedo in High
16 Mountain Asia (HMA), home to over a billion people, from 2003 to 2020. The study establishes
17 strong evidence of anthropogenic agricultural water use over irrigated lands (e.g., Ganges-
18 Brahmaputra) which causes the highest surface albedo decreases ($\leq 1\%/year$). Greening and
19 decreased snow cover from warming also drive changes in visible and near-infrared surface albedo
20 in different areas of HMA. The significant role of human management and human-induced
21 greening in influencing albedo suggests the potential of a positive feedback cycle where albedo
22 decreases lead to increased evaporative demand and increased stress on water resources.

23 **1. Introduction**

24 Surface albedo, the ratio of the solar radiation reflected from the Earth's surface to the solar
25 radiation incident upon it, is an essential variable determining the energy balance at the land
26 surface^{1,2}, in turn influencing local and global climates. A decrease in surface albedo gives rise to
27 a positive radiative forcing, which can counterbalance the negative radiative forcing created by
28 carbon sequestration³ and promote surface warming. Surface albedo also has an influence on the
29 fraction of energy transformed into sensible and latent heat fluxes⁴⁻⁶. Variations of surface albedo
30 are driven by the changes of Earth surface (vegetation, snow coverage, soil moisture, etc.), the
31 solar illumination, and the zenith angle⁷⁻¹². Also, vegetation phenology and seasonality of
32 climate^{13,14} exert influences on the albedo changes at longer timescales. Consequently, natural
33 disturbances such as warming and human activities such as deforestation and irrigation could alter

34 the surface albedo¹⁵, often larger than the biogeophysical mechanisms acting on the radiation
35 budgets at both surface and atmospheric levels^{16–20}. Therefore, quantifying the drivers of surface
36 albedo changes can provide critical inferences on land-use change impacts on the radiative forcing.

37 High-Mountain Asia (HMA, Figure 1) covering the Tibetan Plateau and its surroundings
38 consists of densely populated hydrologic basins (e.g., Ganges-Brahmaputra and the Yangtze)
39 serving over a billion people^{30–33}. HMA basins play a critical role in sustaining the economy,
40 agriculture, and energy of around 10 countries including China, Nepal, Bangladesh, India,
41 Pakistan, and Afghanistan. Land structure heterogeneity over HMA is tremendous, with elevation
42 ranging from the sea level to the world’s highest point, different climatic conditions (westerlies
43 and monsoons), footprints of human activities, and large variations in land cover types. HMA
44 experiences strong changes of land surface characteristics caused by greening^{34,35}, decreases in
45 snow³⁰, and irrigation⁷³. Because greening changes the optical and structural properties of the
46 vegetation canopy and increases the Leaf Area Index (LAI), it affects the surface albedos^{25,36,37}.
47 Decreases in cryospheric storages resulting from warming, changes of precipitation phases, and
48 dust and black carbon deposits also contribute to surface albedo decreases^{38–40}. Lastly, significant
49 irrigation activities also influence surface albedo by decreasing ground reflectance and enhancing
50 vegetation growth.

51 Quantifying the relationships between these cryospheric and biospheric changes and the
52 surface albedo in HMA where land surface processes play a significant role in the
53 hydrodynamics^{41–43} will provide a better understanding of (1) their impacts on the climate system
54 and water resources^{44,45}, (2) the impacts of land surface changes on the radiative forcing, crucial
55 for designing climate change mitigation and adaptation strategies^{46–48}, and (3) the contributions of
56 human management to Earth’s warming and/or cooling. Even though irrigation, warming, and

57 greening are occurring at high rates in HMA, previous studies assessing surface albedo changes
58 were limited to the Tibetan Plateau^{49,50} and the Himalayas³⁹.

59 Satellite remote sensing is an essential technique for estimating surface albedo at various
60 spectral, spatial, and temporal resolutions²². Examining the broadband components of surface
61 albedo such as visible radiation (VIS) with a wavelength between 0.3 and 0.7 μm and near-infrared
62 radiation (NIR) with a wavelength between 0.7 and 5.0 μm ^{22,23} allows assessing changes in
63 different land surface and vegetation states. For example, vegetation canopies reflect a much larger
64 fraction in the NIR than in the VIS, because plant canopies scatter NIR energy^{24,25,26} whereas the
65 VIS has a stronger correlation with the soil moisture and snow cover^{19,27-29}. Here, we rely on a
66 partial information decomposition analysis with remote sensing data to quantify the impacts of
67 changes in (1) LAI, (2) soil moisture, and (3) snow cover on the black sky and white sky surface
68 albedos in VIS and NIR broadband over HMA from 2003 to 2020. We use the albedo climatology
69 provided by MODIS V006 (MCD43A3⁵¹), LAI provided by MCD15A2H Version 6 of MODIS⁵²,
70 snow cover fraction provided by MODIS MOD10CM⁵³, and soil moisture provided by the
71 European Space Agency Climate Change Initiative ESA CCI⁵⁴.

72 Based on the analysis of remote sensing datasets of surface albedo and other land surface
73 variables, this study establishes strong evidence of anthropogenic agricultural water use, with
74 implications for the development of positive radiative forcing in HMA⁷⁹. Specifically, the study
75 demonstrates that increases in soil moisture in irrigated lands (Ganges-Brahmaputra and Indus)
76 drive the highest decreases in surface albedo. Soil moisture drives the reductions in surface albedo
77 in non-irrigated lands of the Indus and the northern HMA while the declines in snow cover from
78 warming decrease surface albedos in the Tibetan Plateau. Although warming, dust, and black
79 carbon induced snow cover decreases exert an influence of the positive radiative forcing, these

80 impacts are limited to the water towers and the winter season. While greening enhances NIR and
81 decreases VIS in snow-free forests (e.g., Yangtze), in snow-covered vegetated areas (e.g.,
82 Himalayas, Amu Darya, and Hwang Ho), it increases both the VIS and the NIR. In addition to the
83 established snow albedo feedback where the reduction in surface albedo over snow-covered areas
84 leads to increased net radiation and sustained melt⁷⁵, the current study outlines another possible
85 positive feedback cycle related to surface albedo. In densely populated areas downstream of the
86 high elevation mountains, human management, and human-induced greening dominate the highest
87 decreases in surface albedo (up to 1%/year), which can lead to increases in the evaporative demand
88 and subsequent increased irrigation water use in a positive feedback cycle. The increased stress on
89 the limited water resources in this region from such impacts is a significant concern. These
90 anthropogenic amplifications should be accounted for in climate modeling studies and in designing
91 mitigation strategies for managing the impacts on the water cycle.

92 **2. Results**

93 **2.1. Surface albedo changes in HMA**

94 Forested basins (Yangtze, Si, Song Hong, and Irrawaddy) have the lowest surface albedos
95 due to their dense canopy (Figure 2). The highest surface albedos (NIR >0.35 and VIS >0.2) are
96 in the Himalayas and the northern HMA due to the presence of snow. In the irrigated lands of
97 Indus and Ganges-Brahmaputra, surface albedo values are in between those of forests and bare
98 soil. Surface albedo trends are bidirectional although the VIS has a decreasing trend almost
99 everywhere (Figure 2). The irrigated lands and Hwang Ho have the highest decreases in both NIR
100 and VIS ($> -2 \cdot 10^{-3}/\text{year}$). The northwestern basins have an increasing trend in NIR ($> 10^{-3}/\text{year}$)
101 whereas some areas show no significant trends to increasing trends of VIS. Tarim and the northern
102 HMA are characterized by decreasing trends in NIR ($< 10^{-3}/\text{year}$) and VIS ($\sim -2 \cdot 10^{-3}/\text{year}$). Forested

103 basins show an increasing trend in NIR ($\sim 10^{-3}$ /year) and a decreasing trend in VIS (from 10^{-4} to
104 10^{-3} /year). Previous studies have reported an increasing trend of surface albedo in central Asia⁵⁵
105 in general and a decreasing trend in the Tibetan Plateau^{49,50} whereas our study highlights that these
106 trends are bidirectional in the surface albedos constituents.

107 Trends of snow cover and LAI are unidirectional with decreasing and increasing trends
108 respectively, whereas the soil moisture has a bidirectional trend (Supplementary Figure 1). Forests
109 have the highest LAI increase and snow cover decrease yet they depict low surface albedo changes.
110 Moreover, Hwang Ho and Tarim characterized by high surface albedos changes do not have large
111 changes of LAI, snow cover, and soil moisture. The long-term patterns of surface albedo changes
112 are, therefore, not explained by the changes in vegetation, snow, and soil moisture alone. This
113 following section describes the key land surface processes and their interactions on influencing
114 albedo.

115 **2.2. Drivers of surface albedo changes in HMA**

116 Figure 3 which shows the unique, synergistic, and redundant information in various drivers
117 of surface albedo changes, indicates that these factors are spatiotemporally heterogeneous in
118 HMA. The unique information from soil moisture, LAI, or snow cover dominates the surface
119 albedo, though in some instances the redundant information across these variables also becomes
120 important. The synergistic information across these factors is generally small. Overall, LAI is the
121 main driver of surface albedo changes in HMA as it dominates the surface albedo changes in
122 forested and northwestern basins. Due to intense irrigation activities, soil moisture is the primary
123 factor influencing surface albedo changes over the irrigated lands of Indus and Ganges-
124 Brahmaputra. For example, the unique information of soil moisture is three to four times higher
125 than those of LAI and snow cover in Indus and Ganges-Brahmaputra. Compared to different areas

126 of HMA, the redundant information between LAI and soil moisture is non-significant over Indus
127 and Ganges-Brahmaputra basins, which reaches a peak in July when the high soil moisture
128 interferes with the soil reflectance by decreasing the VIS component. Further, the enhanced
129 vegetation growth also leads to increasing NIR. LAI is the dominant factor with large unique
130 information in the forested areas of Irrawaddy, Song Hong, and Si; this influence progressively
131 reduces depending on the density of the forest canopy (68% in Irrawaddy, 56% in Song Hong, and
132 32% in Si). Though the unique information of soil moisture is low in these areas, it increases during
133 the monsoon. Snow is a significant factor in influencing the surface albedo in the Tibetan Plateau,
134 the Karakoram and the western Himalayas, and the central Ganges-Brahmaputra and Eastern
135 Himalayas. There is a seasonality to the snow cover unique information which increases in winter.
136 The contrasting seasonal influences of snow cover, soil moisture, and LAI are also observed in
137 several areas. Because multiple processes govern the water and energy balances in the central and
138 eastern Himalayas, Hwang Ho, Tarim, and the northwestern basins (Amu Darya, Syr Darya, and
139 Ili), surface albedo changes in these zones have multiple drivers whose contributions are
140 seasonally dependent. In the Hwang Ho and Yangtze, for example, surface albedo variations are
141 primarily governed by the changes of LAI though snow cover has a non-trivial contribution in
142 winter. Additionally, soil moisture changes in Hwang Ho also affect surface albedo because its
143 vegetated areas (48% of the basin area) are not dense enough to absorb all the solar radiation,
144 hence nonnegligible radiation reaches the soil. In the central and eastern Himalayas, the unique
145 information of LAI and soil moisture peaks in July. Because the increases in soil moisture are due
146 to snowmelt, the unique information of snow cover and soil moisture have opposite monthly
147 variations. During the growing season, the unique information of LAI is two times higher than
148 those of snow cover and soil moisture combined. The partial information analysis presented here

149 provides important insights about the key processes that drive the surface albedo and the
150 subsequent radiative changes in HMA basins. Next, we describe the seasonal and long-term
151 changes in these processes toward influencing surface albedo changes over HMA.

152 **2.2.1. Irrigation induces the highest surface albedo decreases in HMA**

153 The Ganges-Brahmaputra and the Indus are subject to agricultural activities involving
154 intense irrigation⁵⁶ and groundwater pumping⁵⁷. Irrigated lands occupy 49% of the Ganges-
155 Brahmaputra and 22% of the Indus. They have the highest yearly decreases in VIS and NIR in
156 HMA on average equal to $-4.4 \cdot 10^{-4}/\text{year}$ and $-2 \cdot 10^{-4}/\text{year}$, respectively in the Ganges-Brahmaputra
157 and $-6 \cdot 10^{-4}/\text{year}$ for the VIS and $-2 \cdot 10^{-4}/\text{year}$ for the NIR in the Indus. The highest yearly decreases
158 in VIS and NIR are from February to June when the soil moisture increases significantly (Figure
159 4a). In the average seasonal cycle, the VIS increases from January to April because of the decreases
160 in LAI and soil moisture. As soil moisture and LAI keep decreasing to reach their lowest values,
161 the VIS reaches its maximum value (0.1) in June (Figure 4a). The beginning of the rainy season
162 triggers increases in soil moisture and LAI. Hence the VIS starts to decrease. With the increases
163 in LAI, more incoming solar energy is reflected and scattered by the vegetation canopy and only
164 a small proportion of the incoming radiation reaches the ground⁷³. The VIS remains at its lowest
165 value (~ 0.05) for two consecutive months August and September when the average LAI and soil
166 moisture have their highest values 2.5 and 0.29 respectively. The NIR has a monthly variation
167 analogous to that of LAI because of its sensitivity to vegetation reflectance. Though not from
168 irrigation, the influence of soil moisture on albedo is also seen in other areas. In the northern HMA
169 and parts of Indus, soil moisture increases originating from increases in precipitation⁷⁷ decrease
170 the surface albedo at rates equal to $-2.3 \cdot 10^{-4}/\text{year}$ for the VIS and $-1.6 \cdot 10^{-4}/\text{year}$ for the NIR
171 (Supplementary Figure 4).

172 **2.2.2. Greening decreases the VIS and increases the NIR surface albedo over**
173 **forested regions of HMA**

174 Though HMA experiences greening at high rates⁷³, LAI only controls surface albedo
175 changes in forests of Ganges-Brahmaputra, Yangtze, Irrawaddy, Song Hong, and Si. Because of
176 its dense canopy and high precipitation (970 to 1200 mm/year) leading to high soil moisture,
177 annual averages of NIR and VIS surface albedos in the Yangtze are low equal to 0.275 and 0.187
178 respectively (Figure 4b). The Yangtze has one of the highest trends of LAI in HMA (up to 0.02
179 m²m⁻²/year). Nevertheless, the surface albedo trends are low likely due to their small magnitudes.
180 The VIS and NIR surface albedos have contrasting trends and monthly variations due to the
181 presence of forests. The VIS is high in winter due to vegetation senescence with a peak in March
182 while the NIR component becomes high in summer. The lowest VIS (0.05) is from May to August
183 when LAI and soil moisture are high, and snow cover low. VIS decreases as the canopy becomes
184 dense and the wetness of the soil increases to dampen the effects of ground reflectance. As the
185 canopy develops, its NIR reflectance increases due to increased multiple scattering⁷⁴. Similar
186 patterns are found in the forested areas of Ganges-Brahmaputra and Irrawaddy. Ganges-
187 Brahmaputra forests are characterized by a low VIS (0.027, Supplementary Figure 2b). The yearly
188 increasing trends of LAI cause the NIR to increase ($6 \cdot 10^{-4}$ /year) and the VIS to decrease ($-2.8 \cdot 10^{-4}$ /
189 year), consistent with prior studies⁵⁹. In the Irrawaddy, greening increases the NIR (up to $4 \cdot 10^{-4}$ /
190 year) and decreases the VIS (Supplementary Figure 3a). In these domains, the pattern of monthly
191 variations of trends and seasonality in LAI and soil moisture is similar. Consequently, the pattern
192 of their impacts on surface albedo components is also similar.

193 **2.2.3. Snow cover dominates surface albedo changes in high-elevation zones**

194 Snow cover drives surface albedo changes in the Tibetan Plateau, the Karakoram, and the
195 western Himalayas. The latter has an overall increasing trend of surface albedo stemming from an
196 increasing snow cover (Figure 4c). However, this increasing trend is only limited to the winter, as
197 surface albedo has a decreasing trend in summer and fall (Supplementary Figure 7) likely because
198 of dust and black carbon deposits that darken the snow^{38,39,60}. Similar patterns are also observed in
199 the Tibetan plateau, where surface albedo decreases because of the decrease in snow cover
200 (Supplementary Figure 5). The latter has also been attributed to black carbon⁴⁰ and greening in
201 prior studies^{50,61}. The albedo decrease from snow cover influence is, therefore, strongly related to
202 human impacts and climate induced warming on snow cover.

203 **2.2.4. Interactions between decreases in snow cover, increase in soil moisture,** 204 **and greening**

205 In a number of basins in HMA, the simultaneous influence of the changes in snow cover,
206 soil moisture, and vegetation impacts surface albedo changes. For example, because all the three
207 factors controlling surface albedo are preponderant, the Hwang Ho has one of the highest
208 decreasing trends of NIR and VIS in HMA equal to $5 \cdot 10^{-4}$ /year. In the Hwang Ho, the VIS
209 decreases from January to August to reach its lowest value (~ 0.08) then increases as the winter
210 season begins on contrary to the NIR (Figure 5a). In the Tarim, the decreasing trends of NIR and
211 VIS ($> -2 \cdot 10^{-4}$ /year) are due to the decreasing trends of snow cover in winter and soil moisture and
212 LAI from April to November (Supplementary Figure 5). In the Amu Darya and the other
213 northwestern basins, the NIR has an increasing yearly trend and the VIS has an increasing trend
214 due to the yearly increase in LAI (Figure 5b). The increases in VIS are also related to the decreasing
215 trends of soil moisture (Supplementary Figure 6).

216 Decreases in surface albedo equal to $-4 \cdot 10^{-4}$ /year and $-8 \cdot 10^{-5}$ /year for NIR and VIS,
217 respectively in the central and eastern Himalayas characterized by high VIS (0.09) and low NIR
218 (0.11) are governed by LAI, soil moisture, and snow cover (Supplementary Figure 2a). Although
219 surface albedo is decreasing over the years, in winter it is increasing likely because greening
220 enhances snow interception. In forests where snowfall occurs, the canopy increases both VIS and
221 NIR because the intercepted snow offsets the canopy reflectance in all wavelengths⁵⁸. The NIR
222 and VIS increase from January to reach their peak in March as the snow cover is high. As the
223 canopy becomes snow-free and it starts reflecting in the NIR. As such, the decreases in NIR due
224 to the decline of snow are compensated with the increases induced by the canopy reflectance.
225 Therefore, the decreases in NIR are not as sharp as in the VIS. The NIR and VIS increase again in
226 November when the winter begins. Due to the opposite effects of snow and forests on the NIR, the
227 second increase is only detectible in the VIS (Supplementary Figure 2).

228 **3. Discussion**

229 Because irrigated lands have the highest surface albedo decreases, irrigation in HMA could
230 significantly reshape its climate dynamics. Surface albedo decreases driven by human
231 management are likely to have a positive feedback impact on water resource requirements. For
232 example, the reduction in surface albedo due to irrigation could lead to more warming and high
233 evaporative demand, which could subsequently lead to more irrigation demand and the overuse of
234 water resources. Over the Ganges-Brahmaputra and Indus with large populations reliant on
235 irrigated agriculture, these surface albedo decreases are a significant concern. Another positive
236 feedback mechanism related to cold season processes also raises concerns about the shifts in water
237 availability. Surface albedo changes derived from the decreases in snow will further enhance this
238 decrease in snowpack and warming. A decrease in surface albedo increases the surface absorption

239 of the solar radiation, leading to decreases in snow and more water available for vegetation growth
240 and, therefore, boosts greening. In snow-covered forests, on the other hand, greening increases
241 surface albedo and could attenuate warming. The impacts of the changes of land surface features
242 (irrigation, greening, decreases in snow) on the radiative forcing will in turn accentuate these
243 changes and the practices that have caused them. The attributions of the surface albedo changes
244 developed in this study, therefore, are important inferences for future modeling studies for
245 representing these interactions and feedbacks and evaluating their role in climate change. It is also
246 important to account for this feedback in designing climate change mitigation strategies as
247 counterbalancing Earth's warming could involve changes of practices such as irrigation.

248 **4. Methods**

249 **4.1. Selected satellite-based products**

250 We use remote sensing datasets to quantify the changes in surface albedo, LAI, soil
251 moisture, and snow cover.

252 **MODIS MCD43 surface albedo:** We use the surface albedos provided by NASA's MODIS
253 version V006 (MCD43A3) and their associated quality layers⁶². MODIS surface albedo products
254 are generated every 8 days and have a spatial resolution of approximately 500 m. MCD43 provides
255 BSA (directional hemispherical reflectance) which described the albedo under direct illumination
256 condition in the absence of a diffuse component (i.e., when the sun as a point of source of
257 illumination) and WSA (bihemispherical reflectance) is defined as albedo in the absence of a direct
258 component when the diffuse component is isotropic in NIR and VIS.

259 **MODIS MCD14A2H LAI:** LAI, defined as the area of green leaves per unit ground horizontal
260 surface area, is a good indicator of changes in vegetation greenness on Earth. LAI is widely used

261 to analyze greening on Earth^{63,64}. We use the LAI values provided by the MCD15A2H Version 6
262 of MODIS⁵² at a spatial resolution of 500 m and a temporal resolution equal to 8 days.

263 **MODIS Snow Cover fraction:** we assess the monthly snow cover fraction estimates provided by
264 MODIS Snow Cover fraction L3 at a spatial resolution of 0.05°⁵³.

265 **ESA CCI Soil moisture:** we analyze the daily soil moisture provided by the European Space
266 Agency Climate Change Initiative ESA CCI⁵⁴. The ESA CCI soil moisture v05.2 consists of three
267 surface soil moisture data sets. In this study, we use the dataset generated by blending the soil
268 moisture retrievals from active and passive microwave remote sensing instruments.

269 **Statistical analyses**

270 To capture the influence of HMA heterogeneity on albedo changes, we perform our
271 analysis at 500 m, which is the spatial resolution of the surface albedo data. The changes of surface
272 albedo and its potential control variables (LAI, snow cover, and soil moisture) over the past two
273 decades are quantified by computing their trends using the Mann-Kendall test with a confidence
274 level of 95%⁷⁰⁻⁷² given by:

$$275 \quad S = \sum_{i=1}^{n-1} \sum_{j=k+1}^n \text{sign}(x_j - x_i) \quad (1)$$

276 where x is the time series variable. The subscript j and k are the observation
277 time. $\text{sign}(x_j - x_i)$ is equal to +1, 0, or -1, which means increasing, no, and decreasing trends,
278 respectively.

279 Because three variables are likely controlling the changes of surface albedo, we employ
280 the partial information decomposition framework to quantify the interactions and dependencies
281 between these variables and the surface albedo. The partial information decomposition allows to
282 quantify (1) the amount of information that each control variable uniquely contributes to the
283 surface albedo, (2) the redundant information between the three variables, and (3) the information

284 due to the combined knowledge of the three variables called synergistic information. More details
285 about the computation of these metrics can be found in⁶⁹⁻⁷¹. Land surface processes are
286 characterized by strong seasonality and depending on the season the dominant factors, as well as
287 the values of surface albedos, may change^{16,19}, we, therefore, analyze the monthly variations of
288 yearly trends and averages.

289 **Data availability**

290 Datasets used in this study can be found in the following websites:

291 MODIS Albedo: <https://lpdaac.usgs.gov/products/mcd43a3v006/>

292 MODIS LAI: <https://lpdaac.usgs.gov/products/mcd15a2hv006/>

293 MODIS Snow Cover: <https://nsidc.org/data/MOD10A1>

294 ESA CCI soil moisture: <https://www.esa-soilmoisture-cci.org/data>

295 GRACE data: https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/

296 **Author contribution**

297 F.Z.M and S.V.K. contributed with conceptualization, data analysis, and writing.

298 C.G. contributed with the data acquisition.

299 S.V.K. was responsible for funding acquisition. All authors have read and agreed to the published
300 version of the manuscript.

301 **Competing interests**

302 The authors declare that they have no conflict of interest.

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473 **Figure caption**

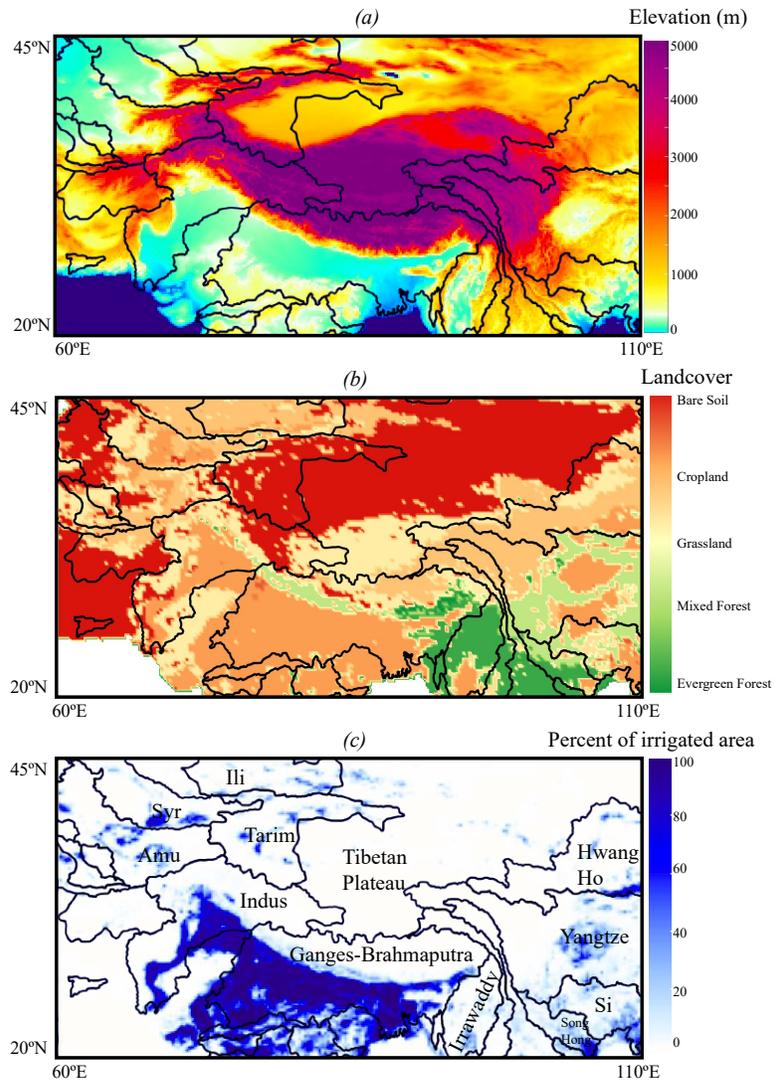
474 Figure 1: Maps of High Mountain Asia. (a) elevation, (b) land cover⁷⁶, and (c) percent of irrigated
475 areas per pixel⁵⁶. The black lines indicate the limits of the hydrologic basins, and their names are
476 indicated in (c).

477 Figure 2: Surface albedo changes and values in High Mountain Asia. Spatial distributions of the
478 yearly (a) averages and (b) trends from 2003 to 2020 of BSA (Black Sky) and WSA (White Sky)
479 surface albedos in both NIR and VIS wavelengths. Trends were computed using the Mann-Kendall
480 test with a confidence level of 95%.

481 Figure 3: Dominant drivers of the surface albedo changes. Spatiotemporal variations of the unique
482 and redundant information of leaf area index, soil moisture, and snow cover about the visible
483 white-sky surface albedo of 16 zones (basin names are indicated in Figure 1c). Note that y-axis is
484 a stacked graph and is not cumulative.

485 Figure 4: Monthly variations of trends and averages of surface albedo, LAI, soil moisture and snow
486 cover. (a) in a basin where irrigation decreases surface albedo: irrigated lands of the Ganges-
487 Brahmaputra, (b) in a basin where greening decreases VIS and increases NIR surface albedo:
488 Yangtze, (c) in a basin where changes in snow cover decreases surface albedo: the Karakoram and
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491 Figure 5: Monthly variations of trends and averages of surface albedo, LAI, soil moisture and snow
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493 cover (a) Hwang Ho, and (b) Amu Darya. Trends were computed using the Mann-Kendall test
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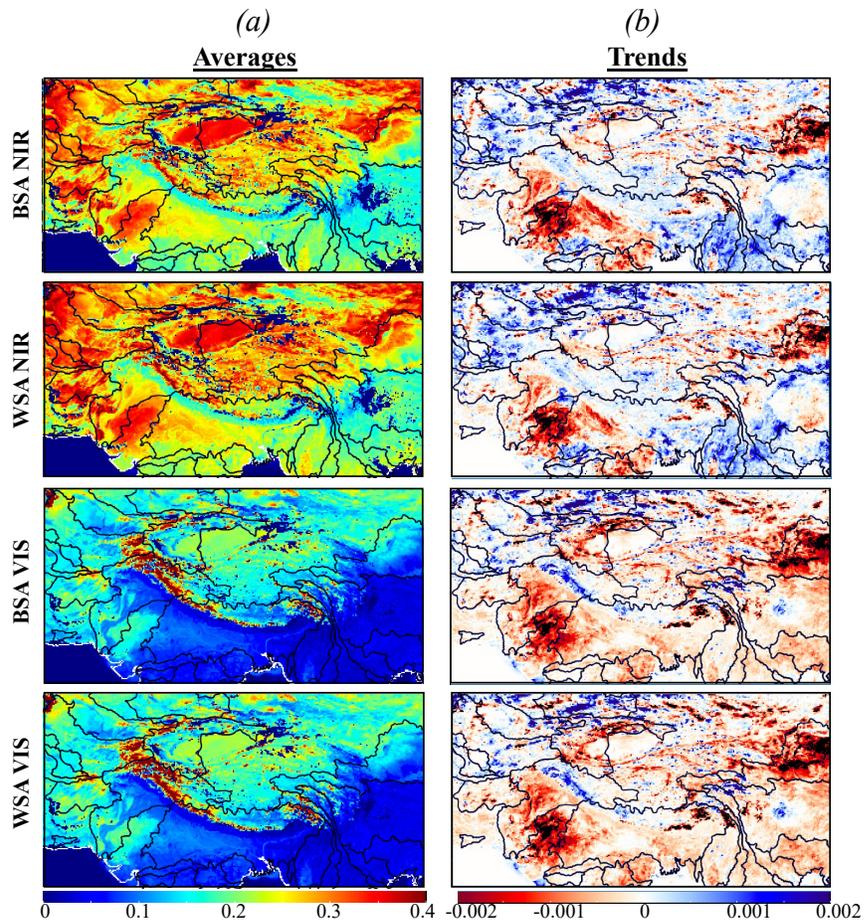


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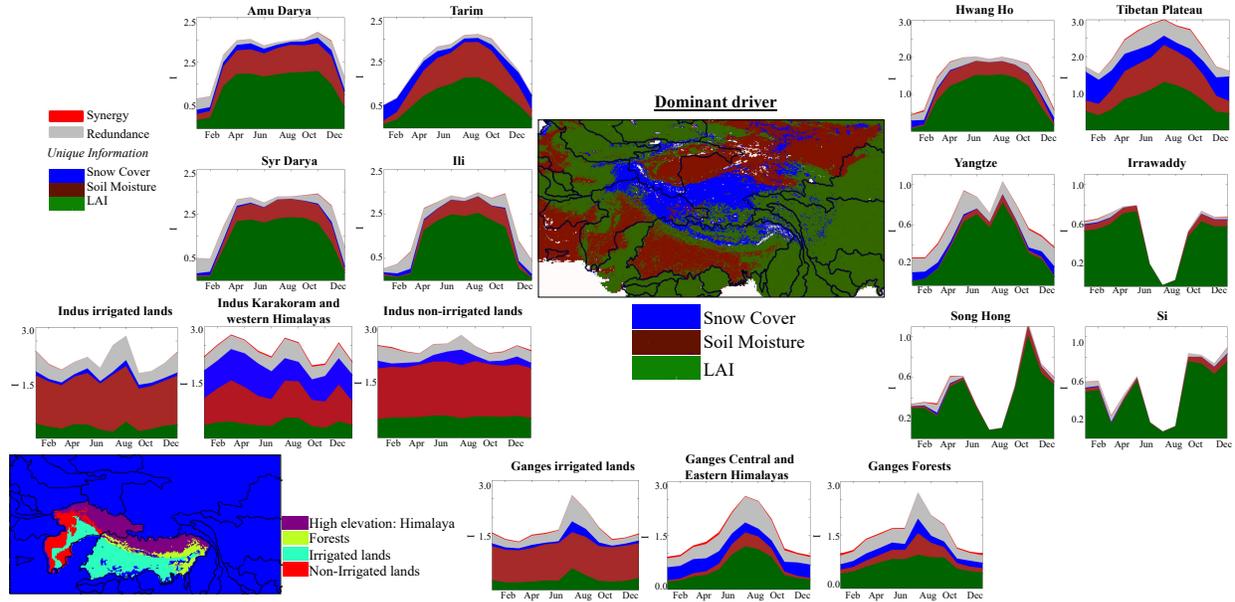
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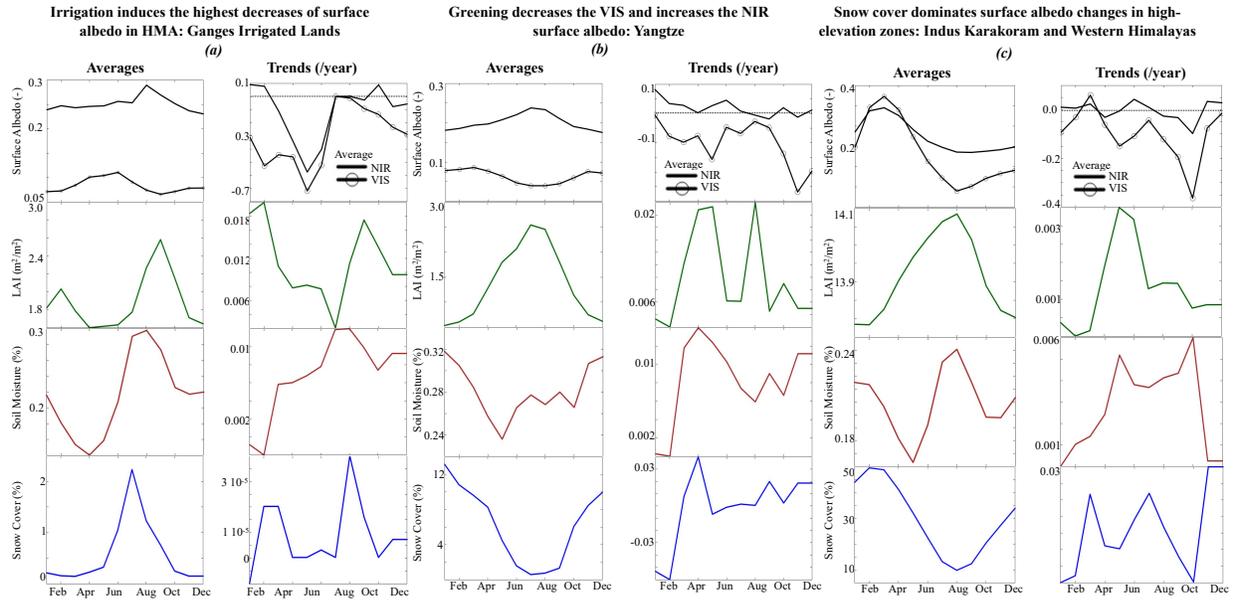
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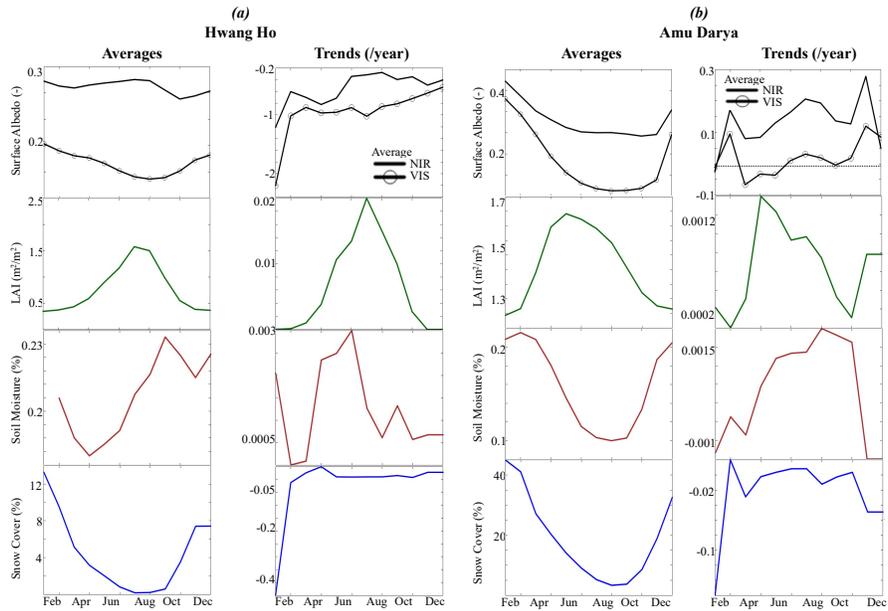
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 515 confidence level of 95%.

Interactions between decreases in snow cover, increase in soil moisture, and greening



516

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