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Unraveling the Multiple Drivers of Greening-Browning and Leaf Area Variability in a Socioeconomically Sensitive Drought-Prone Region

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Table S1. Percentage of geographical area showing significant trends in monthly MK analysis from 2003-04 to 2018-19 (positive, negative, and total) in each division of Maharashtra state.

Division	Positive trend (%)	Negative trend (%)	Total trend (%)
Amravati	41.42	3.77	45.20
Aurangabad	31.13	8.90	40.03
Kokan	55.46	8.88	64.34
Nagpur	19.79	18.30	38.09
Nashik	37.78	9.73	47.51
Pune	74.03	1.23	75.27
Total (Maharashtra)	42.31	8.45	50.76

Table S2. Percentage contribution of each biome to significant positive, negative, and total trend in monthly LAI trend analysis for Maharashtra state. The numbers in brackets under each biome represent the percentage of positive and negative trend within that biome.

Area	Trend	Croplands (%) (1)	Grasslands (%) (2)	Forests (%) (3)	Other (%) (4)	Total area showing significant trend (km^2) (5)
Maharashtra state	Positive	74.82 (83.87)	23.40 (86.32)	0.96 (36.31)	0.81 (81.07)	161130.80
	Negative	72.05 (16.13)	18.58 (13.68)	8.42 (63.69)	0.95 (18.93)	32176.75
	Total	74.36	22.60	2.20	0.83	193307.50

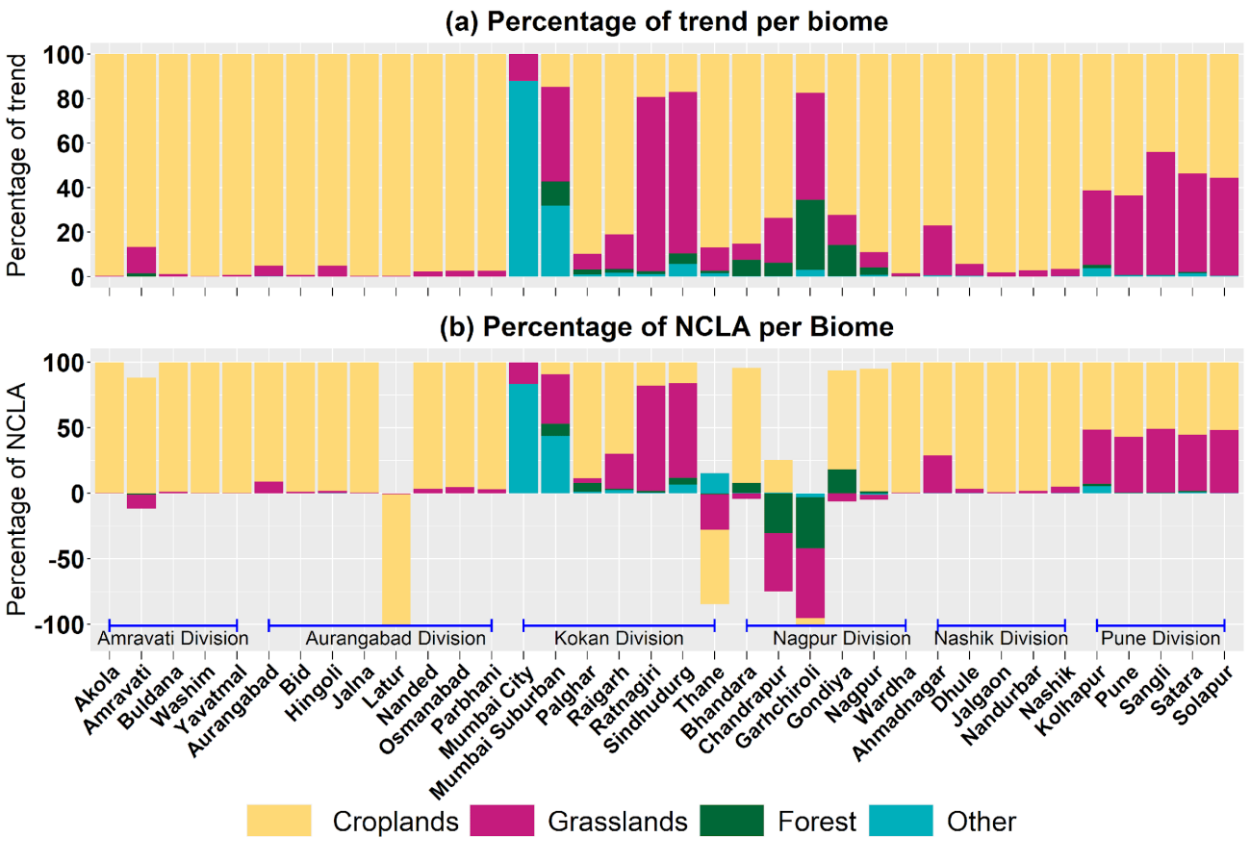

Figure S1. Percentage contribution of each biome per district to (a) significant monthly LAI trend ($p < 0.05$) and (b) NCLA.

Supplementary text S1: Trends in grasslands and forests

Approximately 23% of the significant trend in monthly LAI is represented by grasslands and 2% by forests (Table S2), of which the majority of grasslands have an increasing trend, whereas forests mainly show a decreasing trend. The grassland trend is prominent in Pune and Kokan divisions, whereas the trend in forests is mainly represented in Nagpur division. As the trend statistics depend on the choice of time period and land-use map, although the static map of 2003 was used for analysis, we checked the land-use characteristics of subsequent years to analyze the trend in grasslands, particularly in the Pune division. Annual analysis of the land-use map showed that the grasslands in Pune division decreased by about 39% in 2004, whereas croplands increased by about 29%. It was observed that grasslands were converted to croplands, which is reflected in the high greening trend in grasslands in the Pune division, along with favorable natural conditions and grassland conservation measures in both the divisions. In the case of forests, 78% of the total trend in forests was contributed by Garhchiroli district. The State Forest Report suggests a decrease in the forest cover of Garhchiroli district by 153 km^2. The decrease in forest cover is mainly attributed to rotational felling, diversion of forest land for developmental purposes, submergence, agricultural expansions, and encroachments (https://fsi.nic.in/ (accessed on 30 November 2021), showing the effect of anthropogenic activities on LA variability. Nagpur division also shows a negative trend in grasslands (Figure 4bb), which are unirrigated natural open habitats. Multiple and consecutive droughts, overgrazing, encroachment by human settlements, and agricultural expansions may have cumulatively contributed to high browning in grasslands of Nagpur division.

Table S3. Positive, negative, and total NCLA in each biome in each division observed for monthly MK trend analysis from 2003-04 to 2018-19.

Division	Biome	Positive NCLA (km^2)	Negative NCLA (km^2)	Total NCLA (km^2)
Amravati	croplands	2628.64	-141.61	2487.04
	grasslands	35.08	-127.39	-92.31
	forests	2.14	-13.69	-11.55
	others	0.23	-0.25	-0.02
Aurangabad	croplands	2536.48	-593.74	1942.74
	grasslands	83.30	-9.98	73.32
	forests	0.00	0.00	0.00
	others	0.49	-0.75	0.26
Kokan	croplands	1110.99	-293.61	817.38
	grasslands	2084.73	-96.33	1988.40
	forests	95.42	-24.09	71.33
	others	103.89	-11.07	92.82
Nagpur	croplands	1036.65	-478.05	558.60
	grasslands	134.45	-588.09	-453.64
	forests	154.35	-441.99	-287.64
	others	6.41	-29.39	-22.98
Nashik	croplands	2588.04	-546.12	2041.92
	grasslands	289.76	-12.77	277.00
	forests	0.62	-0.86	-0.23
	others	2.18	-0.60	1.57
Pune	croplands	4396.43	-122.78	4273.65
	grasslands	3615.13	-44.36	3570.77
	forests	56.19	-8.03	48.16
	others	104.94	-2.44	102.50
Total (Maharashtra)	croplands	14297.24	-2175.89	12121.34
	grasslands	6242.45	-878.92	5363.53
	forests	308.73	-488.66	-179.94
	others	218.14	-44.50	173.63

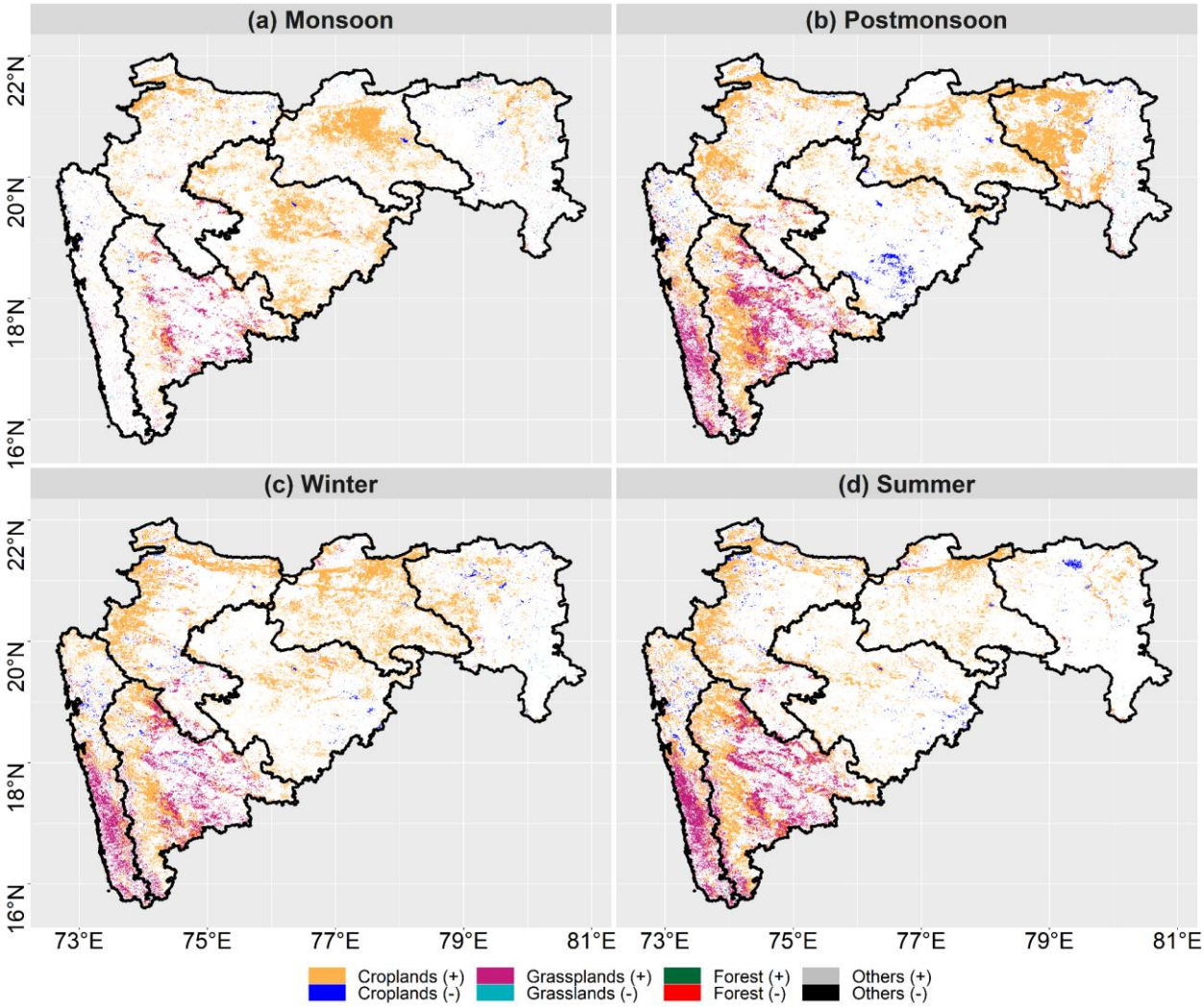

Figure S2. Land use by areas showing significant positive (+) and significant negative (−) trends in seasonal LAI time series from 2003 to 2019 ($p < 0.05$) in (a) monsoon (June–September), (b) postmonsoon (October–December), (c) winter (January–February), and (d) summer (March–May).

Table S4. NCLA in seasonal trend analysis per division from 2003-2004 to 2018-2019.

Division	NCLA (km²)			
	Monsoon	Post-monsoon	Winter	Summer
Amravati	5396.90	3864.30	3890.43	1248.13
Aurangabad	5995.66	1446.83	1758.65	824.59
Kokan	401.42	3146.49	2244.24	2972.06
Nagpur	1234.49	7212.30	1189.41	460.74
Nashik	2681.66	4233.09	3637.24	2040.35
Pune	3903.89	8765.23	4343.04	6400.61

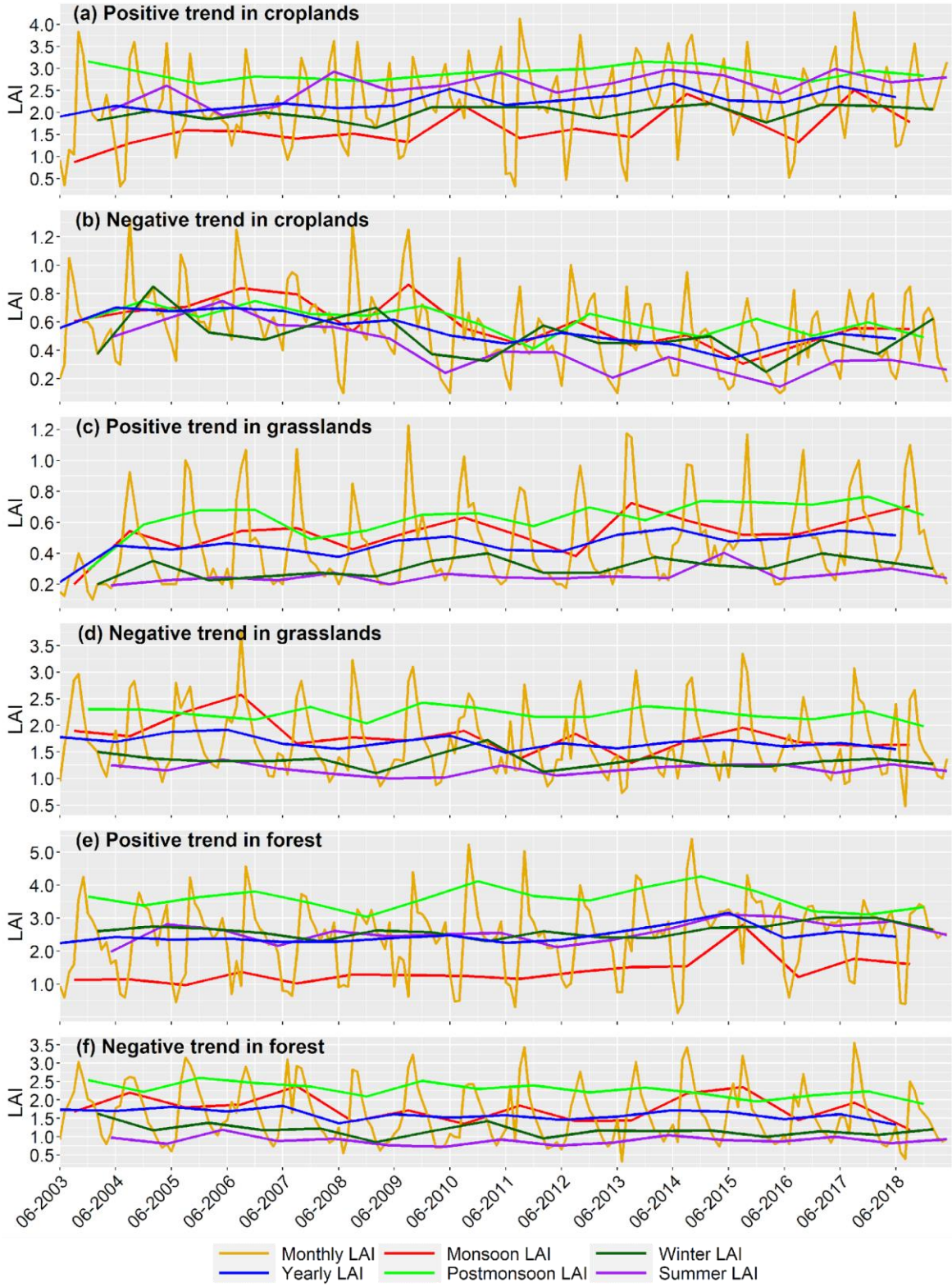

Figure S3. Pixel-based monthly, seasonal, and annual LAI time series for positive and negative trends in croplands, grasslands, and forests.

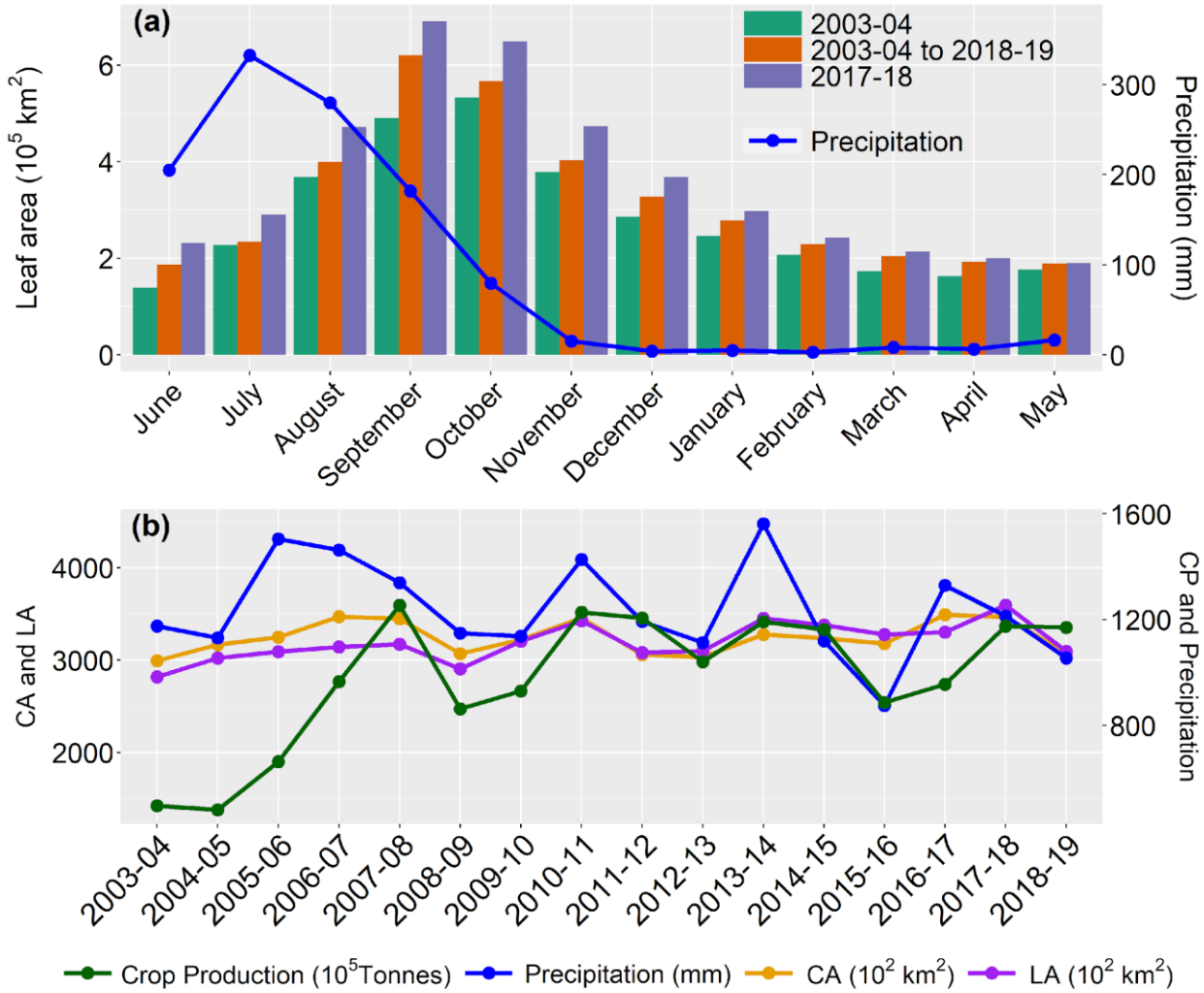

Figure S4. (**a**) Monthly average LA for the years 2003–2004, 2017–2018, and during 2003–2019 and mean monthly precipitation during 2003–2019. (**b**) Annual CP, precipitation, CA, and LA during 2003–2019 throughout Maharashtra state.

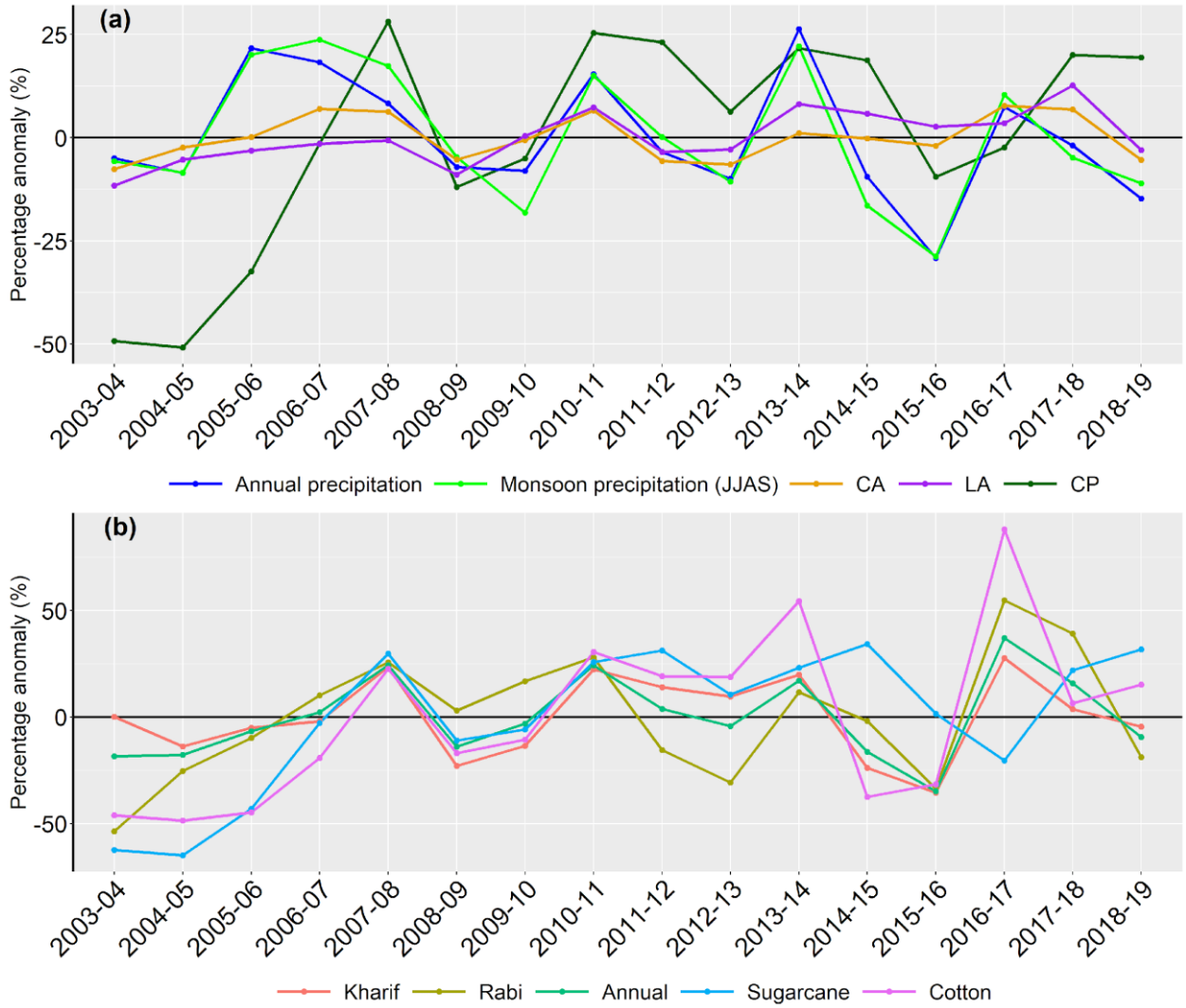

Figure S5. Percentage anomaly in (**a**) precipitation, cropped area, leaf area, and crop production and (**b**) Kharif CP, Rabi CP, annual CP (Kharif + Rabi), sugarcane CP, and cotton CP in the state from 2003-2004 to 2018-2019.

Table S5. Long-term (1989–1990 to 2018–2019) means of seasonal and annual (June–May) precipitation in various administrative divisions and Maharashtra state.

Division	JJAS	OND	JF	MAM	Annual
Amravati	773	76	10	22	881
Aurangabad	658	100	7	32	797
Kokan	2969	149	1	37	3156
Nagpur	1127	68	20	33	1248
Nashik	642	74	3	14	733
Pune	747	127	2	45	921
Total (Maharashtra)	1108	98	8	31	1245

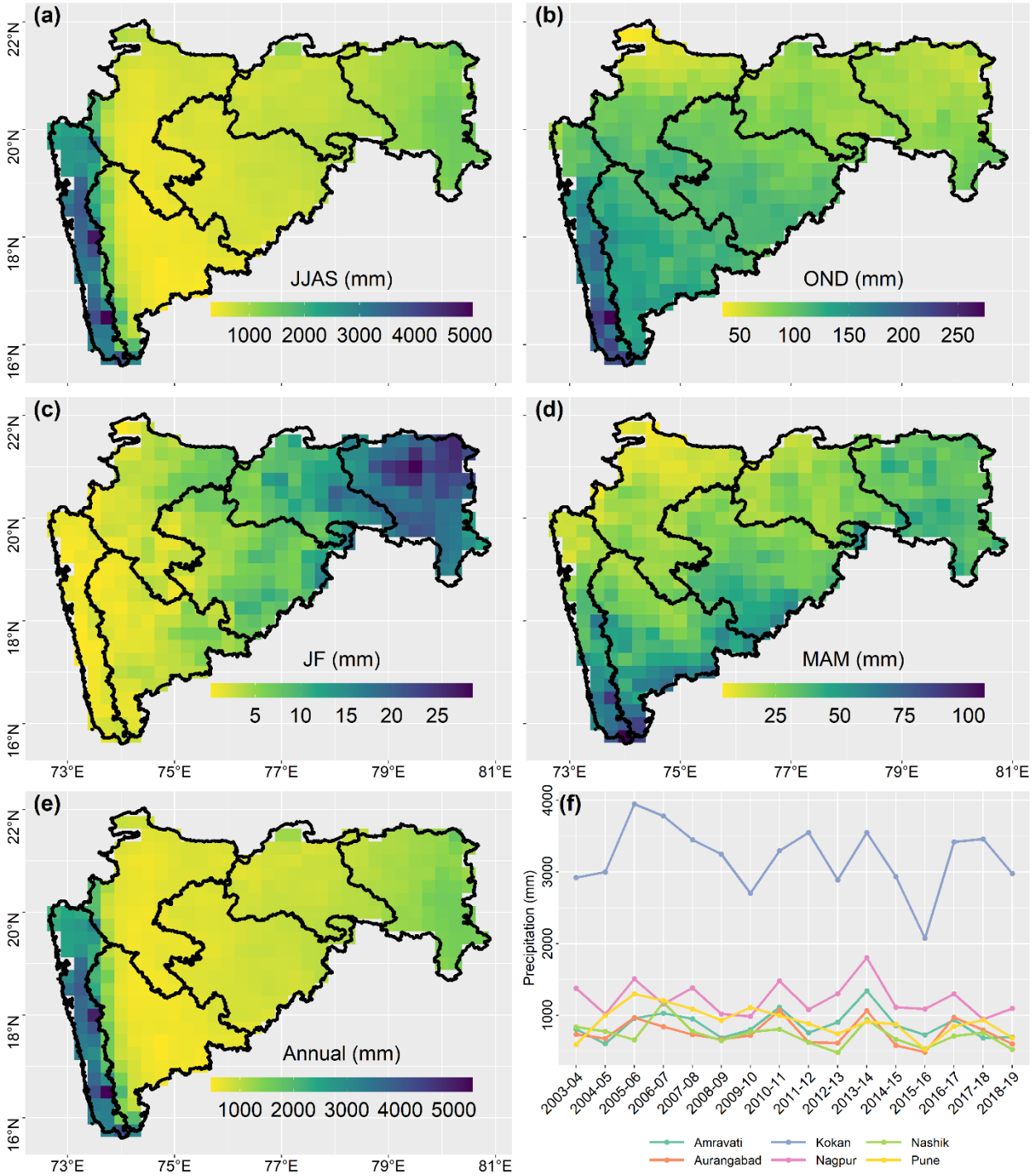

Figure S6. Long-term mean (averaged over 1989–1990 to 2018–2019) of precipitation distribution in (**a**) monsoon (June–September), (**b**) postmonsoon (October–December), (**c**) winter (January–February), (**d**) summer (March–May), and (**e**) annual. (**f**) Annual precipitation in each division from 2003–2004 to 2018–2019.

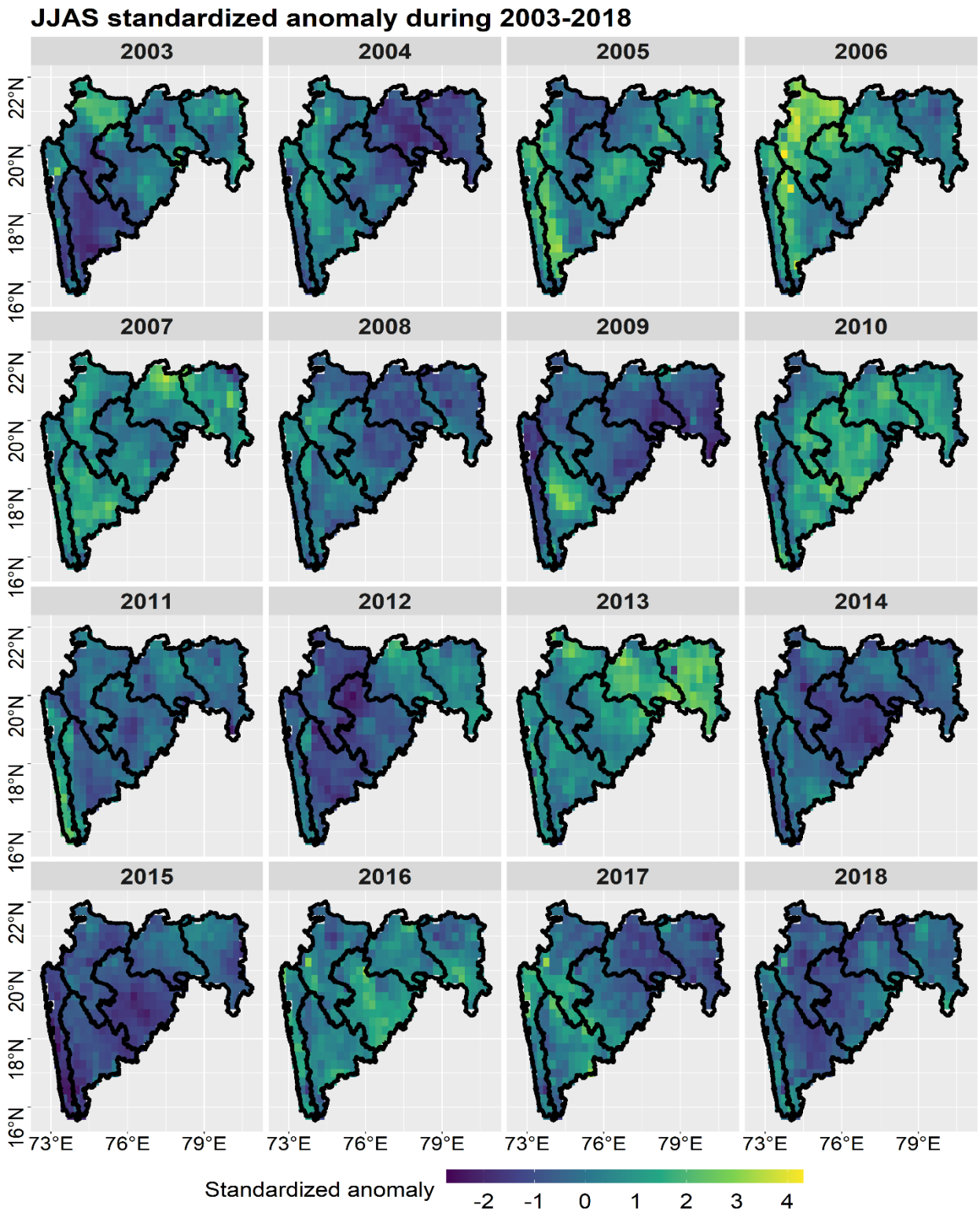

Figure S7. Spatial distribution of standardized monsoon rainfall anomaly (normalized by standard deviation) from 2003 to 2018. A standardized anomaly less than -1 is considered a drought situation for that pixel area.

Table S6. Pearson's correlation between seasonal (Kharif and Rabi) and annual cropland LA, precipitation, and GWS in subdivisions of Maharashtra.

Division	Precipitation and LA			Previous Monsoon Precipitation			GWS and LA		
	Kharif	Rabi	Annual	Rabi LA	Rabi GWS	Rabi CP	Kharif	Rabi	Annual
Amravati	-0.09	0.50	0.54	0.59	0.84	0.51	0.19	0.62	0.50
Aurangabad	0.06	0.65	0.66	0.65	0.73	0.71	0.39	0.80	0.71
Kokan	-0.44	0.31	-0.24	-0.02	0.17	0.10	-0.44	0.34	-0.04
Nagpur	-0.33	0.50	0.29	0.43	0.86	0.17	-0.19	0.36	0.03
Nashik	0.11	0.69	0.33	0.18	0.59	0.14	0.34	0.75	0.65
Pune	0.33	0.50	0.52	0.42	0.55	0.54	0.19	0.77	0.60
Total (Maharashtra)	-0.13	0.64	0.42	0.43	0.70	0.42	0.05	0.78	0.44

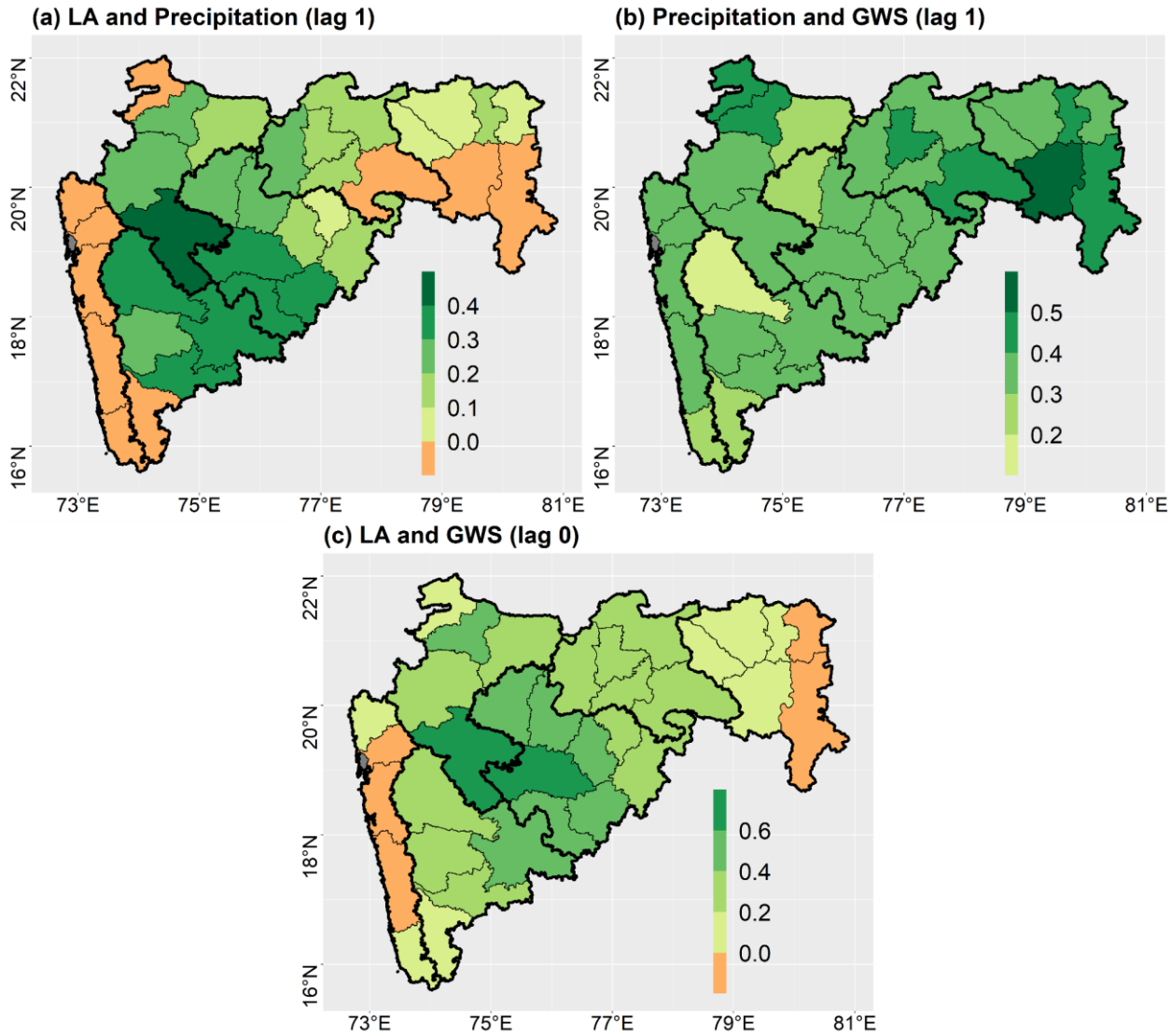

Figure S8. District-wise Pearson correlation coefficient between (**a**) monthly cropland LA and precipitation with one-month lag time, (**b**) precipitation and monthly GWS with one-month lag time, and (**c**) cropland LA and monthly GWS with zero lag from 2003–2004 to 2018–2019. Seasonality was removed from all the datasets before analyzing the correlation.

Table S7. Percentage of average CA and CP of primary crops, including food grains, cereals, pulses, and oilseeds, in Kharif and Rabi season in each division during 2003–2019.

Division	Kharif		Rabi	
	CA (%)	CP (%)	CA (%)	CP (%)
Amravati	74.31	71.37	25.69	28.63
Aurangabad	56.25	59.24	43.75	40.76
Kokan	91.63	95.66	8.37	4.34
Nagpur	74.73	79.52	25.27	20.48
Nashik	57.54	63.31	42.46	36.69
Pune	36.85	49.32	63.15	50.68
Total (Maharashtra)	58.94	65.54	41.06	34.46

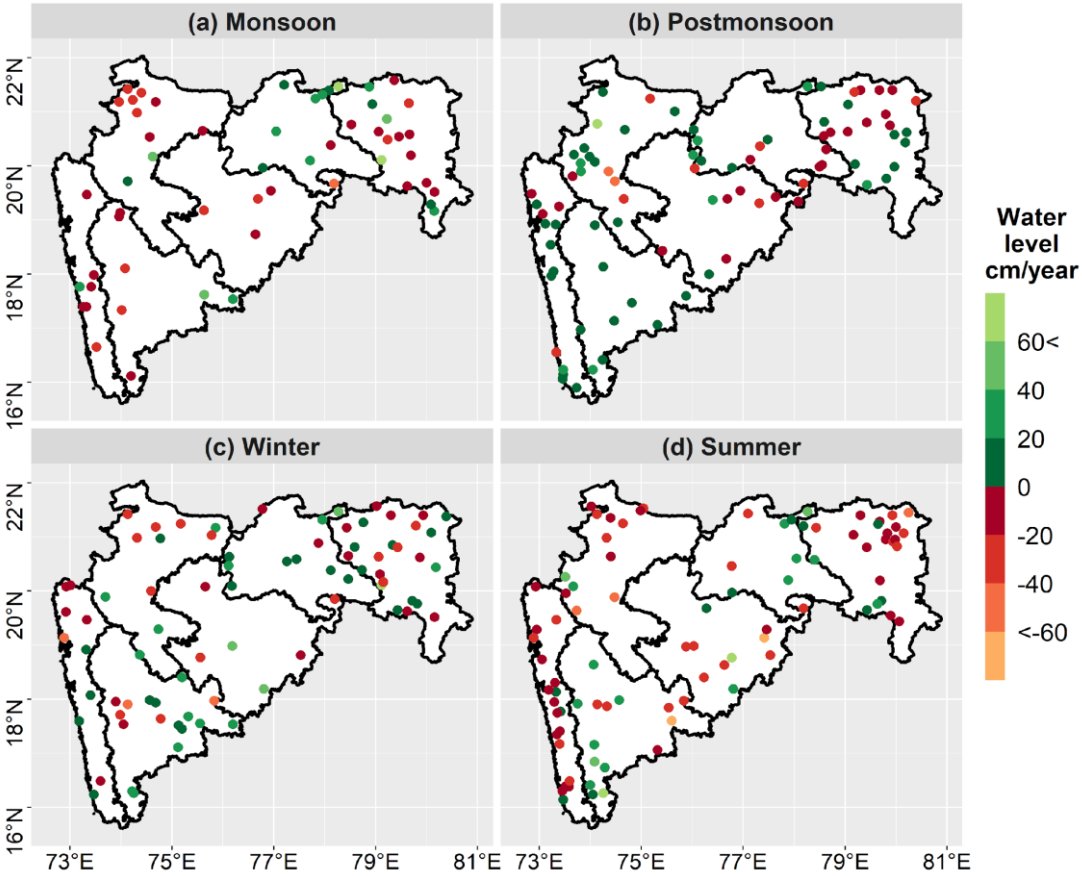

Figure S9. Significant trend in well levels ($p<0.05$) in each season throughout the state: (**a**) monsoon, (**b**) postmonsoon, (**c**) winter, and (**d**) summer. In situ groundwater level data were obtained from the Central Ground Water Board (CGWB, India-WRIS, http://www.india-wris.nrsc.gov.in/wris.html (accessed on 20 January 2021) from June 2003 to May 2019, with observations (mainly located in shallow aquifers) in August for monsoon, in November for postmonsoon, in January for winter, and in May for summer. Data from more than 7,000 wells were obtained and filtered for temporal continuity (observations with two or more consecutive gaps were not considered) and outliers to obtain reliable observations, and MK test ($p<0.05$) was used to analyze the

significant trends. GLDAS GWS data did not show any significant trend during 2003–2019. The in situ groundwater table data show significant decreasing or increasing trends in all parts of the state in each season, signifying the localized and seasonal influence of groundwater abstraction. The percentage of wells showing significant negative trends (65–67%) is higher than those showing positive trends in monsoon and summer seasons, whereas it is lower in postmonsoon and winter seasons (41–47%).

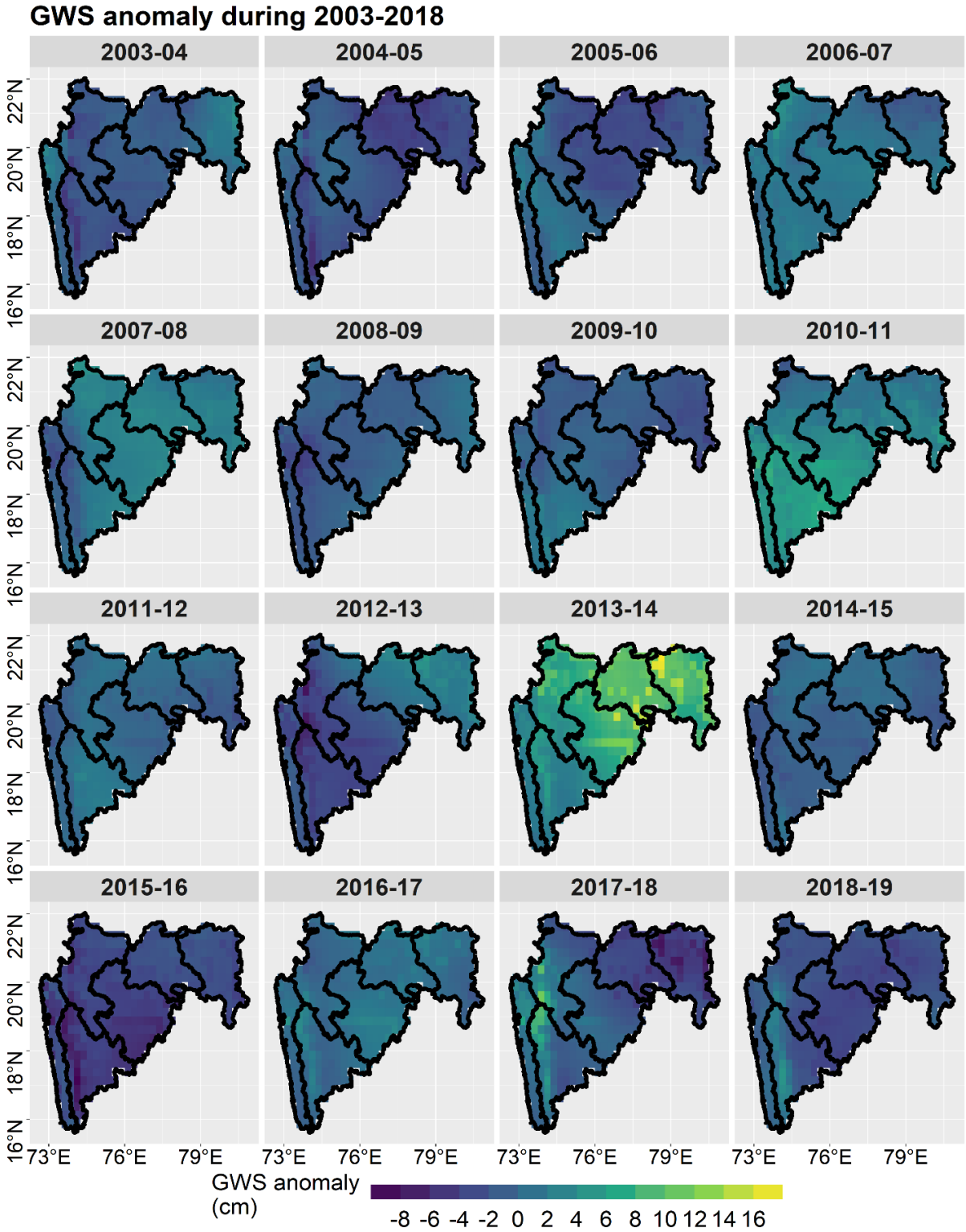

Figure S10. Spatial distribution of GLDAS groundwater storage anomaly from 2003–2004 to 2018–2019.

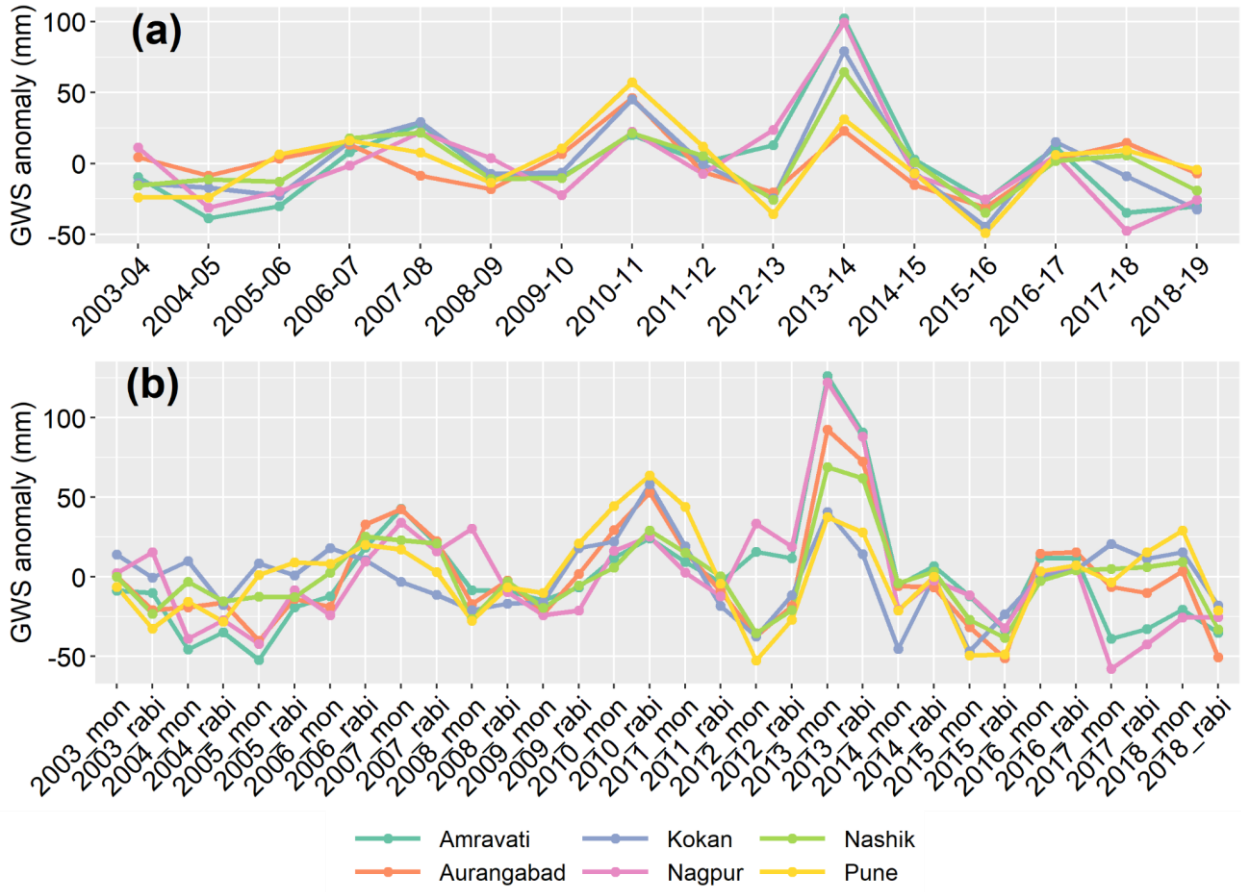

Figure S11. Time series of (**a**) annual GWS anomaly and (**b**) GWS anomaly in Kharif and Rabi seasons (Kharif: June–September, Rabi: October–May) from 2003–2004 to 2018–2019 in each division.

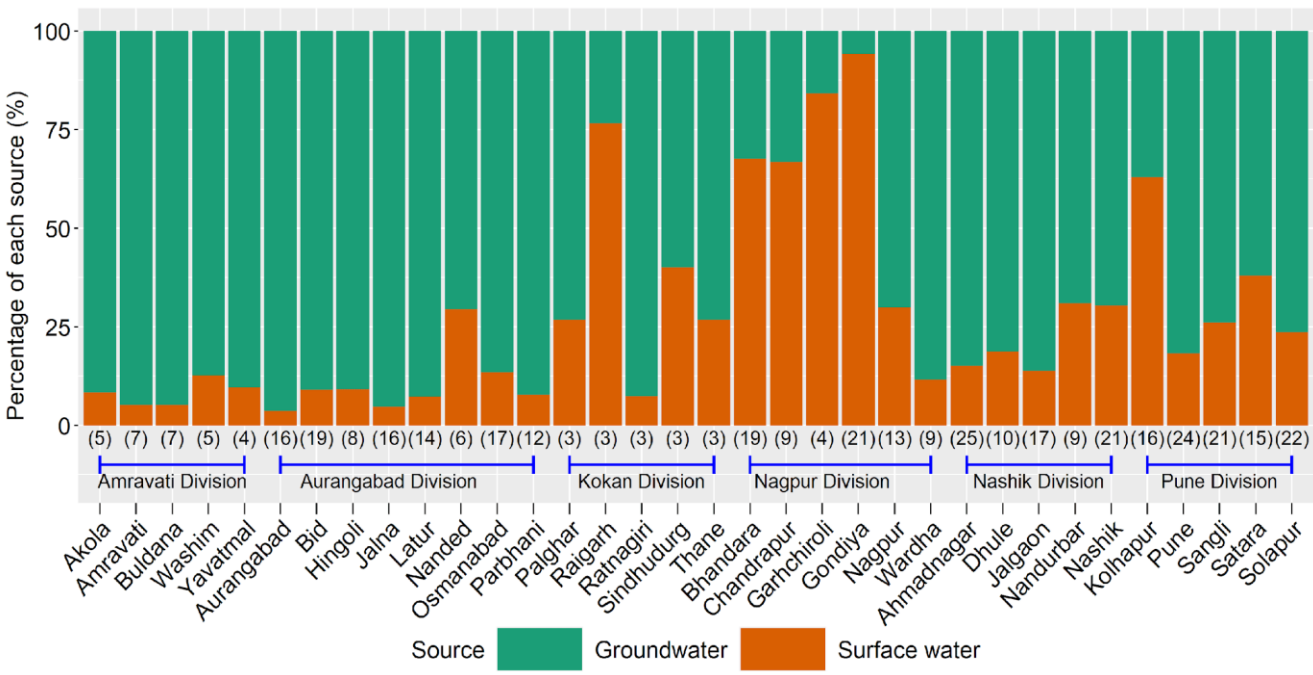

Figure S12. Percentage of irrigation by source in each district as per GMIA developed by FAO. Numbers in brackets at the bottom of each bar indicate the percentage of area equipped for irrigation (AEI) in respective districts, and the colored bars denote the source of irrigation as a percentage of AEI.

Table S8. Water availability per capita and per hectare in subdivisions of Maharashtra state (CCA: culturable command area). Data are compiled from the Kelkar committee's report on balanced regional development issues in Maharashtra (GOM, 2013). Water availability is estimated based on interstate awards on water sharing of major river basins and natural water availability.

Division and State	Water Availability per ha of CCA (m^3 ha^{-1})	Water Availability per Capita (m^3)	Percentage of non-Irrigation Water Use (%)	Category of Water Availability
Amravati	1974	624	8	Deficit
Aurangabad	1383	438	10	Deficit
Kokan	36507	2283	80	Very high
Nagpur	5818	1331	18	Abundant
Nashik	3695	734	22	Normal
Pune	3531	686	15	Normal
Maharashtra state	5587	1121	21.5	Normal

Table S9. Percentage of relative change in CA (ΔCA), CP (ΔCP), and productivity (ΔProductivity) of Kharif, Rabi, sugarcane, and cotton and change in total annual CA, CP, and productivity (including Kharif, Rabi, sugarcane, and cotton) from 2003-04 to 2018-19 (estimated from annual agriculture statistical reports, http://krishi.maharashtra.gov.in/1238/District-Level, (accessed on 29 November 2021). Kharif and Rabi crops include food grains, cereals, pulses, and oilseeds.

Division	Kharif			Rabi			Sugarcane			Cotton			Total		
	ΔCA	ΔCP	ΔProductivity	ΔCA	ΔCP	ΔProductivity	ΔCA	ΔCP	ΔProductivity	ΔCA	ΔCP	ΔProductivity	ΔCA	ΔCP	ΔProductivity
Amravati	-12.52	-12.56	-0.04	127.43	152.45	11.00	-58.61	-61.07	-5.93	-7.42	90.80	106.10	3.10	0.52	-2.50
Aurangabad	-11.92	-29.24	-19.67	-35.39	-3.73	48.99	183.71	170.52	-4.65	79.16	88.69	5.32	-10.25	68.32	87.54
Kokan	-15.61	-18.83	-3.81	-26.72	-38.72	-16.37	0	0	0	0	0	0	-16.57	-19.67	-3.71
Nagpur	-11.95	14.07	29.54	18.86	143.16	104.58	125.47	153.90	12.61	129.82	299.75	73.94	5.00	45.13	38.23
Nashik	-7.69	15.57	25.20	33.95	114.42	60.07	142.17	352.20	86.73	103.37	98.94	-2.18	17.07	186.67	144.87
Pune	12.51	22.74	9.10	1.12	132.48	129.91	170.57	270.18	36.81	-85.52	-89.84	-88.07	13.77	235.75	195.12
Maharashtra	-9.05	-4.62	4.87	1.11	75.09	73.15	162.79	249.73	33.09	52.72	114.06	40.16	2.46	135.26	129.61

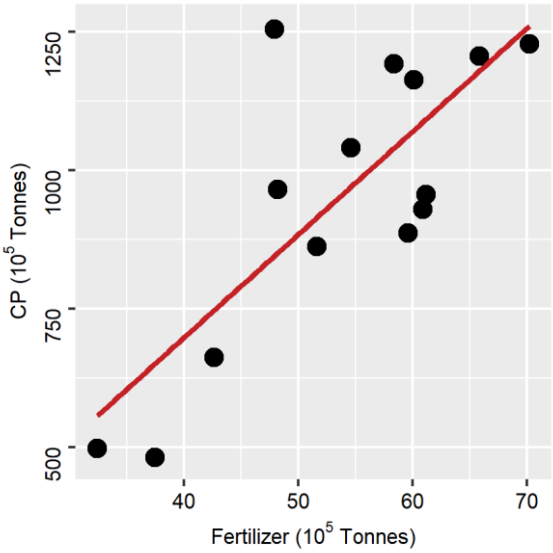

Figure S13. Scatterplot showing correlation between CP and fertilizer use in the state from 2003–2004 to 2016–2017 (r=0.78).

Table S10. Percentage of average contribution of each crop type to total annual CP from 2003-04 to 2018-19.

Division	Food-grains (%)	Cereals (%)	Pulses (%)	Oilseeds (%)	Sugarcane (%)	Cotton (%)
Amaravati	28.76	13.74	15.03	24.66	12.10	5.71
Aurangabad	15.41	11.04	4.37	5.86	61.59	1.74
Kokan	49.25	48.20	1.05	0.42	1.08	0
Nagpur	36.83	30.03	6.80	12.75	11.00	2.59
Nashik	16.62	14.60	2.02	1.73	63.73	1.30
Pune	4.80	4.40	0.40	1.19	89.21	0
Total Maharashtra	12.78	10.25	2.53	3.90	69.54	0.99