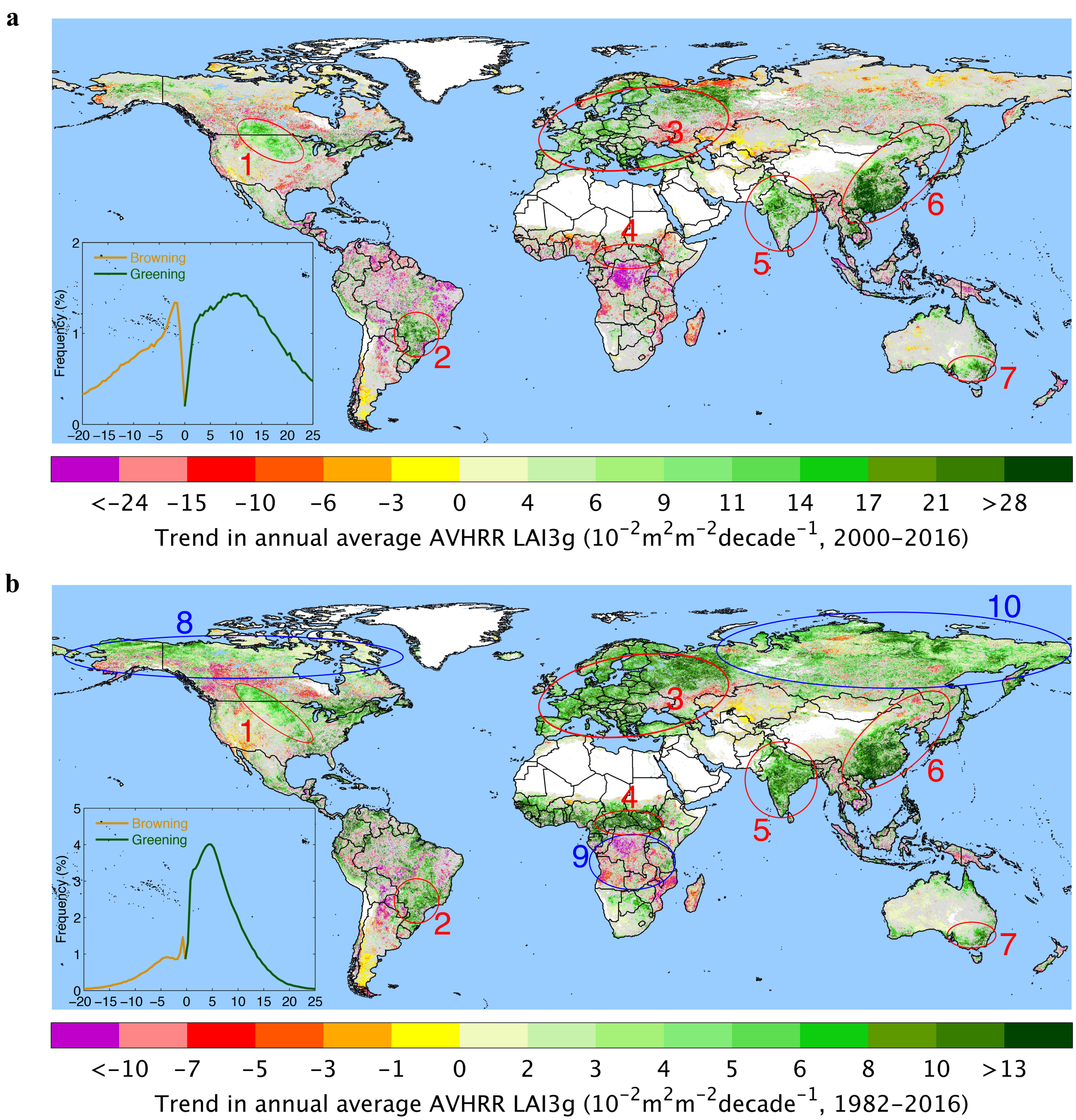
China and India lead in greening of the world through land-use management

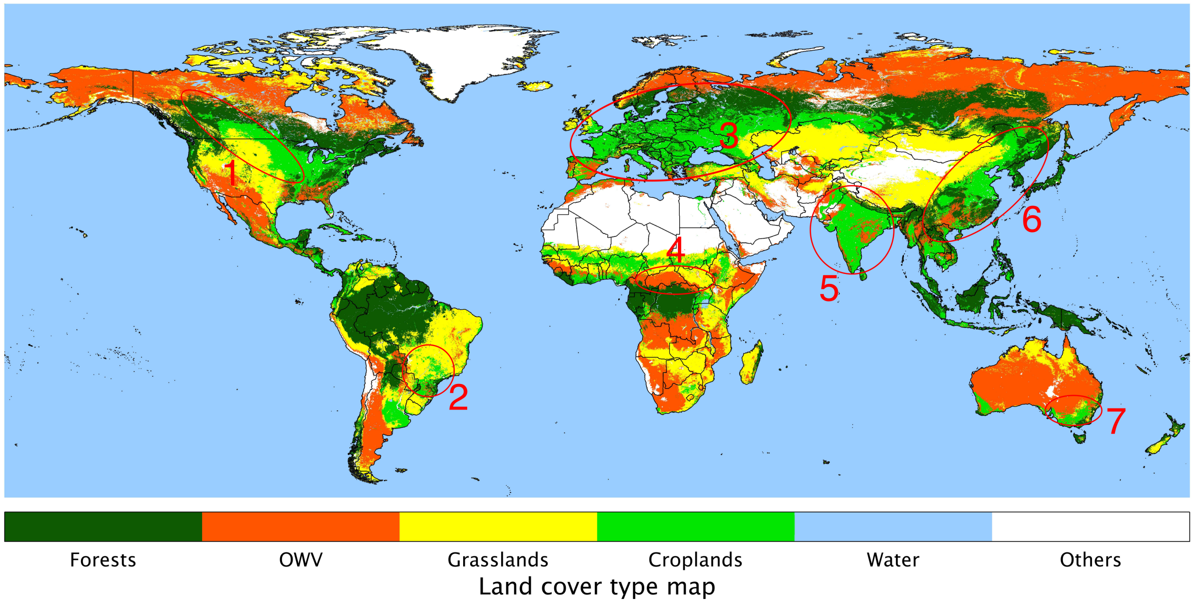
Chi Chen[1], Taejin Park[1], Xuhui Wang[2], Shilong Piao[2], Baodong Xu[1,3], Rajiv K. Chaturvedi[4], Richard Fuchs[5], Victor Brovkin[6], Philippe Ciais[7], Rasmus Fensholt[8], Hans Tømmervik[9], Govindasamy Bala[10], Zaichun Zhu[11], Ramakrishna R. Nemani[12], Ranga B. Myneni[1]

[1]Department of Earth and Environment, Boston University, Boston, MA 02215, USA
[2]Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
[3]College of Resource and Environment, Huazhong Agricultural University, 1 Shizishan Street, Wuhan 430070, China
[4]Birla Institute of Technology and Science, Pilani, Goa 403726, India
[5]Institute of Meteorology and Climate Research – Atmospheric Environmental Research, Karlsruhe Institute of Technology, 82467 Garmisch-Partenkirchen, Germany
[6]Max-Planck-Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany
[7]Laboratoire des Sciences du Climat et de l'Environnement/IPSL, CEA-CNRS-UVSQ, Université Paris Saclay, Gif-sur-Yvette, France
[8]Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark
[9]Norwegian Institute for Nature Research, Fram Centre, 9296 Tromsø, Norway
[10]Center for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, Karnataka 560012, India
[11]Shenzhen Key Laboratory of Circular Economy, Shenzhen Graduate School, Peking University, Shenzhen 518055, China
[12]NASA Ames Research Center, Moffett Field, CA 94035, USA



Supplementary Figure 1 | Maps of trends in annual average AVHRR LAI3g. a, 2000–2016. **b.** 1982–2016**.** Statistically significant trends (Mann-Kendall test, $p \leq 0.1$) are color coded. Grey areas show vegetated lands with statistically insignificant trends. White areas depict barren lands, permanent ice-covered areas, permanent wetlands and built-up areas. Blue areas represent water. The insets show the frequency distribution of statistically significant trends. The highlighted areas in red circles are prominent greening clusters seen in MODIS LAI data (Fig. 1). The greening cluster 4 is only seen in the longer record of AVHRR LAI3g data. Similarly, greening clusters 8 and 10 (in blue) are seen in the longer record of AVHRR LAI3g data only, while the browning cluster 9 (in blue) is seen only in the AVHRR LAI3g data.

a



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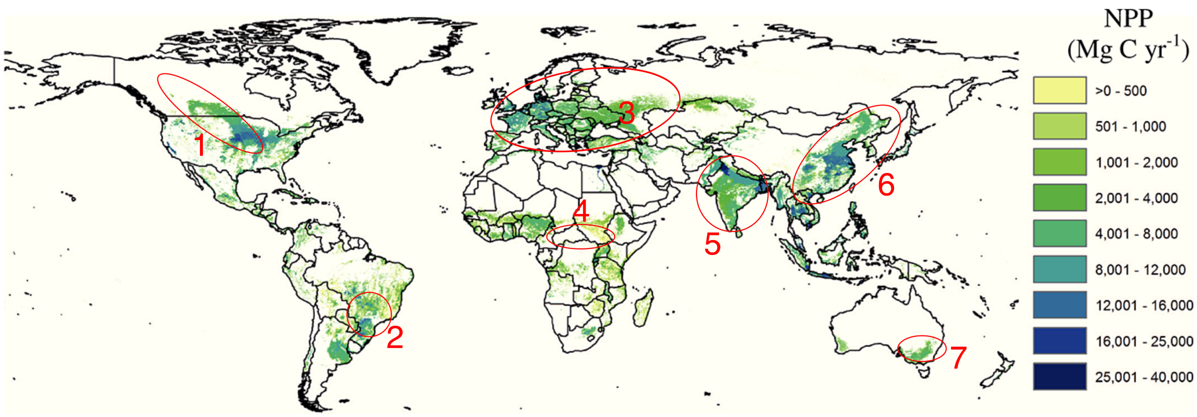
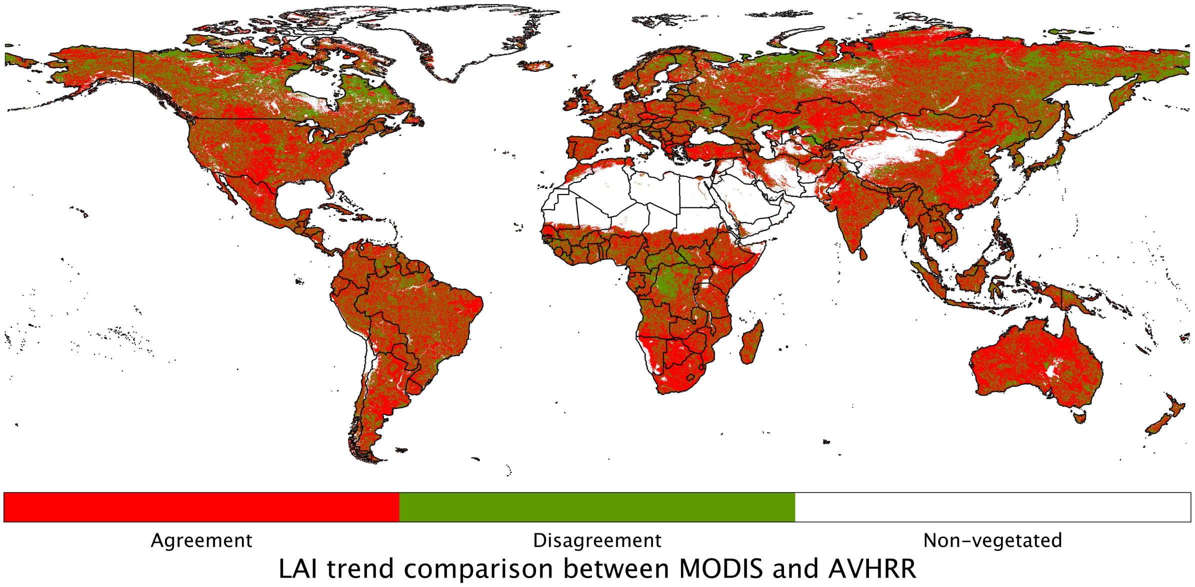


Supplementary Figure 2 | Maps of broad vegetation classes and agricultural Net Primary Production (NPP). a, Global map of the distribution of broad vegetation classes used in presented analysis. The broad vegetation classes are aggregated from year 2007 MCD12C1 product (also known as MODIS land cover type product, see Methods). OWV refers to other woody vegetation. **b,** NPP for global croplands in year 2009 at half-degree resolution, according to Wolf et al.[28]. This underlying image is a screen-shot of Fig. 3 in Wolf et al.[28]. The numbered-circled areas shown on these two maps are identical to the ones shown in Fig. 1 to highlight the strong greening trends in croplands globally.



Supplementary Figure 3 | Comparison of LAI trends from the MODIS and AVHRR sensors for the overlapping period 2000 to 2016. Trends from the two sensors agree in about 61% of the global vegetated area and disagree over the rest. Agreement signifies that the LAI trends from the two sensors show statistically significant greening or browning, or both show statistically insignificant trends. Land areas shown in white are non-vegetated areas, or areas for which data from one or both sensors are lacking. The disagreement is mostly seen in tropical humid areas and Northern high latitudes where data quality is poor due to persistent cloud coverage or extreme sun-sensor geometries. The spatial resolution of MODIS LAI product (500 m) was downgraded to match the spatial resolution of AVHRR data (8 km) to perform this comparison.

Supplementary Table 1 | Comparison of data and processing from AVHRR and MODIS sensors.

AVHRR	MODIS
Broad red and near-infrared wavelength channels. These are not necessarily chosen to be responsive to changes in vegetation as these are meteorological sensors.	Narrow red and near-infrared wavelength channels designed specifically to respond to vegetation changes[60].
No on-board calibration. Sensor calibrated before launch, but loses calibration over time[61].	On-board calibration. Sensor calibrated before launch and during operation regularly. The sensor is also periodically calibrated using the moon[62].
Multiple sequential sensors with no overlap[53]. Each sensor data span is about 3 to 4 years. Inter-sensor data calibration is a major problem.	Two near-simultaneous sensors. The Terra MODIS data stream started in Feb 2000 (Aqua MODIS stream started in May 2002). Overlaps allows inter-sensor calibration.
Satellite loses orbit over time. Data is collected over progressively lower and lower sun angles[63]. Variations in data due to sun angle changes are conflated with changes in vegetation.	Both Terra and Aqua platforms maintain precise orbits. Any orbit loss is periodically corrected by pushing the satellites into their designated orbits. Variations in data due to changes in sun-sensor geometry are explicitly considered during LAI retrievals[1,26].
Minimal correction for atmospheric contamination of signals emanating from vegetation. Sensor lacks additional wavelength channels required for accurate cloud screening, correction for daily tropospheric aerosol contamination and periodic stratospheric aerosol contamination (following volcanic eruptions)[27,53].	Sensor has several channels that are used to accurately screen for clouds, including high cirrus. Atmospheric correction for molecular and tropospheric aerosol contamination is performed accurately with a radiative transfer-based algorithm on a daily basis for each of the seven vegetation channels[64,65].
As no physics-based processing is possible with AVHRR channel data, the daily red and near-infrared channel data are used to compute Normalized Difference Vegetation Index (NDVI) and the maximum value over a 15-day period, which generally corresponds to the data with minimal atmospheric contamination, is provided to users as the end product[53,66].	The physics-based processing removes atmospheric effects and provides users with at-ground reflectance data for each of the seven channels[64].
Leaf area products are derived using black-box approaches such as neural nets. These are trained using AVHRR NDVI and MODIS LAI products from the overlap period (2000 onwards) between the two sensors. Partial validation with ground measurements[27]. No suitable field data prior to 2000 exist for validation.	The channel reflectance data are used in other physics-based algorithms to derive leaf area estimates[1,26] and tree/non-tree fractions[55,67]. The derived products are extensively validated with ground measurements[25,52]. All the algorithms have been periodically updated and the entire archive is re-processed to produce newer versions of the data products. Currently, the 6th version of data products

	are used in our analyses[24,25].
Low spatial resolution (8×8 km^2) and 15-day frequency for the period July 1981 to December 2016[27,53].	Moderate spatial resolution (500×500 m^2), 8-day frequency for the period Feb 2000 to Dec 2017[24,25].
AVHRR LAI data prior to 2000 are not evaluated as required field data are not available. Ground data collected as part of MODIS validation efforts after 2000 were used to test the quality of AVHRR LAI data and these are described in Zhu et al.[27].	The quality of C6 MODIS LAI data sets was comprehensively evaluated against ground-based measurements of LAI and through inter-comparisons with other satellite retrieved LAI products[24,25]. These data sets represent the latest and best quality LAI products currently available. They resulted from two decades of research on the LAI algorithm development, testing, refinement and validation – these efforts are described in over 50 peer-refereed journal articles listed at the MODIS Land validation web site[52].

Supplementary Table 2 | Changes in leaf area globally by sensor and time period.

Sensor & time period	Proportion of vegetated lands showing greening (%)	Proportion of vegetated lands showing browning (%)	Net change in leaf area per decade (million km^2)	Net change in leaf area per decade (%, in comparison with the 1st year of each period)
MODIS (2000–2017)	34.10	4.85	3.17	2.32
AVHRR (2000–2016)	22.42	13.54	1.47	2.19
AVHRR (1982–2016)	40.91	10.59	2.49	1.97

Supplementary Table 3 | Net changes in leaf area per decade (10^{-1} million km^2) globally by biome type, sensor and time period.

Sensor & time period	Forests	Other woody vegetation	Grasslands	Croplands	All vegetation
MODIS (2000–2017)	9.84	6.76	4.61	10.50	31.71
AVHRR (2000–2016)	–0.29	4.44	2.17	8.41	14.73
AVHRR (1982–2016)	6.29	6.68	4.21	7.73	24.91

Supplementary Table 4 | Changes in green leaf area of China and India by sensor and time period.

Sensor & time period	Proportion of vegetated lands showing greening (%)	Net change in leaf area per decade (10^{-1} million km^2)	Net change in leaf area per decade (%, in comparison with the 1st year of each period)
		China	
MODIS (2000–2017)	65.56	7.95	10.47
AVHRR (2000–2016)	44.72	6.87	8.59
AVHRR (1982–2016)	49.41	2.95	3.96
		India	
MODIS (2000–2017)	69.02	2.15	6.53
AVHRR (2000–2016)	48.30	2.25	6.66
AVHRR (1982–2016)	68.94	1.85	5.67

Supplementary Table 5 | Changes in forest area calculated from inventory data in China.

Time period	Forest area (10^6 km^2)	Accumulated afforested area (10^6 km^2)	Forest coverage (%)
1999-2003	1.75	0.54	18.21
2004-2008	1.95	0.62	20.36
2009-2013	2.08	0.69	21.63
Change (1999-2013)	0.33 (19%)	0.16 (30%)	3.42 (19%)

Source: State Forestry Administration of the People's Republic of China at http://data.forestry.gov.cn

Supplementary Table 6 | Major afforestation programs under implementation in China.

Program Name	Brief Summary
Three North Shelterbelt Development Program (TNSDP)	Also known as the "Green Great Wall," this program started in November 1978 with the goal of increasing forest cover from 5.05% (1978) to 15.95% (2050) over the semi-arid "Three North" regions[68]. This is an area of 4.07 million km^2 covering 13 provincial districts in northern China including Beijing, Gansu, Hebei, Heilongjiang, Jilin, Liaoning, Inner Mongolia, Ningxia, Qinghai, Shaanxi, Shanxi, Tianjin and Xinjiang. The afforestation program is designed for (1) sandstorm and (2) soil and water erosion reduction, (3) vegetation restoration, (4) forest conservation and (5) cropland protection. It has been reported that the forest cover reached 13.02% in 2016[69].
Beijing-Tianjin Sand Source Control Program (BSSCP)	This has been implemented since 2001 with the aim of reducing impacts of sandstorms. The first stage was completed in 2010, which covered 0.46 million km^2 over five provincial districts (i.e. Beijing, Hebei, Inner Mongolia, Shanxi, and Tianjin)[70]. The second stage, which expanded to Shaanxi province, was launched in 2013 and is expected to finish in 2022[71]. Forest inventory data shows that forest cover within BSSCP has increased by 12.13% from 2000 to 2013[72].
Natural Forest Conservation Program (NFCP)	This program has been launched in 1998 and it is projected to run through 2050[73]. Three stages have been adopted: experimentation stage (1998-2000), stage I (2001-2010) and stage II (2011-2016). The program aims to protect ecological environment and enrich biodiversity, e.g. facilitating forest restoration by controlling harvests and minimizing the impact of natural disturbance[71,73]. The program covers 18 provincial districts: Chongqing, Gansu, Guizhou, Hainan, Heilongjiang, Henan, Hubei, Hunan, Inner Mongolia, Jiangxi, Jilin, Ningxia, Qinghai, Shaanxi, Shanxi, Sichuan, Xinjiang and Yunnan. Compared to the TNSDP, NFCP covers many regions in southern China because most of the natural forests in China are in the south.
Grain to Green Program (GTGP)	It is China's largest ecological engineering program that was initiated in 1999, mainly focusing on mountainous regions[71,72]. This program aims to (1) reclaim croplands back to forests, (2) afforest semi-arid mountainous regions and (3) reinforce forest

	conservation[71,74]. This program centralizes the croplands which increased crop production by 24% in 2013 as compared to 1998. By 2013, there are still 10% of the cropland areas that have the potential to be restored to forests in the future[71]. The program covers 25 provincial districts: Anhui, Beijing, Chongqing, Gansu, Guangxi, Guizhou, Hainan, Hebei, Heilongjiang, Henan, Hubei, Hunan, Inner Mongolia, Jiangxi, Jilin, Liaoning, Ningxia, Qinghai, Shaanxi, Shanxi, Sichuan, Tianjin, Tibet, Xinjiang and Yunnan.

Supplementary Table 7 | Areal statistics for trends in LAI and NDVI for India.

	Forests	Other woody vegetation	Grasslands	Croplands	All vegetation
Areal fraction (%)	8.9	17.38	1.81	71.92	100 (2.94 million km^2)
			LAI 2000-2017		
Greening (%)	2.79 (31.36)	10.29 (59.25)	0.81 (45.09)	55.12 (76.65)	69.02
Browning (%)	0.30 (3.33)	0.19 (1.07)	0.03 (1.70)	0.28 (0.39)	0.79
			NDVI 2000-2017		
Greening (%)	4.19 (47.04)	9.48 (54.55)	0.73 (40.16)	52.55 (73.06)	66.94
Browning (%)	0.10 (1.16)	0.07 (0.43)	0.02 (0.88)	0.24 (0.33)	0.43
			NDVI 2001-2014		
Greening (%)	1.68 (18.88)	7.96 (45.79)	0.45 (24.73)	48.33 (67.20)	58.41
Browning (%)	0.72 (8.13)	0.72 (4.17)	0.05 (2.71)	0.69 (0.96)	2.19

Numbers inside parenthesis are relative areal fraction whose denominator is the area of each vegetation type. Numbers outside parenthesis are absolute areal fraction whose denominator is the area of all vegetation.

Supplementary Table 8 | Statistics from FAO of the top four agricultural countries and European Union[75,76].

Country	2000	2014	Change (%)
Dry matter production (million tonnes)			
Brazil	165.3	354.7	114.6%
China	569.9	792.9	39.1%
India	347.8	470.6	35.3%
USA	424.5	536.5	26.4%
EU	341.9	381.3	11.5%
Fertilizer application (million tonnes)			
Brazil	5.8	13.9	138.2%
China	29.7	47.2	58.9%
India	16.2	25.6	58.0%
USA	17.5	18.8	7.5%
EU	18.9	14.1	–25.1%
Harvested area (1000 ha)			
Brazil	50485	75679	49.0%
India	177421	199976	12.7%
China	161330	178059	10.4%
United States	101414	102751	1.3%
EU	88793	83392	-6.1%

These “big five” account for about 70% of global food production and fertilizer application.

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