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Characteristics, drivers and feedbacks of global greening

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Table. S1 | Categorization of vegetation indices based on three derivative forms of surface reflectance with respect to wavelength. Details for the derivative forms can be found in ref. 1.

Type	Vegetation Index
Type 1	NDVI (Normalized Difference Vegetation Index; ref. 2), SR (Simple Ration; ref. 3), SAVI (Soil Adjusted Vegetation Index; ref. 4), TSAVI (Transformed Soil Adjusted Vegetation Index; ref. 5), OSAVI (Optimized Soil Adjusted Vegetation Index; ref. 6), PVI (Perpendicular Vegetation Index; ref. 7), WDVI (Weighted Difference Vegetation Index; ref. 8), GCI (Green Chlorophyll Index, ref. 9), GNDVI (Green Normalized Difference Vegetation Index; ref. 10), GRVI (Green Ratio Vegetation Index; ref. 11), PRI (Photochemical Reflectance Index; ref. 12), DVI (Difference Vegetation Index; ref. 13), NDWI (Normalized Difference Water Index; ref. 14), CCI (Chlorophyll/Carotenoid Index; ref. 15)
Type 2	GEMI (Global Environmental Monitoring Index; ref. 16), Greenness (ref. 17), NLI (Non-Linear Index; ref.18), NIRv (Near-Infrared Reflectance of Vegetation, ref. 19)
Type 3	EVI (Enhanced Vegetation Index, ref. 20), ARVI (Atmospherically Resistant Vegetation Index; ref. 21), SARVI (Soil Adjusted and Atmospherically Resistant Vegetation Index; ref. 21), GARI (Green Atmospherically Resistant Index; ref. 22)

Table. S2 | Summary of satellite global NDVI products.

NDVI Product	Time span	Data input source	Ground Sampling Distance	Frequency	Reference
MODIS[#,*]	2000 (2002) – Present	Terra(Aqua)/MODIS C6 reflectance	250 m, 500 m, 1 km, and 0.05°	16-day & Monthly	Ref. 23
VIIRS[#,*]	2012 - Present	Suomi-NPP/VIIRS reflectance	500 m, 1 km, and 0.05°	16-day & Monthly	Ref. 24
DSCOVR[#]	2015 – Present	DSCOVR/EPIC reflectance	10 km	Hourly & daily	Ref. 25
NDVI3g	1981 - 2018	AVHRR GAC level-1b data	1/12°	Biweekly	Ref. 26
VIP4	1981 - 2016	LTDR3 AVHR09C1 and MOD09CMG data	0.05°	Daily, 7-day, 15-day, monthly	Ref. 27
LTDR5[#]	1981 - Present	AVHRR GAC level-1b data	0.05°	Daily	Ref. 28
CGLS[#] (or GEOV2)	1999 - Present	SPOT/VGT & PROBA-V reflectance	1/112°	10-day	Ref. 29

[#]: The product has been operationally generated, archived, and disseminated.

[*]: EVI (Enhanced Vegetation Index) is also available in this product.

Table. S3 | Comparison of data and processing from AVHRR, MODIS, SPOT-VGT and MERIS sensors.

AVHRR	MODIS	SPOT-VGT	MERIS
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 [30].	Moderately narrow red and near-infrared wavelength channels designed specifically to respond to vegetation changes[31].	Very narrow red and near-infrared wavelength channels designed specifically to respond to vegetation changes.
No on-board calibration. Sensor calibrated before launch, but loses calibration over time[32].	On-board calibration. Sensor calibrated before launch and during operation regularly. The sensor is also periodically calibrated using the moon[33].	No on-board calibration. Sensor calibrated before launch, but loses calibration over time[31].	Sensor calibrated before launch and during operation regularly. MERIS on-board calibration is based on on-board measurements of sunlight[34].
Multiple sequential sensors with little or no overlap[26]. 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.	Two sensors. VEGETATION 1 (VGT1) on board SPOT4, launched in March 1998, and VEGETATION 2 (VGT2) on board SPOT5 launched in May 2002[35]. After February 2003, VGT1 has no longer been used for VI products. Overlaps allows inter-sensor calibration.	One sensor. The ENVISAT MERIS LAI data stream started in July 2002 and ended in March 2012[36]. No official products for NDVI and EVI.

Satellite loses orbit over time. Data is collected over progressively lower and lower sun angles[37]. 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[38,39] .	The signal is stable. Irradiance variations due to sun-earth distance and sun-sensor geometry are explicitly corrected[31].	Orbital information is unknown.
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)[40].	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[41,42].	A simplified physics-based atmospheric correction algorithm (based on the 6S method) is employed for water vapor, ozone, and tropospheric aerosol[31].	Several different radiative transfer-based algorithms are used for atmospheric correction for aerosol optical thickness, columnar water vapor and surface reflectance, as well as for LAI retrieval[36,43].
No physics-based processing is possible with AVHRR channel data. NDVI and EVI generally correspond	The physics-based processing removes atmospheric effects and provides users with at-ground reflectance data for each of the seven	A simplified physics-based processing removes atmospheric effects and provides users with at-	No official products available for NDVI and EVI. Various approaches were proposed based on top of

to the data with minimal atmospheric contamination[26,44].	channels, and for NDVI and EVI products[20,42].	ground reflectance data for NDVI and EVI products.	atmosphere reflectance and surface reflectance.
LAI products are derived using black-box approaches such as neural nets. Partial validation with ground measurements[40]. 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[39,45]. The derived products are extensively validated with ground measurements[46]. All the algorithms have been periodically updated and the entire archive is re-processed to produce newer versions of the data products.	LAI products are derived using black-box approaches i.e., neural networks. The product has been extensively validated with ground measurements[47].	The LAI retrieval based on the BEAM MERIS vegetation processor. This algorithm is trained by neural networks with a suite of simulated top-of-atmosphere radiances, using the Scattering by Arbitrarily Inclined Leaves (SAIL), PROSPECT and a simplified method for atmospheric correction[36].
Low spatial resolution (8×8 km^2) and 15-day frequency for the period July 1981 to December 2016[26,40].	Moderate spatial resolution (500×500 m^2), 8-day/16-day frequency for the period Feb 2000 to Dec 2018[20,46,48].	1/112° ×1/112° spatial resolution (1×1 km^2), 10-day frequency for the period 1999-present[47].	1/360° ×1/360° spatial resolution (300×300 m^2), 10-day frequency for the from 2002-2012[36].

Table. S4 | Summary of satellite global LAI products.

LAI Product	Time span	Data input source	Ground Sampling Distance	Frequency	Algorithm	Reference
MODIS#	2000 (2002) – Present	Terra(Aqua)/MODIS C6 reflectance	500 m	8-day (4-day for Terra/Aqua combined)	LUT based on 3D RT	Ref. 46,48
VIIRS#	2012 – Present	Suomi-NPP/VIIRS reflectance	500 m	8-day	LUT based on 3D RT	Ref. 49
DSCOVR#	2015 – Present	DSCOVR/EPIC reflectance	10 km	Hourly & daily	LUT based on 3D RT	Ref. 50
LAI3g	1981 – 2018	GIMMS NDVI3g	1/12º	Biweekly	ANN trained with MODIS LAI	Ref. 40
GLASS	1981 – 2017	NOAA/AVHRR LTDR reflectance & Terra/MODIS C6 reflectance	0.05º (1km available from 2000)	8-day	GRNN trained with CYCLOPES and MODIS LAIs	Ref. 51
TCDR#	1981 – Present	NOAA/AVHRR TCDR reflectance	0.05º	Daily	ANN trained with MODIS LAI	Ref. 52
GLOBMAP	1981 – 2017	GIMMS NDVI & Terra/MODIS C6 reflectance	1/13.75º	Biweekly, 1982 – 1999/2 8-day, 2000/3 – 2017	LUT based on RT	Ref. 53

CGLS[#] (or GEOV2)	1999 – Present	SPOT/VGT & PROBA-V reflectance	1/112º	10-day	ANN trained with CYCLOPES and MODIS LAIs	Ref. 29
MERIS	2002-2012	ENVISAT/MERIS reflectance	1/360º	10-day	ANN trained with 1D RT	Ref. 36

[#]: The product has been operationally generated, archived, and disseminated.

Data Archives

MODIS: https://earthdata.nasa.gov/
VIIRS: https://earthdata.nasa.gov/
GLASS: http://globalchange.bnu.edu.cn/research/lai
TCDR: https://www.ncei.noaa.gov/data/avhrr-land-leaf-area-index-and-fapar/access/
LAI3g: http://sites.bu.edu/cliveg/datacodes/
GLOBMAP: http://www.globalmapping.org/
CGLS LAI: https://land.copernicus.eu/global/products/lai
CGLS NDVI: https://land.copernicus.eu/global/products/ndvi
NDVI3g: https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/
VIP4: https://vip.arizona.edu/viplab_data_explorer.php
LTDR5: https://ltdr.modaps.eosdis.nasa.gov/cgi-bin/ltdr/ltdrPage.cgi?fileName=products

Table. S5 | CMIP5 models used in this study.

Model abbreviation	Historical	RCP2.6	RCP4.5	RCP6.0	RCP8.5
bcc-csm1-1	√	√	√	√	√
Bcc-csm1-1-m	√	√	√	√	√
BNU-ESM	√	√	√		√
CCSM4	√	√	√	√	
CESM1-BGC	√		√		√
CESM1-CAM5	√	√	√	√	√
CanESM2	√	√	√		√
GFDL-CM3	√		√		
GFDL-ESM2G	√	√		√	√
GFDL-ESM2M	√		√	√	√
HadGEM2-CC	√		√		√
HadGEM2-ES	√	√	√	√	√
IPSL-CM5A-LR	√	√	√	√	√
IPSL-CM5A-MR	√	√	√	√	√
MIROC-ESM-CHEM	√	√	√	√	√
MIROC-ESM	√	√	√	√	√
MPI-ESM-LR	√	√	√		√
MPI-ESM-MR	√	√	√		√
NorESM1-ME	√	√	√	√	√
NorESM1-M	√	√	√	√	√
inmcm4	√		√		√

References

1. Myneni, R. B. *et al.* The meaning of spectral vegetation indices. *IEEE Trans. Geosc. Remote Sens.* **33**, 481-486 (1995).

2. Rouse, J., Haas, R.H., Schell, J.A. & Deering, D.W. Monitoring vegetation systems in the Great Plains with ERTS. *In Proceedings of the 3rd ERTS Symposium, Washington DC, USA, NASA SP-351*, 309-317 (1974).

3. Birth, G. S., & McVey, G. R. Measuring the color of growing turf with a reflectance spectrophotometer 1. *Agron. J.* **60**, 640-643 (1968).

4. Huete, A.R. A soil-adjusted vegetation index (SAVI). *Remote Sens. Environ.* **25**, 295-309 (1988).

5. Baret, F., Guyot, G. and Major, D.J. TSAVI: a vegetation index which minimizes soil brightness effects on LAI and APAR estimation. *In 12th Canadian Symposium on Remote Sensing Geoscience and Remote Sensing Symposium* **3**, 1355-1358 (1989).

6. Rondeaux, G., Steven, M. & Baret, F. Optimization of soil-adjusted vegetation indices. *Remote Sens. Environ.* **55**, 95-107. (1996).

7. Richardson, A.J. & Wiegand, C.L. Distinguishing vegetation from soil background information. *Photogramm. Eng. Remote Sens.* **43**, 1541-1552 (1977).

8. Clevers, J.G.P.W. Application of a weighted infrared-red vegetation index for estimating leaf area index by correcting for soil moisture. *Remote Sens. Environ.* **29**, 25-37 (1989).

9. Gitelson, A.A., Gritz, Y. & Merzlyak, M.N. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in

higher plant leaves. *J. Plant Physiol.* **160**, 271-282 (2003).

10. Gitelson, A.A. & Merzlyak, M.N. Remote sensing of chlorophyll concentration in higher plant leaves. *Adv. Space Res.* **22**, 689-692 (1998).
11. Sripada, R.P., Heiniger, R.W., White, J.G. & Meijer, A.D. Aerial color infrared photography for determining early in-season nitrogen requirements in corn. *Agron. J.* **98**, 968-977 (2006).
12. Gamon, J.A., Penuelas, J. & Field, C.B. A narrow-waveband spectral index that tracks diurnal changes in photosynthetic efficiency. *Remote Sens. Environ.* **41**, 35-44 (1992).
13. Tucker, C.J. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens. Environ.* **8**, 127-150 (1979).
14. McFeeters, S.K. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *Int. J. Remote Sens.* **17**, 1425-1432 (1996).
15. Gamon, J.A. *et al*. A remotely sensed pigment index reveals photosynthetic phenology in evergreen conifers. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 13087-13092 (2016).
16. Pinty, B. & Verstraete, M.M. GEMI: a non-linear index to monitor global vegetation from satellites. *Vegetatio* **101**, 15-20 (1992).
17. Jackson, R.D. Spectral indices in n-space. *Remote Sens. Environ.* **13**, 409-421 (1983).
18. Goel, N.S. & Qin, W. Influences of canopy architecture on relationships between various vegetation indices and LAI and FPAR: A computer simulation. *Remote Sens. Rev.* **10**, 309-347 (1994).
19. Badgley, G., Field, C. B. & Berry, J. A. Canopy near-infrared reflectance and terrestrial photosynthesis. *Sci. Adv.* **3**, e1602244 (2017).

20. Huete, A., Didan, K., Miura, T., Rodriguez, E. P., & Gao, X. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.* **83**, 195-213 (2002).

21. Kaufman, Y.J. & Tanre, D. Atmospherically resistant vegetation index (ARVI) for EOS-MODIS. *IEEE Trans. Geosci. Remote Sens.* **30**, 261-270 (1992).

22. Gitelson, A.A., Kaufman, Y.J. & Merzlyak, M.N. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. *Remote Sens. Environ.* **58**, 289-298 (1996).

23. Didan, K., Munoz, A.B., Solano, R. & Huete, A., MODIS vegetation index user's guide (MOD13 series). *Vegetation Index and Phenology Lab, The University of Arizona,* 1-38 (2015).

24. Didan, K., Munoz, A.B., Compton, J.T. & Pinzon, J.E. Suomi-VIIRS Vegetation Index Product Suite User Guide & Abridged Algorithm Theoretical Basis Document. *Vegetation Index and Phenology Lab, The University of Arizona,* 1-100 (2017).

25. Knyazikhin, Y., Song, W., Yang, B., Park, T. & Myneni, R.B. DSCOVR EPIC Vegetation Earth System Data Record Science Data Product Guide (2018).

26. Pinzon, E. J. & Tucker, J. C. A Non-Stationary 1981–2012 AVHRR NDVI3g Time Series. *Remote Sens.* **6**, 6929-6960 (2014).

27. Barreto-munoz, A., Didan, K., Miura, T. & Tsend-Ayush, J. December. Version 4 of the Vegetation Index and Phenology Earth Science Data Records. *In AGU Fall Meeting Abstracts* (2014).

28. Pedelty, J. *et al*. Generating a long-term land data record from the AVHRR and MODIS

instruments. *In 2007 IEEE International Geoscience and Remote Sensing Symposium* 1021-1025 (2007).

29. Baret, F., *et al.* GEOV1: LAI and FAPAR essential climate variables and FCOVER global time series capitalizing over existing products. Part1: Principles of development and production. *Remote Sens. Environ.* **137**, 299-309 (2013).
30. Justice, C. O., Townshend, J., & Vermote, E. F. An overview of MODIS Land data processing and product status. *Remote Sens. Environ.* **83**, 3-15 (2002).
31. Toté, C. *et al.* Evaluation of the SPOT/VEGETATION Collection 3 reprocessed dataset_ Surface reflectances and NDVI. *Remote Sens. Environ.* **201**, 219-233 (2017).
32. Staylor, W. F. Degradation rates of the AVHRR visible channel for the NOAA 6, 7, and 9 spacecraft. *J. Atmos. Oceanic Technol.* **7**, 411-423 (1990).
33. Xiong, X., Wu, A., & Cao, C. On-orbit calibration and inter-comparison of Terra and Aqua MODIS surface temperature spectral bands. *Int. J. Remote Sens.* **29**, 5347-5359 (2008).
34. Bourg, L., & Delwart, S. MERIS instrument calibration. *In Second MERIS and AATSR Calibration and Geophysical Validation Workshop, Frascati, Italy* 20-24 (2006).
35. Deronde, B. *et al.* 15 years of processing and dissemination of SPOT-VEGETATION products. *Int. J. Remote Sens.* **35**, 2402-2420 (2014).
36. Tum, M., *et al*. Global gap-free MERIS LAI time series (2002–2012). *Remote Sens.* **8**, 69 (2016).
37. Kaufman, R. K. *et al.* Effect of orbital drift and sensor changes on the time series of AVHRR vegetation index data. *IEEE Trans. Geosci. Remote Sens.* **38**, 2584-2597 (2000).

38. Knyazikhin, Y. *et al.* Synergistic algorithm for estimating vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from MODIS and MISR data. *J. Geophys. Res. D: Atmos.* **103**, 32257-32275 (1998).

39. Myneni, R. B. *et al*. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**, 698-702 (1997).

40. Zhu, Z. *et al.* Global Data Sets of Vegetation Leaf Area Index (LAI)3g and Fraction of Photosynthetically Active Radiation (FPAR)3g Derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the Period 1981 to 2011. *Remote Sens.* **5**, 927-948 (2013).

41. Frey, R. A. *et al.* Cloud Detection with MODIS. Part I: Improvements in the MODIS Cloud Mask for Collection 5. *J. Atmos. Oceanic Technol.* **25**, 1057-1072 (2008).

42. Vermote, E. F., Saleous, El, N. Z., & Justice, C. O. Atmospheric correction of MODIS data in the visible to middle infrared: first results. *Remote Sens. Environ.* **83**, 97-111 (2002).

43. Guanter, L., Gómez-Chova, L., & Moreno, J. Coupled retrieval of aerosol optical thickness, columnar water vapor and surface reflectance maps from ENVISAT/MERIS data over land. *Remote Sens. Environ.***112**, 2898-2913 (2008).

44. Holben, B. N. Characteristics of maximum-value composite images from temporal AVHRR data. *Int. J. Remote Sens.* **7**, 1417-1434 (1986).

45. Knyazikhin, Y. *et al.* Estimation of vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from atmosphere-corrected MISR data. *J. Geophys. Res. D: Atmos.* **103**, 32239-32256 (1998).

46. Yan, K. *et al.* Evaluation of MODIS LAI/FPAR Product Collection 6. Part 2: Validation and Intercomparison. *Remote Sens.* **8**, 460 (2016).

47. Verger, A., Baret, F., & Weiss, M. GEOV2/VGT: near real time estimation of global biophysical variables from VEGETATION-P data. *In MultiTemp 2013: 7th International Workshop on the Analysis of Multi-Temporal Remote Sensing Images*, 1-4 (2013).

48. Yan, K. *et al.* Evaluation of MODIS LAI/FPAR Product Collection 6. Part 1: Consistency and Improvements. *Remote Sens.* **8**, 359 (2016).

49. Yan, K. *et al.* Generating global products of lai and fpar from snpp-viirs data: Theoretical background and implementation. *IEEE Trans. Geosci. Remote Sens.* **56**, 2119-2137 (2018).

50. Yang, B., *et al.* Estimation of leaf area index and its sunlit portion from DSCOVR EPIC data: Theoretical basis. *Remote Sens. Environ.* **198**, 69-84 (2017).

51. Xiao, Z., Liang, S., Wang, T., & Jiang, B. Retrieval of Leaf Area Index (LAI) and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) from VIIRS Time-Series Data. *Remote Sens.* **8**, 351 (2016).

52. Claverie, M., Matthews, J., Vermote, E. & Justice, C. A 30+ year AVHRR LAI and FAPAR climate data record: Algorithm description and validation. *Remote Sens.* **8**, 263 (2016).

53. Liu, Y., Liu, R., & Chen, J. M. Retrospective retrieval of long-term consistent global leaf area index (1981-2011) from combined AVHRR and MODIS data. *J. Geophys. Res. Biogeosci.* **117**, G04003 (2012).