Cite as: Z. Zhu *et al.*, *Science* 10.1126/science.abg5673 (2021).

Comment on "Recent global decline of CO_2 fertilization effects on vegetation photosynthesis"

Zaichun Zhu[1]*, Hui Zeng[1], Ranga B. Myneni[2], Chi Chen[3,4], Qian Zhao[1], Junjun Zha[1], Simin Zhan[1], Ian MacLachlan[1]

[1]Peking University Shenzhen Graduate School, Peking University, Shenzhen 518055, Guangdong, China. [2]Department of Earth and Environment, Boston University, Boston, MA 02215, USA. [3]Department of Earth and Environmental Sciences, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA. [4]Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, USA.

*Corresponding author. Email: zhu.zaichun@pku.edu.cn

Wang *et al.* (Research Articles, 11 December 2020, p. 1295) reported a large decrease in CO_2 fertilization effect (CFE) across the globe during the period 1982–2015 and suggested that ecosystem models underestimate the rate of CFE decline. We find that their claims are artifacts of incorrect processing of satellite data and problematic methods for deriving and comparing CFE between satellite data and model simulations.

Using satellite data as proxies of gross primary production (GPP), Wang *et al.* presented a statistical analysis quantifying changes in CO_2 fertilization effect (CFE) on global vegetation photosynthesis (*1*). They concluded that "global CFE has declined across most terrestrial regions of the globe from 1982 to 2015" and attributed this decline in CFE partly to nutrient limitations. However, we notice in their analysis a relatively constant CFE decline across much of the global vegetated land, including regions with both decreasing (e.g., Europe) and increasing (e.g., China and India) nitrogen and phosphorus deposition (*2*) [see figures 2 and S31 of (*1*)], which suggests that nutrient limitations are unlikely to explain the reported CFE decline. The relatively uniform rate of CFE decline over the highly heterogeneous global land, where the environmental control of photosynthesis varies enormously, raises the concern that their derived CFE could actually be an artifact of the data and/or model used in their study.

In Wang *et al.*, the main satellite proxy for pre-2000 vegetation photosynthesis was derived from the Advanced Very High Resolution Radiometers (AVHRR), which have large uncertainties in monitoring vegetation dynamics [see table S1 in (*3*) for a detailed description]. To correct this issue, Wang *et al.* merged the AVHRR (1982–2000) and the more advanced Moderate Resolution Imaging Spectroradiometer (MODIS) (2001–2015) data using a cumulative distribution frequency (CDF)–matching approach [text S1 in (*1*)]. However, rather than adjusting the less accurate and unreliable AVHRR data according to the more accurate and reliable MODIS data, they corrected the MODIS data to match the AVHRR data. Thus, their analysis brings even more uncertainties into their fused dataset. To test how this data fusion may have affected β—the regression-derived coefficient of CO_2 against GPP proxies that Wang *et al.* inferred as CFE (*1*)—we calculated MODIS NIRv (2001–2015) from the MODIS reflectance product (MCD43C4 C6) following the methodology in (*4*) without adjustments. This original MODIS NIRv shows a larger increasing trend than the CDF-adjusted MODIS NIRv (Fig. 1A). Hence, $\beta^{2001-2015}_{\text{MODIS NIRv (original)}}$ (18.3 ± 32.3% 100 ppm^{-1}) is significantly larger than $\beta^{2001-2015}_{\text{MODIS NIRv (CDF-adjusted)}}$ (13.4 ± 29.1% 100 ppm^{-1}) (Fig. 1, B and C).

Similar problems also exist in the way that Wang *et al.* use leaf area index (LAI) data. They used the GIMMS LAI3g and a CDF-fused GIMMS+MODIS LAI data (degrading the more accurate MODIS LAI data to match GIMMS LAI3g) to help substantiate the large decreasing trend in β during 1982–2015. However, these two LAI datasets inherit the same large uncertainties from AVHRR-derived LAI before 2000 (*5*, *6*). To test the robustness of LAI-derived β changes, we performed the same analyses as in (*1*) using the latest version of GIMMS LAI3g, GLASS LAI, GLOBMAP LAI, MODIS LAI, and CGLS (Copernicus Global Land Service) LAI. These widely used long-term LAI data show large discrepancies (Fig. 1D). Furthermore, except for GIMMS LAI3g, analyses with other LAI data do not show a clear decreasing trend in β during 1982–2015 (Fig. 1E). Indeed, analyses with LAI data derived from the more advanced sensors (i.e., MODIS LAI and CGLS LAI) reveal much higher β values during 2001–2015 (19.3 ± 33.6% 100 ppm^{-1} and 37.7 ± 49.7% 100 ppm^{-1}, respectively) than that estimated from the AVHRR-based LAI data (Fig. 1F).

In addition to problematic uses of satellite data, we also find the claim that TRENDY models underestimated the decreasing rate of CFE (*1*) to be incorrect. The authors drew this conclusion by comparing regression-based β trends from satellite proxies and factorial simulation–based β trends from TRENDY models [figure 2D in (*1*)]. We used the same methods as in (*1*) to derive both regression-based and factorial simulation–based β trends from TRENDY models, and found the two quantities completely unrelated (Fig. 2). This suggests that β derived from regression models does not represent CFE. Furthermore, the comparison in (*1*) is also fundamentally flawed because the regression-based β was derived from observations and simulations with varying climate, whereas the simulation-based β was derived from simulations with pre-industrial climatic conditions.

The magnitude of CFE on plants in a CO_2-richer world is still poorly understood. A careful examination of Wang *et al.* (*1*) reveals their main conclusion of a large decline in CFE during 1982–2015 to be an artifact of incorrect processing of satellite data and the regression methods used. Furthermore, their comparison between CFE changes estimated from a regression model with satellite data and from factorial simulations with TRENDY models is flawed and the claim of underestimated CFE changes by TRENDY models is unjustified. Thus, Wang *et al.* have at best proven a declining trend of an unknown quantity based on dubious data and faulty methods. Therefore, we suggest the use of all available remote sensing and in situ data and model simulations to carefully account for uncertainties in the quantification of CFE before drawing firm conclusions.

REFERENCES

1. S. Wang, Y. Zhang, W. Ju, J. M. Chen, P. Ciais, A. Cescatti, J. Sardans, I. A. Janssens, M. Wu, J. A. Berry, E. Campbell, M. Fernández-Martínez, R. Alkama, S. Sitch, P. Friedlingstein, W. K. Smith, W. Yuan, W. He, D. Lombardozzi, M. Kautz, D. Zhu, S. Lienert, E. Kato, B. Poulter, T. G. M. Sanders, I. Krüger, R. Wang, N. Zeng, H. Tian, N. Vuichard, A. K. Jain, A. Wiltshire, V. Haverd, D. S. Goll, J. Peñuelas, Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. *Science* **370**, 1295–1300 (2020). doi:10.1126/science.abb7772 Medline
2. X. Liu, Y. Zhang, W. Han, A. Tang, J. Shen, Z. Cui, P. Vitousek, J. W. Erisman, K. Goulding, P. Christie, A. Fangmeier, F. Zhang, Enhanced nitrogen deposition over China. *Nature* **494**, 459–462 (2013). doi:10.1038/nature11917 Medline
3. C. Chen, T. Park, X. Wang, S. Piao, B. Xu, R. K. Chaturvedi, R. Fuchs, V. Brovkin, P. Ciais, R. Fensholt, H. Tømmervik, G. Bala, Z. Zhu, R. R. Nemani, R. B. Myneni, China and India lead in greening of the world through land-use management. *Nat. Sustain.* **2**, 122–129 (2019). doi:10.1038/s41893-019-0220-7 Medline
4. G. Badgley, C. B. Field, J. A. Berry, Canopy near-infrared reflectance and terrestrial photosynthesis. *Sci. Adv.* **3**, e1602244 (2017). doi:10.1126/sciadv.1602244 Medline
5. C. Jiang, Y. Ryu, H. Fang, R. Myneni, M. Claverie, Z. Zhu, Inconsistencies of interannual variability and trends in long-term satellite leaf area index products. *Glob. Change Biol.* **23**, 4133–4146 (2017). doi:10.1111/gcb.13787 Medline
6. S. Piao, X. Wang, T. Park, C. Chen, X. Lian, Y. He, J. W. Bjerke, A. Chen, P. Ciais, H. Tømmervik, R. R. Nemani, R. B. Myneni, Characteristics, drivers and feedbacks of global greening. *Nat. Rev. Earth Environ.* **1**, 14–27 (2019). doi:10.1038/s43017-019-0001-x
7. Z. Zhu, J. Bi, Y. Pan, S. Ganguly, A. Anav, L. Xu, A. Samanta, S. Piao, R. Nemani, R. Myneni, 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). doi:10.3390/rs5020927
8. Y. Liu, R. G. Liu, J. M. Chen, 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). doi:10.1029/2012JG002084
9. Z. Xiao, S. Liang, J. Wang, Y. Xiang, X. Zhao, J. Song, Long-Time-Series Global Land Surface Satellite Leaf Area Index Product Derived From MODIS and AVHRR Surface Reflectance. *IEEE Trans. Geosci. Remote Sens.* **54**, 5301–5318 (2016). doi:10.1109/TGRS.2016.2560522
10. K. Yan, T. Park, G. Yan, C. Chen, B. Yang, Z. Liu, R. Nemani, Y. Knyazikhin, R. Myneni, Evaluation of MODIS LAI/FPAR Product Collection 6. Part 1: Consistency and Improvements. *Remote Sens.* **8**, 359 (2016). doi:10.3390/rs8050359
11. A. Verger, F. Baret, M. Weiss, Near Real-Time Vegetation Monitoring at Global Scale. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* **7**, 3473–3481 (2014). doi:10.1109/JSTARS.2014.2328632

ACKNOWLEDGMENTS

The authors are grateful for the contributions of several colleagues who made suggestions for improvement of the manuscript. **Funding:** Supported by the National Natural Science Foundation of China (41901122). R.B.M. acknowledges with gratitude funding by NASA Earth Science Division. C.C. is supported by the US Department of Energy Office of Science Biological and Environmental Research, Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation Scientific Focus Area. **Author contributions:** Conceptualization, Z.Z., H.Z., R.B.M.; investigation, all authors; validation, all authors; writing–original draft, Z.Z., R.B.M.; writing–review and editing, all authors. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** The datasets used to compute CO_2 fertilization effect were derived from the MODIS reflectance product (https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/6/MCD43C4/), MODIS LAI (https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/6/MCD15A2H/), GIMMS LAI3g (http://sites.bu.edu/cliveg/datacodes/), GLOBMAP LAI (courtesy of R. Liu), GLASS LAI (courtesy of Z. Xiao), and CGLS LAI (https://land.copernicus.eu/global/products/lai), air temperature and vapor pressure from the Climatic Research Unit (https://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.01/), and GPP from 12 ecosystem models (i.e., CABLE, CLM4.5, DLEM, ISAM, JULES, LPJ-GUESS, LPJ-wsl, LPX-Bern, ORCHIDEE-MICT, ORCHIDEE, VEGAS, and VISIT) participating in the TRENDY project (http://dgvm.ceh.ac.uk/node/9).

14 January 2021; accepted 13 August 2021
Published online 24 September 2021
10.1126/science.abg5673

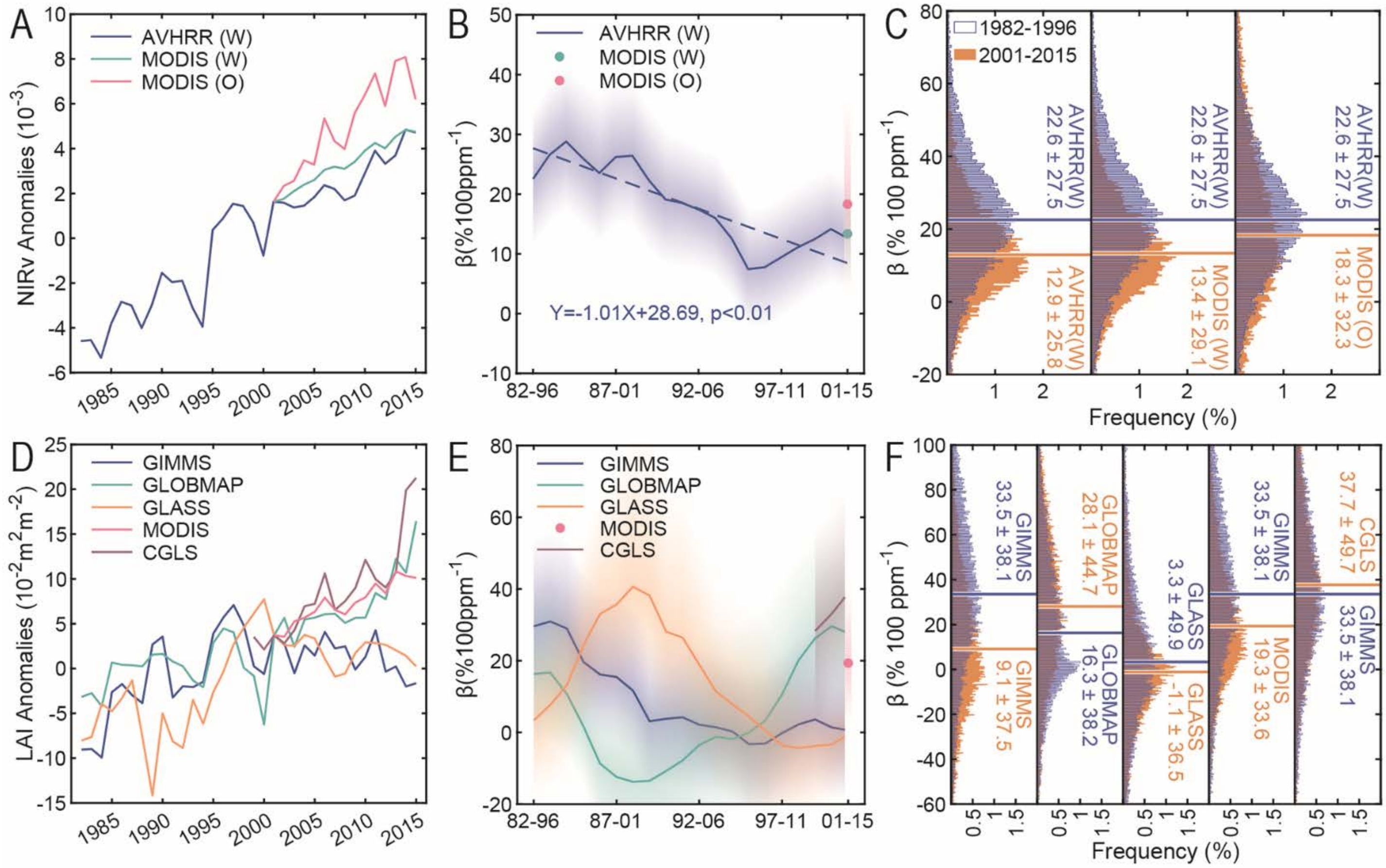

Fig. 1. Changes in CO_2 fertilization effect (CFE) on global vegetation. (**A**) Interannual changes in anomalies of the growing season mean NIRv derived from AVHRR NIRv and MODIS NIRv obtained from (*1*) [AVHRR (W) and MODIS (W), respectively], and the original MODIS NIRv (*4*) [MODIS (O)]. (**B**) Changes in CFE (β) estimated from the NIRv datasets with 15-year moving windows. (**C**) Histograms showing the distribution of β across all pixels during 1982–1996 (blue) and 2001–2015 (orange) based on the NIRv datasets. (**D**) Interannual changes in anomalies of the growing season mean leaf area index (LAI) derived from the GIMMS LAI3g (*7*), GLOBMAP LAI (*8*), GLASS LAI (*9*), MODIS LAI (*10*), and CGLS LAI (*11*). (**E**) Changes in β estimated from the LAI datasets with 15-year moving windows. (**F**) Histograms showing the distribution of β across all pixels during 1982–1996 (blue) and 2001–2015 (orange) based on the LAI datasets.

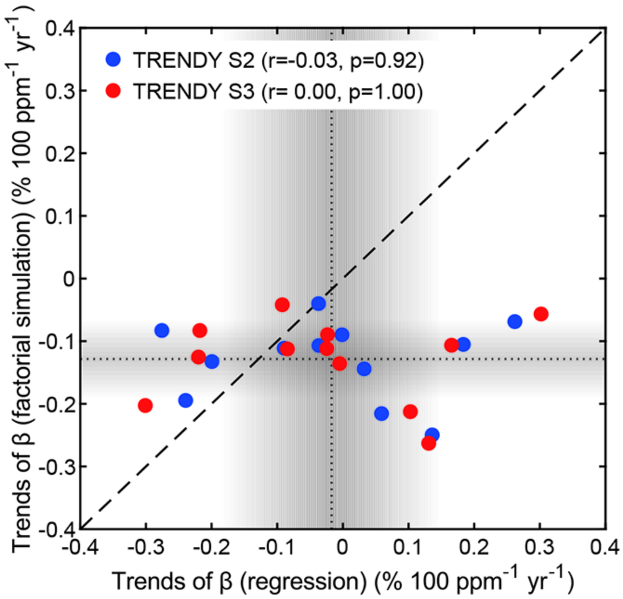

Fig. 2. Comparison between regression-based and factorial simulation–based β trends derived from 12 TRENDYv6 models using the methods in (*1*). The dotted lines and shadings show the mean and SD of the β trends.

Science

Comment on “Recent global decline of CO fertilization effects on vegetation photosynthesis”

Zaichun Zhu, Hui Zeng, Ranga B. Myneni, Chi Chen, Qian Zhao, Junjun Zha, Simin Zhan, and Ian MacLachlan

Science, 373 (6562), eabg5673. • DOI: 10.1126/science.abg5673

Science (ISSN 1095-9203) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.