

## Supplementary material for

A decade of missed opportunities: how Europe went off-track to reduce nitrogen pollution over the last decade

Masooma Batool<sup>1,\*</sup>, Wim de Vries<sup>2</sup>, Gerard H. Ros<sup>2</sup>, Mark A. Sutton<sup>3</sup>, Fanny J. Sarrazin<sup>4</sup>, Udit Bhatia<sup>5</sup>, Shekhar Sharan Goyal<sup>1</sup>, Guy Peer<sup>6</sup>, Rohini Kumar<sup>1,\*</sup>

<sup>1</sup>UFZ-Helmholtz Centre for Environmental Research, Leipzig, Germany.

<sup>2</sup>Université Paris-Saclay, INRAE, UR HYCAR, 92160 Antony, France.

<sup>3</sup>Earth Systems and Global Change Group, Wageningen University and Research, Wageningen, Netherlands.

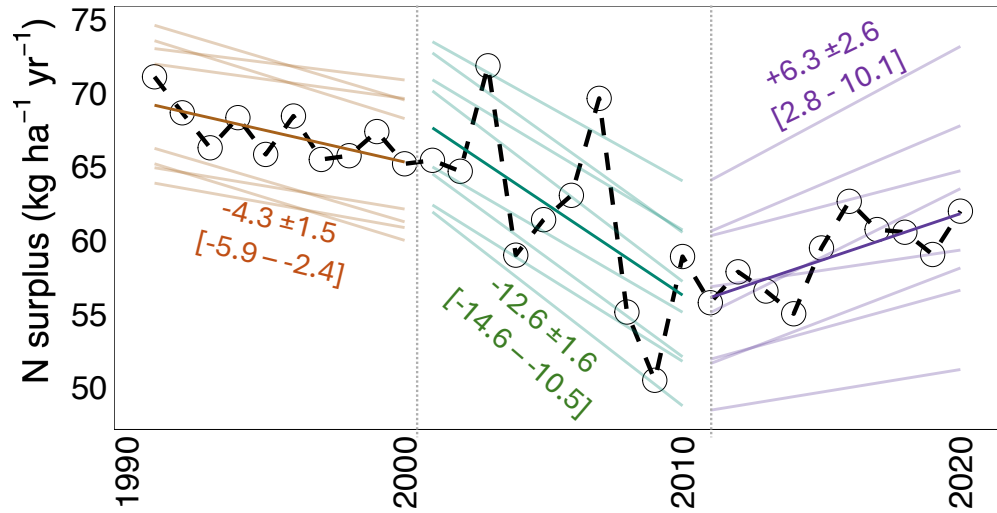
<sup>4</sup>Centre for Ecology and Hydrology, Edinburgh Research Station, Bush Estate, Penicuik, Midlothian EH26 0QB, United Kingdom.

<sup>5</sup>Discipline of Civil Engineering, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar, Gujarat, India, Dr. Kiran C. Patel Center of Sustainable Development, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar, Gujarat, India.

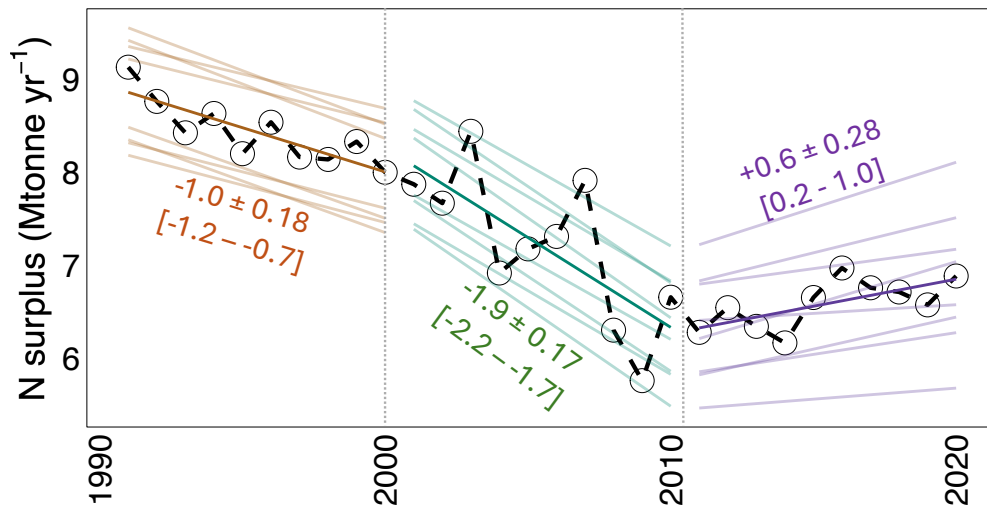
<sup>6</sup>Synthesis Centre (sDiv) of the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany, UFZ - Helmholtz Centre for Environmental Research, Leipzig, Germany, University of Leipzig, Leipzig, Germany.

\*masooma.batool@ufz.de; rohini.kumar@ufz.de.

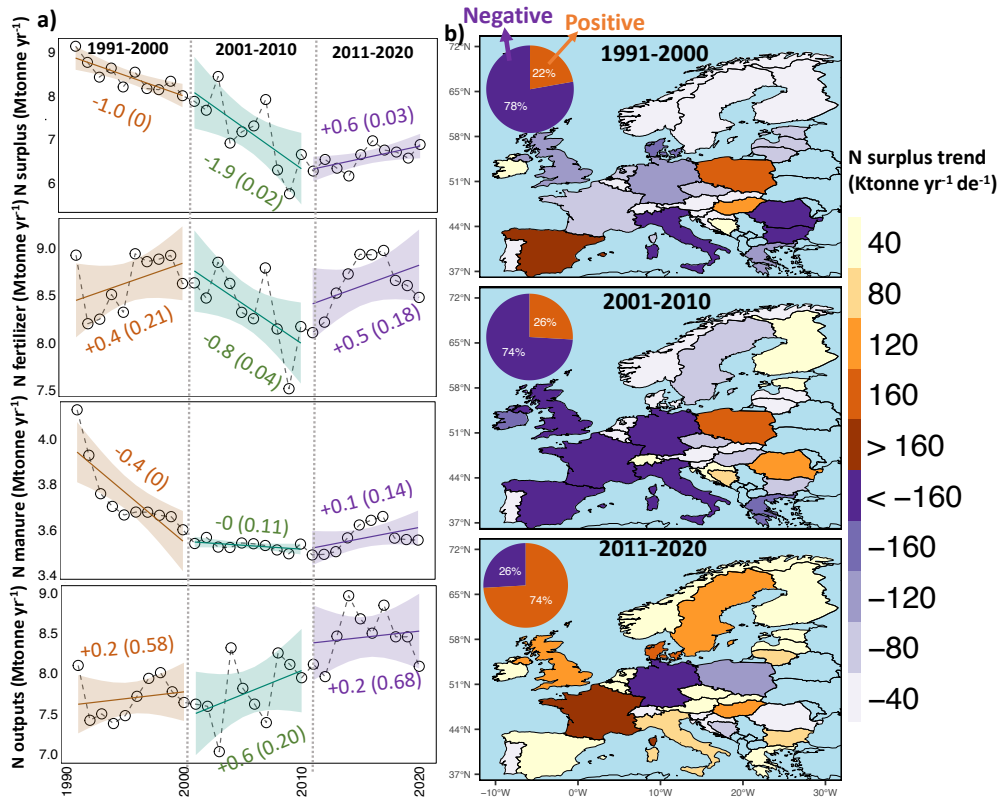
The PDF file includes **Supplementary Figures** supporting the main manuscript.



**Fig. S1 Time series analysis of 8 nitrogen (N) surplus trends in the EU27 from 1991 to 2020.** The figure displays annual fluctuations in N surplus, shown as  $kg\ ha^{-1}\ yr^{-1}$ , across cropland areas. Circles represent annual data points, reflecting changes in N management. Linear regressions for each decade, expressed as  $kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$ , indicate whether N fluxes are increasing (positive values) or decreasing (negative values). The text provides the mean of the eight N surplus trends  $\pm$  one standard deviation (SD), and the corresponding minimum–maximum range in square brackets, all given in  $kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$ .



**Fig. S2 Time series analysis of 8 nitrogen (N) surplus trends in the EU27 from 1991 to 2020.** The figure displays annual fluctuations in N surplus, shown as  $Mtonne\ yr^{-1}$ , across cropland areas. Circles represent annual data points, reflecting changes in N management. Linear regressions for each decade, expressed as  $Mtonne\ yr^{-1}\ decade^{-1}$ , indicate whether N fluxes are increasing (positive values) or decreasing (negative values). The text provides the mean of the eight N surplus trends  $\pm$  one standard deviation (SD), and the corresponding minimum–maximum range in square brackets, all given in  $Mtonne\ yr^{-1}\ decade^{-1}$ . *Mtonne* in the unit stands for million tonnes.



**Fig. S3 Nitrogen surplus trends in the EU27 (1991-2020).** Panel a provides a time series analysis of nitrogen (N) surplus, alongside inputs from N synthetic fertilizers and N animal manure, and the N output at the EU27 level. The circles represent the annual data and show the fluctuations in N management, given as  $Mtonne\ yr^{-1}$ . Linear regressions for each decade (de), expressed in  $Mtonne\ yr^{-1}\ decade^{-1}$ , indicate increasing (positive values) or decreasing (negative values) trends in N fluxes. Numbers in brackets are the  $p$ -values of the decade-specific trends. Panel b maps country-level N surplus trends in the EU, revealing diverse N management approaches across member states in three distinct decades. The pie chart in panel b shows the percentage of countries with positive (orange) and negative (purple) N surplus trends. Mtonne in the unit stands for million tons

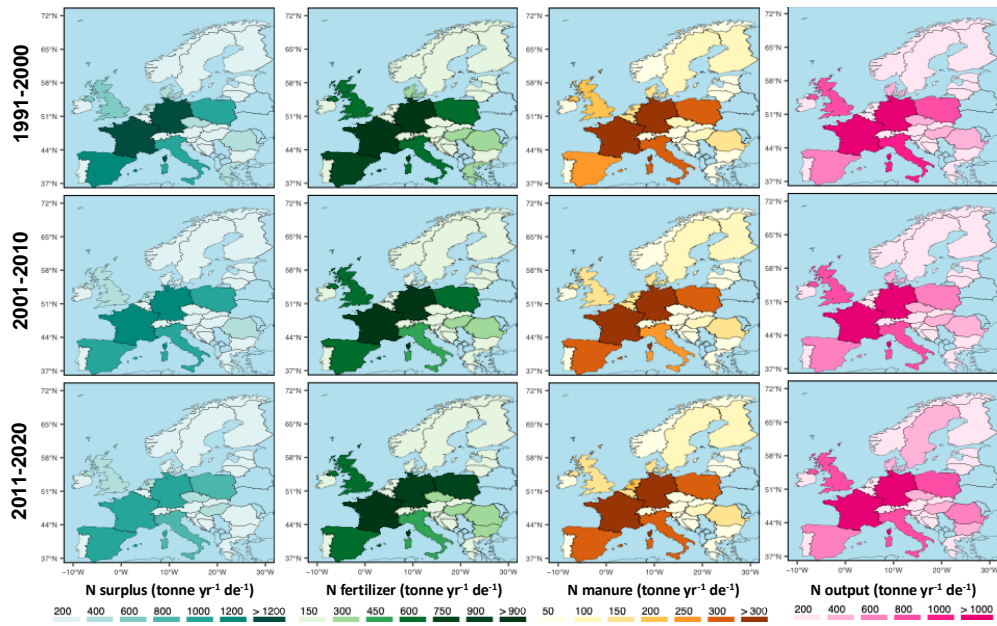
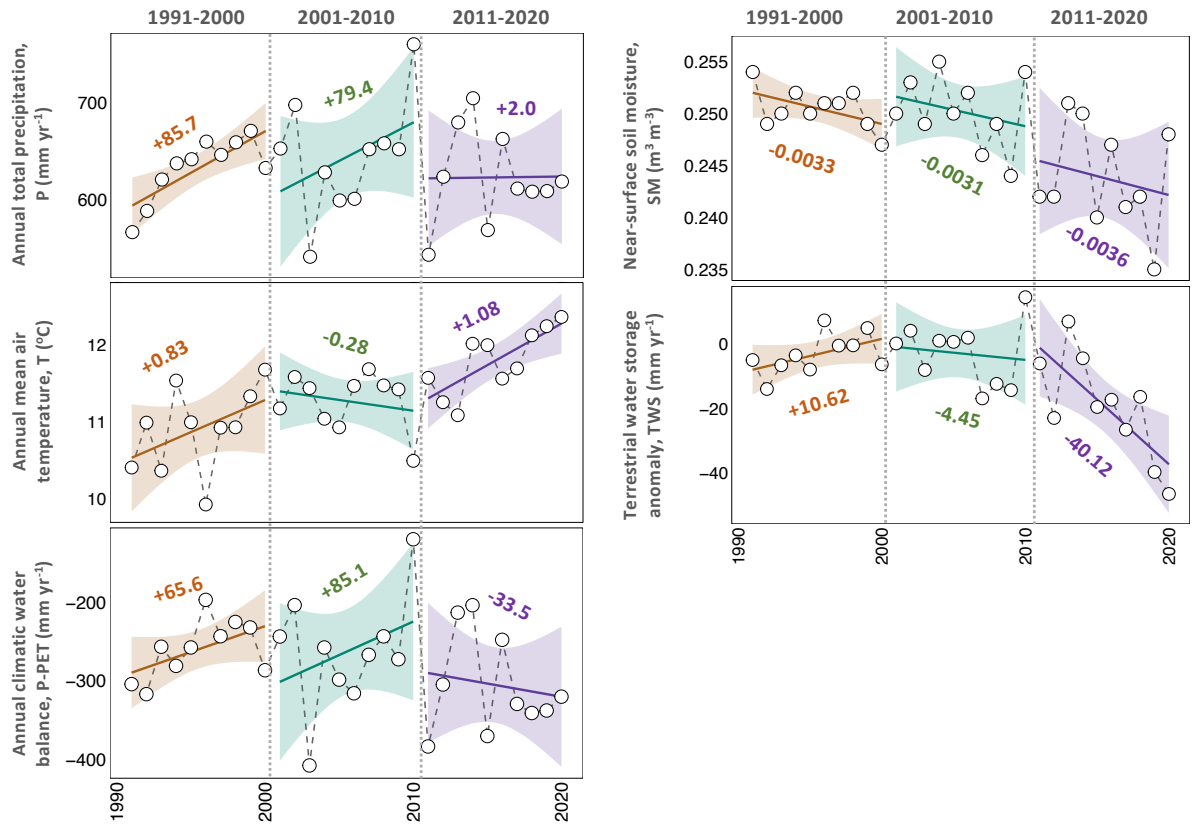
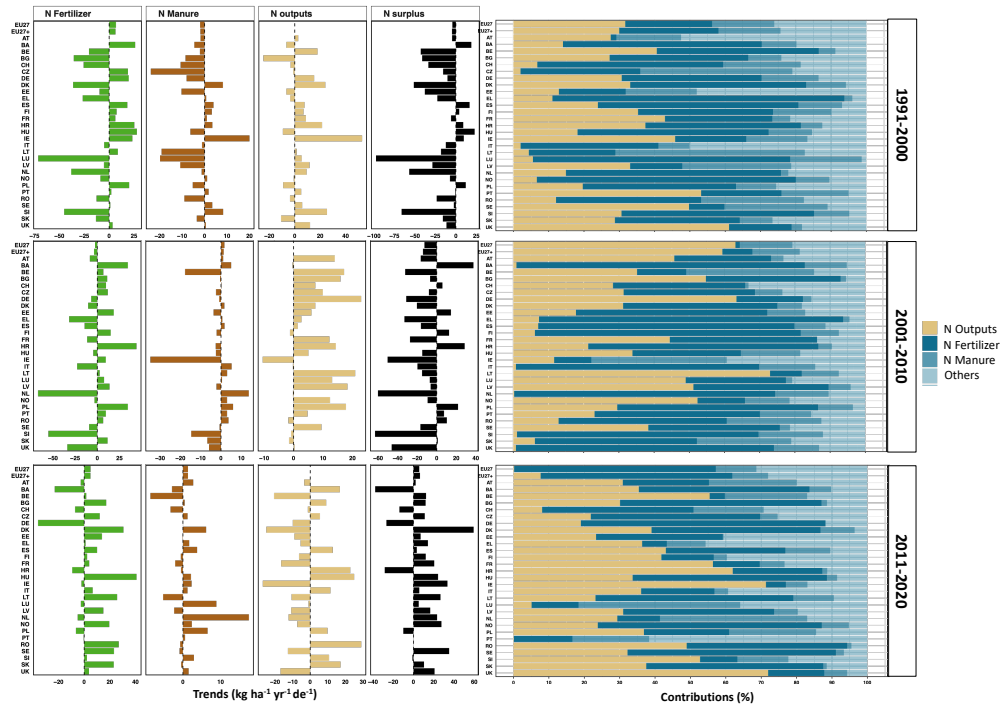


Fig. S4 Nitrogen surplus and its components in three decades.



**Fig. S5 Interannual variability of hydroclimatic states aggregated across European croplands over the last three decades (1991-2020).** The left panels depict variability in annual total precipitation (P), mean air temperature (T), and climatic water balance, expressed as the difference between annual precipitation and potential evapotranspiration (P-PET). These variables are derived from the E-OBS gridded meteorological dataset (v25.0e; [1]), with PET estimated using the Hargreaves and Samani method [2]. The right panels show variability in near-surface soil moisture from the European Space Agency Climate Change Initiative (ESA-CCI) long-term climate data record of merged multi-satellite observations [3], and Terrestrial Water Storage (TWS) anomalies augmented based on the GRACE and GRACE-FO missions data [4] – reflecting variations in overall water storage. As in the other figures, linear regression fits (solid lines, with corresponding uncertainty) are shown for each decade and variable. Trends are reported in respective units at  $\text{de}^{-1}$ , where positive (negative) values indicate increasing (decreasing) trends. Multiple lines of evidence indicate adverse climatic conditions and reduced water storage availability across European croplands during the recent decade (2011-2020), which likely constrained adequate crop growth and contributed to the smaller increase in N output compared to previous decades.



**Fig. S6** Decadal contributions to nitrogen (N) surplus trends at country level in EU27 in three decades (1991-2020). This figure illustrates the trends in synthetic fertilizer, animal manure, and N output, with a focus on their contributions to N surplus trends at the country level in the three decades.

## References

- [1] Cornes, R.C., Schrier, G., Besselaar, E.J.M., Jones, P.D.: An ensemble version of the e-obs temperature and precipitation data sets. *Journal of Geophysical Research: Atmospheres* **123**(17), 9391–9409 (2018) <https://doi.org/10.1029/2017JD028200>  
<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2017JD028200>
- [2] Hargreaves, G.H., Samani, Z.A.: Reference crop evapotranspiration from temperature. *Appl. Engrg. in Agri.* **1**, 96–99 (1985)
- [3] Preimesberger, W., Stradiotti, P., Dorigo, W.: Esa cci soil moisture gapfilled: an independent global gap-free satellite climate data record with uncertainty estimates. *Earth System Science Data* **17**(9), 4305–4329 (2025) <https://doi.org/10.5194/essd-17-4305-2025>
- [4] Palazzoli, I., Ceola, S., Gentile, P.: Graice: reconstructing terrestrial water storage anomalies with recurrent neural networks. *Scientific Data* **12**(1), 146 (2025) <https://doi.org/10.1038/s41597-025-04403-3>