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## Assessment of the relationship between tropospheric NO<sub>2</sub> and photosynthetic activity across seasonal croplands in India

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## Changes in air quality influence vegetation and crop growth

- Large-scale statistical analyses link **satellite NO<sub>2</sub> concentrations** to vegetation activity.
- Results suggest that **changes in NO<sub>2</sub> pollution can influence crop greenness at regional scales.**

SCIENCE ADVANCES | RESEARCH ARTICLE

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ENVIRONMENTAL STUDIES

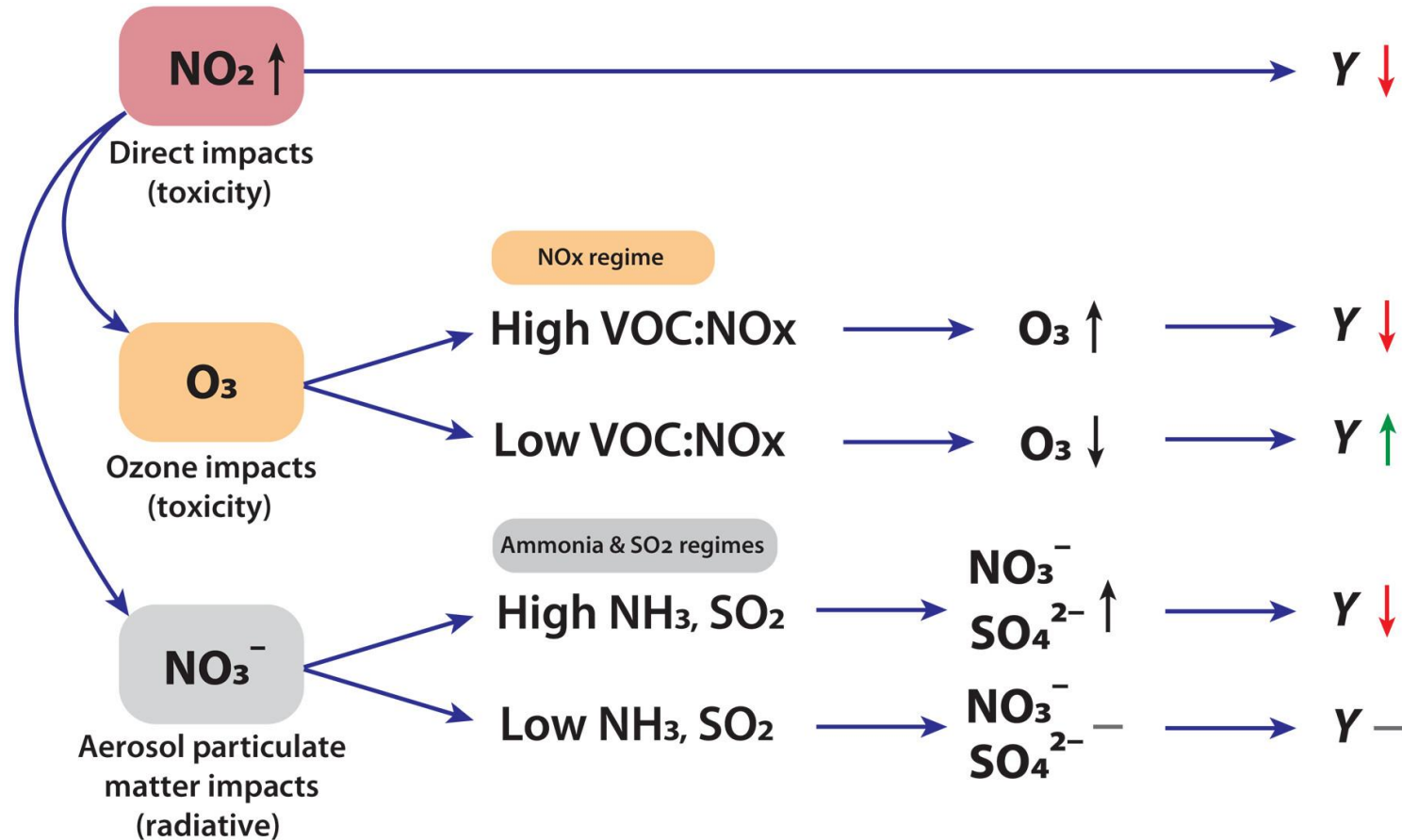
## Globally ubiquitous negative effects of nitrogen dioxide on crop growth

David B. Lobell<sup>1\*</sup>, Stefania Di Tommaso<sup>1</sup>, Jennifer A. Burney<sup>2</sup>

Nitrogen oxides (NO<sub>x</sub>) are among the most widely emitted pollutants in the world, yet their impacts on agriculture remain poorly known. NO<sub>x</sub> can directly damage crop cells and indirectly affect growth by promoting ozone (O<sub>3</sub>) and aerosol formation. We use satellite measures of both crop greenness and NO<sub>x</sub> during 2018–2020 to evaluate crop impacts for five major agricultural regions. We find consistent negative associations between NO<sub>2</sub> and greenness across regions and seasons. These effects are strongest in conditions where O<sub>3</sub> formation is NO<sub>x</sub> limited but remain significant even in locations where this pathway is muted, suggesting a role for direct NO<sub>x</sub> damage. Using simple counterfactuals and leveraging published relationships between greenness and growth, we estimate that reducing NO<sub>x</sub> levels to the current fifth percentile in each region would raise yields by ~25% for winter crops in China, ~15% for summer crops in China, and up to 10% in other regions.

# Introduction

## Pathways of impact for $\text{NO}_2$ on crop yields



Source: Lobell et al. (2022)

# Introduction

## A more mechanistic indicator

- Most studies rely on NDVI or EVI, which measure canopy structure and greenness.
- Structural vegetation changes can occur after physiological stress.
- Solar Induced Fluorescence (**SIF**) is directly linked to photosynthetic activity. It responds rapidly to physiological stress in plants.
- Satellite SIF therefore provides a more mechanistic indicator of crop response to atmospheric pollution.

## Key Questions

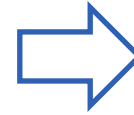
- 1. Does atmospheric NO<sub>2</sub> exposure suppress photosynthetic activity in seasonal croplands of India?*
- 2. Does this relationship remain significant after controlling for climatic drivers?*
- 3. Is the response stronger in high-NO<sub>2</sub> pollution regions?*

# Data

Tropospheric NO <sub>2</sub>	Global daily High Spatial–Temporal Coverage Merged tropospheric NO <sub>2</sub> ( <b>HSTCM-NO<sub>2</sub></b> ) ( <b>Quin et al., 2024</b> )
SIF	Global dataset of solar-induced chlorophyll fluorescence ( <b>GOSIF</b> ) ( <b>Li and Xiao., 2019</b> )
Mean Temperature (T <sub>mean</sub> ) and Precipitation (Precip.)	High-resolution India Meteorological Dataset ( <b>INDmet</b> ) ( <b>Kushwaha et al., 2025</b> )
Root Zone Soil Moisture (RZSM)	High-resolution Soil Moisture Product for India ( <b>Chuphal et al., 2026</b> )
Vapour pressure deficit (VPD)	Derived from <b>ERA-5</b> 2m-air temperature and dew point temperature
Direct and diffuse photosynthetically active radiation	Breathing Earth System Simulator ( <b>BESS</b> ) framework ( <b>Ryu et al., 2018</b> )

All datasets are:

- regridded to a common spatial resolution (0.25°)
- aggregated to monthly values
- analysed over the crop growing areas (wheat and rice) and seasons



## Correlation analysis

Pearson correlation is used to assess relationships between SIF and NO<sub>2</sub> for rice (kharif) and wheat (rabi) growing regions (grids with at least 25% of cropland area is considered)



## Two-way fixed-effects panel MLR

- To control for spatial and temporal heterogeneity
- Isolates within-location variations over time

$$SIF_{it} = \beta_1 NO_{2it} + \beta_n X_{it} + \alpha_i + \gamma_t + \varepsilon_{it}$$

$\alpha_i$  - grid-cell fixed effects

$\gamma_t$  - time fixed effects



## Multiple linear regression (MLR)

- To estimate relationships between SIF and environmental drivers

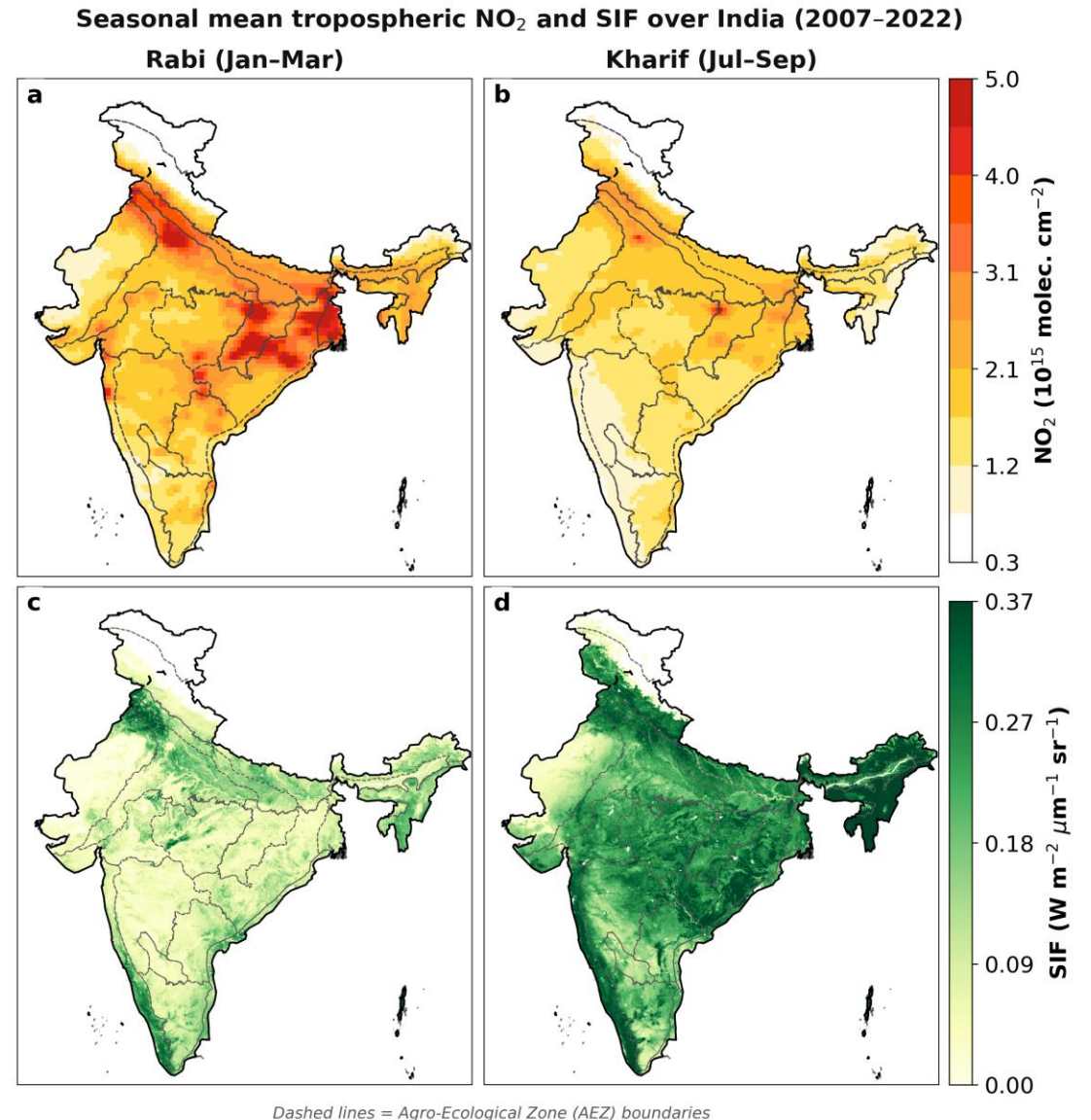
$$SIF_{it} = \beta_1 NO_{2it} + \beta_n X_{it} + \varepsilon_{it}$$

Here, 'i' is grid-cell, 't' is time, ' $\beta$ ' is coefficient, 'X' is vector of climate variables and ' $\varepsilon$ ' is residual

# Results

## Seasonal mean NO<sub>2</sub> column concentration and SIF

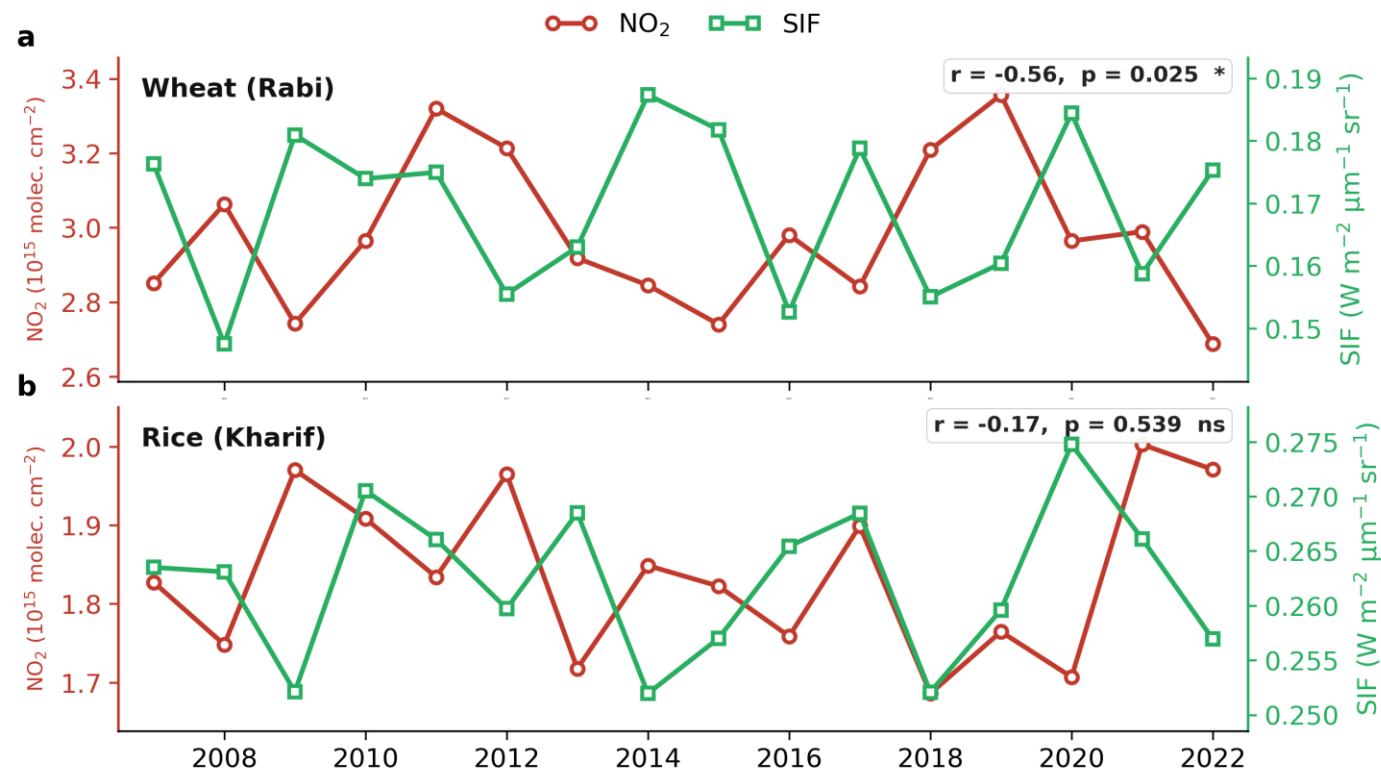
- Rabi season shows elevated NO<sub>2</sub> levels across Indo-Gangetic Plain (IGP).
- Major cropland regions with high pollution overlap with wheat-growing areas.
- SIF patterns reflect seasonal crop productivity, with higher values during the kharif growing season.



# Results

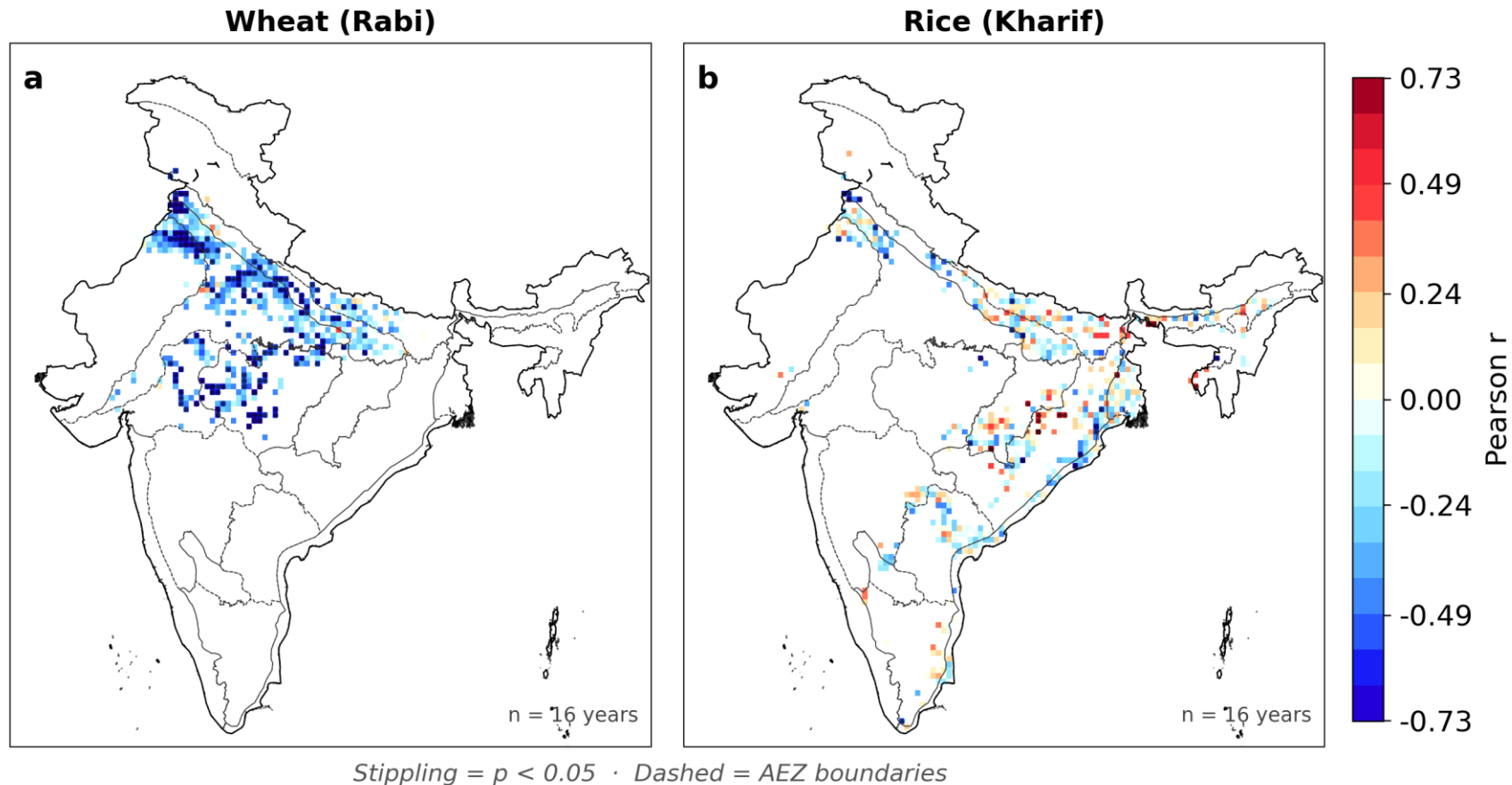
## Correlation between NO<sub>2</sub> and SIF

- Significant negative correlation ( $r=-0.56$ ) between detrended NO<sub>2</sub> and SIF for wheat growing areas in the rabi season
- Rice growing areas in the kharif season shows weak and insignificant negative correlation ( $-0.17$ ).



# Results

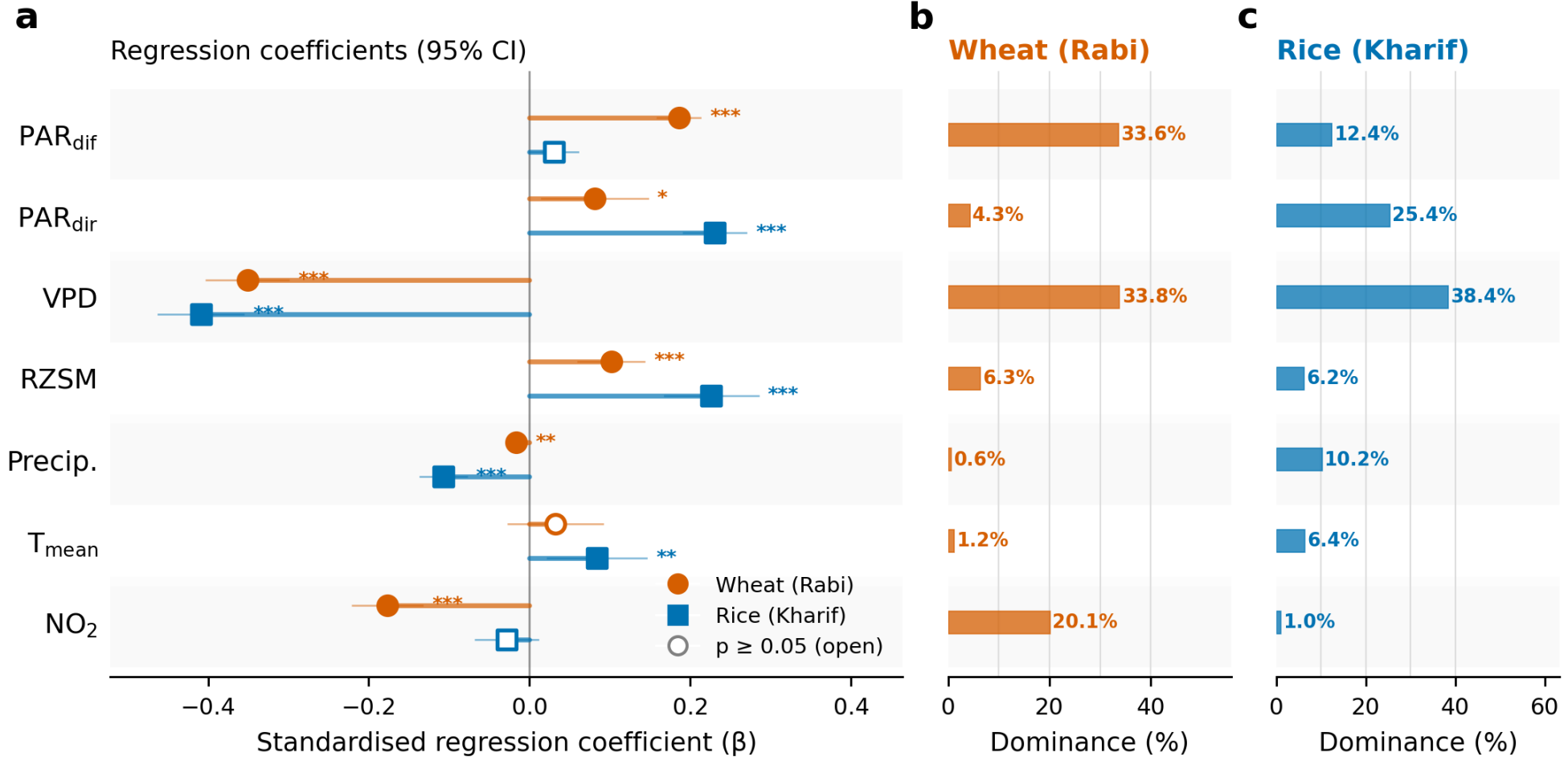
Grid-wise Pearson correlation between  $\text{NO}_2$  and SIF over croplands (2007–2022)



Grid-wise correlations also show widespread significant negative values for wheat, whereas rice show mixed signals which are weak and insignificant

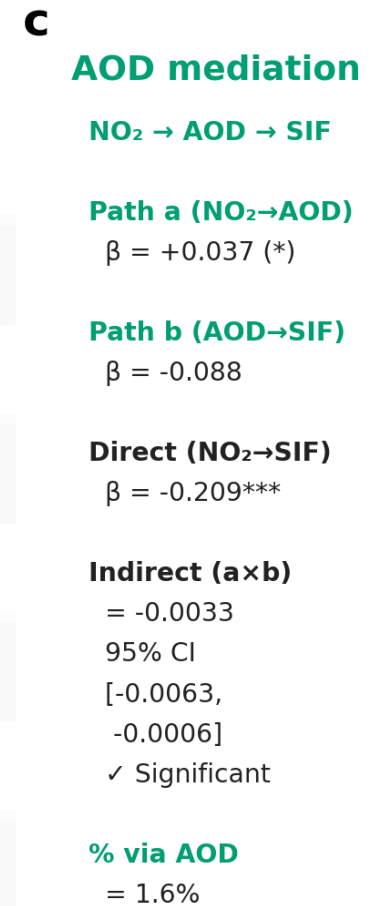
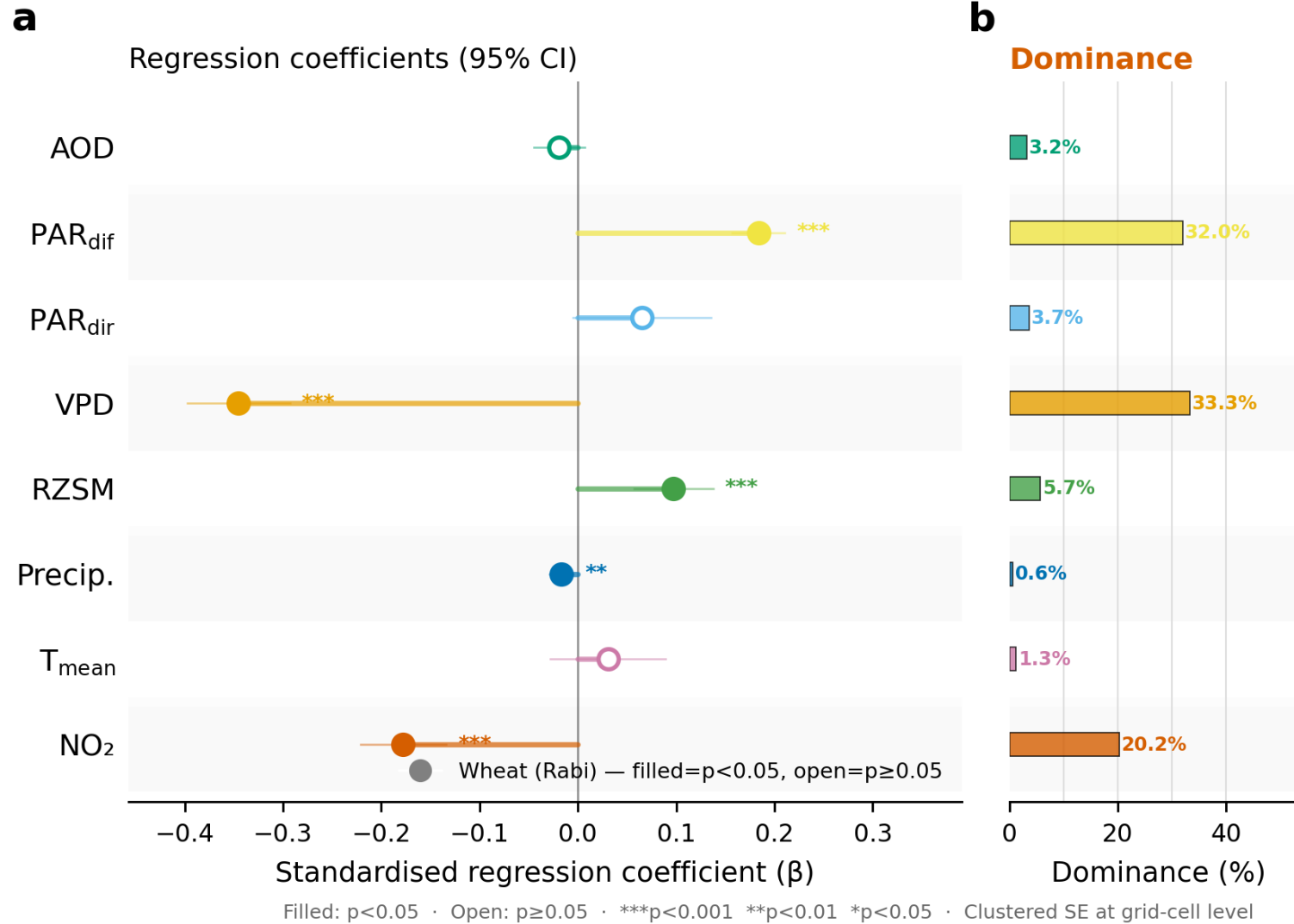
# Results

## Panel fixed-effects MLR



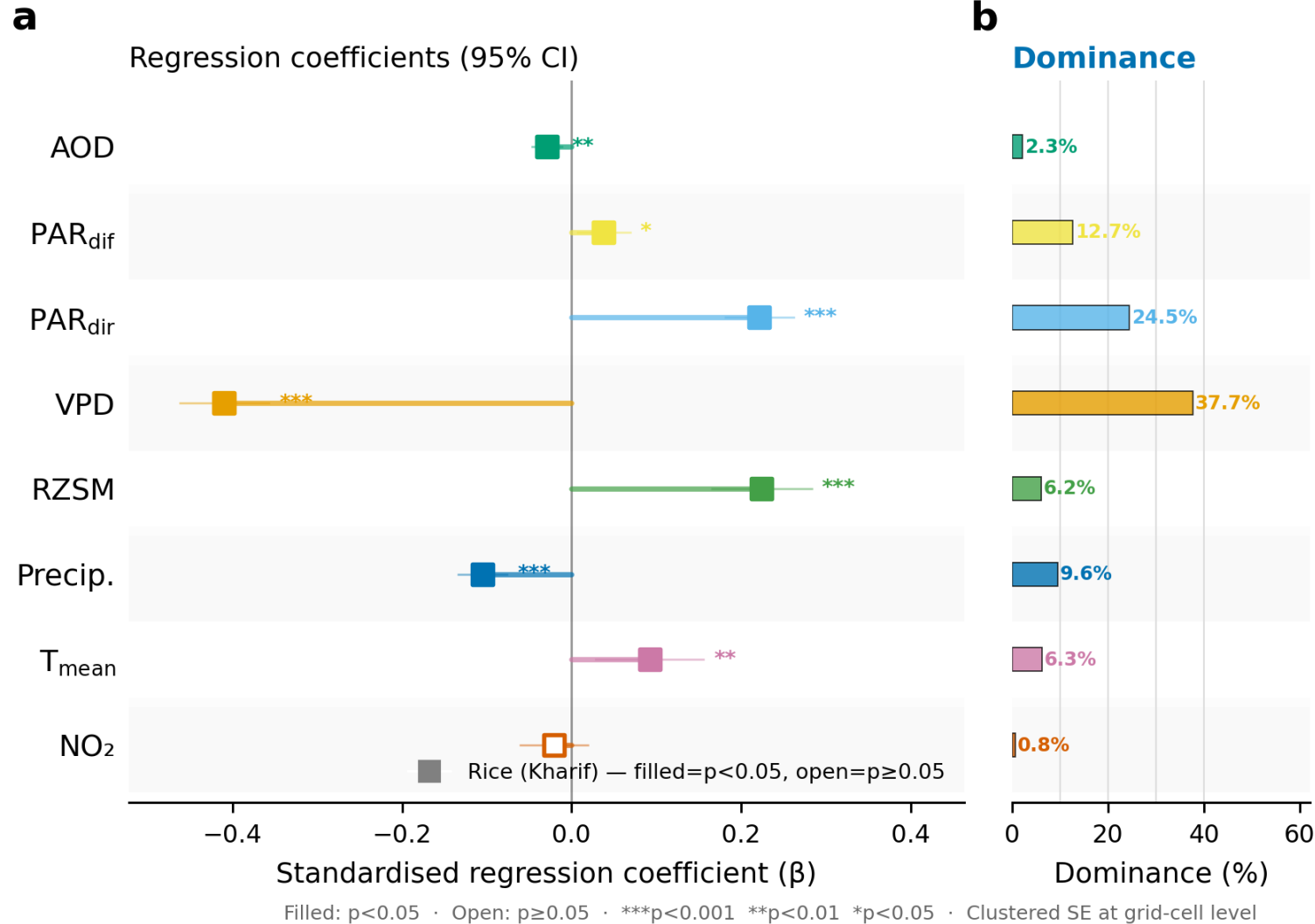
# Results

## Mediation through Aerosol Optical Depth (AOD) : Wheat



# Results

## Mediation through Aerosol Optical Depth (AOD) : Rice



**c** AOD mediation

NO<sub>2</sub> → AOD → SIF

Path a (NO<sub>2</sub>→AOD)

$\beta = +0.233$  (\*\*\*)

Path b (AOD→SIF)

$\beta = -0.039$

Direct (NO<sub>2</sub>→SIF)

$\beta = -0.048$

Indirect (a×b)

= -0.0090

95% CI

[-0.0136,

-0.0048]

✓ Significant

% via AOD

= 15.9%

# Conclusion

- Elevated NO<sub>2</sub> exposure overlaps with wheat-growing regions during rabi.
- Strong negative impact on photosynthesis for wheat, while rice shows weak response.
- Effect remains robust after controlling for climate using two-way fixed effects.
- Limited mediation via aerosols (AOD) → dominant effect is likely physiological.
- Air pollution is a season- and crop-dependent constraint on productivity

# Selected References

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