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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

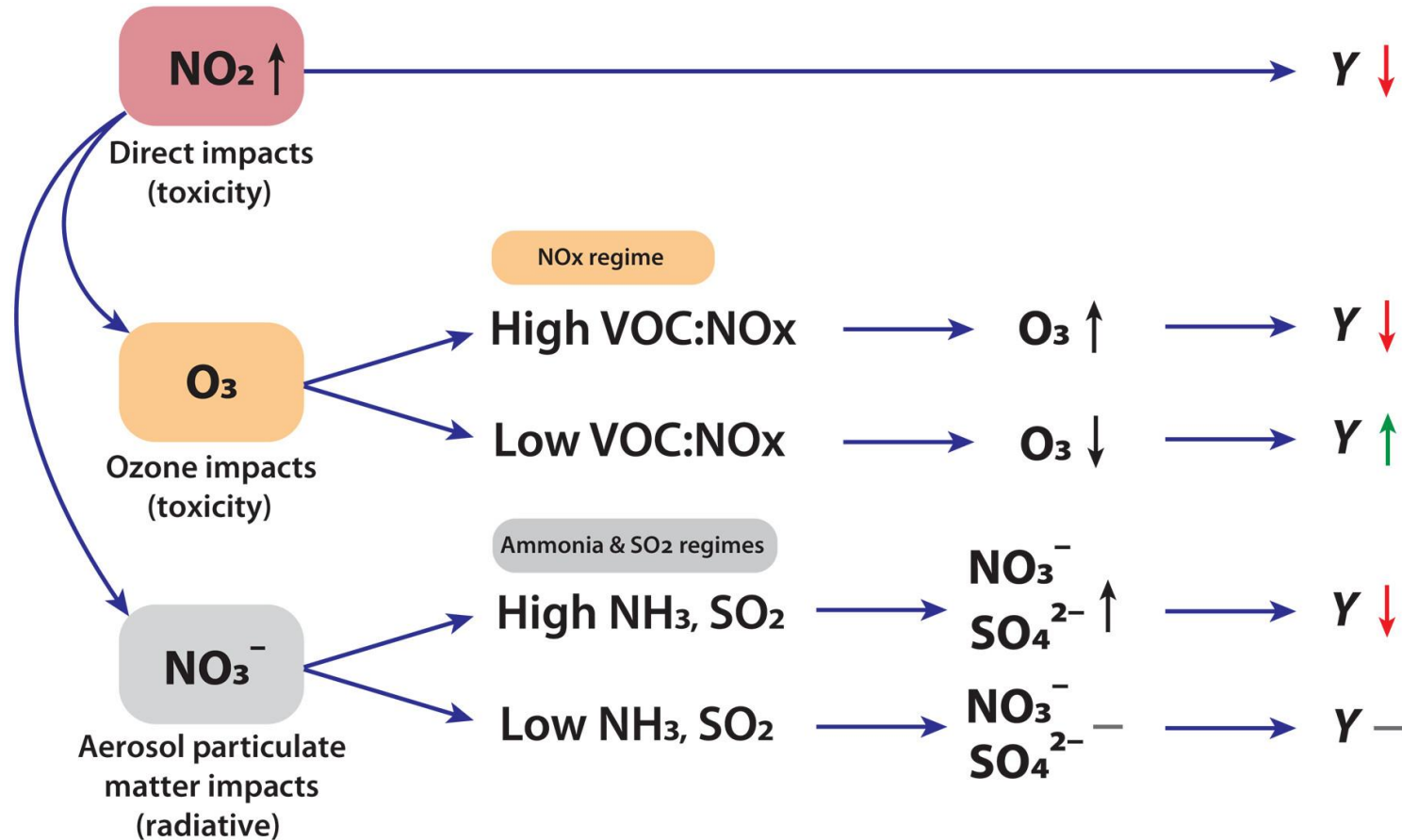
## Globally ubiquitous negative effects of nitrogen dioxide on crop growth

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

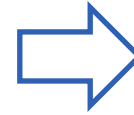
- 1. Does atmospheric NO<sub>2</sub> exposure suppress photosynthetic activity in seasonal croplands of India?*
- 2. Does this relationship remain significant after controlling for climatic drivers?*
- 3. Is the response stronger in high-NO<sub>2</sub> pollution regions?*

# 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

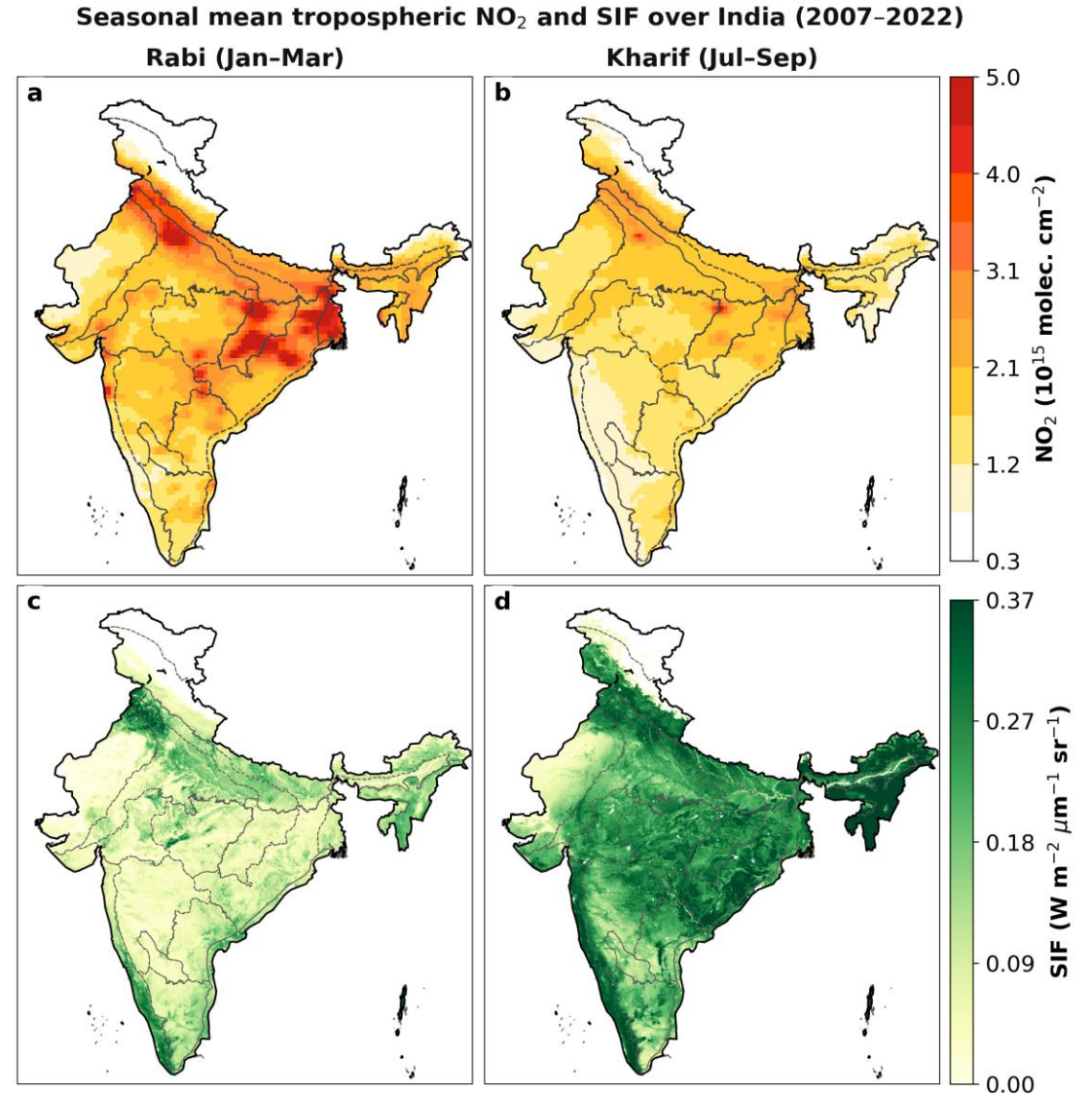
$$SIF_{it} = \beta_1 NO_{2it} + \beta_n X_{it} + \varepsilon_{it}$$

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

# Results

## Seasonal mean $\text{NO}_2$ column concentration and SIF

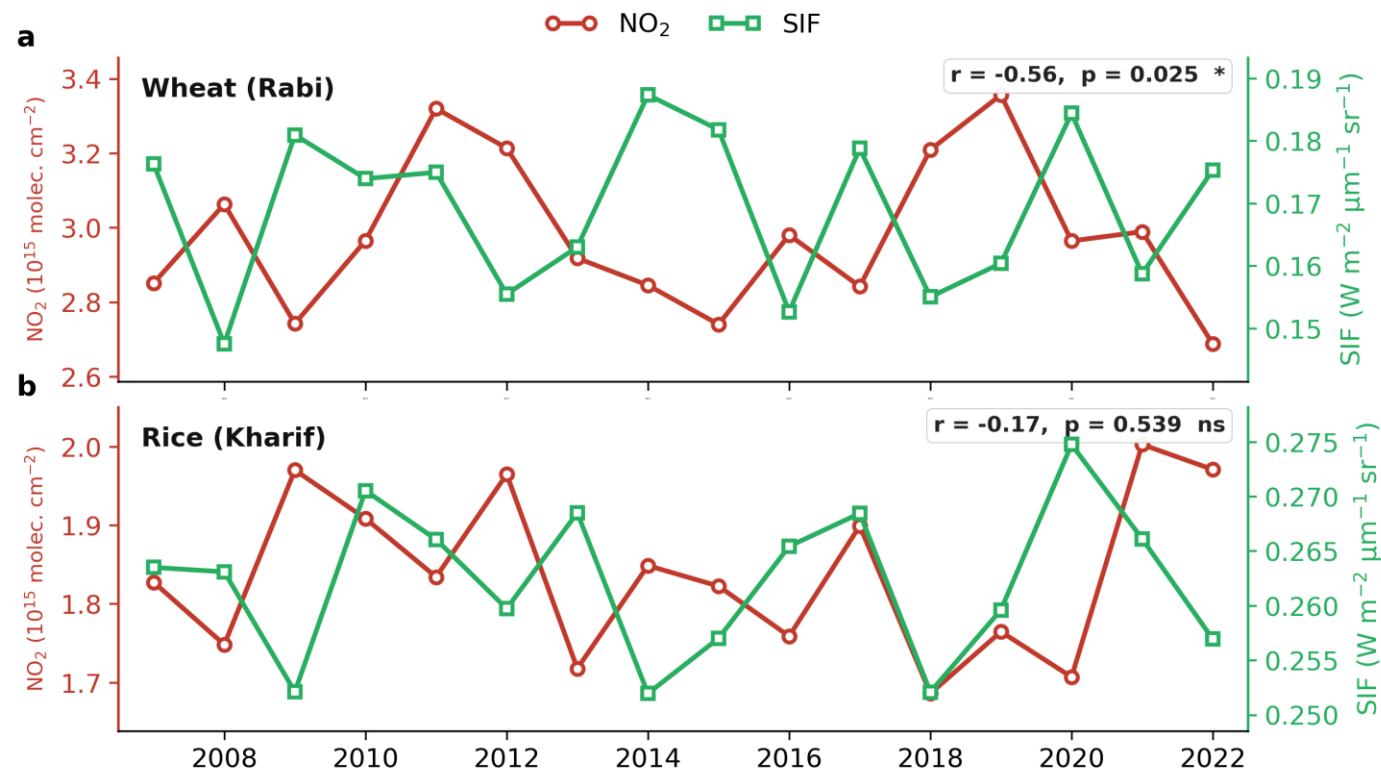
- Rabi season shows elevated  $\text{NO}_2$  levels across Indo-Gangetic Plain (IGP).
- Major cropland regions with high pollution overlap with wheat-growing areas.
- SIF patterns reflect seasonal crop productivity, with higher values during the kharif growing season.



# Results

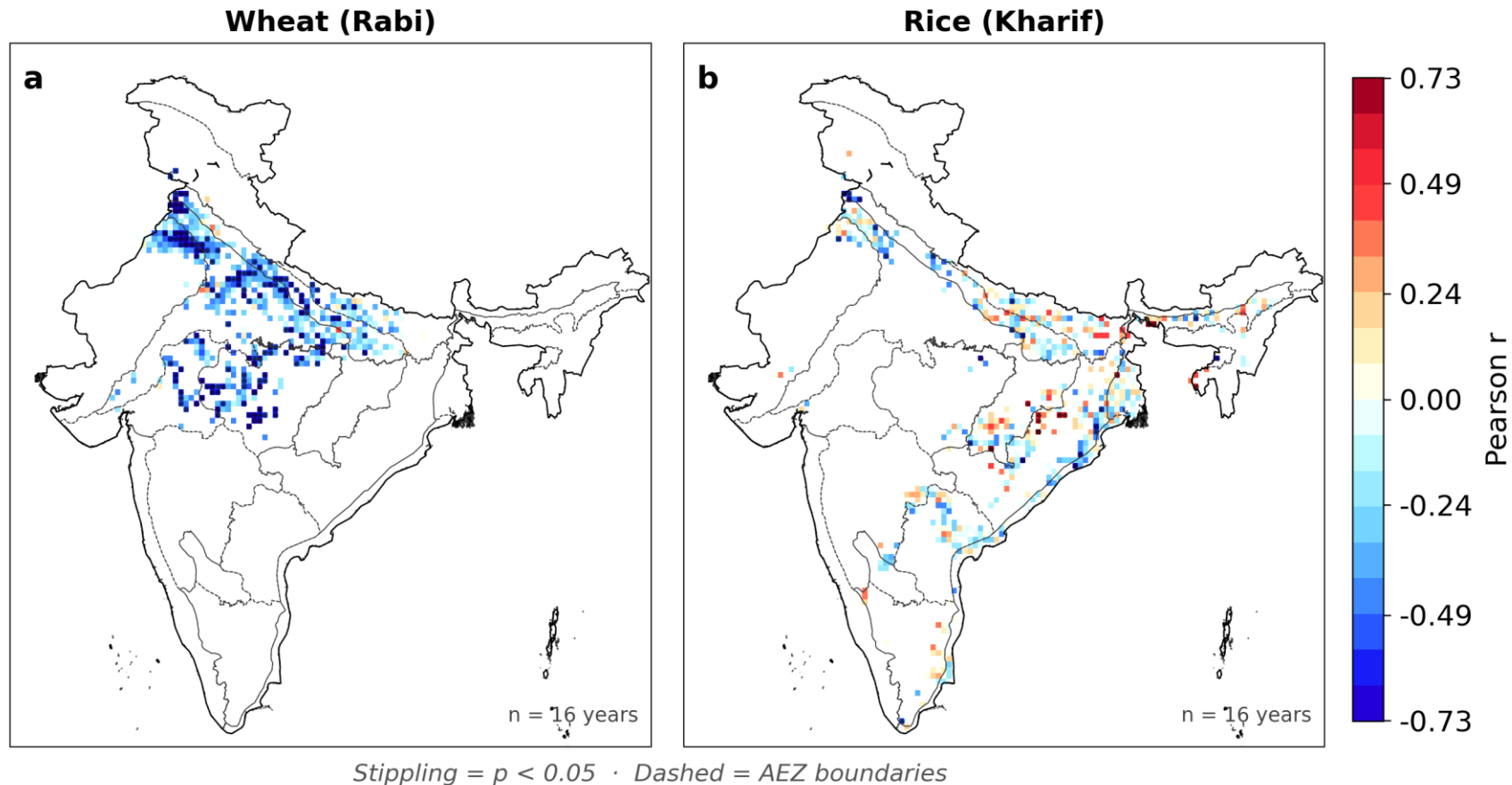
## Correlation between NO<sub>2</sub> and SIF

- 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

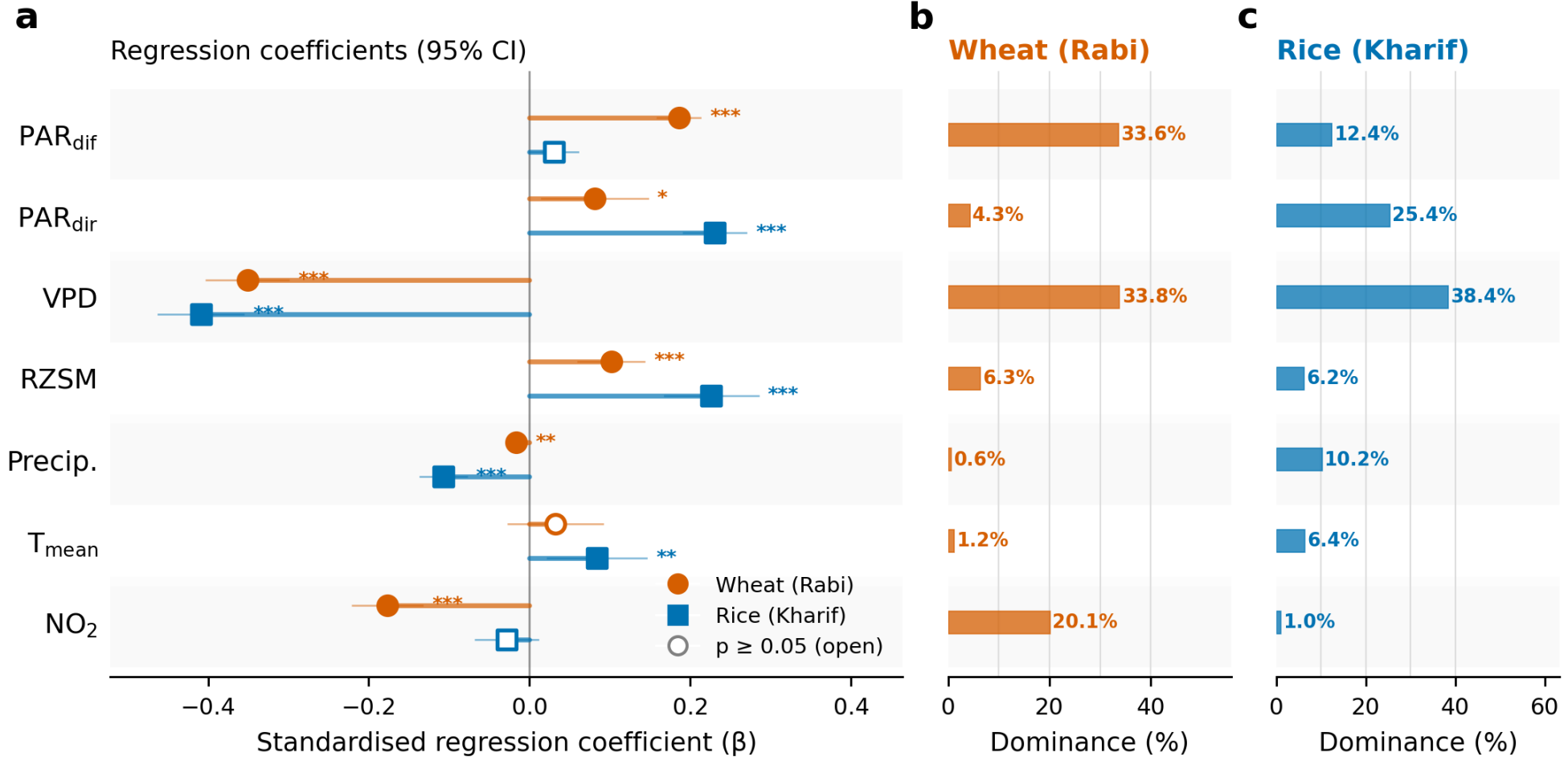
Grid-wise Pearson correlation between  $\text{NO}_2$  and SIF over croplands (2007–2022)



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

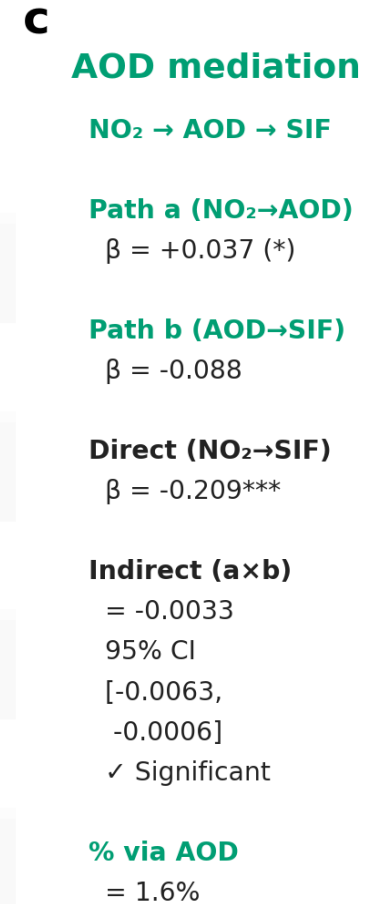
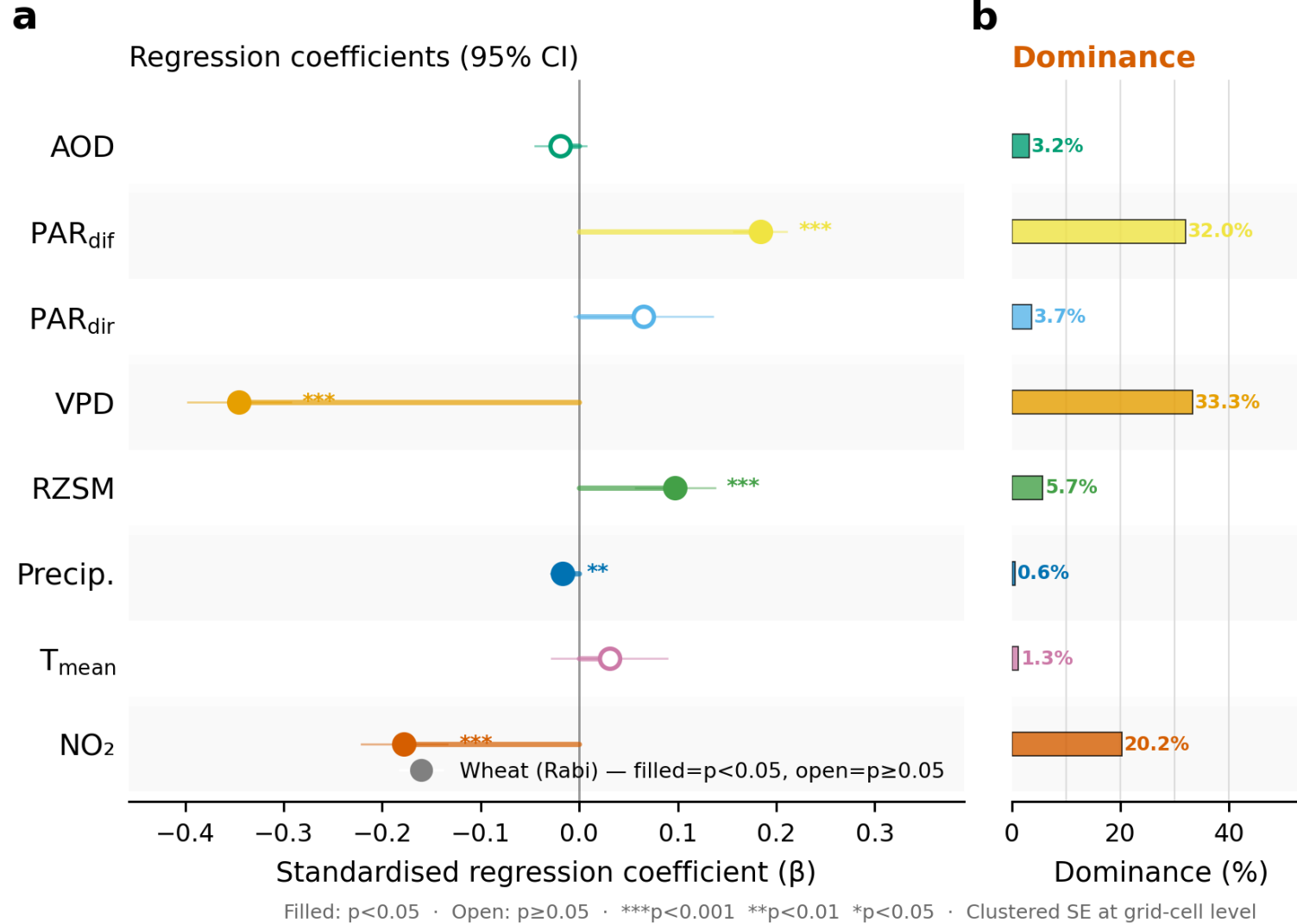
# Results

## Panel fixed-effects MLR



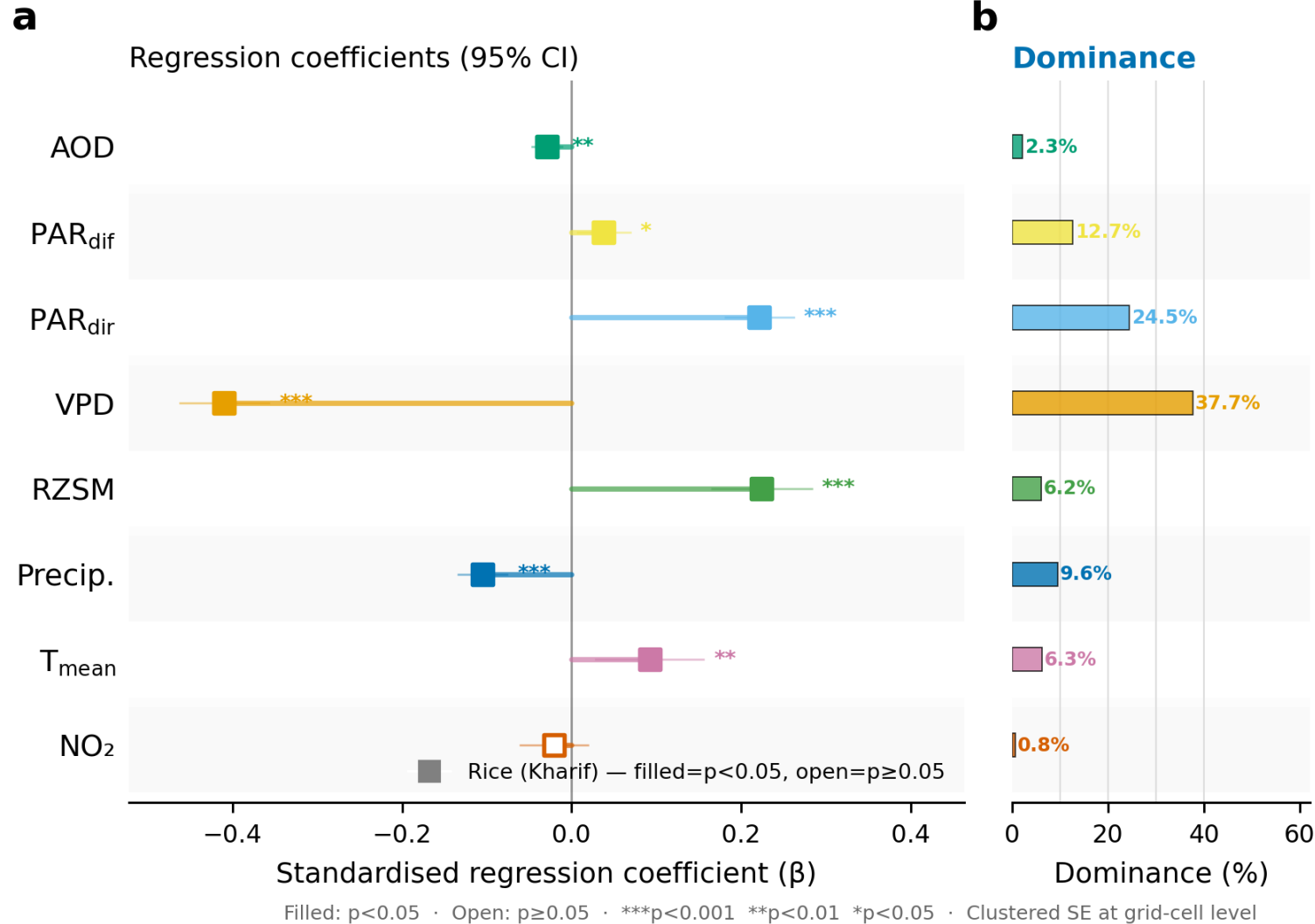
# Results

## 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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## Extended summary

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

Tropospheric nitrogen dioxide (NO<sub>2</sub>) is a major atmospheric pollutant associated with fossil fuel combustion, biomass burning and agricultural emissions. In addition to its role in atmospheric chemistry and ozone formation, increasing evidence suggests that NO<sub>2</sub> exposure can negatively influence vegetation productivity and crop growth. However, the physiological impacts of NO<sub>2</sub> variability on agricultural ecosystems remain insufficiently quantified, particularly over India, where croplands are frequently exposed to elevated pollution levels.

Recent studies indicate increasing tropospheric NO<sub>2</sub> concentrations across several urban and agricultural regions of India, while satellite observations also show increasing vegetation productivity and photosynthetic activity over parts of the Indian subcontinent. However, increases in vegetation activity may also reflect technological improvements, irrigation expansion, fertiliser application, crop management practices and CO<sub>2</sub> fertilisation. Consequently, potential negative effects of atmospheric pollution may remain partially masked within broader productivity trends. This raises the possibility that atmospheric NO<sub>2</sub> variability acts as an underlying or “hidden” environmental stressor on crop physiological functioning. Therefore, comprehensive statistical analyses are necessary to isolate the atmospheric pollution signal from long-term agricultural intensification and climatic influences. This study investigates the relationship between tropospheric NO<sub>2</sub> variability and crop photosynthetic activity across India using satellite-derived Solar Induced Fluorescence (SIF), a direct proxy for photosynthesis. Unlike conventional vegetation indices such as Normalised Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI), SIF responds rapidly to physiological stress and therefore provides a more mechanistic indicator of vegetation functioning under atmospheric pollution exposure.

Tropospheric NO<sub>2</sub> data are obtained from the High Spatial–Temporal Coverage Merged NO<sub>2</sub> dataset (HSTCM- NO<sub>2</sub>; 2007–2022), which integrates multiple satellite NO<sub>2</sub> observations (OMI and GOME-2) in combination with machine learning (eXtreme Gradient Boosting) to provide consistent long-term atmospheric composition estimates (Quin et al., 2024). Photosynthetic activity is represented using the Global OCO-2 SIF (GOSIF) dataset derived from Orbiting Carbon Observatory-2 (OCO-2) observations (Li and Xiao, 2019). Climatic controls including temperature, precipitation, root-zone soil moisture (RZSM), vapour pressure deficit (VPD) and photosynthetically active radiation (PAR) are also incorporated. All datasets are regridded to a common spatial resolution of 0.25° and analysed over seasonal cropland regions corresponding to wheat (rabi; winter) and rice (kharif; summer) cultivation.

Results show elevated NO<sub>2</sub> concentrations across the highly fertile Indo-Gangetic Plain (IGP) during the rabi season, overlapping with major wheat-growing regions. Correlation analysis reveals a strong negative relationship between detrended NO<sub>2</sub> and SIF for wheat-growing regions during rabi ( $r = -0.56$ ,  $p = 0.025$ ), whereas rice-growing regions during kharif exhibit weak and statistically insignificant relationships ( $r = -0.17$ ,  $p = 0.54$ ). Grid-wise analyses further show widespread negative correlations across wheat croplands, indicating spatial consistency in the observed response.

To isolate the effect of atmospheric NO<sub>2</sub> variability from climatic influences, two-way fixed-effects (FE) panel multiple linear regression (MLR) models are applied. The negative effect of NO<sub>2</sub> on SIF remains robust after controlling for climatic drivers and accounting for spatial and temporal heterogeneity. For wheat-growing regions during rabi, NO<sub>2</sub> exhibits a significant negative regression coefficient ( $\beta \approx -0.2$ ), whereas rice-growing regions during kharif show comparatively weak and statistically insignificant responses. Dominance analysis further indicates that although diffuse photosynthetically active

radiation ( $PAR_{diff}$ ) and vapour pressure deficit (VPD) remain the primary environmental controls (~33% each) on photosynthetic variability,  $NO_2$  contributes substantially (20%) to explained variability in SIF for wheat during the rabi season. These results suggest that the observed relationship reflects an independent atmospheric pollution signal rather than purely climatic variability.

As  $PAR_{diff}$  exhibited a relatively strong positive influence on SIF, the potential role of aerosol-mediated radiative effects was further investigated using Aerosol Optical Depth (AOD). Atmospheric  $NO_2$  can contribute to the formation of secondary aerosols, including nitrate and sulphate aerosols, which may influence vegetation productivity through modifications in radiation regimes. Mediation analysis using MODIS AOD suggests that only a limited fraction of the  $NO_2$ –SIF relationship is explained through aerosol pathways (1.6%), indicating that radiative aerosol effects alone do not account for the observed response. Instead, the dominant mechanism is likely associated with atmospheric oxidant-related physiological stress. Because  $NO_2$  and ozone are strongly coupled through atmospheric photochemistry, the observed relationship likely reflects broader atmospheric oxidant variability rather than isolated  $NO_2$  toxicity alone.

Overall, the results demonstrate that atmospheric composition variability can directly influence crop photosynthetic activity in India. The strongest impacts are observed where elevated  $NO_2$  exposure coincides with critical crop growth periods, highlighting atmospheric pollution variability as a season-dependent environmental stressor with potential implications for agricultural productivity.

#### **Study limitations and future directions**

This study focuses on statistical relationships between atmospheric  $NO_2$  variability and photosynthetic activity at regional scales. Because  $NO_2$  and ozone are photochemically coupled, further work incorporating oxidant chemistry and  $NO_x$ –VOC regimes would help disentangle individual pollutant effects more explicitly. Future analyses integrating crop yield observations, chemistry-transport modelling and additional atmospheric composition datasets could further clarify the mechanistic pathways linking air pollution variability and agricultural productivity.