

DOES DRY RICE CULTIVATION REDUCE METHANE EMISSIONS?

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Research Cluster

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Does Dry Rice Cultivation Reduce Methane Emissions?

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1 Introduction

Rice is the primary source of calories for over 3 billion people (International Rice Research Institute, 2026), and the flooded paddies that produce rice are a major source of methane emissions. Methane has about 80 times the warming potential of carbon dioxide over a 20-year period (IPCC, 2021). Because it stays in the atmosphere for roughly a decade, methane reductions can slow warming sooner than CO₂ reductions (Shindell et al., 2012; UNEP and CCAC, 2021; Ocko et al., 2021). Methane is therefore a candidate for near-term mitigation. By 2024, 159 countries and the European Commission had joined the Global Methane Pledge, committing to cut global methane emissions by at least 30% by 2030 relative to 2020 (Global Methane Pledge, 2024). And agriculture, particularly rice, is the focus of many methane reduction efforts (UNEP and CCAC, 2021).

China’s national agricultural water-saving strategy has promoted controlled irrigation in rice-growing regions since at least 2012 (General Office of the State Council of the People’s Republic of China, 2012). Dry rice cultivation practices can include ridge planting, furrow irrigation, and alternate wetting and drying. A global meta-analysis found that alternate wetting and drying can reduce methane emissions at the plot level by 52% (relative to continuous flooding), but the net global warming potential impact is partially offset by increased nitrous oxide emissions (Zhao et al., 2024). Other studies have shown that the net effect varies by other factors including field drying severity, soil conditions, and crop management practices (Jiang et al., 2019; Qian et al., 2023). There is also uncertainty about the extent to which these plot-level effects translate into measurable reductions in atmospheric methane at regional or national scales.

To address these questions, we combine satellite land-use data that classifies rice area as

rainfed or irrigated with methane estimates from the CAMS atmospheric inversion model. We find that rice-sector methane rose in all 24 sample provinces between 2009–2012 and 2020–2023. However, it rose more slowly in provinces where the rainfed rice share increased. A one-percentage-point increase in the rainfed rice share is associated with about 350 fewer tons of growing-season methane attributed to rice, or a decline of about 0.03% in a province’s own rice methane.

We consistently find the expected negative relationship between dry rice cultivation and methane emissions across empirical specifications, though the precision and magnitude vary. But in all cases, the effect is small: even high province-level adoption of dry cultivation practices would offset only a few percent of the rice methane emissions as assigned by the CAMS model, well below what plot-level studies have found. Further, we find no distinguishable association with reported rice yields, sown area, or output.

However, these findings should be read as suggestive and correlational given limitations of the data and our empirical approach. First, our land use data that classifies rainfed versus irrigated rice is measured with error. Second, our main methane outcome depends on the CAMS inversion model’s rice sector attribution, which is largely inherited from a prior emissions inventory rather than measured. Third, we do not find a similarly negative relationship between dry rice cultivation and methane emissions using the TROPOMI satellite methane product. Finally, we observe temporal misalignment in the methane response: next year’s rainfed rice share predicts this year’s methane about as well as the current year does. Section 4.4 takes up these limitations.

2 Background

2.1 Rice, methane, and food security

China harvested 207 million metric tons of rice from 28.9 million hectares in 2023, according to the National Bureau of Statistics (National Bureau of Statistics of China, 2023). National policy designates rice production zones to protect staple-grain supply (State Council of the People’s Republic of China, 2017).

Traditional rice farming involves flooding paddies with standing water for much of the growing season. Flooding prevents oxygen from reaching the soil, creating anaerobic conditions in which methanogens break down organic matter and release methane. Emissions vary with water regime, temperature, soil characteristics, and organic amendments (Yan et al., 2003; Qian et al., 2023). Published national estimates differ substantially by method and

reference year. A high-resolution empirical model estimates 4.75 million metric tons in 2015 (Sun et al., 2020), while earlier bottom-up work reports roughly 7–8 million metric tons (Yan et al., 2003; Peng et al., 2016). An inversion of 2019 TROPOMI observations estimates 11.9 million metric tons (Chen et al., 2022). Globally, rice paddies account for about 8% of human-caused methane (UNEP and CCAC, 2021).

Methane is the second most important greenhouse gas after carbon dioxide, responsible for about 30% of the warming observed since the pre-industrial era (UNEP and CCAC, 2021). The IPCC assesses a total atmospheric lifetime of about 9 years and an emissions-perturbation lifetime of about 12 years. For biogenic methane such as rice emissions, it reports global warming potentials of about 80 over 20 years and about 27 over 100 years (IPCC, 2021).

Reducing rice production would threaten food security for billions, so mitigation has to come from changing cultivation practices, including dry cultivation.

2.2 Water-saving rice cultivation in China

The State Council’s National Agricultural Water-Saving Outline for 2012–2020 called for controlled rice irrigation in the Northeast, the Huang–Huai–Hai region, and southern China (General Office of the State Council of the People’s Republic of China, 2012). Controlled irrigation can keep only part of a field saturated or allow periodic drainage, shortening the anaerobic period that generates methane. The satellite variable used below classifies rice area more broadly, as rainfed or irrigated, and does not identify a particular irrigation technique or observe surface inundation directly.

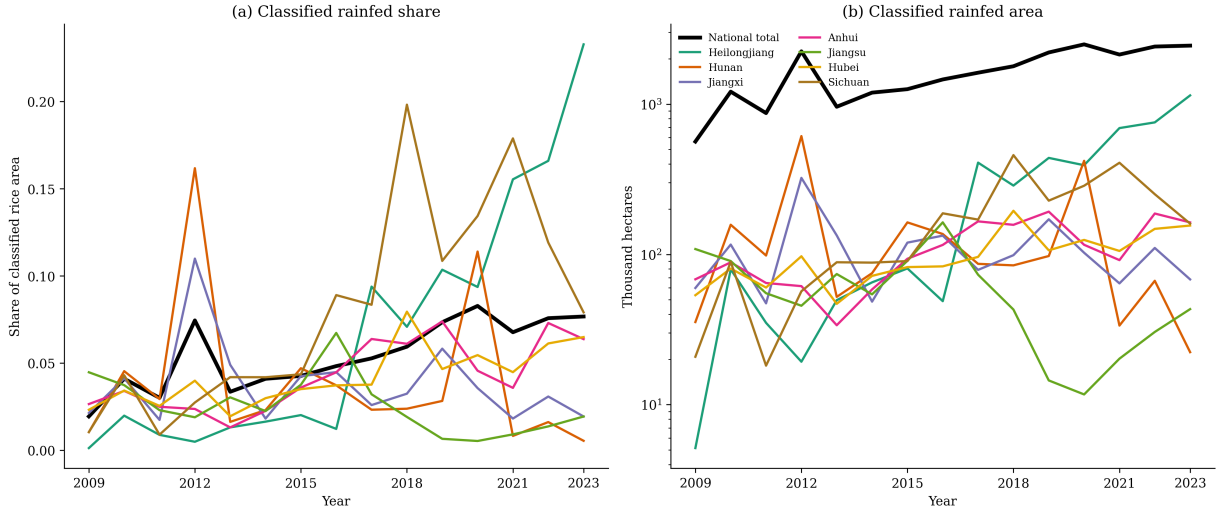
We attempted to date each province’s adoption of water-saving rice policies, but the available sources do not establish comparable start dates: they mix local demonstrations, retrospective accounts, general irrigation programs, and changes in the opposite direction. The analysis therefore uses annual variation in the satellite-classified land-use measure rather than a policy rollout indicator.

3 Data and methods

We combine three data sources:

1. **Rice cultivation classes from satellite products.** We combine separately constructed county-year series of classified rainfed and irrigated rice area. We produce the rainfed series at 500 m resolution in Google Earth Engine, following established

Figure 1: Classified rainfed rice share and area over time.



Notes: Panel (a) shows the area-weighted national average *DryShare* and the trajectories of seven large rice-growing provinces over 2009–2023. Panel (b) shows the corresponding national total and provincial trajectories of classified rainfed rice area in thousand hectares on a log scale. The legend in Panel (b) applies to both panels. In the harmonized irrigated-area series, combined double-season footprints in 2021–2023 count two crop seasons, matching the separate early- and late-season layers in 2017–2020.

phenology-based rice-mapping methods (Xiao et al., 2005). Inputs are MODIS vegetation and water indices (Didan, 2021), CHIRPS precipitation (Funk et al., 2015), and SRTM slope (Farr et al., 2007). The irrigated-area series combines official high-resolution single- and double-season rice maps (Shen et al., 2023a,b; Pan et al., 2021, 2022) with provincial controls anchored to MIRCA-OS benchmark years (Kebede et al., 2025, 2024). We winsorize each county series at its 5th and 95th percentiles, then sum the two series separately within each province-year. We calculate *DryShare* as rainfed area divided by the sum of rainfed and irrigated crop-season area. This rainfed share of classified rice area is related to irrigation infrastructure. It does not directly observe whether a field was inundated in a given season. Appendix A documents the construction.

Figure 1 shows how classified rainfed rice area changed across provinces over the study period. The series varies substantially across space and time, providing the within-province variation used in the analysis.

2. **Methane emissions from atmospheric inversion models.** We use the Copernicus Atmosphere Monitoring Service (CAMS) v24r2 surface-plus-satellite inversion-optimised methane-flux product at 1-degree resolution, covering 2007–2024 (Copernicus Atmosphere Monitoring Service, 2026a). We aggregate the monthly grids to

provinces using a fixed gridcell assignment and calculate growing-season totals. Atmospheric inversions use a transport model to relate observed concentrations to surface fluxes; sectoral estimates depend on prior emission inventories (Jacob et al., 2022; Crippa et al., 2024). GOSAT and TROPOMI measure column-averaged methane and do not observe surface emissions directly (National Institute for Environmental Studies, 2026; Lorente et al., 2021).¹

3. **Rice yields from the China Statistical Yearbook.** We compile provincial rice output, sown area, and yield for 2004 to 2022 from the National Bureau of Statistics yearbook series (National Bureau of Statistics of China, 2025). The source workbook contains 2023 rows, but the provincial rice output and sown-area fields are empty. The Bureau’s 2023 grain announcement also reports provincial total grain while giving rice output only as a national aggregate (National Bureau of Statistics of China, 2023). The rice panel therefore ends in 2022 for lack of provincial observations. Official crop statistics can contain discrepancies across administrative levels (Liu et al., 2020). We treat these variables as reported provincial aggregates that may contain measurement error.

Figure 2 shows the spatial distribution of rice cultivation and methane emissions, along with changes in methane across provinces.

We estimate all regressions at the province-year level because the methane grid cannot separately identify county emissions. A 1-degree gridcell covers roughly 10,000 km² at typical study latitudes, about 6.4 times the median county area of 1,564 km² in our boundary file. Across retained provinces, the median number of contributing CAMS gridcells is 23.5.

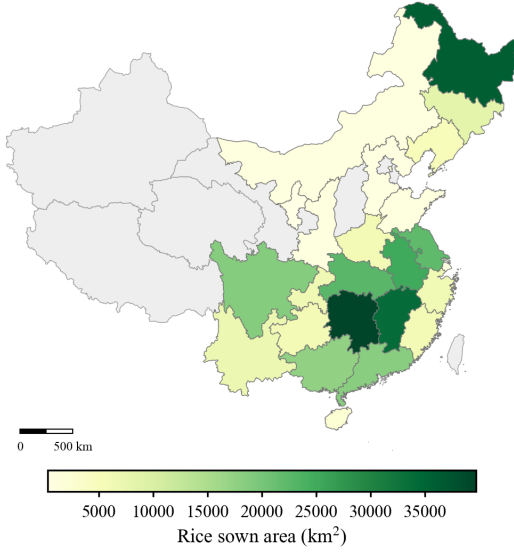
The analysis covers 24 provinces over 2009 to 2023, totaling 360 province-year observations. Of the 31 provincial units in the methane series, we exclude Beijing, Tianjin, Xinjiang and Qinghai because the satellite products report no rice area there. We also exclude provinces averaging 100 km² of rice or less. Shanxi, Gansu and Tibet average 37, 78 and 100 km², compared with more than 800 km² for the next-smallest province retained.

Our analysis relates within-province changes in classified rainfed share to methane, conditional on province and year fixed effects. Province fixed effects absorb permanent differences across provinces, and year fixed effects absorb national changes common to all provinces. Standard errors are clustered by province. This continuous two-way fixed-effects design estimates an association and does not rely on policy adoption dates.

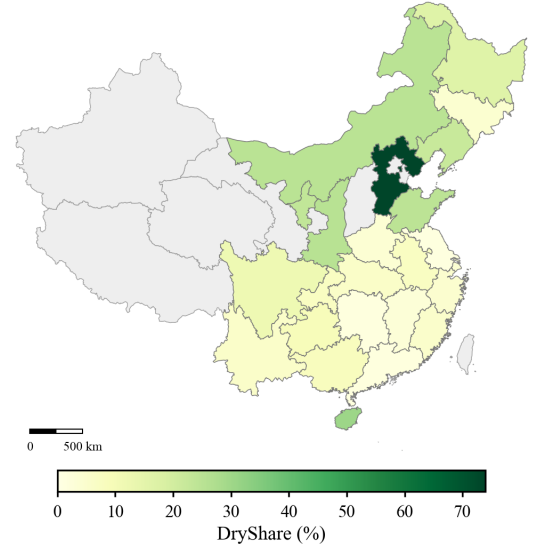
¹Sector-specific inversion levels can differ from bottom-up inventories because posterior fluxes depend on transport, observation coverage, and prior sector allocation.

Figure 2: Spatial distribution of rice area, classified rainfed share, and methane outcomes.

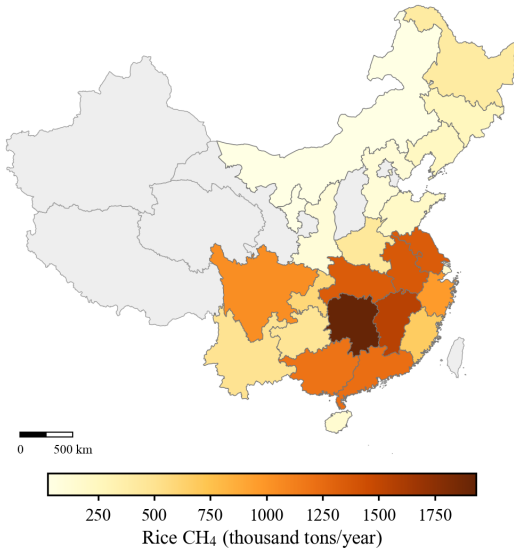
(a) Rice area, 2022



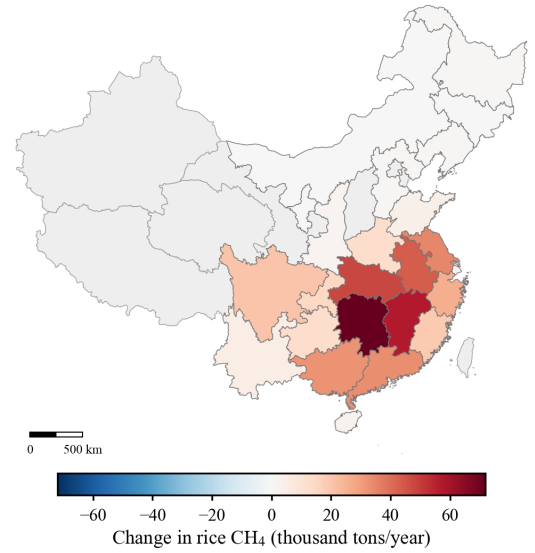
(b) Classified rainfed share, 2022



(c) Growing-season methane, 2009-2023



(d) Methane change, 2020-2023 vs. 2009-2012



Notes: Panel (a) shows province-level rice sown area in 2022, and Panel (b) shows the classified rainfed share of rice area (DryShare) in 2022. Panel (c) shows average growing-season rice methane emissions over 2009–2023. Panel (d) shows the change in growing-season rice methane, comparing the 2020–2023 mean to the 2009–2012 mean. The color scale is centered at zero so blue indicates declines and red indicates increases. The maps show the mainland China study area. Areas outside the estimation sample are shaded in light grey.

4 Results

4.1 Classified rainfed rice share and rice methane emissions

The main estimates test whether measured land-use change tracks methane. Table 1 uses the classified rainfed share of rice area in Panel A and rainfed area alone in Panel B. Panel B thus avoids normalizing rainfed area by total classified rice area.

Table 1: Classified rainfed rice share and rice methane emissions

	Rice CH ₄ (tons)	Rice CH ₄ (tons, weighted)	log Rice CH ₄ (log points)	log Rice CH ₄ (log points, weighted)
<i>Panel A: DryShare, rainfed share of rice area (0–1)</i>				
DryShare _{it}	–35,380** (12,850) [p = 0.011]	–71,570*** (18,340) [p < 0.001]	–0.0297*** (0.0066) [p < 0.001]	–0.0541*** (0.0118) [p < 0.001]
<i>Panel B: Rainfed rice area, per 1,000 km²</i>				
RainfedArea _{it}	–2,300** (1,070) [p = 0.044]	–2,090*** (670) [p = 0.005]	–0.0018*** (0.0004) [p < 0.001]	–0.0018*** (0.0002) [p < 0.001]
Observations	360	360	360	360
Provinces	24	24	24	24
Years	2009–2023	2009–2023	2009–2023	2009–2023
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Within R ²	0.028	0.030	0.082	0.076

Notes: Each estimate comes from a separate province-year regression with province and year fixed effects. Standard errors are clustered by province and reported in parentheses. The outcome is growing-season (May–October) methane attributed to rice by the CAMS atmospheric inversion, in tons or log points. Weighted columns use each province’s mean rice area over 2009–2023 as a time-invariant weight; other columns weight provinces equally. The panels differ only in their measure of classified rainfed rice area. Panel A uses DryShare, rainfed area divided by total classified rice area (rainfed plus irrigated) from satellite land-use products. Coefficients give the change associated with moving DryShare from 0 to 1. The estimate for a one-percentage-point increase is one hundredth of the coefficient. Panel B uses rainfed area, the unnormalised numerator of DryShare, per additional 1,000 km². It therefore does not depend on the measured total rice area. Within R² reports the share of residual variation explained by DryShare after absorbing province and year fixed effects, for Panel A in each column. Appendix Table 3 reports total methane, which does not require the inversion’s sector attribution. *** p<0.01, ** p<0.05, * p<0.1.

A one-percentage-point increase in classified rainfed share is associated with about 350 fewer tons of provincial growing-season rice methane per year (Table 1, Panel A, column 1). This comparison is relative to other provinces in the same year. The log specification gives a 0.03% reduction (column 3). The corresponding province-clustered *p*-values are 0.011 and below 0.001, respectively. Weighting provinces by their mean rice area yields about 720 fewer tons and about a 0.05% reduction (columns 2 and 4). Appendix Table 3 reports a negative

but imprecise total growing-season methane estimate in levels ($-57,480$ tons per unit of DryShare, $p = 0.390$). Its log estimate is negative (-0.0698 , $p = 0.012$), so inference differs between the two functional forms. In Table 1, Panel B, each additional km^2 of classified rainfed rice is associated with about 2.3 fewer tons of rice methane per year ($p = 0.044$).

Appendix Table 3 reports how the estimates change across specifications and samples. Province-specific linear trends reduce the level estimate to $-26,790$ tons per unit of DryShare ($p = 0.021$). The weighted level specification with province trends is less precise ($-27,970$; $p = 0.217$), while its log estimate remains negative ($p = 0.001$). Absorbing four-region-by-year fixed effects gives $-26,440$ tons ($p = 0.010$), close to the trend-adjusted result. Excluding Hebei strengthens the estimate but also changes the estimation sample. Because a spatially smoothed product can generate dependence across provinces, we also cluster by both province and year. The two-way-clustered p -value is 0.055 in levels and 0.015 in logs. The log estimates are more precise across these choices, but they fail a placebo check reported in Section 4.4; inference for the levels result is marginal under two-way clustering.

Holding total rice area at its province mean yields a numerator-only estimate of $-38,750$ tons ($p = 0.004$). Holding rainfed area at its province mean yields a denominator-only estimate of $-4,770$ tons ($p = 0.006$). The 2009–2016 and 2017–2023 subsamples both have negative point estimates, at $-46,070$ ($p = 0.104$) and $-22,610$ ($p = 0.036$), respectively. These checks assess sensitivity to the area measure and sample period.

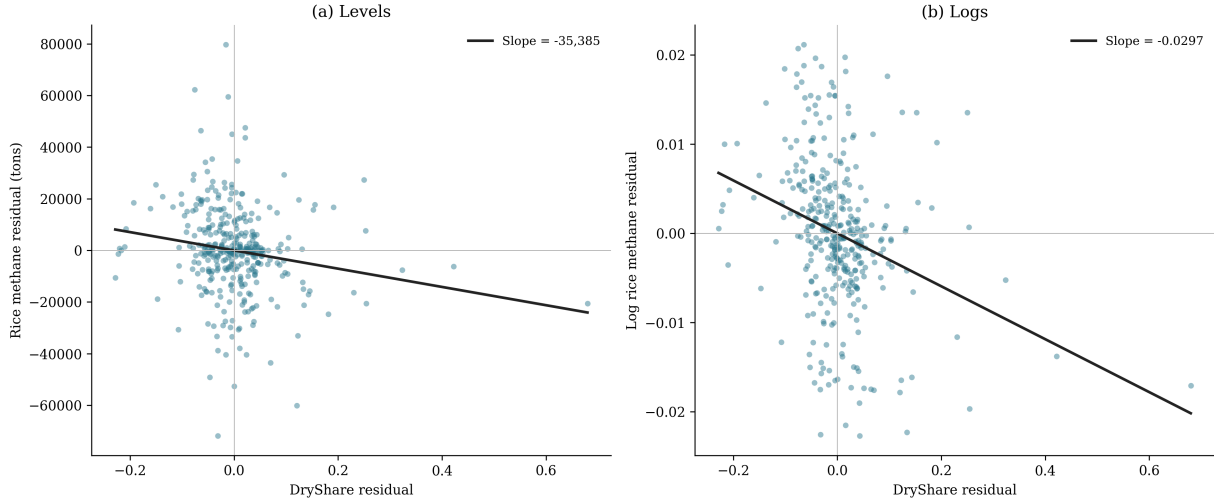
Figure 3 displays the variation underlying the two-way fixed-effects estimates. Both axes are residualized by province and year, so the plotted slope equals the unweighted Table 1 coefficient. The levels panel reflects large differences in provincial scale; the log panel expresses proportional methane changes.

4.2 Rice yields and production

Changes in rice cultivation can coincide with changes in yields, sown area, or output, which are important outcomes and potential confounders.

Table 2 applies the same continuous specification to the Yearbook outcomes. A 10-percentage-point increase in classified rainfed share is associated with a 0.63% reduction in reported yield ($p = 0.210$). The corresponding estimates are a 0.97% increase in sown area ($p = 0.365$) and a 0.35% increase in output ($p = 0.814$). The within R^2 values are 0.013, 0.007, and 0.001, respectively. These estimates are imprecise and explain little of the within-province residual variation. The positive area and output point estimates leave production scale as a potential confounder that may vary with classified land use. They

Figure 3: Two-way fixed-effects residuals for classified rainfed share and rice methane.



Notes: Each point is one province-year observation. DryShare and the methane outcome are separately residualized with province and year fixed effects. Panel (a) uses methane in tons; Panel (b) uses log methane. The fitted lines are unweighted ordinary least squares through the residualized observations.

Table 2: Classified rainfed rice share, yield, and production

	log(Rice Yield)	log(Rice Sown Area)	log(Rice Output)
DryShare _{it}	-0.063 (0.049) [p = 0.210]	0.097 (0.105) [p = 0.365]	0.035 (0.145) [p = 0.814]
Observations	336	336	336
Provinces	24	24	24
Years	2009–2022	2009–2022	2009–2022
Province FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Within R ²	0.013	0.007	0.001

Notes: Each estimate comes from a separate province-year regression with province and year fixed effects. Standard errors are clustered by province and reported in parentheses. Outcomes are reported rice yield, sown area, and output from the China Statistical Yearbook, a source independent of the CAMS methane outcome. All three outcomes are in logs, so coefficients give the log-point change associated with moving DryShare from 0 to 1. DryShare is the continuous satellite-classified rainfed share used in Table 1. The Yearbook rice series ends in 2022, so the sample covers 2009–2022 for the 24 provinces in Table 1. Province-clustered *p*-values are reported in square brackets. Within R² reports the share of residual variation explained by DryShare after absorbing province and year fixed effects.

neither establish expansion nor rule out economically relevant changes.

4.3 Illustrative sample-wide scaling

For scale, consider a one-percentage-point increase in classified rainfed share across all 24 sample provinces. If the association were causal, the baseline estimate would imply about 8,500 tons less growing-season rice methane per year. This uniform change is an extrapolation because year fixed effects absorb changes shared by all provinces. The regression identifies the coefficient from differences in DryShare changes across provinces. The scenario is equivalent to about 230,000 tons of CO₂e using the 100-year biogenic-methane global warming potential of 27 (IPCC, 2021). It represents about 0.05% of the 16.34 million tons of growing-season rice methane that CAMS assigns to the sample provinces in an average year.

This calculation inherits the measurement and spatial-attribution uncertainty discussed in Section 4.4. It illustrates scale within the sample; we do not extend it to a national total.

The marginal relationship may vary with soil type, climate, and baseline farming practices. As an upper bound, moving the classified rainfed share from 0 to 1 in every sample province would imply a reduction of roughly 3 to 5% of the rice methane CAMS assigns to these provinces, depending on specification. This is far below the average plot-level reduction reported for alternate wetting and drying (Zhao et al., 2024). The two quantities are not defined identically. A change in classified rainfed area does not map one-for-one onto a specific water-management practice, and measurement error in the satellite series attenuates the estimate. The gap may reflect partial practice change within reclassified area, attenuation, or a smaller effect at scale, and these data cannot separate the three.

The World Bank’s Climate Smart Staple Crop Production Project in Anhui and Henan provides a related benchmark. The project was approved in August 2014 and closed in September 2020. Its completion review reports an actual cost of \$33.481 million. This comprised a \$5.081 million Global Environment Facility grant and \$28.40 million in government financing. The review attributes 29,782 metric tons of CO₂e to emission reductions and 99,565 metric tons to carbon sequestration, a combined 129,347 metric tons. It also reports 1.45 million m³ of water savings and an 8% increase in the average staple-crop yield indicator (World Bank, 2021). The intervention combined efficient rice irrigation, improved input use, and crop-residue retention across several staple crops. These totals therefore do not identify the marginal cost or effect of classified rainfed rice area.

The EPA’s 2023 report provides a second benchmark for valuing methane reductions. For methane emitted in 2020, its three-damage-module average is \$1,600 per metric ton at a

2.0% near-term Ramsey discount rate. The value is expressed in 2020 dollars (Table 4.1.1) (U.S. Environmental Protection Agency, 2023). Table 3.1.2 separately reports \$1,600 for the GIVE damage module at a 2.5% rate. We use \$1,600 as an illustrative valuation; the report gives different values across discount rates and damage modules. Applied to the sample-wide scenario above, it gives a gross climate benefit of about \$13.6 million per year. Using the IPCC’s 100-year biogenic-methane GWP of 27, the EPA value is about \$59 per ton of CO₂e. A national fiscal comparison would require implementation, subsidy, monitoring, and administrative costs measured on a comparable basis. Potential water, health, yield, and ecosystem co-benefits remain outside the monetary calculation.

4.4 Potential confounds and data limitations

Five limitations define the interpretation of the main result.

We lack a credible external source of province-level policy timing or other plausibly exogenous variation in DryShare. A lead diagnostic also shows that next year’s DryShare is strongly associated with current methane. Entered jointly, the lead coefficient is $-23,402$ tons ($p = 0.018$), while the contemporaneous coefficient is $-33,688$ tons ($p = 0.109$). This pattern is consistent with non-random trends or slow-moving classification changes. The lead provides a falsification diagnostic, not a formal pre-trend test for a policy event. We therefore interpret the estimates as associations and avoid claims about causal or policy effects.

DryShare measures satellite land classification related to irrigation infrastructure; it does not directly observe field inundation or adoption of alternate wetting and drying. An auxiliary ML-LSWI flooding measure has a positive but weak correlation with DryShare ($r = 0.252$ across 315 observations), consistent with their different measurement targets. Direct field observations or a validated high-resolution flooding series would be needed to identify water-management practice itself.

The irrigated-area series changes source in 2017, when available high-resolution raster observations replace county estimates allocated from interpolated provincial controls. The transition is especially visible in Hebei, where winsorized irrigated area falls from about 1,757 km² in 2016 to 132 km² in 2017. Harmonizing the series, excluding Hebei, and estimating separate pre- and post-2017 specifications reduce dependence on this transition. Historical interpolation and county-share extrapolation remain modeling assumptions, however, and these diagnostics cannot fully separate cultivation change from classification or source change.

The CAMS rice series carries little independent province-year information. Province and year

fixed effects absorb 99.99% of the variance in log rice methane, leaving a residual standard deviation of 0.008 log points, under 1% of the level. The share of provincial growing-season methane assigned to rice is close to a province constant: its standard deviation is 0.250 across provinces but 0.016 within them. Jiangxi’s share stays between 71% and 77% in all fifteen years, and Inner Mongolia’s near 0.6%. Comparing the 2020–2023 mean to the 2009–2012 mean, rice methane rises in all 24 provinces, within a band from 0.2% to 3.8%. Residual rice methane has a correlation of only 0.08 with residual total methane over the same gridcells, although rice accounts for 35% of the sample’s growing-season total; the total-methane level estimate is imprecise. The estimates in Table 1 therefore describe small relative movements in a series whose sector split is largely inherited from the prior inventory rather than resolved from the atmospheric observations.

CAMS aggregates emissions on a coarse 1-degree grid, so transport can spread a surface signal across cells and provincial boundaries (Jacob et al., 2022). Its rice series also depends on the agricultural-soils category in the EDGAR v8.0 prior and on the inversion’s allocation across source groups (Copernicus Atmosphere Monitoring Service, 2026b; Crippa et al., 2024). The 2019–2023 TROPOMI comparison does not independently confirm the rice-sector result. Its XCH_4 coefficient is 5.71 ppb per unit of DryShare ($p = 0.189$), although atmospheric mixing and column averaging limit the test’s power (Lorente et al., 2021). The sample’s mean growing-season CAMS rice attribution is 16.34 million tons, roughly two to three and a half times the annual bottom-up estimates cited in Section 2. Log specifications are more precise than levels but not more credible: they weight small-emission provinces heavily, and in logs DryShare predicts non-rice methane more strongly than rice methane (-0.163 , $p < 0.001$), which no cultivation channel explains. Higher-resolution inversions or direct flux measurements would be needed to separate cultivation effects from spatial and sector-allocation assumptions.

5 Conclusion

We combine satellite estimates of classified rainfed rice area with atmospheric methane products to study their relationship across China. A higher measured rainfed share is associated with lower CAMS rice-sector methane within provinces after accounting for common year changes. The checks in Section 4.4 show that trends, classification changes, and sector-allocation assumptions remain possible explanations for this relationship.

Satellite land-use measures can help document changes that administrative records do not capture, subject to validation of the underlying classification. Direct measures of on-farm

water management and a defensible source of policy timing would be required for a policy-impact design.

Evaluating dry cultivation at scale requires resolving spatial attribution and accounting for the nitrous oxide trade-off (Zhao et al., 2024). Higher-resolution atmospheric transport inversions, combined with direct, simultaneous methane and nitrous oxide flux measurements, would allow a fuller greenhouse-gas assessment. Applying this remote-sensing approach in other major rice-producing countries would also test whether the findings extend to different agricultural and institutional settings.

A DryShare construction

DryShare is the ratio of classified rainfed rice area to total classified rice area. The rainfed and irrigated series are constructed separately and aggregated to province-year as follows:

1. **Rainfed rice area, the numerator.** The production script runs in Google Earth Engine for 2008–2024 at 500 m resolution. We use the MODIS/061/MOD13A1 product for vegetation and water indices at 16-day intervals. Other inputs are UCSB-CHG/CHIRPS/DAILY precipitation, USGS/SRTMGL1_003 elevation, and the project county boundary asset (Didan, 2021; Funk et al., 2015; Farr et al., 2007). From MODIS, we use the enhanced vegetation index (EVI), normalized difference vegetation index (NDVI), and day of year. We also use its near-infrared reflectance (NIR) and shortwave-infrared reflectance (SWIR).

A pixel is classified as rainfed rice when all thirteen province-specific conditions hold. These comprise lower bounds for annual maximum NDVI and EVI, lower and upper bounds for NDVI-season length, and a lower bound for NDVI amplitude. They also include lower and upper bounds for peak month and slope. The remaining conditions set lower bounds for maximum LSWI, number of wet months, annual LSWI standard deviation, and growing-season precipitation. The land surface water index is $LSWI = (NIR - SWIR)/(NIR + SWIR)$; a wet month has monthly mean LSWI above -0.1 . Twelve non-EVI thresholds and two growing-season month bounds are fixed by province.

We calibrate the EVI threshold to minimize the absolute difference from MIRCA-OS rainfed-rice area in 2000, 2005, 2010, and 2015 (Kebede et al., 2025, 2024). We search over $[0, 0.95]$ and then refine the threshold with a 0.001-step local search. Piecewise cubic Hermite interpolation (PCHIP) through each province’s four benchmark optima supplies annual thresholds for 2008–2024. We hold the 2015 threshold fixed for subsequent years through 2024. For each year, we multiply the binary mask by pixel area and sum over county polygons with `reduceRegions`. The analysis clips each province-county time series to its empirical 5th and 95th percentiles.

2. **Irrigated rice area, a component of the denominator.** Official single-season and double-season rice rasters provide county irrigated area for 2017–2023 (Shen et al., 2023a,b; Pan et al., 2021, 2022). We assign positive raster pixels to county polygons by pixel centre and calculate their areas on the WGS84 ellipsoid. The double-season product supplies separate early- and late-season layers in 2017–2020 and a combined double-rice footprint in 2021–2023. We count the combined footprint twice to express

area in comparable annual crop seasons throughout.

Before 2017, we allocate county values from provincial controls anchored to the 2000, 2005, 2010, and 2015 MIRCA-OS benchmarks (Kebede et al., 2025, 2024). Provinces outside the high-resolution calibration sample retain their MIRCA-OS benchmark values. We allocate the remaining national benchmark total using the represented provinces’ mean 2017–2023 shares, preserving each national benchmark total. We interpolate provincial controls between benchmarks with a nonnegative cubic spline and distribute them within provinces using normalized county shares. Observed raster values replace the model estimates for years from 2017 onward.

3. **Province-year aggregation.** Provincial controls bind the model-generated county totals in 2008–2016. From 2017 onward, source-raster county values take priority and are not rescaled to the controls. The analysis clips each irrigated province-city-county series to its empirical 5th and 95th percentiles. Finally, it sums rainfed and irrigated area separately within province-year, retains province-years observed in both products, and computes

$$\text{DryShare}_{it} = \frac{R_{it}}{R_{it} + I_{it}}.$$

Aggregating the two county series separately before the province-year merge prevents unmatched county records from being discarded. The resulting pre-exclusion panel contains 432 province-years for 27 provinces over 2008–2023. The main sample retains 24 provinces and 360 observations over 2009–2023.

4. **Auxiliary flooding checks.** Separately, we construct ML-LSWI, GLAD, and SAR-based measures of surface flooding. The ML-LSWI check trains a Gradient Boosting rice mask and applies the Xiao flooding criterion (Xiao et al., 2005). The matched panel covers 21 provinces over 2009–2023 and contains 315 observations. Its correlation with DryShare is positive but weak ($r = 0.252$), consistent with their different measurement targets. DryShare captures land-use and irrigation classification, while ML-LSWI captures observed surface-water presence.

B Specification sensitivity

Table 3 reports DryShare estimates in levels and logs across alternative specifications, samples, and decompositions of the regressor. It also reports estimates using total methane as the outcome.

Table 3: Specification sensitivity of the DryShare estimate

	CH ₄ (tons)	log CH ₄ (log points)	N
<i>Panel A: Specification and sample, rice methane</i>			
Baseline	−35,380** (12,850)	−0.0297*** (0.0066)	360
Excluding Hebei	−57,970*** (14,990)	−0.0409*** (0.0092)	345
Province linear trends	−26,790** (10,830)	−0.0231*** (0.0046)	360
Weighted, province trends	−27,970 (22,020)	−0.0289*** (0.0073)	360
Region-by-year fixed effects	−26,440** (9,490)	−0.0249*** (0.0035)	360
<i>Panel B: Decomposing DryShare, rice methane</i>			
Numerator only (rainfed area)	−38,750*** (12,170)	−0.0267*** (0.0077)	360
Denominator only (measured area)	−4,770*** (1,570)	−0.0065*** (0.0012)	360
2009–2016 only	−46,070 (27,220)	−0.0101 (0.0084)	192
2017–2023 only	−22,610** (10,160)	−0.0201*** (0.0057)	168
<i>Panel C: Total methane, no sector attribution</i>			
Total methane	−57,480 (65,650)	−0.0698** (0.0255)	360
Total methane, weighted	−70,990 (89,180)	0.0013 (0.0324)	360
<i>Panel D: North–south split, rice methane</i>			
Northern provinces	−2,730 (3,150)	−0.0070 (0.0078)	135
Southern provinces	−40,150** (14,990)	−0.0199** (0.0074)	225

Notes: The unit is the province-year. Panels A and B use growing-season (May–October) CAMS rice-sector methane; Panel C uses total growing-season methane. Each coefficient comes from a separate regression with province and year fixed effects and province-clustered standard errors in parentheses. Coefficients give the change from moving DryShare from 0 to 1. The baseline reproduces Table 1, Panel A. Hebei is excluded where noted because of its large 2017 source transition. The region-year row replaces year effects with four-region-by-year effects. Numerator only holds total rice area at its province mean; denominator only holds rainfed area at its province mean. The period rows split the sample at the 2017 irrigated-series transition. Panel D splits the sample geographically. The northern group is the Northeast plus the provinces north of the Qinling-Huai line: Hebei, Shandong, Henan, Shaanxi, Ningxia, Inner Mongolia, Liaoning, Jilin and Heilongjiang. Year effects are re-estimated within each subsample, so the two rows are descriptive and do not decompose the pooled estimate. The split matters because the squared two-way DryShare residual, the variation that identifies the coefficient, is 53% Hebei and 74% northern, while rice accounts for under 10% of provincial growing-season methane in five of the nine northern provinces. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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