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Renewable energy adoption and its associations with cereal productivity and carbon emissions in Algeria, Egypt, Morocco and South Africa

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Abstract

This study examines the energy-food-climate nexus in Algeria, Egypt, Morocco and South Africa using an annual country-year panel assembled from six public datasets. The analysis combines modern renewables as a share of total energy supply, cereal yield, territorial fossil-fuel and industrial CO_2 emissions per capita, GDP per capita, fertilizer use per hectare of cropland, and annual precipitation. The common six-variable sample contains 232 observations over 1965–2022. Dynamic two-way fixed-effects models show strong persistence in per-capita CO_2 emissions (lag coefficient = 0.801, $p < 0.001$). Conditional on persistence, GDP per capita, cereal yield, country effects and year effects, renewable-energy share is not statistically associated with contemporaneous CO_2 emissions (beta = -0.0007, $p = 0.947$). In the agricultural-productivity equation, renewable-energy share is positively associated with cereal yield (beta = 0.0829, $p = 0.010$); precipitation (beta = 0.1742, $p = 0.006$) and GDP per capita (beta = 0.4854, $p = 0.001$) are also positive. Static fixed-effects estimates show a stronger negative renewable-emissions association, indicating that failure to model emissions persistence can materially alter inference. The evidence suggests potential complementarity between modern renewable-energy adoption and cereal productivity, while short-run national emissions effects are difficult to identify after accounting for persistence and common shocks. Results are deliberately bounded to the four economies covered by the supplied modern-renewables series.

1 Introduction

African economies face the linked challenge of expanding reliable modern energy, improving food-system productivity and limiting greenhouse-gas emissions. Energy services support irrigation, pumping, mechanization, cold chains, storage and processing, while agricultural intensification changes energy demand and input use. Climate variability simultaneously affects crop productivity and the returns to energy-using agricultural technologies. These interdependencies motivate analysis of an energy-food-climate nexus rather than isolated sectoral outcomes.

Recent evidence for sub-Saharan Africa shows that renewable energy, agricultural activity and carbon emissions are empirically connected, but the agricultural dimension has often been represented by agricultural land or aggregate sector measures rather than physical land productivity [1]. The distinction matters: expansion of cultivated land and improvement in yield are economically and environmentally different processes. This study therefore uses cereal yield (tonnes per hectare) as its agricultural-productivity outcome.

The study makes three contributions. First, it measures agriculture through cereal productivity rather than agricultural land. Second, it estimates two linked equations: an emissions equation and a cereal-yield equation, allowing renewable-energy adoption to be examined against both environmental and food-system outcomes. Third, it explicitly models persistence in emissions. National energy systems and carbon-intensive capital adjust slowly; omitting lagged emissions can therefore attribute persistent historical differences to contemporaneous renewable-energy variation.

The realized data structure also determines the estimator. The supplied modern-renewables series yields complete six-variable observations for Algeria, Egypt, Morocco and South Africa, producing a panel with N = 4 and T = 58. Difference and System GMM are primarily designed for panels with many cross-sectional units and relatively short time dimensions [8, 9]. Applying them mechanically to this four-country, long-T panel would be poorly justified. The analysis instead uses dynamic two-way fixed effects, robust inference, and static fixed-effects specifications as a transparency check.

2 Materials and methods

2.1 Data sources and variable construction

The dataset merges six annual series by ISO country code and year. Modern renewables as a share of total energy supply are drawn from Energy Institute, Smil and U.S. Energy Information Administration sources with processing by Our World in Data (OWID) [2, 7]. The measure excludes traditional biomass and is therefore conceptually different from renewable shares of total final energy consumption. Cereal yield and fertilizer intensity are based on FAOSTAT/FAO series processed by OWID [3, 7]. Territorial fossil-fuel and industrial CO_2 emissions per capita are from the Global Carbon Budget with OWID processing [4, 7]. GDP per capita is from the Maddison Project Database [5], and annual precipitation is based on Copernicus ERA5 data [6].

Strictly positive cereal yield, CO_2 per capita, GDP per capita, fertilizer intensity and precipitation are transformed using natural logarithms. Renewable-energy share remains in percentage points so that its coefficient is a semi-elasticity when the dependent variable is logged.

2.2 Sample coverage

After restricting the supplied files to sovereign African countries and merging all six variables, the complete-case sample contains Algeria, Egypt, Morocco and South Africa from 1965 through 2022. Each country contributes 58 annual observations, for 232 observations in the balanced panel. This restriction is driven by the African country coverage of the supplied modern-renewables series rather than discretionary deletion. The empirical claims are therefore limited to these four economies.

Table 1
Realized country coverage and selected sample means.

Country	Period	N	Renewables (%)	Cereal yield (t/ha)	CO_2 (t/person)	Status
Algeria	1965–2022	58	0.321	0.990	2.885	Balanced
Egypt	1965–2022	58	3.133	5.705	1.531	Balanced
Morocco	1965–2022	58	2.149	1.135	1.102	Balanced
South Africa	1965–2022	58	0.297	2.546	7.963	Balanced

2.3 Econometric specification

The dynamic emissions model is:

ln(CO2_it) = alpha ln(CO2_i,t-1) + beta1 Renewable_it + beta2 ln(Yield_it) + beta3 ln(GDPpc_it) + mu_i + lambda_t + epsilon_it.

The agricultural-productivity model is:

ln(Yield_it) = rho ln(Yield_i,t-1) + gamma1 Renewable_it + gamma2 ln(CO2_it) + gamma3 ln(Fertilizer_it) + gamma4 ln(Precipitation_it) + gamma5 ln(GDPpc_it) + mu_i + lambda_t + nu_it.

Both equations include country fixed effects (mu_i) and year fixed effects (lambda_t). HC1 heteroskedasticity-robust standard errors are reported. With only four countries, conventional country-clustered standard errors would rely on too few clusters for dependable asymptotic inference. The long time dimension reduces, but does not eliminate, dynamic fixed-effects bias; results are consequently interpreted as conditional panel associations rather than definitive causal effects. Static two-way fixed-effects models provide a robustness comparison.

3 Results

3.1 Descriptive statistics

Table 2
Descriptive statistics for the complete six-variable panel.

Variable	N	Mean	SD	Min	Median	Max
Cereal yield (t/ha)	232	2.594	2.161	0.245	1.602	7.556
Renewables (%)	232	1.475	1.659	0.000	0.887	7.883
CO_2 (t/person)	232	3.371	2.836	0.474	2.274	9.678
Fertilizer (kg/ha)	232	105.694	134.675	0.140	47.850	461.440
Precipitation	232	232.329	216.019	13.758	159.408	742.084
GDP per capita	232	6,629.230	3,303.631	1,742.000	6,081.976	14,198.272

Pairwise correlations are descriptive rather than causal. Renewable share is negatively correlated with log CO_2 per capita (r = -0.714) and log GDP per capita (r = -0.585), while log cereal yield is strongly correlated with log fertilizer intensity (r = 0.842). These relationships motivate multivariate specifications with fixed effects.

3.2 Dynamic emissions model

Table 3
Dynamic two-way fixed-effects model for log CO_2 emissions per capita. N = 228; R2 = 0.9925. Country and year fixed effects included; HC1 robust standard errors.

Regressor	Coefficient	Robust SE	p value
Lagged ln(CO_2)	0.8011	0.0408	< 0.001
Renewables (%)	-0.0007	0.0110	0.947
ln(Cereal yield)	-0.0347	0.0219	0.113
ln(GDP per capita)	0.1589	0.0554	0.004

The dominant feature is emissions persistence. The coefficient on lagged emissions is 0.801 ($p < 0.001$), indicating slow adjustment in country-level emissions. Conditional on this persistence, GDP per capita, cereal yield, country effects and year effects, the renewable-energy coefficient is close to zero and statistically insignificant. This does not imply that renewable energy cannot reduce emissions; it indicates that annual variation in the renewable share has no separately identified contemporaneous association in this historical four-country panel after conditioning on the existing emissions path.

3.3 Dynamic cereal-productivity model

Table 4
Dynamic two-way fixed-effects model for log cereal yield. N = 228; R2 = 0.9379. Country and year fixed effects included; HC1 robust standard errors.

Regressor	Coefficient	Robust SE	p value
Lagged ln(Yield)	0.0564	0.0784	0.472
Renewables (%)	0.0829	0.0320	0.010
ln(CO_2 per capita)	-0.4027	0.1203	0.001
ln(Fertilizer)	-0.0302	0.0576	0.600
ln(Precipitation)	0.1742	0.0634	0.006
ln(GDP per capita)	0.4854	0.1504	0.001

Renewable-energy share is positively associated with cereal productivity. With log yield as the dependent variable and renewables measured in percentage points, the coefficient implies an approximate 8.3% conditional difference in yield for a one-percentage-point increase in renewable share. The magnitude is large and should not be interpreted as a structural causal effect given the small cross-section and possible simultaneity. Precipitation and GDP per capita are also positive and statistically significant.

3.4 Static fixed-effects robustness

Table 5
Static two-way fixed-effects robustness estimates.

Outcome / regressor	Coefficient	Robust SE	p value
ln(CO_2): Renewables (%)	-0.0675	0.0213	0.002
ln(CO_2): ln(Cereal yield)	-0.2217	0.0545	< 0.001
ln(CO_2): ln(GDP per capita)	0.5212	0.1118	< 0.001
ln(Yield): Renewables (%)	0.0678	0.0287	0.018
ln(Yield): ln(CO_2)	-0.3789	0.1022	< 0.001
ln(Yield): ln(Fertilizer)	-0.0456	0.0563	0.418
ln(Yield): ln(Precipitation)	0.1834	0.0580	0.002
ln(Yield): ln(GDP per capita)	0.3996	0.1469	0.007

The static emissions model produces a sizeable negative renewable coefficient (-0.0675, p = 0.002), whereas the dynamic estimate is essentially zero. This contrast is substantively important: omitting persistence can attribute slow-moving historical emissions differences to contemporaneous renewable-energy variation. The positive renewable coefficient in the cereal-yield equation, by contrast, remains statistically significant in both static and dynamic specifications.

4 Discussion

The results point to an asymmetric energy-food-climate nexus. Renewable-energy adoption is positively associated with cereal productivity in the four selected economies, but the contemporaneous emissions association is not robust to explicitly modeling emissions persistence. This pattern is plausible because renewable electricity and modern energy systems can support irrigation, pumping, refrigeration, processing and rural infrastructure, while national CO_2 trajectories remain dominated by legacy generation fleets, transport, industry and fossil-fuel capital that adjust slowly.

The difference between static and dynamic emissions estimates also has methodological implications. A closely related SER study uses GMM for a much larger panel of 38 sub-Saharan African countries over 2000–2019 [1]. The present study addresses a different data geometry and agricultural concept: a four-country long-T panel, physical cereal productivity, and modern-renewables share of total energy supply. The contrast illustrates why estimator choice should follow the realized N and T rather than be transferred mechanically across studies.

The fertilizer coefficient is not statistically significant after controlling for country and year effects, precipitation, income, emissions and renewables. This is not evidence that fertilizer is agronomically unimportant. Fertilizer intensity is strongly correlated with cereal yield in levels, while within-country annual use may respond endogenously to expected harvest conditions, prices and policy.

5 Policy implications

Three implications follow. First, energy-transition and agricultural-modernization policies should be coordinated because modern energy can complement irrigation, storage, processing and other productivity-enhancing infrastructure. Second, decarbonization policy should recognize path dependence: annual changes in renewable share need not immediately overcome legacy fossil-fuel capital. Third, climate adaptation remains central. The positive precipitation coefficient indicates that weather variation remains materially related to cereal productivity even after economic and input controls, supporting complementary investment in water management, drought resilience and climate information.

6 Limitations

The principal limitation is external validity. The modern-renewables series supplied for this analysis yields complete African observations for only Algeria, Egypt, Morocco and South Africa. These economies do not represent the continent's full income, biomass-use, agroecological or electricity-access distribution. Second, N = 4 rules out a defensible standard Difference/System-GMM application and makes conventional country-clustered inference unreliable. Third, simultaneity remains possible: agricultural modernization can increase demand for modern energy, while economic development jointly affects renewables, yields and emissions. Fourth, national annual precipitation is a coarse climate

measure. Broader renewable-energy coverage and crop-specific temperature, rainfall-anomaly, irrigation, electricity-access and energy-price data would strengthen future identification.

7 Conclusions

Using 232 annual observations for Algeria, Egypt, Morocco and South Africa over 1965–2022, this study finds that inference about the energy-food-climate nexus depends materially on dynamic specification. CO_2 emissions are highly persistent. Once that persistence is modeled, renewable-energy share has no statistically detectable contemporaneous association with emissions, despite a strong negative coefficient in a static fixed-effects model. Renewable-energy share is positively associated with cereal yield in both static and dynamic specifications. The findings support integrated energy and agricultural policy while cautioning against interpreting static renewable-emissions correlations as immediate decarbonization effects. They should be read as carefully bounded four-country evidence rather than continent-wide estimates.

Abbreviations

CO_2
carbon dioxide
ERA5
ECMWF Reanalysis v5
FAO
Food and Agriculture Organization of the United Nations
GDP
gross domestic product
GMM
generalized method of moments
HC1
heteroskedasticity-consistent covariance estimator
OWID
Our World in Data.

Declarations

Ethics approval and consent to participate

Not applicable. The study uses publicly available country-level secondary data and involves no human participants, human tissue, or identifiable personal data.

Clinical trial number

Clinical trial number: not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

A.B.D. contributed to the conceptualization of the study, literature review, data collection and curation, methodology, interpretation of the findings, and preparation of the original manuscript. A.D. contributed to the conceptualization, methodology, supervision, validation of the empirical analysis, interpretation of the results, and critical review and editing of the manuscript. Both authors contributed to the development of the study, reviewed and revised the manuscript, and read and approved the final manuscript.

Data Availability

The country-year data analyzed in this study were assembled from six publicly accessible Our World in Data datasets: modern renewables as a share of total energy supply (https://ourworldindata.org/grapher/energy-mix); cereal yield (https://ourworldindata.org/grapher/cereal-yield); CO_2 emissions per capita (https://ourworldindata.org/grapher/co-emissions-per-capita); GDP per capita from the Maddison Project Database (https://ourworldindata.org/grapher/gdp-per-capita-maddison-project-database); fertilizer use per hectare of cropland (https://ourworldindata.org/grapher/fertilizer-use-per-hectare-of-cropland); and annual precipitation (https://ourworldindata.org/grapher/average-precipitation-per-year). The analytical panel was constructed by merging these series by ISO country code and year for Algeria, Egypt, Morocco and South Africa over 1965–2022. Original data providers are acknowledged in the References.

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