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Sitong Wang, Xiuming Zhang, Ouping Deng & Baojing Gu

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Interplay of urbanization and agricultural modernization shapes nitrogen use in global croplands

Sitong Wang[1, 2, 3], Xiuming Zhang[4], Ouping Deng[2, 5], Baojing Gu[1, 2, 3*]

[1]State Key Laboratory of Soil Pollution Control and Safety, Zhejiang University, Hangzhou, China
[2]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China
[3]Policy Simulation Laboratory, Zhejiang University, Hangzhou, China
[4]International Institute for Applied Systems Analysis, Laxenburg, Austria
[5]College of Resources, Sichuan Agricultural University, Chengdu, China

*Corresponding, email: bjgu@zju.edu.cn (B.G.)

Abstract

Urbanization reshapes agricultural systems through labor and land-use changes, interacting with modernization processes including farm size expansion, mechanization, and irrigation to drive nonlinear trends in cropland nitrogen use. Using a 61-year dataset from 139 countries, here we show that the association between urbanization and nitrogen outcomes is profoundly nonlinear and contingent on development stages. In low-income countries, urbanization initially increases fertilizer use while suppressing nitrogen yield and efficiency, though larger farm sizes mitigate these early losses. As countries reach upper-middle-income levels, modernization enhances nitrogen efficiency but introduces trade-offs between environmental gains and yield growth. In high-income countries, advanced modernization mitigates adverse urban impacts, reversing nitrogen use efficiency from a 4% decline to a 12% gain at high urbanization levels. These findings indicate that there is no universal sustainability pathway. Instead, integrating land consolidation, mechanization, and precision irrigation can transform urbanization into a catalyst for sustainable management and resilient food systems.

Introduction

Urbanization, one of the most significant global trends of the 21st century, profoundly reshapes population distribution and land-use patterns, with implications for agricultural systems and global food security[1-3]. A critical nexus in this transformation is the agricultural nitrogen cycle. While nitrogen-driven agricultural intensification has been instrumental in global food security [4, 5], its inefficient management has triggered severe, cascading environmental challenges[6-8]. Consequently, understanding the drivers that shape nitrogen management practices is paramount for navigating the trade-offs between productivity and sustainability in an increasingly urbanized world.

Existing literature has extensively explored the multifaceted associations of urbanization on agriculture with a dualistic view. One highlights the challenges, such as the irreversible loss of cropland and disruptions to rural labor markets[2, 3, 9-11]. Another suggests that urbanization can be a catalyst for agricultural modernization by fostering technology adoption and farm consolidation[12-14]. While insightful, these studies often focus on estimating a net average effect, potentially overlooking that the association of urbanization with agricultural outcomes is neither linear nor uniform. A critical knowledge gap exists in understanding this conditional heterogeneity: how does the association evolve with socioeconomic development in a country, and how is this evolution linked to the pace of its own agricultural modernization? Specifically, as urbanization coincides with rural labor migration and land consolidation, how do the resulting changes in farm size, machinery intensity, and irrigation intensity act as moderating variables that can either amplify or buffer the outcomes associated with urbanization at different stages? Answering these questions requires moving beyond a simple net-effect estimation to a more dynamic, interactive framework that can systematically map these nonlinear and context-dependent pathways.

To fill this gap, the central conceptual innovation of this study lies in integrating urbanization, agricultural modernization, and nitrogen trends into a unified, nonlinear moderating framework. Prior research has largely examined these domains in isolation. While linear global models are insightful, they often focus on estimating a net average effect, thereby masking critical threshold effects and structural phase transitions. Conversely, regional case studies offer rich granular details but often lack the macro-level perspective necessary to generalize how these relationships evolve across distinct stages of economic development. By capturing these joint nonlinearities, our approach yields macro-systemic insights that neither linear models nor regional studies can provide alone.

We hypothesize that the association of urbanization with nitrogen fertilizer application, nitrogen yield, and nitrogen use efficiency (NUE) is not uniform, but is profoundly nonlinear and critically contingent upon the stage of economic development and the prevailing levels of farm size, machinery intensity, and irrigation intensity. In low-income countries, the primary challenge is whether farm size can grow fast enough to compensate for labor loss and create a viable scale for machinery intensity[15, 16]. In contrast, in high-income countries, the challenges shift to managing the trade-offs of a highly optimized system, questioning whether further advances in machinery intensity and irrigation intensity can provide resilience against diminishing returns[17]. To test these hypotheses, we compiled a comprehensive panel dataset spanning 139 countries from 1961 to 2021. Recognizing the heterogeneity described above, our analytical approach moves beyond a single global model. We employ a dynamic, nonlinear analytical framework based on two-way fixed-effects models, a strategy specifically designed to robustly control for temporal dynamics and unobserved country-specific heterogeneity. This study provides a systematic, data-driven assessment of how the interplay between urbanization and agricultural modernization, contingent on development stage, jointly shapes the sustainability of global food production.

Results and discussion

Changes of urbanization and nitrogen cycle

Between 1961 and 2021, global patterns of urbanization and nitrogen use underwent profound transformations. The proportion of the global population living in urban areas rose from 31% to 56% (Fig. 1a), reflecting a worldwide transition from rural to urban societies. Although this urban shift occurred across all income groups, it was particularly pronounced in developing regions that started with low urbanization levels in 1961. East and Southeast Asia, Sub-Saharan Africa, West Asia, and Latin America experienced the most rapid increases (Fig. 1b–d), driven largely by demographic expansion in these regions[18]. In parallel, key indicators of agricultural modernization, farm size, machinery intensity, and irrigation intensity, also underwent significant and spatially heterogeneous changes (Fig. S1).

Over the past six decades, nitrogen fertilizer application on global cropland has risen dramatically. The global mean application rate increased from 9 kg N ha^{-1} in 1961 to 67 kg N ha^{-1} in 2021 (Fig. 1e). Most regions followed a steady upward trajectory, reflecting the broad diffusion of synthetic fertilizers after World War II. A notable deviation occurred in Eastern Europe, where nitrogen fertilizer application fell sharply in the 1990s after the dissolution of the Soviet Union (Fig. 1e, h). Despite favorable agricultural conditions provided by extensive black soils and high natural fertility[19], the collapse of state-subsidized systems, rising input costs, and disrupted production and supply chains during the economic transition led to a substantial reduction in nitrogen fertilizer application[20, 21]. In contrast, China and India showed substantial increases in nitrogen fertilizer application, paralleling rapid agricultural intensification and sustained gains in crop production (Fig. 1f–h).

Global crop nitrogen yield, defined as nitrogen harvested per hectare based on model estimates, rose from 15 kg N ha⁻¹ in 1961 to 46 kg N ha⁻¹ in 2021 (Fig. 1i). This increase reflects advances in crop breeding[22], improved management practices[23], and the expanded use of nitrogen fertilizers[5]. The most substantial gains occurred in China, India, Europe, and North America, where intensive farming and technological innovations supported sustained productivity growth[24]. In contrast, Central Asia, particularly countries such as Kazakhstan and Uzbekistan, experienced stagnation and even sharp declines in nitrogen yield during the 1990s (Fig. 1j–l). The breakdown of Soviet-era agricultural systems, difficulties in transitioning to market economies, and restricted access to essential inputs severely constrained productivity[21]. Environmental stressors such as arid climates, soil degradation, and long-standing irrigation challenges further amplified these declines[25, 26].

Despite the global surge in nitrogen inputs and yields, nitrogen use efficiency (NUE) declined markedly from roughly 45% in the 1960s to about 35% in the 1990s (Fig. 1m). This decline indicates that nitrogen fertilizer application growth far exceeded nitrogen yield improvements, producing diminishing returns[27]. Since the 1990s, however, NUE has gradually recovered to around 45% in the 2020s, driven largely by improved fertilizer management and more efficient production systems, especially in developed countries[28]. Some nations achieved higher nitrogen yields while reducing nitrogen fertilizer application. For example, Denmark[29] and the Netherlands[30] have substantially improved NUE through precision farming and optimized nutrient management[28]. Conversely, many rapidly industrializing countries such as China[31] and India[32] experienced declining NUE during periods of input-driven intensification, as nitrogen fertilizer application expanded faster than nitrogen yield gains. These contrasting trajectories underscore the intertwined evolution of urbanization, nitrogen use, and nitrogen losses across regions (Fig. 1n–p).

Average transmission pathways of urbanization

To elucidate the mechanisms underlying the macro-level trends, we employ a path analysis framework grounded in dynamic panel models (see Methods for detailed specifications). In this context, "average transmission pathways" refer to the baseline, unmoderated direct and indirect effects of urbanization on the nitrogen cycle. This approach enables the estimation of both direct and indirect pathways through which urbanization and agricultural modernization jointly influence the agricultural nitrogen cycle, providing a baseline for understanding the more complex nonlinear dynamics.

The direct association between urbanization and nitrogen yield and use efficiency evolves with economic development. In low- and lower-middle-income countries, a one percentage point increase in the urbanization rate corresponds to an average 0.67% increase in nitrogen fertilizer application, while its average direct associations with nitrogen yield and NUE remain statistically insignificant (Fig. 2a). This pattern suggests that, in early development, urbanization primarily drives input intensification rather than efficiency gains. As countries advance to upper-middle-income status, urbanization's average direct effects on nitrogen fertilizer, yield, and NUE become non-significant. While the former two lack a clear association, the neutrality for yield is due to a significant U-shaped curve (quadratic term: 0.97, $p<0.05$) where negative and positive effects offset each other (Fig. 2b). In high-income countries, the direct effects of urbanization on nitrogen yield and NUE also remain insignificant overall, but both exhibit significant U-shaped relationships, supported by positive quadratic coefficients for nitrogen yield (1.45, $p < 0.05$) and NUE (1.68, $p < 0.05$) (Fig. 2c). The emergence of this robust nonlinear pattern marks a key transition in advanced stages of development.

The mediating role of farm size also transforms fundamentally across income levels. Its association shifts from lower nitrogen yield in low-income countries to a central role in reducing machinery intensity, irrigation intensity, and nitrogen fertilizer application in high-income economies. The link between urbanization and farm size peaks during the upper-middle-income stage, when a one percentage point increase in urbanization corresponds to a 0.11% decrease in farm size, likely reflecting intensified land competition and peri-urban fragmentation. The association of farm size with lower input intensity per hectare becomes increasingly pronounced across development stages. In low-income countries, a 1% increase in farm size is associated with a significant 0.06% decrease in machinery intensity, while its associations with other inputs are not statistically significant (Fig. 2a). In the upper-middle-income stage, the same increase in farm size corresponds to significant declines of 0.05% in machinery intensity, 0.07% in irrigation intensity, and a marginally significant 0.09% reduction in nitrogen fertilizer application (Fig. 2b). By the high-income stage, this pattern becomes comprehensive: a 1% increase in farm size corresponds to decreases in machinery intensity, irrigation intensity, and nitrogen fertilizer application by 0.06%, 0.03%, and 0.10%, respectively (Fig. 2c). While farm size is weakly linked to lower nitrogen yield in low-income countries (−0.09%), it becomes positively associated with NUE in upper-middle-income economies (+0.05%).

The pathways governing nitrogen yield and NUE also reconfigure with development. In low- and lower-middle-income countries, nitrogen yield responds to multiple inputs: a 1% increase in machinery intensity, irrigation intensity, and nitrogen fertilizer application is associated with 0.02%, 0.03%, and 0.02% increases in nitrogen yield, respectively. In contrast, NUE is primarily constrained by nitrogen fertilizer application, with a 1% increase in nitrogen fertilizer application corresponding to a 0.08% decrease in NUE (Fig. 2a). As economies advance to upper-middle-income levels, the contribution of machinery intensity becomes negligible, while irrigation intensity emerges as a dominant factor, with a 1% increase in irrigation intensity yielding a 0.11% increase in nitrogen yield and a marginally significant 0.05% increase in NUE, indicating a potential synergy between productivity and efficiency (Fig. 2b). In high-income countries, the associations of both machinery intensity and irrigation intensity become insignificant, leaving nitrogen yield almost entirely dependent on f nitrogen fertilizer application, where a 1% increase in nitrogen fertilizer application corresponds to a 0.14% increase in nitrogen yield. Yet, this comes at a cost: the same increase in nitrogen fertilizer application is linked to a 0.28% decline in NUE, underscoring the growing trade-off between productivity and efficiency that characterizes advanced agricultural systems (Fig. 2c).

Nonlinear effects of urbanization

While the path analysis captures the average transmission channels between urbanization and nitrogen outcomes, it simplifies the inherently nonlinear and conditional nature of these relationships. To systematically examine these dynamics, we constructed conditional nonlinear marginal association curves (Fig. 3). These curves reveal two interrelated processes: the evolution of urbanization's marginal association across its full spectrum and the systematic reshaping of this trajectory as a function of agricultural modernization. To illustrate this moderation, we compared "Low Modernization" and "High Modernization" scenarios, defined by holding farm size, machinery, and irrigation intensity at specific lower and upper bounds within each income group (see Methods for detailed visualization construction and robustness checks).

In low- and lower-middle-income countries, higher agricultural modernization corresponds to a more favorable trajectory in the association between urbanization and nitrogen outcomes. For nitrogen fertilizer application, higher modernization tempers the initial surge in nitrogen fertilizer application linked to urbanization and shifts the vertex of the inverted U-shaped curve from an urbanization level of 37% to 53% (Fig. 3a, d). For nitrogen yield, urbanization exerts a prolonged suppressive effect under low modernization. This aligns with recent evidence of widespread yield stagnation among African smallholders[33, 34]. This stagnation is driven by rural outmigration and capital constraints that hinder mechanization[35]. Our framework reveals that larger farm size acts as a critical structural buffer against these early losses. Scaling-up of farm size helps overcoming capital barriers, as productivity rises significantly only after farms reach a viable size for mechanization[36]. Consistent with this technological threshold, the impact of urbanization on nitrogen yield reverses dramatically under high modernization: the turning point of the U-shaped curve moves from 52% to 34% urbanization, indicating that the shift to a positive association occurs much earlier (Fig. 3b, e). Similarly, for NUE, higher modernization mitigates the initial efficiency losses associated with early urbanization. Although the turning point shifts from 30% to 50%, the entire curve is elevated upward, implying that the initial decline is less severe (Fig. 3c, f).

In upper-middle-income countries, higher modernization brings clear environmental co-benefits but also introduces nuanced trade-offs with efficiency gains. Under high modernization, the vertex of the U-shaped curve for nitrogen fertilizer application shifts markedly rightward, from 44% to 72% urbanization, prolonging the phase during which urbanization is associated with declining nitrogen fertilizer application (Fig. 3a, d). For nitrogen yield, the curvature of the relationship remains similar, but the entire curve is higher in the early stages and lower in the later stages of urbanization, crossing at the global mean (Fig. 3b, e). This pattern suggests a shift from maximizing output toward optimizing resource use. Under high modernization, the positive association between urbanization and NUE weakens notably: the vertex of the U-shaped curve shifts from beyond the observed range to an early 27% urbanization level, and the later-stage improvement in NUE becomes visibly smaller compared with the low modernization scenario (Fig. 3c, f). These results indicate that once agricultural modernization reaches a high level, further efficiency gains rely less on structural urban transitions and more on internal technological and managerial improvements.

In high-income countries, the relationship reveals a structural bottleneck, where modernization primarily mitigates the adverse effects of advanced urbanization. For nitrogen fertilizer application, the association follows a U-shaped curve, but higher modernization shifts the vertex rightward (from 68% to 77%), delaying the onset of recovery (Fig. 3a, d). For both nitrogen yield and NUE, urbanization is initially associated with positive outcomes that turn negative at very high urbanization levels. High modernization exerts a dual moderating effect: it dampens early positive associations while slowing the rate of decline at later stages. Consequently, the curve lies lower in early stages but higher in later stages, reflecting a substantial mitigation of eventual negative outcomes (Fig. 3b, c, e, f). Around the vertices, the lowest points of the curves are consistently higher under high modernization, signaling reduced vulnerability to adverse effects. This resilience is especially pronounced for NUE in highly urbanized contexts. At 75% urbanization, high modernization elevates the marginal effect on NUE from a negative value to near zero, while at 90% urbanization, it shifts the effect from –4% to +12%, representing a swing of more than 16 percentage points. This striking reversal underscores the pivotal capacity of agricultural modernization to buffer, and even counteract, the negative impacts of advanced urbanization. Identifying the specific modernization components responsible for this resilience is therefore a central focus of the subsequent analysis.

Moderating role of agricultural modernization

To identify which components of agricultural modernization most strongly reshape urbanization's association with nitrogen outcomes, we decomposed the interaction terms into a moderation heatmap (Fig. 4). By evaluating urbanization's marginal effects at early (25%), middle (50%), and late (75%) transition stages across low and high levels of each moderator, this framework reveals which specific technological or structural factor exerts the most dominant influence in a given developmental context (see Methods for analytical decomposition and robustness checks).

In low- and lower-middle-income countries, farm size emerges as the dominant moderator in the early phase of urbanization, mitigating adverse effects on nitrogen yield and NUE. In later stages, agricultural modernization contributes to buffering the negative marginal associations for nitrogen fertilizer application. Early in the urban transition, larger farm size plays a crucial stabilizing role, reversing the initially negative association of urbanization with nitrogen yield and NUE, thereby acting as a structural safeguard against early disruptions (Fig. 4). However, this influence is largely stabilizing rather than growth-inducing, as the effects hover near zero (Fig. S2). Machinery intensity and irrigation intensity exert limited moderating effects during this early phase but gain importance later, when all three factors collectively buffer the decline in nitrogen fertilizer application (Fig. 4). This coordinated response highlights a key developmental insight: while early urbanization challenges can be mitigated by scaling up farm size, sustained improvement requires multifaceted modernization. Such a combined buffering effect is particularly relevant where nitrogen fertilizer application remains below agronomic recommendations, making nitrogen yield stability more critical than further input reduction.

In upper-middle-income countries, the early stages of urbanization exhibit a more complex interplay of moderating effects. Machinery intensity and irrigation intensity intensities enhance the nitrogen fertilizer application-reducing effect of urbanization, producing clear environmental benefits. This reflects the input substitution phase where urban labor pull drives severe fertilizer overuse to compensate for lacking fixed inputs[37, 38]. However, our results demonstrate that this trade-off can be optimized. Consistent with recent empirical studies, land consolidation must be coupled with mechanization to achieve genuine efficiency gains and positive regional spillovers[39, 40]. This synergy provides the necessary scale to significantly reduce fertilizer intensity[41]. However, they also intensify the negative association of urbanization with nitrogen yield. Irrigation intensity plays a particularly dual role: it accelerates nitrogen fertilizer application reduction, offering strong environmental co-benefits, while simultaneously amplifying nitrogen yield losses (Fig. 4). In contrast, machinery intensity consistently acts as a stabilizer, mitigating early nitrogen yield declines and reinforcing later gains. Farm size expansion, however, exerts a persistently adverse moderating influence, intensifying downward pressures on both nitrogen yield and NUE (Fig. 4; Fig. S3). This divergence underscores a key policy challenge for middle-income economies: distinct modernization strategies carry distinct trade-offs. Policies prioritizing irrigation for environmental benefits may sacrifice nitrogen yield, while emphasizing consolidation may undermine efficiency. Effective navigation of this transitional stage requires balanced modernization portfolios, such as coupling irrigation investments with mechanization to sustain nitrogen productivity while maintaining environmental gains.

In high-income countries, modernization dynamics fundamentally shift. Farm size expansion, once a driver of efficiency, now acts as a negative moderator, exacerbating the decline in both nitrogen yield and NUE (Fig. 4). This reversal indicates diminishing or even negative returns to scale. It aligns with recent evidence that highly optimized and large-scale operations face yield stagnation and limited environmental benefits[42-44]. In contrast to further scale expansion, technological modernization through machinery intensity and irrigation intensity emerges as the principal source of resilience. These components consistently buffer the adverse impacts of high urbanization levels, albeit with a characteristic trade-off: slightly lower peak performance in early stages in exchange for greater stability in later phases (Fig. S4). In the advanced stages, machinery intensity becomes particularly decisive, being associated with both strengthened reductions in nitrogen fertilizer application and, crucially, a shift in the marginal association between urbanization and NUE from neutral to positive (Fig. 4). This nuanced finding refines the average positive role of farm size by delineating its limits. For high-income economies, sustainable nitrogen management in the face of continued urbanization will depend less on further farm consolidation and more on technology-driven intensification, emphasizing mechanization and irrigation efficiency to balance productivity, resource use, and environmental resilience.

Policy implications

Urbanization exerts a profound and heterogeneous influence on agricultural land availability and management, demanding policy responses tailored to each country's developmental stage. Our findings demonstrate that a "one-size-fits-all" approach to agricultural modernization in an urbanizing world is not only ineffective but may also produce counterproductive outcomes. Instead, policymakers must navigate evolving trade-offs among productivity, efficiency, and resilience as economies develop.

For low- and lower-middle-income countries, where urbanization initially undermines agricultural nitrogen yields[3], the immediate policy challenge lies in managing the transition away from labor-intensive smallholder systems. Early urbanization often triggers a cascade of adverse effects: the loss of prime cropland to urban expansion, the outmigration of skilled rural labor, and widespread underutilization of farmland, as seen in parts of Sub-Saharan Africa[45]. Although larger farm size can partially offset labor shortages through more efficient resource allocation, scale expansion alone is insufficient. Persistent technological stagnation, rooted in barriers such as credit constraints, weak markets, and inadequate infrastructure, often prevents scale gains from translating into higher productivity[46]. Without complementary technological upgrading, land consolidation can even intensify trade-offs between farm size and food security[47]. Policies must therefore pursue synergistic modernization, coupling consolidation initiatives with "smart" subsidies that target appropriate-scale mechanization and productive inputs[48]. Experiences such as Rwanda's Crop Intensification Program and the Sustainable Agricultural Mechanization for Africa (SAMA) framework[49, 50] illustrate how linking land and technology policies can transform early urbanization pressures into drivers of sustainable agricultural growth. Modernization components can also diverge. In fragmented systems like South Asia, mechanization often decouples from consolidation via machinery rental and custom hiring services[51]. Policymakers should support these service-oriented models through cooperatives and credit, rather than relying exclusively on land consolidation[52-54].

As economies advance toward upper-middle-income status, the policy focus must shift from foundational capacity building to balancing environmental sustainability with continued productivity gains[55-57]. Our analysis identifies irrigation as a powerful lever for improving nitrogen efficiency and reducing nitrogen fertilizer application, while machinery intensity emerges as a key determinant of late-stage nitrogen yield growth. The optimal balance between these levers depends heavily on each country's farm structure. For smallholder-dominated systems such as China and Vietnam, policy evolution has followed a two-stage trajectory, from early market liberalization and infrastructure expansion to contemporary efforts targeting nitrogen surpluses and water scarcity[56, 58]. Similar economies must integrate environmental and food security objectives within a single policy framework, ensuring that ecological limits are internalized into growth strategies. Conversely, countries such as Brazil and Mexico, characterized by dualistic agricultural structures dominated by large commercial farms, face a different challenge: ensuring the sustainability of already modernized systems[59, 60]. For these economies, maintaining productivity without exacerbating environmental degradation requires embedding sustainability practices, such as precision irrigation and nutrient monitoring, within mechanized production frameworks[61, 62]. Policies that coordinate water, energy, and land management can prevent resource competition while safeguarding both nitrogen yields and environmental integrity.

In high-income countries and those transitioning into this category, the central policy concern shifts from optimization to resilience. Our results show that at very high levels of urbanization, even advanced agricultural systems encounter diminishing returns, with potential declines in nitrogen yield and NUE. At this stage, expanding farm size is no longer a viable pathway to sustainability; further consolidation can generate negative externalities, including biodiversity loss, soil degradation, and social inequities[3, 63]. Japan exemplifies this inflection point: a highly mechanized, small-scale system now constrained by severe labor shortages and declining marginal returns, prompting a strategic pivot toward technological innovation and resilience building. Similarly, Poland's post-socialist agricultural transformation, guided by the EU's Common Agricultural Policy (CAP), reflects a decisive policy reorientation toward environmental sustainability and system stability[64]. For these advanced economies, the policy priority should be technology-driven intensification rather than scale expansion[65, 66]. This entails promoting precision agriculture through robotics, sensors, and data analytics, an approach aligned with Japan's "Society 5.0" agricultural vision[67], to optimize input use and minimize waste. At the same time, embedding circular economy principles is essential to enhance nutrient recycling and reduce system-wide nitrogen losses[68]. Integrating urban and peri-urban agriculture into broader land-use planning frameworks can further offset the ecological costs of urban sprawl[13]. Collectively, these strategies can help highly urbanized nations build resilient, resource-efficient, and climate-adaptive food systems capable of sustaining agricultural productivity in an increasingly urban world.

Limitations and future research

While our dynamic panel models, combined with country-level fixed effects and climate anomaly controls (see Methods and Supplementary Note S1.3), provide robust macro-systemic insights, navigating the urbanization-agriculture nexus at finer scales remains a critical frontier. Given the significant sub-national heterogeneity in urbanization patterns and soil health dynamics, future research employing grid-level data and precise farm structural metrics could identify targeted regional hotspots. Furthermore, although our path analysis mitigates primary endogeneity concerns, employing simultaneous equation modeling or quasi-experimental approaches could further refine the causal precision of these complex feedback loops. Finally, as sustainable intensification involves a multifaceted set of outcomes, extending this framework to analyze synergies between nitrogen management, water footprint, and biodiversity will provide a more holistic picture of how to optimize agricultural development in an urbanizing world [69, 70, 71].

Methods

We compiled national-level data from 139 countries spanning 1961 to 2021, sourced from FAOSTAT[72], the USDA database[73], FAO's Aqua-stat database[74], World Bank[75], and the CHANS model[31], widely recognized datasets for agricultural analysis, to investigate how urbanization is associated with nitrogen use and nitrogen losses in global croplands. Using nitrogen as an indicator of agricultural intensification and environmental impact, we incorporated farm size, machinery intensity, and irrigation intensity as mediating variables and developed empirical regression models stratified by mediator levels to estimate how nitrogen fertilizer application, nitrogen yield and NUE respond to urbanization. Subsequently, we constructed an impact pathway, modeled using SEM, to trace how urbanization relates to nitrogen use indicators through its association with the mediators. Finally, we conducted a counterfactual analysis based on historical data and aggregated the results by income groups to assess how the estimated effects of urbanization on nitrogen dynamics vary across different economic contexts.

Data sources and processing. In this study, urbanization level, population, and cropland area data for the period 1961–2021 were obtained from FAOSTAT. PGDP (GDP per capita) data is obtained from World Development Indicators Database of World Bank[75]. Farm size was estimated as the cropland area per agricultural laborer. This metric provides a more direct measure of agricultural operational scale by linking land resources to the active agricultural workforce, thereby avoiding potential endogeneity that could arise from using total rural population as a denominator. Data for the agricultural labor force were obtained from the FAOSTAT database.

We conducted a regression analysis on the samples where ‘Cropland area per agricultural laborer’ and ‘Actual farm size’ could be matched by country and year, using the same fixed-effects settings as the main model (Table S1). Data for the latter, obtainable from the World Census of Agriculture[76], is scarce, unevenly distributed, and lacks consistent statistical standards across countries, making it unsuitable for the main model's formal analysis. The results show that the coefficient for "Cropland area per agricultural laborer" is positive and highly significant. This indicates that after controlling for all country-level fixed characteristics and common time trends, the changes in "Cropland area per agricultural laborer" and "Actual farm size" are strongly and positively correlated. Furthermore, the goodness-of-fit for the model was 96.7%, suggesting that our proxy, in combination with country and year fixed effects, can account for 96.7% of the fluctuations in "Actual farm size". This demonstrates that the dynamic changes in "Cropland area per agricultural laborer" can indeed effectively capture the important trends in the changes in agricultural operation scale. For clarity and impact in discussing our results and policy implications, we refer to this proxy as 'farm size' throughout the text, with its precise definition and validation detailed herein.

Information regarding agricultural machinery was extracted from the September 2023 release of the USDA's International Agricultural Productivity database[73]. This dataset supplies national-level estimates of total machinery stock, expressed in metric horsepower (CV), spanning the years 1961 through 2021. To capture the concentration of mechanized capital investment independent of population shifts, we calculated machinery intensity by dividing the total machinery power by the corresponding cropland area (CV ha^{-1}).

Irrigation statistics were obtained from the FAO AQUASTAT database. We explicitly utilized the metric 'actually irrigated area under full control irrigation'[74]. This specific category purposefully omits spate irrigation, equipped lowlands, and areas possessing inactive irrigation infrastructure. We omitted these elements because their reliance on floodwater means they remain highly vulnerable to climate fluctuations, unlike full-control systems. Moreover, their inclusion would artificially lower the calculated cropping intensity, distorting the actual agronomic advantages of active irrigation[77,78]. We then determined irrigation intensity by calculating the ratio of this actively controlled irrigated area to the total cropland area (%), serving as a proxy for the prevalence of advanced water management practices.

For the nitrogen budget, we relied on the CHANS model, which employs a comprehensive mass balance approach[31]. This framework combines top-down regional and global reactive nitrogen data with bottom-up flux estimations across 14 distinct subsystems (such as croplands, livestock, forests, wastewater, and atmospheric deposition). By synthesizing these diverse inputs and outputs, the CHANS model offers a holistic, multi-scalar evaluation of nitrogen flows and cycling.

In this study, the term 'nitrogen fertilizer application' specifically refers to the amount of nitrogen (N) applied to cropland from synthetic fertilizers, measured in kg N ha^{-1}. This is denoted as $N_{fertilizer}$ in our nitrogen budget calculations and is a core input flux derived from the CHANS model, which synthesizes data from sources including the International Fertilizer Association (IFA) and FAOSTAT. The total nitrogen output from cropland (N_{output}) includes harvested nitrogen ($N_{harvest}$), which is calculated as the sum of nitrogen content in the harvested grain and straw components. This calculation is based on annual crop production data from FAOSTAT and crop-specific nitrogen content coefficients established in the scientific literature. Our 'nitrogen yield' indicator, termed 'nitrogen harvested per hectare,' is calculated as the total modeled nitrogen harvested in crop grain and straw ($N_{harvest}$) divided by the cropland area. This output flux is calculated within the CHANS model based on annual crop production data (from FAOSTAT) and crop-specific nitrogen content coefficients.

The nitrogen budget for cropland used in this study encompasses all crops (including staple crops and cash crops) from 1961 to 2021 and is calculated using the following equations (1)-(4):

$$N_{input} = N_{fertilizer} + N_{manure} + N_{deposition} + N_{Fixation} + N_{irrigation} \quad (1)$$

$$N_{output} = N_{harvest} + N_{gas} + N_{runoff} + N_{leaching} \tag{2}$$

$$N_{harvest} = N_{grain} + N_{straw} \tag{3}$$

$$NUE = \frac{N_{harvest}}{N_{input}} \tag{4}$$

where N_{input} represents the total nitrogen input to cropland, encompassing contributions from all crops. This includes $N_{fertilizer}$, which accounts for synthetic nitrogen fertilizer applications; N_{manure} ,denoting organic nitrogen fertilizer use; $N_{Fixation}$, referring to biological nitrogen fixation; $N_{irrigation}$, representing nitrogen supplied through irrigation; and $N_{deposition}$, signifying atmospheric nitrogen deposition.

N_{output} denotes the total nitrogen output from cropland, where $N_{harvest}$ refers to the total harvested nitrogen, encompassing both grain nitrogen (N_{grain}) and straw nitrogen (N_{straw}). Additionally, N_{gas} indicates nitrogen gas emissions from cropland, which include NH_3, NOx, N_2O, and N_2. N_{runoff} reflects nitrogen runoff emissions from cropland, while $N_{leaching}$ pertains to the leaching of nitrogen into groundwater.

Statistical analysis

The urbanization level and PGDP data were standardized to a mean of 0 prior to statistical analysis to ensure comparability of regression coefficients. Additionally, due to the inherent right-skewed distribution of the raw PGDP data, a natural logarithm transformation was applied before standardization to better approximate a normal distribution. For the visualization of response curves, while the model inputs remained standardized values, the horizontal axis (urbanization level) was plotted using the original data scale to facilitate the practical interpretation of curve inflection points. This dual approach preserved computational accuracy in model estimation while retaining intuitive interpretability of results within the original measurement context. All results of main model are shown in Tables S2-S5.

Dynamic panel interaction model

To investigate the complex and potentially heterogeneous relationships between urbanization, agricultural modernization, and nitrogen outcomes, we developed and applied a dynamic panel interaction model. This analytical framework is designed to capture two critical features of the underlying data generating process. First, the 'dynamic' component acknowledges that nitrogen outcomes (e.g., nitrogen yield, NUE) exhibit strong temporal persistence due to systemic inertia, such as soil nitrogen legacy and the path-dependency of farming behaviors. We therefore incorporate a one-year lagged value of the dependent variable to account for this state dependence. Crucially, the inclusion of this autoregressive term directly dictates the interpretational role of our estimates. Because the lagged dependent variable absorbs the historical accumulation of effects, the estimated coefficients for urbanization and modernization must be interpreted strictly as short-run (contemporaneous) marginal effects. They quantify the immediate shift in nitrogen outcomes conditional on the system's state in the previous year, rather than the cumulative long-run equilibrium effects, thereby yielding a more conservative and precise measure of contemporary dynamics. Second, the 'interaction' component allows us to model how the effects of urbanization on nitrogen use indicators vary continuously and nonlinearly with the levels of key agricultural modernization mediators: farm size, machinery intensity, and irrigation intensity.

The urbanization level and all continuous control variables were centered (i.e., demeaned) prior to analysis. This ensures that the estimated coefficients are comparable and mitigates potential multicollinearity when including quadratic and interaction terms. As mentioned, PGDP was log-transformed prior to centering to address its right-skewed distribution.

Our core empirical specification is a multi-dimensional fixed-effects model, estimated using the following general form:

$$Y_{it} = b_0 + c_0 Y_{i,t-1} + c_1 U_{it} + c_2 U_{it}^2 + \sum_{k=1}^{K} (d_k M_{kit} + e_k M_{kit}^2) + \sum_{k=1}^{K} (f_k U_{it} \cdot M_{kit}) + g' W_{it} + \eta_i + \tau_t + \zeta_j + \nu_{it} \tag{5}$$

where the subscripts i and t denote country and year, respectively. Y_{it} represents the dependent variables: the natural logarithms of nitrogen fertilizer application, nitrogen yield, and NUE. $Y_{i,t-1}$ is the one-year lag of the dependent variable, with its coefficient $\mathbf{c}_0$ capturing the degree of temporal persistence or autoregression. U_{it} is the centered urbanization rate. Its quadratic term, U_{it}^2, is included to capture the nonlinear (U-shaped or inverted U-shaped) effects of urbanization. M_{kit} is the k-th centered mediator of agricultural modernization, including farm size (cropland area per agricultural laborer), machinery intensity (CV ha^{-1}), and irrigation intensity (proportion of irrigated cropland). Their quadratic terms, M_{kit}^2, are also included to account for their own nonlinear impacts. $U_{it} \cdot M_{kit}$ represents the interaction term between urbanization and each modernization mediator. The coefficients of primary interest, f_k, capture how the marginal effect of urbanization on Y_{it} is moderated by the level of agricultural modernization. W_{it} is a vector of time-varying control variables, including the natural logarithm of per capita GDP (lnPGDP), precipitation, and temperature, along with their quadratic terms. To further account for system dynamics, this vector also includes cross-dynamic controls (e.g., lagged nitrogen fertilizer application, $\mathrm{N}_{fertilizer,it}$, when modeling nitrogen yield, $\mathrm{N}_{yield,it}$) to capture inter-temporal feedback between different nitrogen cycle components. η_i, τ_t, and ζ_j are country, year, and crop-type fixed effects, respectively. These absorb unobserved time-invariant heterogeneity at the country level (e.g., geography, culture), common time shocks affecting all countries (e.g., global technological trends), and variations specific to dominant crop systems. ν_{it} is the idiosyncratic error term, clustered at the country level to produce robust standard errors.

To systematically examine heterogeneity across development stages, we partitioned the full sample into three sub-groups based on World Bank income classifications: (1) Low- and Lower-middle-income, (2) Upper-middle-income, and (3) High-income countries. We estimated the complete interaction-term model independently for each sub-group. This classification is based on the World Bank's income group designations for the most recent year of our dataset (2021). This approach ensures that each country remains in the same group throughout the analysis, allowing us to interpret the results as the average developmental trajectory for countries that have achieved a certain income status. We acknowledge that some countries transitioned between groups during the 60-year study period, and we explore the implications for these transitioning economies in our Policy Implications section. This strategy allows all model coefficients, including those for quadratic and interaction terms, to vary freely across income groups, thereby avoiding the imposition of homogeneity constraints. This approach enables a granular examination of how the mechanisms linking urbanization to agricultural nitrogen cycles differ fundamentally across countries at varying levels of economic development.

The results from these models form the basis for our main findings, which are presented through a series of visualizations designed to illustrate the conditional marginal effects of urbanization across different scenarios of agricultural modernization and income levels.

To operationalize this for Fig. 3, the moderating variables (farm size, machinery, and irrigation intensity) were held constant at either the 10th percentile (defining the "Low Modernization" scenario) or the 90th percentile (defining the "High Modernization" scenario) within each income group. While this discrete comparison simplifies the visualization, it effectively represents the main trend of what is, in reality, a continuous moderation process. We verified this by plotting the smooth shifts and deformations of the effect curves across the full 1st-to-99th percentile spectrum of modernization levels (Figs. S5–S7), confirming that the 10th and 90th percentiles serve as robust representative bounds.

Furthermore, we rigorously tested the stability of these nonlinear patterns against historical outliers. A secondary analysis excluding countries that experienced major structural breaks (e.g., severe armed conflicts or state dissolution) yielded highly consistent curve shapes and vertices (Supplementary Note S3; Figs. S8-S10; Tables S6-S10). This confirms that the estimated nonlinear trajectories are driven by fundamental economic and agricultural transition mechanisms rather than anomalous geopolitical shocks. To address potential omitted variable bias from time-varying environmental factors, we conducted a second robustness check to ensure our findings are not sensitive to interannual climate variability (Fig. S11-13, Table S11-14).

To construct the moderation heatmaps (Fig. 4), we systematically decomposed the multidimensional interaction terms ($U_{it} \cdot M_{kit}$) from the main empirical models. This involved evaluating the analytical derivative of the outcome with respect to urbanization at three representative urban transition stages (25%, 50%, and 75%), conditioned on the 10th and 90th percentiles of each specific moderator. The relative moderating strength visualized by the color intensity of each cell, was calculated as the difference in the marginal effect of urbanization between the high and low modernization scenarios, scaled by the baseline effect. The robustness of these distinct moderating patterns is further corroborated by the continuous nature of the underlying interactions, as mapped across the full data distribution (Figs. S5–S7).

Dynamic path analysis

To analyze the causal pathways linking urbanization to nitrogen outcomes while rigorously addressing the temporal dynamics inherent in our panel data, we replaced the conventional structural equation modeling (SEM) framework with a path analysis constructed from a system of dynamic panel regression models. This approach involves estimating a separate regression equation for each endogenous variable in our conceptual model (e.g., farm size, machinery intensity, nitrogen fertilizer application, nitrogen yield, and NUE). The estimated coefficients from this system of equations are then used to construct the final path diagram (Fig. 2).

Prior to estimation, all continuous variables were centered by subtracting their respective sample means to aid in the interpretation of coefficients. To handle extreme outliers, key agricultural modernization indicators (farm size, machinery intensity, and irrigation intensity) were winsorized at the 99th percentile.

The general form for each equation in the system is a two-way fixed-effects model with a lagged dependent variable:

$$Y_{it} = \rho Y_{i,t-1} + \beta_1 U_{it} + \beta_2 U_{it}^2 + \delta' Z_{it} + \mu_i + \gamma_t + \kappa_j + \varepsilon_{it} \tag{6}$$

where the subscripts *i*, *t*, and *j* denote country, year, and dominant crop type, respectively. Y_{it} is the centered outcome variable for a specific equation in the path model. $Y_{i,t-1}$ is its one-year lag, included to capture the dynamic adjustment process and mitigate bias from serial autocorrelation. Empirically, our estimations yielded consistently high self-lagged coefficients (typically ranging from 0.6 to 0.9; Tables S2–S3). These high values reflect strong systemic inertia, such as the persistence of local farming habits and soil nutrient carry-over. By explicitly absorbing these historical accumulation effects into the lagged term, our model successfully isolates the immediate net impact of urbanization. U_{it} is the centered urbanization rate. Its quadratic term, U_{it}^2, is included to capture the nonlinear effects of urbanization on each endogenous variable. Z_{it} is a vector of control variables specific to each equation. It includes other endogenous variables that are causally prior in the path diagram (e.g., farm size is included when modeling machinery intensity), as well as a set of exogenous controls: centered ln(PGDP), precipitation, temperature, and their quadratic terms. To further account for system dynamics, this vector also includes lags of other relevant endogenous variables (e.g., lagged nitrogen yield and nitrogen fertilizer application when modeling NUE). These cross-lagged terms explicitly account for complex feedback loops where past outcomes influence current agricultural management decisions. μ_i, γ_t, and κ_j are country, year, and crop-type fixed effects, respectively. These absorb unobserved heterogeneity at the country level (e.g., geography), common time shocks (e.g., global technological trends), and variations specific to crop systems. This two-way fixed-effects specification also substantially mitigates concerns about non-stationarity by de-trending the series. ε_{it} is the idiosyncratic error term. Standard errors for all models are clustered at the country level to ensure robust statistical inferences in the presence of arbitrary within-country serial correlation and heteroskedasticity.

This entire system of equations was estimated separately for three distinct income sub-groups (Low- & Lower-middle, Upper-middle, and High-income), allowing all path coefficients to vary across different stages of economic development.

All coefficients reported in the path diagram (Fig. 2) represent the average marginal effect, which is calculated for a typical case where predictor variables are at their mean values. Because the dynamic specification controls for historical states, these coefficients must be strictly interpreted as short-run marginal effects, capturing the contemporaneous changes within a single year. This value quantifies the expected change in the outcome variable for a one-unit change in the predictor.

Data availability

The annual panel data for 139 countries (1961–2021) used in this study were obtained from FAO (https://www.fao.org/faostat/en/#data/OA; https://data.apps.fao.org/aquastat/?lang=en; https://www.fao.org/faostat/en/#data/WCAD), the World Bank (https://datatopics.worldbank.org/world-development-indicators/), and the USDA International Agricultural Productivity dataset (https://ers.usda.gov/data-products/international-agricultural-productivity/). The processed datasets generated in this study have been deposited in the Figshare database under accession code https://doi.org/10.6084/m9.figshare.31612852. The data for visualized are provided in the Source Data file.

Code availability

The Stata scripts used for the fixed-effects models and path analysis, have been deposited in the Figshare database under accession code https://doi.org/10.6084/m9.figshare.31612852.

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Author Contributions Statement

B.G. designed the research. S.W. conducted the research and performed the analysis. X.Z. provided the nitrogen supply data. S.W., O.D. and B.G. wrote the first draft. And all authors contributed to the discussion and revision of the paper.

Competing Interests Statement

All authors have no conflicts of interest to report.

Additional information

Supplementary information is available for this paper.

Fig. 1 | Changes in urbanization level and nitrogen use in cropland from 1961 to 2021. (a) Global average urbanization level; (b) Urbanization level in 1961; (c) Urbanization level in 2021; (d) Change in urbanization level from 1961 to 2021; (e) Global weighted-average nitrogen fertilizer application intensity change from 1961 to 2021; (f) Nitrogen fertilizer application in 1961; (g) Nitrogen fertilizer application in 2021; (h) Change in nitrogen fertilizer application from 1961 to 2021; (i) Global weighted-average nitrogen yield change from 1961 to 2021; (j) Nitrogen yield in 1961; (k) Nitrogen yield in 2021; (l) Change in nitrogen yield from 1961 to 2021; (m) Global weighted-average NUE change from 1961 to 2021; (n) NUE in 1961; (o) NUE in 2021; (p) Change in NUE from 1961 to 2021. The basemaps used in this figure were generated using data from GADM (https://gadm.org/).

Fig. 2 | Average transmission pathways of urbanization's impact on nitrogen fertilizer application, nitrogen yield and NUE across income groups. The diagrams illustrate the direct and indirect pathways for (a) Low & low-middle, (b) Upper-middle, and (c) High-income countries. All path coefficients are estimated using two-way fixed-effects models that include a lagged dependent variable to account for dynamic adjustments. All coefficients represent the average marginal effect, which is calculated for a typical case where predictor variables are at their mean values. Blue arrows indicate a statistically significant positive effect ($p < 0.1$), and red arrows indicate a significant negative effect. The significance of each effect is denoted by asterisks (*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$). All models include a quadratic term for urbanization to capture potential nonlinear relationships. Full regression results are provided in Tables S2-S3. “Farm size” is proxied by cropland area per agricultural laborer.

Fig. 3 | Agricultural modernization reshapes the nonlinear effects of urbanization on nitrogen fertilizer application, nitrogen yield and NUE. The panels compare the conditional nonlinear effect curves of urbanization under "Low Modernization" (top row, a-c) and "High Modernization" (bottom row, d-f) scenarios. The effects are shown for (a, d) Nitrogen fertilizer application, (b, e) Nitrogen yield, and (c, f) NUE across three income groups. Each curve represents the conditional effect of urbanization on the natural logarithm of the outcome variable, calculated by holding all moderating variables (farm size, machinery intensity, irrigation intensity) at the 10th or 90th percentile within each income group, respectively. By comparing the top and bottom panels, the moderating role of agricultural modernization—in shifting the curves' position, shape, and vertices—is visualized. Triangular markers indicate the vertex of each quadratic curve, representing the point at which the marginal effect of urbanization changes sign. Shaded areas represent 90% confidence intervals (calculated as ± 1.645 SE). Boxplots show the distribution of urbanization rates for each income group. “Farm size” is proxied by cropland area per agricultural laborer.

Fig. 4 | Agricultural modernization reshapes the effects of urbanization by exerting divergent moderating roles across development stages. This heatmap deconstructs how individual components of agricultural modernization (Farm Size, Machinery intensity, Irrigation intensity) modulate the marginal effect of urbanization on nitrogen fertilizer application, nitrogen yield and

NUE. The analysis is stratified by income group (rows) and key stages of urbanization (columns, evaluated at 0.25, 0.50, and 0.75 levels). Each cell contains two values: the conditional marginal effect of urbanization when the specified moderator is low (top number; 10th percentile) versus high (bottom number; 90th percentile). The cell's color visualizes the relative moderating strength: the change in urbanization's marginal effect (as the moderator shifts from its 10th to 90th percentile), scaled by the baseline marginal effect (evaluated at the moderator's mean). To guide interpretation, statistically significant findings are highlighted. Cells where at least one marginal effect is significant ($p < 0.1$) are rendered as raised buttons, while insignificant findings appear as flat squares. The significance of each marginal effect is denoted by asterisks (*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$). “Farm size” is proxied by cropland area per agricultural laborer.

Editor’s Summary

Researchers show how modernization helps nations turn urbanization from a challenge into a catalyst for nitrogen efficiency. By integrating technology and land consolidation, countries can achieve sustainable farming in an increasingly urban world.

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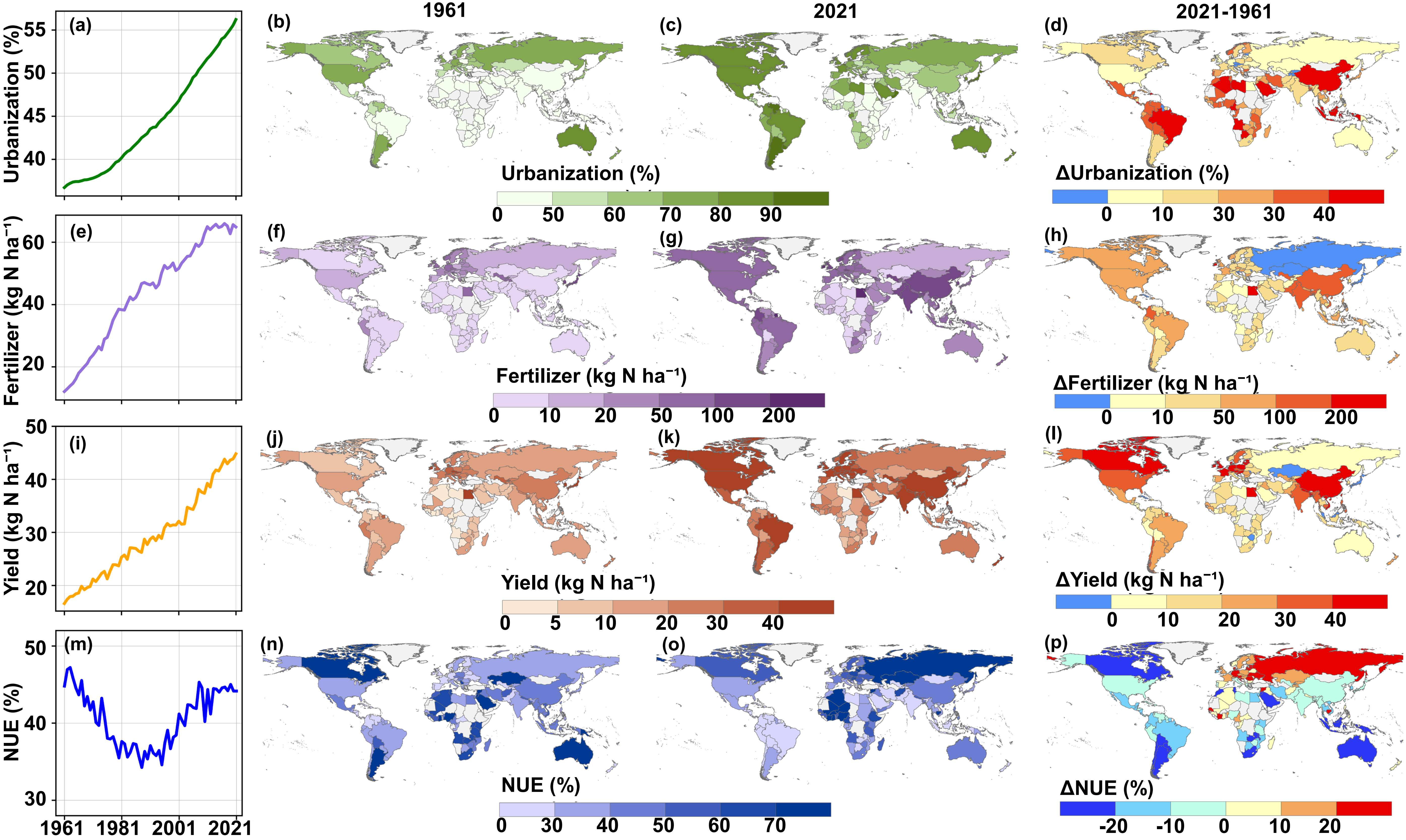
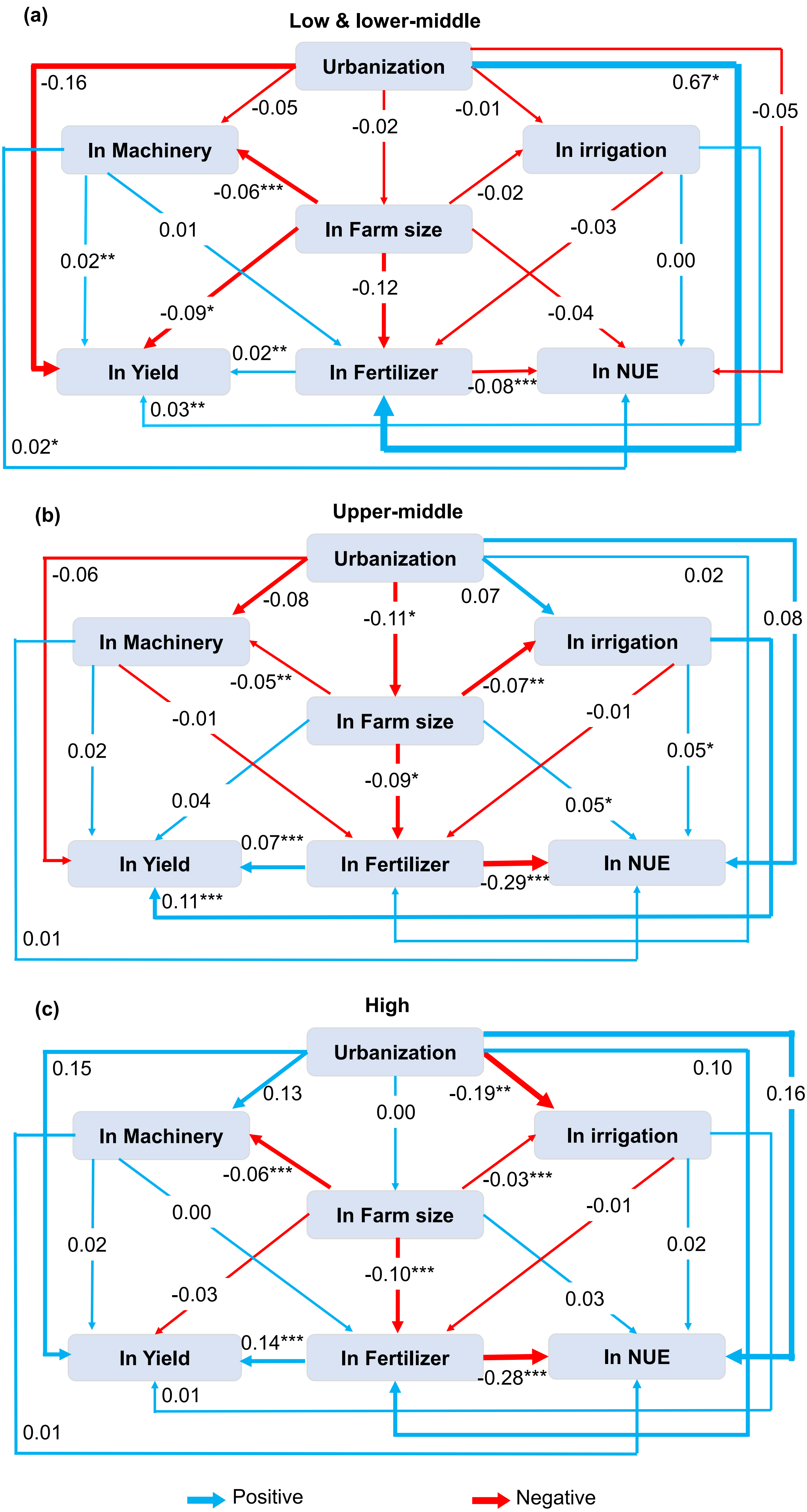
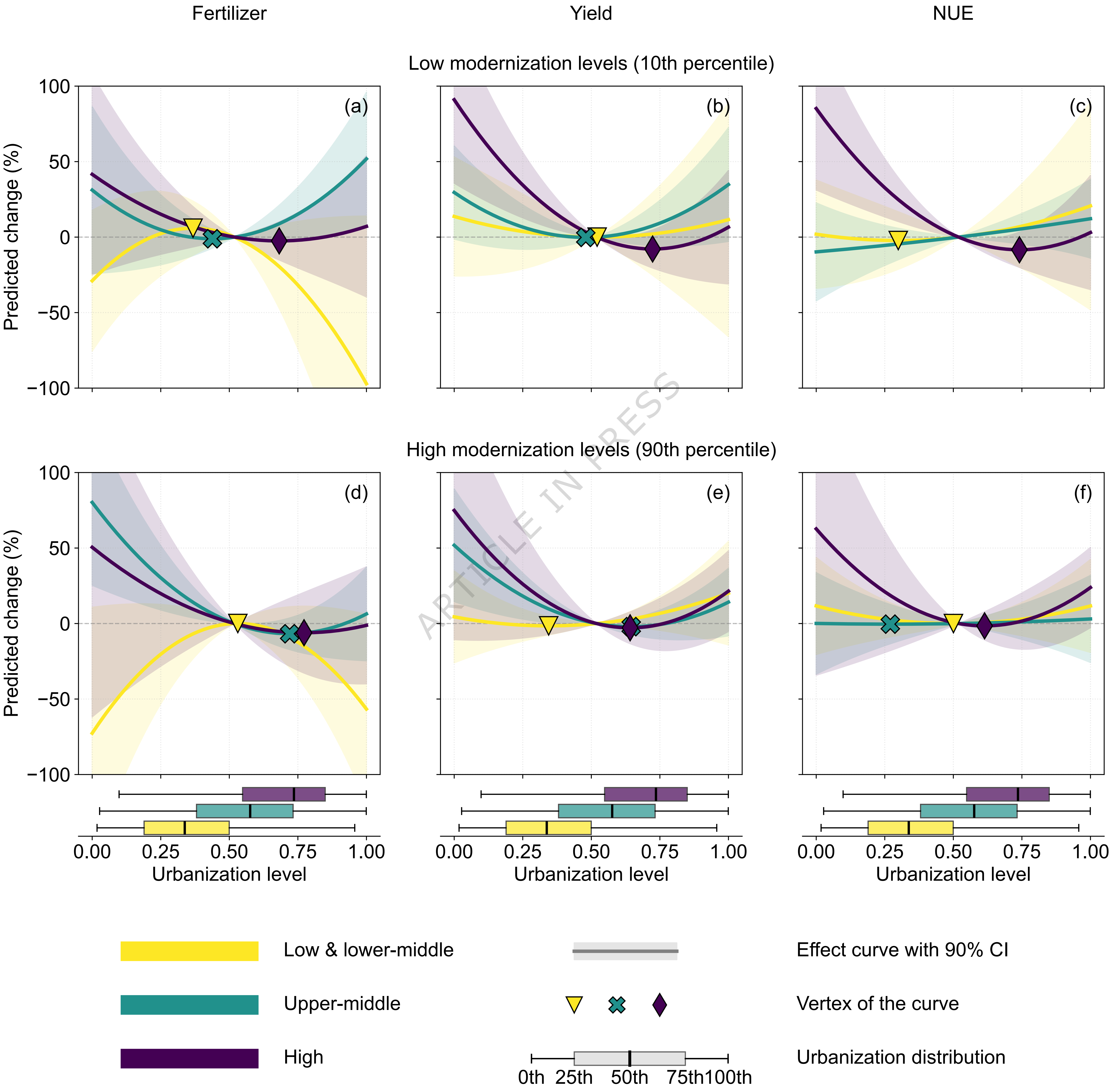
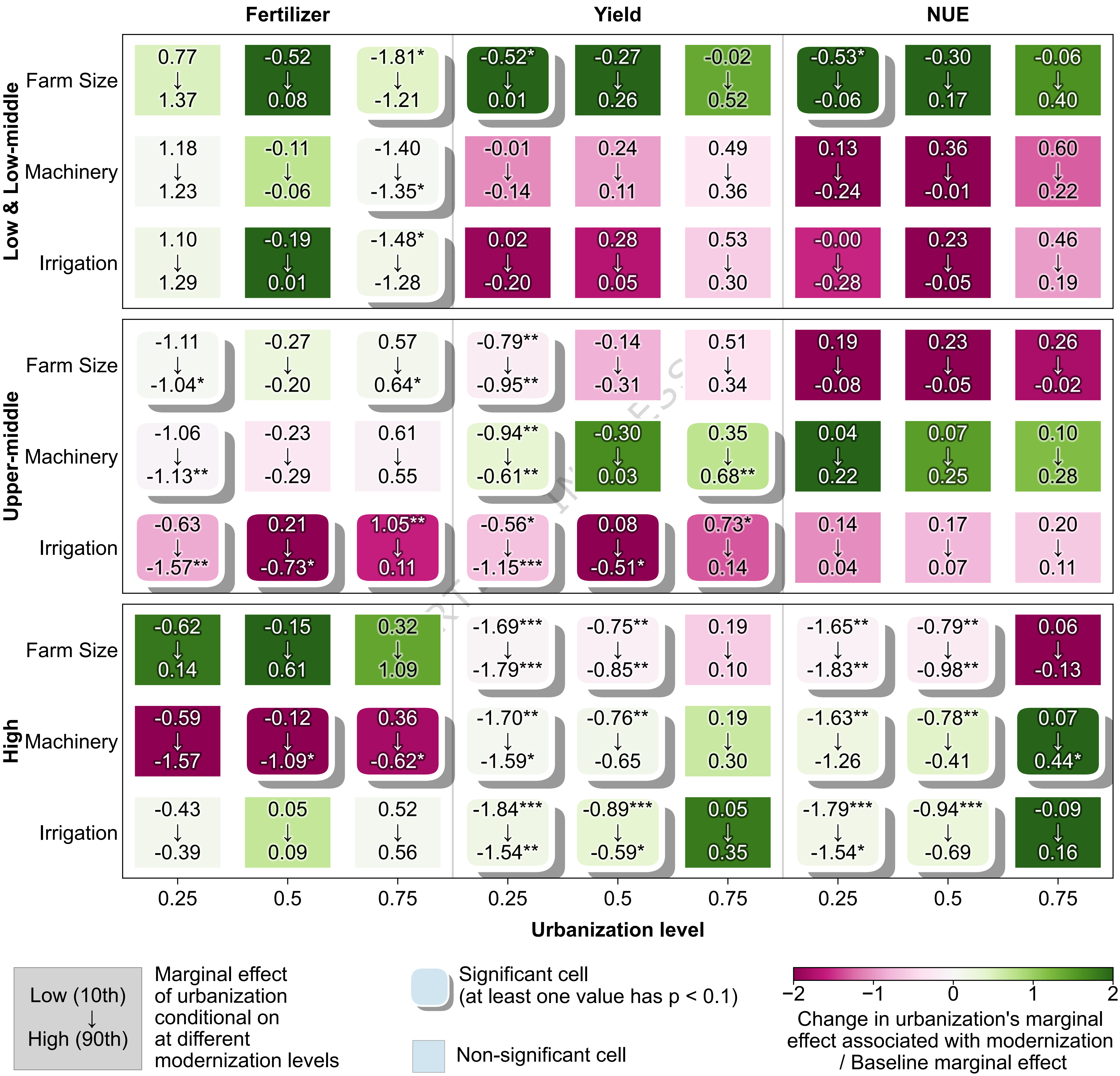

1961
2021
2021-1961
(a)
Urbanization (%)
55
50
45
40
(b)
(c)
(d)
Urbanization (%)
0
50
60
70
80
90
ΔUrbanization (%)
0
10
30
30
40
(e)
Fertilizer (kg N ha⁻¹)
60
40
20
(f)
(g)
(h)
Fertilizer (kg N ha⁻¹)
0
10
20
50
100
200
ΔFertilizer (kg N ha⁻¹)
0
10
50
100
200
(i)
Yield (kg N ha⁻¹)
50
40
30
20
(j)
(k)
(l)
Yield (kg N ha⁻¹)
0
5
10
20
30
40
ΔYield (kg N ha⁻¹)
0
10
20
30
40
(m)
NUE (%)
50
40
30
1961
1981
2001
2021
(n)
(o)
(p)
NUE (%)
0
30
40
50
60
70
ΔNUE (%)
-20
-10
0
10
20


(a)
Low & lower-middle
Urbanization
ln Machinery
ln irrigation
ln Farm size
ln Yield
ln Fertilizer
ln NUE
-0.16
-0.05
-0.02
-0.01
0.67*
-0.05
-0.06***
-0.02
0.01
0.02**
-0.03
0.00
-0.12
-0.09*
-0.04
0.02**
-0.08***
0.03**
0.02*
(b)
Upper-middle
Urbanization
ln Machinery
ln irrigation
ln Farm size
ln Yield
ln Fertilizer
ln NUE
-0.06
-0.08
-0.11*
0.07
0.02
0.08
-0.05**
-0.07**
-0.01
0.02
-0.01
0.05*
-0.09*
0.04
0.05*
0.07***
-0.29***
0.11***
0.01
(c)
High
Urbanization
ln Machinery
ln irrigation
ln Farm size
ln Yield
ln Fertilizer
ln NUE
0.15
0.13
0.00
-0.19**
0.10
0.16
-0.06***
-0.03***
0.00
0.02
-0.01
0.02
-0.10***
-0.03
0.03
0.14***
-0.28***
0.01
0.01
Positive
Negative


Fertilizer
Yield
NUE
Low modernization levels (10th percentile)
High modernization levels (90th percentile)
(a)
(b)
(c)
(d)
(e)
(f)
Predicted change (%)
100
50
0
−50
−100
0.00
0.25
0.50
0.75
1.00
Urbanization level
Low & lower-middle
Upper-middle
High
Effect curve with 90% CI
Vertex of the curve
Urbanization distribution
0th
25th
50th
75th
100th


Fertilizer
Yield
NUE
Low & Low-middle
Farm Size
0.77 ↓ 1.37
-0.52 ↓ 0.08
-1.81* ↓ -1.21
-0.52* ↓ 0.01
-0.27 ↓ 0.26
-0.02 ↓ 0.52
-0.53* ↓ -0.06
-0.30 ↓ 0.17
-0.06 ↓ 0.40
Machinery
1.18 ↓ 1.23
-0.11 ↓ -0.06
-1.40 ↓ -1.35*
-0.01 ↓ -0.14
0.24 ↓ 0.11
0.49 ↓ 0.36
0.13 ↓ -0.24
0.36 ↓ -0.01
0.60 ↓ 0.22
Irrigation
1.10 ↓ 1.29
-0.19 ↓ 0.01
-1.48* ↓ -1.28
0.02 ↓ -0.20
0.28 ↓ 0.05
0.53 ↓ 0.30
-0.00 ↓ -0.28
0.23 ↓ -0.05
0.46 ↓ 0.19
Upper-middle
Farm Size
-1.11 ↓ -1.04*
-0.27 ↓ -0.20
0.57 ↓ 0.64*
-0.79** ↓ -0.95**
-0.14 ↓ -0.31
0.51 ↓ 0.34
0.19 ↓ -0.08
0.23 ↓ -0.05
0.26 ↓ -0.02
Machinery
-1.06 ↓ -1.13**
-0.23 ↓ -0.29
0.61 ↓ 0.55
-0.94** ↓ -0.61**
-0.30 ↓ 0.03
0.35 ↓ 0.68**
0.04 ↓ 0.22
0.07 ↓ 0.25
0.10 ↓ 0.28
Irrigation
-0.63 ↓ -1.57**
0.21 ↓ -0.73*
1.05** ↓ 0.11
-0.56* ↓ -1.15***
0.08 ↓ -0.51*
0.73* ↓ 0.14
0.14 ↓ 0.04
0.17 ↓ 0.07
0.20 ↓ 0.11
High
Farm Size
-0.62 ↓ 0.14
-0.15 ↓ 0.61
0.32 ↓ 1.09
-1.69*** ↓ -1.79***
-0.75** ↓ -0.85**
0.19 ↓ 0.10
-1.65** ↓ -1.83**
-0.79** ↓ -0.98**
0.06 ↓ -0.13
Machinery
-0.59 ↓ -1.57
-0.12 ↓ -1.09*
0.36 ↓ -0.62*
-1.70** ↓ -1.59*
-0.76** ↓ -0.65
0.19 ↓ 0.30
-1.63** ↓ -1.26
-0.78** ↓ -0.41
0.07 ↓ 0.44*
Irrigation
-0.43 ↓ -0.39
0.05 ↓ 0.09
0.52 ↓ 0.56
-1.84*** ↓ -1.54**
-0.89*** ↓ -0.59*
0.05 ↓ 0.35
-1.79*** ↓ -1.54*
-0.94*** ↓ -0.69
-0.09 ↓ 0.16
0.25
0.5
0.75
0.25
0.5
0.75
0.25
0.5
0.75
Urbanization level
Low (10th) ↓ High (90th)
Marginal effect of urbanization conditional on at different modernization levels
Significant cell (at least one value has p < 0.1)
Non-significant cell
−2
−1
0
1
2
Change in urbanization's marginal effect associated with modernization / Baseline marginal effect