Bilim
Innovatsiya
Barqaror rivojlanish

Noyabr
№ 11, 2026

AGROBIZNES, FAN VA TEXNOLOGIYALAR

ILMIY-AMALIY
ELEKTRON
JURNAL

Агробизнес, наука и технологии

Agribusiness, science and technology



№ 083688

ISSN:
3060-5245

Toshkent-2026

Platform & workflow by
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Manzil: Toshkent viloyati, Qibray tumani, Universitet ko'chasi, 2-uy.
Jurnalning telegram manzili:
t.me/agrobiznes_elektronjurnal
E-mail: licht-1989@mail.ru
Jurnalning rasmiy sayti:
https://www.agrobiznesjournal.uz
Tel: +(998) 93 439 30 00

JURNALNING ILMIYLIGI:

Ma'lumot uchun, OAK Rayosatining 30.11.2024-yildagi №364/5-sonli qarori bilan 08.00.00-Iqtisodiyot fanlari bo'yicha, 08.05.2025-yildagi №370/5-sonli qarori bilan 06.00.00-Qishloq xo'jaligi fanlari bo'yicha "Dissertatsiyalar asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro'yxati"ga kiritilgan.

Elektron nashr, 362-sahifa.
2026-yil, №11. noyabr.

Jurnal har oyda bir marotaba elektron shaklda jurnalning rasmiy sayti orqali nashr etiladi.

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EFFICIENCY–RESILIENCE COUPLING AND SPATIAL SPILLOVERS IN CROSS-BORDER ARID AGGLOMERATIONS: AN ANALYTICAL FRAMEWORK AND TESTABLE PROPOSITIONS

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Abstract. The article moves the analysis of efficiency–resilience coupling from the description of coordination states to the identification of spatial mechanisms. For cross-border arid agglomerations along the Central Asian segment of the Silk Road Economic Belt, it specifies how local coupling is converted into green resilience competitiveness through three channels — factor allocation, green technological innovation, treated here as technology iteration, and infrastructure sharing — and how that conversion propagates to neighbouring cities through a weight matrix. Within that matrix the technology diffusion channel is the operational counterpart of new technology transfer in the ecological-environmental field: it registers the movement of green standards, patents, process know-how and supplier capability between city nodes, including across national borders, where enforcement, statistical definitions and water rights all change. Because the spatial Durbin model is inverted rather than read off its coefficients, the total effect of the transfer is decomposed into a direct component retained by the transferring city and an indirect component accruing to receiving cities, and the two components together are read as the economic benefit of new technology transfer. The framework separates positive diffusion from negative pollution and water cost displacement within a single specification, and submits the coupling effect to a threshold gate defined by water constraint intensity, city size and development stage. Five propositions are derived, each paired with the observational pattern that would support it and the pattern that would falsify it. No estimates are reported; the contribution is a mechanism-based design whose claims can be rejected.
Keywords: coupling coordination, spatial spillovers, spatial Durbin model, mediation, threshold effects, urban agglomeration, Central Asia, green resilience competitiveness, technology iteration, technology transfer.

Annotatsiya. Maqolada samaradorlik va chidamlilik bog‘lanishini tahlil qilish muvofiqlik holatlarini tavsiflashdan fazoviy mexanizmlarni aniqlashga o‘tkaziladi. “Buyuk ipak yo‘li” iqtisodiy kamarining Markaziy Osiyo qismidagi transchegaraviy qurg‘oq shahar klasterlari uchun mahalliy bog‘lanish yashil chidamli raqobatbardoshlikka uch kanal — omillar taqsimoti, yashil texnologik innovatsiya va infratuzilmadan birgalikda foydalanish — orqali qanday aylantirilishi va bu aylanish og‘irlik matritsasi yordamida qo‘shni shaharlarga qanday tarqalishi ko‘rsatilgan. Ushbu matritsada texnologik diffuziya kanali ekologik muhit sohasidagi yangi texnologiyalar transferining operatsion ifodasi sifatida qaraladi: u yashil standartlar, patentlar, texnologik bilim va yetkazib beruvchilar salohiyatining shahar tugunlari o‘rtasida, shu jumladan davlat chegaralari orqali harakatini qayd etadi. Yashil texnologik innovatsiya texnologik iteratsiya sifatida talqin qilinadi. Fazoviy Durbin modeli matritsani teskari aylantirish yo‘li bilan hisoblanganligi sababli transferning to‘liq ta'siri o‘tkazuvchi shaharda qoladigan bevosita komponentga va qabul qiluvchi shaharlarga o‘tadigan bilvosita komponentga bo‘linadi; bu ikki komponent birgalikda yangi texnologiyalar transferining iqtisodiy samarasini ifodalaydi. Tahliliy asos ijobiy texnologik diffuziyani salbiy ifloslanish va suv xarajatlarining ko‘chirilishidan bitta fazoviy Durbin spetsifikatsiyasi doirasida ajratadi, to‘liq ta'sirlarni bevosita va bilvosita komponentlarga ajratadi hamda bog‘lanish ta'sirini suv cheklovi, shahar hajmi va rivojlanish bosqichi bilan belgilanadigan chegaraviy shartga bo‘ysundiradi.
Kalit so‘zlar: bog‘lanish uyg‘unchiligi, fazoviy tarqalish effektlari, fazoviy Durbin modeli, mediatsiya, chegaraviy ta'sirlar, shahar klasteri, Markaziy Osiyo, yashil chidamli raqobatbardoshlik, texnologik iteratsiya, texnologiyalar transferi.

2026-yil, noyabr.
№11-son.
ISSN: 3060-5245

Аннотация. В статье анализ сопряжения эффективности и резильентности переводится с описания состояний согласованности на идентификацию пространственных механизмов. Для трансграничных аридных агломераций центральноазиатского участка Экономического пояса Шёлкового пути показано, как локальное сопряжение превращается в зелёную резильентную конкурентоспособность через три канала — распределение факторов, зелёные технологические инновации и совместное использование инфраструктуры — и как это превращение распространяется на соседние города через матрицу весов. В этой матрице канал технологической диффузии выступает операциональным выражением передачи новых технологий в сфере экологии: он фиксирует перемещение зелёных стандартов, патентов, технологического знания и компетенций поставщиков между городскими узлами, в том числе через государственные границы. Зелёные технологические инновации трактуются как технологическая итерация. Поскольку пространственная модель Дурбина оценивается через обращение матрицы, совокупный эффект передачи раскладывается на прямую компоненту, остающуюся в передающем городе, и косвенную компоненту, достающуюся принимающим городам; вместе эти компоненты характеризуют экономический эффект передачи новых технологий. Аналитическая рамка разделяет позитивную технологическую диффузию и негативное перемещение загрязнения и водозатрат в рамках единой пространственной модели Дурбина, раскладывает совокупные эффекты на прямые и косвенные компоненты и подчиняет эффект сопряжения пороговому условию, задаваемому водным ограничением, размером города и стадией развития. Выведены пять гипотез, каждая с поддерживающим и опровергающим наблюдательным паттерном.
Ключевые слова: согласованность связности, пространственные эффекты перелива, пространственная модель Дурбина, медиация, пороговые эффекты, городская агломерация, Центральная Азия, зелёная резильентная конкурентоспособность, технологическая итерация, передача технологий.

INTRODUCTION

Research on the coupling of economic efficiency and ecological resilience has produced a large stock of coordination scores. Cities and agglomerations are graded as moderately or highly coordinated, the grades are mapped over time, and the maps are read as evidence of a green transition in progress. What the grades do not answer is the question that matters for policy: through which channels does a better matching of efficiency and resilience become a better competitive position, and how far does that conversion reach across space? The coordination literature has been productive in measurement and reserved in explanation, and the reservation is costly in a region where the most consequential processes cross national borders.

Central Asia is such a region. Warming there exceeds the global mean, and heat extremes and droughts are increasing in frequency and intensity, so that the water constraint is not a stationary background but a moving one [1][2]. The five countries had a combined population of about 82.26 million in 2024, with urbanisation rates ranging from 26.2 per cent in Tajikistan to 62.1 per cent in Kazakhstan, and population and activity concentrate in a small number of nodes [3][4]. Water is allocated along two transboundary rivers whose upstream and downstream positions differ, so that efficiency gains achieved upstream by reducing return flow and expanding storage change the water available to downstream cities [5]. Air pollution, dust and salt transport cross borders independently of administrative jurisdiction, as the Aral Sea experience demonstrates at the scale of a whole basin [6][7]. Industrial linkages created by the

2026-yil, noyabr.
№11-son.
ISSN: 3060-5245

Silk Road Economic Belt connect agglomerations across Kazakhstan, Uzbekistan and Kyrgyzstan, and evidence along the route indicates that the effect of cross-border infrastructure and investment on green productivity is strongly heterogeneous across countries and stages, so that the same intervention can diffuse technology in one node and displace resource-intensive activity in another. Uzbekistan's green economy strategy for 2019–2030 and its nationally determined contributions set aggregate emission-intensity targets for exactly this territory [8][9], and the question is how those targets reach the nodes. The governance of these flows is national, while the flows themselves are regional: this is the spatial mismatch that a state-level coordination score cannot represent.

The direction of spillovers is also genuinely uncertain, and that uncertainty is theoretical rather than empirical. Agglomeration economies, labour pooling and supplier linkages predict positive diffusion: a city that raises its green efficiency may transmit technologies, standards and demand to its neighbours. Pollution haven and cost-displacement arguments predict the opposite: a city that tightens environmental constraints may export dirty production and water-intensive activity to jurisdictions with weaker enforcement, so that its own indicators improve while the region degrades. Both mechanisms can operate at the same time, on different channels, with different signs, and between the same pair of cities. A model that estimates a single average spillover coefficient and reports it as the effect of coupling therefore averages two opposing processes and reports neither.

This article develops the analytical framework needed to separate them. It specifies how local coupling coordination is converted into green resilience competitiveness through three transmission channels, how the conversion propagates through four spillover channels embedded in a weight matrix, and under what conditions the sign of the propagation reverses. The design uses a spatial Durbin specification with direct and indirect effect decomposition, mediation tests on the three transmission channels, and a panel threshold model whose gate variable is water constraint intensity. The article reports no estimates. Its contribution is a set of five propositions, each stated together with the observational pattern that would support it and the pattern that would falsify it, so that the empirical stage of the research can fail.

Three terminological choices carry the argument, and they are fixed here so that the design can be read against the questions that motivate it. First, green technological innovation is treated as technology iteration rather than as an innovation stock: what the second transmission channel measures is the successive replacement of resource-intensive routines, standards and equipment by less resource-intensive ones under a binding environmental constraint, which is why its indicators are the green patent stock and exports of green technology products rather than research expenditure alone. Second, the technology diffusion channel of the weight matrix is the operational counterpart of new technology transfer in the ecological-environmental field: it registers the movement of green standards, patents, process know-how and supplier capability

2026-yil, noyabr.
№11-son.
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from one city node to another, including across national borders, where enforcement, statistical definitions and water rights all change. Third, the economic benefit of that transfer is read not from a single spillover coefficient but from the decomposition: the direct effect is the benefit retained by the transferring city, the indirect effect is the benefit or cost that accrues to receiving cities, and the two are reported separately because a gain in one node that is paid for in another is not a regional gain. These three correspondences are maintained throughout the article, which is written within a research programme on ecological-environmental technology iteration and the economic benefits of new technology transfer.

Three contributions follow from that choice. First, coordination is treated as a mechanism rather than a state: the dependent variable is not the coordination score but the competitiveness that coordination is supposed to produce, which removes the circularity of regressing one composite on another and makes the outcome of technology iteration something that can be measured independently of the iteration itself. Second, positive diffusion and negative displacement are specified as distinct channels with distinct indicators and distinct expected signs, so that new technology transfer is estimated as two separable flows — a transfer of capability and a transfer of cost — rather than as a residual, and the average spillover parameter is no longer asked to carry an interpretation it cannot support. Third, the threshold gate makes the conditionality explicit and, together with the exact decomposition of total effects, makes the economic benefit of technology transfer reportable separately for the sending and the receiving node: the framework predicts where coupling helps, where it stops helping, and who bears the cost when it stops, instead of asserting a monotone relationship that the literature on efficiency–resilience trade-offs has already given reason to doubt [10][11].

ANALYSIS OF LITERATURE ON THE TOPIC

The coupling coordination degree model characterises, through a capacity coupling coefficient and a comprehensive coordination index, the extent to which two subsystems reinforce or constrain each other, and it has been applied extensively to urbanisation–eco-environment and economy–resource–environment relationships. Its analytical value lies in revealing the matching state between systems that grow at different rates. Its limits are now well documented. The coordination degree is a relative indicator, so that two low-performing subsystems can display high coordination; the literature usually reports grades and rankings without asking what the grades imply for performance; the model assumes positive coupling by construction and therefore cannot represent the case in which efficiency gains are obtained by depleting the redundancy that resilience depends on; and the coefficient is computed from normalised values, which conceals differences in absolute scale between countries with very different income levels.

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Spatial econometrics supplies the tools that the second problem requires. Exploratory spatial data analysis identifies clustering and outliers through global and local indicators of spatial association [12]. The spatial Durbin model decomposes spillovers into direct and indirect effects through the spatial lag of the dependent variable and of the explanatory variables, and the decomposition is exact rather than approximate once the spatial multiplier is inverted [13][14]. Existing applications have used these tools to identify spillovers of green efficiency on urban resilience, but most samples are Chinese agglomerations, the direction of the spillover is usually reported as a single coefficient, and the conditionality of its sign is rarely examined.

The direction question has its own literature. Agglomeration economies, labour market pooling and input–output linkages predict technology diffusion and productivity convergence across neighbouring cities; pollution haven and cost-displacement arguments predict that stringent regulation relocates dirty activity to weaker jurisdictions. Both predictions have empirical support in different contexts, which suggests that the sign is conditional on industrial structure, on the strength of linkages and on the asymmetry of environmental enforcement. In a cross-border setting the conditionality is sharper still, because enforcement, water rights and statistical definitions all change at the border, and because upstream–downstream positions create a hydrological asymmetry that has no counterpart within a single country.

Mechanism identification requires more than a spatial lag. Mediation analysis decomposes the effect of an explanatory variable into a direct part and an indirect part transmitted through an intermediate variable [15], and in a spatial setting the intermediate variables must themselves be spatial: factor allocation, innovation and infrastructure are all channel variables that operate within a city and across cities at the same time. Threshold estimation supplies the tools for the conditionality claim: the panel threshold model tests whether a coefficient changes structurally when a threshold variable crosses a critical value, without imposing the location of that value in advance [16]. A related identification caution is the reflection problem, which arises whenever the behaviour of a group is explained by the behaviour of its members and the two are not separately identified [17]; it applies with full force to spillover models in which neighbours' outcomes and neighbours' characteristics enter the same equation.

Finally, the resilience literature provides the reason to expect asymmetry rather than monotonicity. Efficiency and resilience do not always move together, and over-optimisation narrows the room a system has for coping with uncertainty [10]. Regional resilience research stresses that the response to a shock has phases — resistance, recovery, reorientation and renewal — and that measurement must specify the shock and the window [11]. If a city raises efficiency by removing redundancy, its measured coordination may improve while its capacity to absorb the next drought declines, and the cost of that decline may be borne by neighbours that share the same water source. The mechanism framework developed below is built to make exactly this pattern observable.

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RESEARCH METHODOLOGY

The study constructs an analytical framework and a specification design rather than reporting estimates. It proceeds in four steps: specification of the transmission chain from coupling to competitiveness; specification of the spillover channels and their signs; construction of the econometric design, including effect decomposition, mediation and thresholds; and stipulation of the identification strategy and its limits. The unit of analysis is the city node, thirty-two of which form ten agglomerations along the Central Asian segment of the Silk Road Economic Belt, observed annually from 2010 to 2024. Three weight matrices are used in parallel — geographical distance, economic distance and transport connectivity — because the choice of matrix is a substantive statement about which flows matter, not a technical default.

The core specification is a spatial Durbin model of the form

$$GRC_{it} = \rho WGRC_{it} + \beta X_{it} + \theta WX_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where the core explanatory variable in X is the local coupling coordination D_it, and the controls are the level of economic development, population size, industrial structure, openness, infrastructure and climate zone. The spatial autoregressive parameter ρ captures dependence in outcomes; β captures local effects; θ captures the effect of neighbours' characteristics on a city's own outcome; and W encodes the flow structure. Total effects are obtained from the partial derivatives of the reduced form,

$$(I - \rho W)^{-1}(\beta I + \theta W)$$

whose diagonal elements give direct effects and whose off-diagonal row sums give indirect effects. Reporting only the point estimates of β and θ, as is often done, would misstate both magnitudes and interpretation.

Mediation is tested along three channels: factor allocation efficiency, measured by capital and labour misallocation indices; green technological innovation, measured by the green patent stock and by exports of green technology products; and infrastructure sharing, measured by transport and energy network connectivity between city pairs. Stepwise regression is combined with bootstrap interval tests, and reverse causality between mediators and the outcome is controlled by lagging the mediators and by instrumenting innovation with the provincial or regional research budget allocated before the period. The mediation claim is only accepted if the indirect effect survives the change of weight matrix, which is a stricter requirement than statistical significance in a single specification.

Threshold tests use water constraint intensity, city size and stage of economic development as threshold variables in a panel threshold model, in order to test whether the coefficient of coupling changes structurally across regimes [16]. Where an inverted-U relation is found, quadratic terms and piecewise regression are used as cross-validation, because a single threshold and a smooth curvature are different claims and should not be conflated. Two identification problems are treated explicitly. The first is weight endogeneity: if W is built from trade or commuting flows, it is itself an outcome of the process being explained, and the

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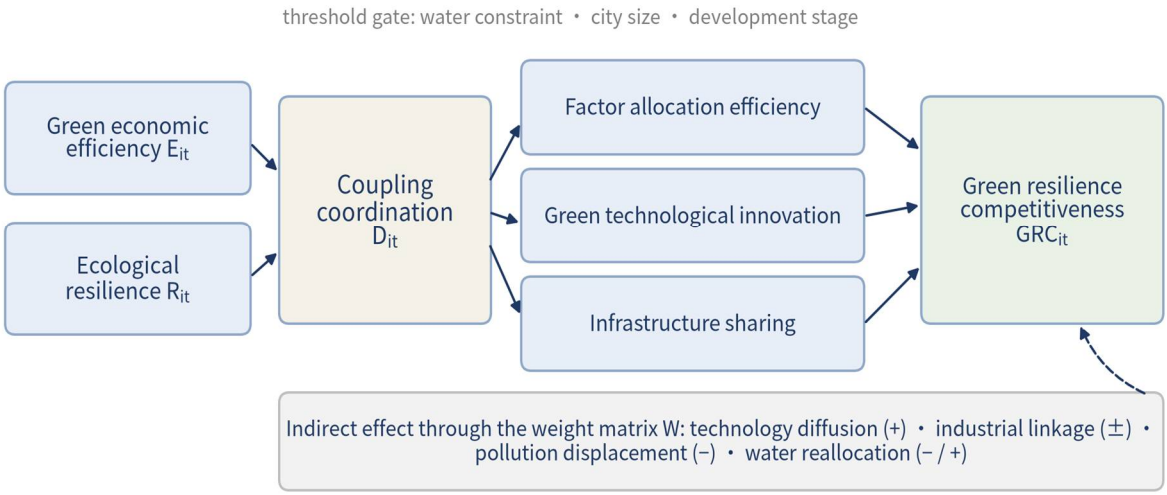
framework therefore uses exogenous matrices — geographical distance, a pre-period transport network and an administrative neighbourhood matrix — with the flow-based matrix reserved for robustness. The second is omitted spatial structure: cross-border discontinuities in enforcement and statistical definition can generate apparent spillovers, and the design includes border-pair subsamples and country fixed effects interacted with time in order to separate them from genuine neighbour effects.

Finally, qualitative material is used for mechanism interpretation rather than for estimation. Semi-structured interviews with officials in ecology and climate agencies, project officers of international organisations and urban planners serve three purposes: they identify which channels are plausible in which agglomeration, they help to read the direction of a spillover where quantitative evidence is ambiguous, and they expose cases in which an apparent diffusion is in fact a relocation. Interview material is thematically coded and triangulated with the quantitative results, and disagreements are reported rather than resolved by assertion.

ANALYSIS AND RESULTS

The framework rests on a chain with four links. In the first link, green economic efficiency and ecological resilience combine into a local coupling state: the matching of how much output a city extracts per unit of resource and environmental pressure with how much capacity it retains to absorb, adapt and transform under shocks.



Source: developed by the author on the basis of the literature reviewed.

Figure 1. Transmission and spillover channels from coupling coordination to green resilience competitiveness

In the second link, that matching is converted into competitiveness through three channels: better factor allocation, because a city that matches efficiency and resilience reallocates capital and labour away from activities that are productive

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only while water is cheap; green innovation, because the constraint induces substitution and the matching provides the stability that long-horizon investment requires; and infrastructure sharing, because agglomerations that coordinate on networks obtain capacity at lower cost than cities that duplicate it. In the third link, the conversion propagates to neighbouring cities through the weight matrix. In the fourth link, the propagated effect returns to the originating city, since the competitiveness of a city depends partly on the competitiveness of the system it belongs to.

Table 1 states the four spillover channels as separate objects of measurement. The separation is the analytical device that allows positive diffusion and negative displacement to be estimated within one specification instead of being averaged into a single coefficient.

Table 1

Spillover channels, indicators and expected signs

Channel	Mechanism	Indicator in the weight or interaction term	Expected sign
Technology diffusion	Standards, patents and supplier upgrading travel with investment and labour flows	Green patent citations between city pairs; share of investment from neighbouring agglomerations	+
Industrial linkage	Input–output relations transmit demand and capacity utilisation	Inter-city trade in intermediate goods; co-movement of industrial value added	±
Pollution displacement	Stringent local enforcement relocates dirty production outward	Change in SO2 and PM2.5 in downwind neighbours; relocation of energy-intensive firms	−
Water reallocation	Upstream efficiency and storage change return flow available downstream	Change in irrigation withdrawal and river discharge at downstream nodes	− / +

Source: developed by the author.
Note: the technology diffusion entry is the operational counterpart of new technology transfer in the ecological-environmental field, and it is the only channel in the table whose expected sign is unambiguously positive; the sign of water reallocation is negative for downstream agricultural nodes and positive for nodes that gain reliable supply from storage.

Proposition one concerns the local link. Coupling coordination raises green resilience competitiveness, but the effect is concave: the first improvements in matching remove the most obvious misallocations, while later improvements require increasingly costly institutional coordination. The supporting pattern is a positive coefficient on D_it that declines across the threshold regimes of city size; the falsifying pattern is a monotone and undiminished coefficient across all regimes, or a coefficient indistinguishable from zero once efficiency and resilience are entered separately.

Proposition two concerns transmission. The effect of coupling on competitiveness operates partly through the three channels, and the share transmitted differs by agglomeration type: allocation dominates where industrial structure is biased towards water-intensive activity, innovation dominates where

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the agglomeration has a research base, and infrastructure sharing dominates where city nodes are close enough for network effects to operate. The supporting pattern is a significant indirect effect that survives changes of weight matrix and a channel-specific share that varies systematically across types; the falsifying pattern is a direct effect that absorbs the whole relationship, which would mean that coordination is a local phenomenon with no transmission content.

Proposition three concerns direction. Spillovers from coupling are positive where industrial linkage is strong and absorptive capacity in the receiving city is high, and negative where water or air linkage is asymmetric and enforcement capacity in the receiving jurisdiction is weak. This is the central claim of the framework, and it is stated as a conditional rather than as a net effect. The supporting pattern is a sign reversal of the indirect effect across subsamples defined by linkage strength and enforcement capacity; the falsifying pattern is a stable positive or stable negative indirect effect across all subsamples, which would indicate that one mechanism dominates and the other should be dropped from the framework.

Proposition four concerns the threshold. The positive effect of coupling weakens and may turn negative once water constraint intensity passes a critical level, because beyond that level the reallocation of water that makes local coordination possible imposes costs on the surrounding system that exceed the local gain. The supporting pattern is an inverted-U in the threshold variable with a turning point identifiable from the data; the falsifying pattern is a monotone relationship, or a turning point outside the observed range of the threshold variable, which would make the threshold claim untestable rather than wrong.

Proposition five concerns asymmetry. Where efficiency improves without a corresponding improvement in resilience, the neighbours of the improving city experience negative effects even though the city's own competitiveness rises. This is the mechanism behind the efficiency–resilience paradox at the spatial scale: the gain is local and the cost is regional. The supporting pattern is a positive direct effect combined with a negative indirect effect in city pairs where the efficiency component of coupling rose faster than the resilience component; the falsifying pattern is indirect effects that are neutral or positive in exactly those pairs.

Table 2

Expected sign of the indirect effect by agglomeration type

Agglomeration type	Dominant linkage	Diffusion	Displacement	Expected net
Oasis-agricultural	Water, labour	Weak	Strong downstream	Negative
Energy-mining	Capital, energy	Moderate	Strong downwind	Ambiguous
Ecologically fragile	Ecological services	Weak	Strong	Negative
Capital-city composite	Knowledge, services	Strong	Weak	Positive

Source: developed by the author.
Note: the entry states a theoretical expectation to be tested, not an estimated result.

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The value of stating propositions together with their falsifying patterns is that the empirical stage cannot quietly reinterpret a null result as support. Table 3 makes the commitment explicit and is intended to be reproduced, with estimates, in the reporting stage of the research.

Table 3

Propositions, supporting and falsifying observational patterns

Proposition	Supporting pattern	Falsifying pattern
P1: concave local effect	Positive, declining coefficient across city-size regimes	Monotone coefficient, or zero effect once components are separated
P2: three-channel transmission	Significant indirect effect, stable across weight matrices	Direct effect absorbs the whole relationship
P3: conditional direction	Indirect effect changes sign across linkage and capacity subsamples	Stable sign across all subsamples
P4: water-constraint threshold	Inverted-U with an interior turning point	Monotone relation, or turning point outside observed range
P5: efficiency–resilience asymmetry	Positive direct with negative indirect effect in divergent pairs	Neutral or positive indirect effect in divergent pairs

Source: developed by the author.
Note: falsifying patterns are fixed before estimation in order to prevent post hoc reinterpretation.

Two interpretation rules follow. The first is that the direct and indirect effects must be reported separately and never summed into a single number presented as the effect of coupling: a policy that raises coordination in one city and damages its neighbours is not a success at the regional scale, whatever its local coefficient. The second is that the sign of the indirect effect should be read as a property of the channel, not of the region: a negative average spillover in an oasis corridor may coexist with positive diffusion in the capital-city agglomeration, and policy should be designed for the channel that dominates locally.

Three limitations constrain what the design can deliver. The first is the small number of city nodes: with thirty-two units and ten agglomerations, spatial parameters are estimated with wide intervals, and subsample tests such as those implied by Proposition three are underpowered. The second is measurement of the channel variables; inter-city trade in intermediate goods and firm relocation are observed indirectly in all five countries, and both displacement and diffusion are inferred from changes rather than from records. The third is that the framework is deliberately conditional: it predicts that the sign of the spillover depends on linkage and capacity, but it does not specify the weights that the two mechanisms receive, and that weighting is an empirical question which the present article does not answer.

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CONCLUSION AND RECOMMENDATIONS

Coordination scores describe a state; they do not explain an outcome. The framework developed here converts the coupling literature's central variable into a mechanism with three transmission channels and four spillover channels, embeds it in a spatial Durbin design with exact effect decomposition, and submits it to a threshold gate whose variable is water constraint intensity. Seven recommendations follow for research and for policy practice in the region.

1. Regress the outcome, not the score. Coupling coordination should be used as an explanatory variable for a performance outcome measured independently, not as a dependent variable reconstructed from similar indicators.

2. Estimate channels separately. Diffusion and displacement should be specified as distinct channels with distinct indicators; a single net spillover coefficient conceals the two mechanisms whose conflict is the substance of the problem.

3. Report direct and indirect effects in full. The spatial multiplier should be inverted and both components reported, because a positive local effect with a negative regional effect is a policy failure disguised as a success.

4. Choose weight matrices for substantive reasons. Geographical, economic and transport matrices should be reported in parallel, and flow-based matrices should be treated as endogenous and used for robustness only.

5. Locate the threshold before drawing the policy conclusion. The claim that coupling stops helping beyond a water-constraint level is only meaningful if the turning point falls inside the observed range; otherwise the threshold should be reported as untested rather than as confirmed.

6. Treat inter-city coordination as a water instrument. Where the dominant channel is reallocation, the relevant policy is a basin-level agreement on return flow and storage, not a city-level efficiency target, because the city-level target is what creates the downstream loss [5].

7. Use the asymmetry test as an early-warning indicator. City pairs in which efficiency rises faster than resilience while neighbours' indicators deteriorate are the pairs in which the regional cost is accumulating; monitoring that divergence is cheaper than remediating it.

The empirical stage will estimate the five propositions on the panel and report which of them survive. If Proposition three fails because the sign is stable, the framework loses its central claim and should be reduced to a diffusion model; if Proposition five fails, the efficiency–resilience trade-off does not operate spatially in this region, which would itself be an important finding. The design is arranged so that either outcome is reportable, which is the minimum condition for a mechanism framework to be worth testing.

Acknowledgement. This article forms part of the research project“Research on Ecological-Environmental Technology Iteration and the Economic Benefits of New Technology Transfer”(Grant No. XKZD2609), and the support of the project

is gratefully acknowledged. The three correspondences specified in the introduction — between green technological innovation and technology iteration, between spatial technology diffusion and new technology transfer in the ecological-environmental field, and between the decomposed direct and indirect effects and the economic benefits of that transfer — state the mapping between the framework developed here and the research objects of the project.

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Musahhih: Boltayev Nurali
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“Agrobiznes, fan va texnologiyalar” ilmiy-amaliy elektron jurnali O‘zbekiston Respublikasi Oliy ta’lim, fan va innovatsiyalar vazirligi huzuridagi Oliy attestatsiya komissiyasi rayosatining 30.11.2024-yildagi №364/5-sonli qarori bilan 08.00.00-Iqtisodiyot fanlari bo‘yicha, 08.05.2025-yildagi №370/5-sonli qarori bilan 06.00.00-Qishloq xo‘jaligi fanlari bo‘yicha “Dissertatsiyalar asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro‘yxati”ga kiritilgan.

“Agrobiznes, fan va texnologiyalar” ilmiy-amaliy elektron jurnali 2023-yil 23-maydan O‘zbekiston Respublikasi Prezidenti Administratsiyasi huzuridagi Axborot va ommaviy kommunikatsiyalar agentligi tomonidan **C-5669225** reyestr raqami tartibi bo‘yicha ro‘yxatdan o‘tkazilgan.
Litsenziya raqami: №083688

Manzilimiz: Toshkent viloyati, Qibray tumani, Universitet ko‘chasi, 2-uy