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Achieving sustainable development goals: coupling coordination between agricultural industrialization and rural infrastructure with the case of China

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Benign coordinated interactions between agricultural industrialization (AI) and rural infrastructure (RI) help achieve sustainable development goals (SDG). However, current studies fail to explicitly explain their coordinated interactions, making SDG less efficient and effective. To fill the gaps and explore their coupling coordination interactions, we establish a coupling coordination mechanism and an evaluation system to depict their dynamics theoretically. Then, we analyze the development status (D) and coupling coordination status (CCS) temporally and spatially in the case of China with the analytic hierarchy process, information entropy method and the technique for order preference by similarity to an ideal solution (TOPSIS); thirdly, we explore the main influencing factors and propose specific countermeasures based on the factors. We find that (1) AI and RI may not develop concurrently, and 2018 was a watershed year for AI-D as it witnessed apparent fluctuations; (2) better regions in AI-D are dotted while better-performing regions in RI-D are connected; (3) CCS is spatially correlated, and CCS values in different regions vary because of various reasons; (4) “technologicalization” and “mechanization” are critical dimensions to affect RI, while RI is increasingly affecting AI comprehensively. This study contributes to coupling coordination theory in AI and RI, to the coupling coordination practice to achieve SDG, and to enhance sustainability by proposing differentiated countermeasures.

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Introduction

Sustainability is increasingly important globally; the UN proposed 17 sustainable development goals (SDG), and one goal (namely SDG-9) is to encourage sustainable industrialization with innovation and construct more resilient infrastructure (Nations, 2023). Rural areas are vital to achieving SDG: rural development reduces poverty, promotes health, education, economy, and agricultural industry, and upgrades local infrastructure. On the one hand, agricultural industrialization helps achieve SDG: it creates complete industrial and value chains connecting stakeholders and economic entities, like villagers, agricultural businesses, and markets, which increases the added value of products, promotes rural economic growth, and contributes to SDG-9 (Li et al. 2023b; Rajakal et al. 2021; Zhang et al. 2024a; Zhang and Zeng, 2022); besides, Agricultural industrialization optimizes production processes and upgrades processing equipment, which improves resource efficiency and leads to cleaner, more sustainable agricultural practices (Chandio et al. 2024; Liu, 2022; Liu and Wang, 2022). On the other hand, rural infrastructure helps achieve SDG: it leads to greater investment and more rural jobs, enhancing villagers' well-being and reducing poverty (Dihlmann and Helbrecht, 2025; Pearsall et al. 2021; Wang et al. 2022b; Yuan and Wang, 2024); besides, sustainable agricultural infrastructure enhances villages' overall disaster resilience and fosters coordinated urban-rural development (Shi et al. 2024; Wang and Bai, 2023). Agricultural industrialization and rural infrastructure help achieve SDG-9 in rural places; therefore, promoting agricultural industrialization and rural infrastructure and exploring how they interact is necessary for SDG-9.

SDG-9 aims to promote inclusive and sustainable industrialization, build resilient infrastructure, and foster innovation; agricultural industrialization and rural infrastructure development represent the specific practice of SDG-9 in agriculture and rural areas. Agricultural industrialization and rural infrastructure intertwine with complexity, and their interactions contribute to SDG-9; in other words, it is necessary to explore their coupling coordination status, which is believed correct in different countries. However, how they achieve coupling coordination still needs to be determined. Previous studies around the globe have demonstrated that they have complicated correlations. Briefly speaking, on the one hand, agricultural industrialization may positively and negatively affect rural infrastructure; for instance, the spillover effects of digital technology and the Internet of Things in agricultural industrialization enhances rural digital, information, and transportation infrastructure (Li et al. 2024b; Pang et al. 2024; Ren et al. 2025; Zeng et al. 2024). Mechanization in the agricultural industrialization process reduces agricultural labor input, making villagers willing to participate in constructing rural infrastructure or related activities to obtain more non-farm income (Meng et al. 2024). At the same time, rural land-use regulations may restrict land-use conditions, leading to agricultural industrial parks encroaching on rural infrastructure areas and hindering rural infrastructure expansion (Liu et al. 2025b). On the other hand, rural infrastructure also positively and negatively affects agricultural industrialization; for instance, better rural infrastructure enhances environmental livability and the environment for agricultural industrialization (Cui et al. 2024; Fan et al. 2024). That boosts villagers' well-being, reduces population losses, stimulates consumption, and provides talent for agricultural industrialization (Li et al. 2025; Parraga et al. 2024; Tang et al. 2024). Better rural infrastructure also accelerates market connectivity, improves the market environment, and attracts industrial clusters, promoting the agricultural industrialization process (Bao et al. 2024; Huang and Ke, 2025; Li et al. 2024a). Meanwhile, rural infrastructure construction may change

the living habits and values of the local villagers (for instance, they may cause the NIMBY effects on some agriculture-related factories), hindering agricultural industrialization to some degree (Jin et al. 2021; Mao and Li, 2022; Santoso et al. 2022).

Different countries have taken various actions to enhance agricultural industrialization and rural infrastructure. For instance, from the agricultural industrialization perspective, the United States is trying to make agriculture diversified, as it has been proved that agricultural diversity promotes agricultural industrialization by optimizing industrial structures (Fiszbein, 2022); China has used Internet finance to support agricultural industrialization, providing sufficient and targeted financial service to small-sized agricultural production enterprises; the agricultural industrialization process effectively stimulates rural infrastructure construction (Wang et al. 2021b). From the rural infrastructure perspective, Malaysia has tried to integrate communities, governments, and stakeholders to design an efficient and effective rural infrastructure (Tuah et al. 2024); India has considered devising policies to construct rural infrastructure to conserve rural land and water and to strengthen rural safety (Kannan et al. 2021); these countermeasures are beneficial to rural infrastructure, and further indirectly or directly promotes agricultural industrialization. Agricultural industrialization and rural infrastructure are intertwined; however, we must admit that we still need more understanding of how they coordinate to achieve SDG-9. Therefore, we need to construct the coupling coordination mechanism theoretically, comprehensively analyze their coupling coordination interactions, and explore the main affecting factors so that we can take detailed and applicable actions to help them achieve coordination, which is beneficial to realize SDG-9.

The key concepts and research objects are defined as follows. "Agricultural industrialization" (AI) refers to the modernized mode of agriculture operation. It is market-oriented, focuses on the effectiveness and efficiency of agricultural elements' input and output, enhances the competitiveness of agricultural products, and promotes agricultural development. Specifically, AI focuses on the agricultural industry's mechanization, technologization, modernization, professionalization, marketization, and sustainability (Li, 2023; Li et al. 2023b). Some scholars may replace "agricultural industrialization" with "agricultural mechanization," "agricultural technologization," or "agricultural modernization," but generally speaking, the terms mentioned above depict certain aspects or dimensions of "agricultural industrialization" (Liu et al. 2025b; Zhao et al. 2025). Besides, "Rural infrastructure" (RI) refers to constructing rural infrastructure (such as roads, electricity, and water supply) to guarantee villagers' lives and production activities. Specifically, RI includes agricultural production facilities, villagers' living facilities, rural social services facilities, and ecological protection facilities (Cui et al. 2024; Jiang et al. 2023b; Masakure and Makombe, 2023). AI and RI have differences and similarities. They are different because they have different definitions and connotations; the former is a process, while the latter is a system. They are similar because they have some sharing elements (such as machinery production facilities) and contribute to SDG-9 targets (sustainable industrialization and resilient infrastructure construction) (Fourie, 2022; Geng et al. 2024c). The research object is the coupling coordination between AI and RI. Coupling coordination refers to the interaction status between systems. We can explore the coordination interactions between AI and RI to enhance their contributions to sustainability.

Although the interactions between AI and RI can achieve SDG-9, current research regarding their interactions faces several challenges. First, the coupling coordination mechanism does not

address specific targets or fundamental elements of SDG-9. Second, there is insufficient understanding of these two systems' coupling coordination states across regions via temporal and spatial comparisons. Third, formulating differentiated countermeasures based on varying coupling coordination states among regions remains difficult. Therefore, to comprehensively discover their coupling coordination evolution to achieve SDG-9 and clarify the specific actions to enhance the coupling coordination status, we first construct the coupling coordination mechanism aligned with the SDG-9 to discuss their mutual relations theoretically; secondly, we construct the evaluation system based on the mechanism, and evaluate the development status (D) and the coupling coordination status (CCS) temporally and spatially with the provincial case of China; thirdly we analyze the main influencing factors dynamically and propose region-specific and differentiated actions based on the analysis results to solve the research gaps.

This study's significance is as follows. (1) Expand coupling coordination to new fields: We build a coupling coordination mechanism between AI and RI and analyze their coordination status theoretically, thus further expanding the applicability of the coupling coordination mechanism in new fields (AI and RI). (2) Provide new insight into achieving SDG-9: We propose that the coupling coordination mechanism can be applied to achieve SDG-9 and claim that the coupling coordination between the two aspects of SDG-9 (AI and RI) helps achieve SDG-9; the idea provides useful references to sustainability development. (3) Propose new solutions to SDG-9: Based on the coupling coordination results, we propose differentiated and targeted countermeasures for regions with different scenarios, which can effectively guide their practices to achieve SDG-9 by accelerating AI and RI.

Literature review

The positive effects between AI and RI. Agricultural industrialization and rural infrastructure affect each other mutually positively.

On the one hand, agricultural industrialization positively impacts rural infrastructure. Firstly, agricultural industrialization requires planning by the local governments; the authorities may carefully consider how to properly use farmland and resources to achieve agricultural industrialization, which promotes the effective planning and utilization of rural infrastructure (Wang et al. 2019; Wang et al. 2021a). Secondly, agricultural industrialization emphasizes mechanized agricultural production on a scale, which apparently enhances production efficiency, reduces pollutants, and thus reduces the pressure on rural infrastructure construction; for instance, by using machines, the phosphorus use efficiency increases and pollution reduces, which means authorities can save much money for building more pollutant treatment facilities (Jiang et al. 2022; Shen et al. 2023). Thirdly, agricultural industrialization provides necessary resources for rural infrastructure construction. For instance, agricultural industrialization clarifies farmland ownership and villagers' rights, thus freeing villagers from pure cultivating land; public-owned farmland (for instance, owned by the country) means there might be more land to coordinate by the authority for rural infrastructure; free villagers means there might be more sufficient labor resources to rural infrastructure (Chu et al. 2022; Zhuo et al. 2020). Fourth, agricultural industrialization enriches local villages, enabling them to invest in rural infrastructure. In specific, agricultural industrialization accelerates villages' economic transition, enhances productivity, develops the agriculture industry, and increases annual income; the above results make local villages richer, enabling them to collectively spend money

on renewing equipment for rural infrastructure, optimizing production and living spaces, and upgrading or building new rural infrastructure (Brunier and Pinaud, 2022; Li et al. 2023c; Mazungunye and Punt, 2022; Zhang et al. 2020). Practically, some villages in China and Malaysia have successfully accelerated rural infrastructure through agricultural industrialization. Fifth, agricultural industrialization fosters technological innovation, prompting villagers to adopt new technologies and enhance their skills; this enables more intelligent villagers to upgrade rural infrastructure sustainably (Wang et al. 2024). At last, agricultural industrialization optimizes the rural digital industry structure and accelerates the construction and use of digital infrastructure (such as communication networks and smart devices), which enhances network coverage and smart terminal penetration in rural areas, laying a foundation for the digital transformation of rural infrastructure (Zhu et al. 2024).

On the other hand, rural infrastructure also has positive impacts on agricultural industrialization. Firstly, rural infrastructure provides abundant support and instruments to accelerate agricultural industrialization. For instance, water infrastructure guarantees adequate water for agricultural product processing; rural internet infrastructure plays a vital role in remotely managing greenhouses and agricultural equipment (Carrillo, 2021; Jing and Jie, 2021; Zou and Mishra, 2022). In addition, better rural infrastructure helps to optimize rural economic structure and stimulates local rural economic growth; more prosperous villages or village-owned enterprises usually have more money to enhance agricultural industrialization (Stacherzak and Heldak, 2019); studies have proved that rural infrastructure may have increasing marginal effects on agricultural industrialization (Qin et al. 2020). Furthermore, better rural infrastructure improves rural living quality and enhances rural education, sanitary, and security services; such improvement attracts professionals and entrepreneurs to support and initiate agriculture-related factories in or around villages, thus continuously enhancing the local agricultural industrialization process (Akbar et al. 2022; Mickovic et al. 2020; Shigute, 2022; Zhu et al. 2022). Besides, improved rural transportation infrastructure boosts agricultural industrialization; better rural transport services speed up the circulation of agricultural products and lowers transportation costs, which increases profit margins in agriculture and improves production efficiency to support rural industrialization (Zeng and Wang, 2025). Additionally, agricultural infrastructure drives the green transformation of agricultural industrialization; improved agricultural infrastructure boosts supply chain efficiency and increases energy utilization, which promotes carbon balance in the agricultural industrialization process (Huang et al. 2024b). Furthermore, rural digital infrastructure helps agricultural industrialization from many aspects; for instance, fast-speed internet makes intensive intelligent agricultural management and the smart device application in agricultural productions possible; information exchange platforms connect the agricultural supply and demand sides, making more convenient industry upgradation and agricultural industrialization feasible; digital inclusive finance supports agricultural technology upgradation, enhancing the effectiveness of agricultural industrialization (Lin and Li, 2023; Wang et al. 2022a; Zhong et al. 2022). Specifically, cases have proved that digital rural infrastructure benefits green and sustainable agricultural industrialization (Lin and Li, 2023). Finally, official authorities usually endorse rural infrastructure construction programs with public and private sector involvement; such programs are usually accompanied by other poverty alleviation plans and rural development allowances, which contribute to cheaper resources such as labor and electricity. The lower cost of agricultural industrialization stimulates

resource coordination and the sustainability of agricultural industrialization (Zhang and Wu, 2022; Zhang et al. 2019).

The negative effects between AI and RI. Agricultural industrialization and rural infrastructure have mutual negative impacts. From the agricultural industrialization perspective, firstly, it occupies many rural resources (such as rural water, land, and electricity) and puts pressure on the local rural environment, which to some degree is a burden on rural infrastructure; authorities have to devote more budgets to constructing more rural infrastructure to meet the requirement of agricultural industrialization (Tian et al. 2021; Zou et al. 2022). Even though the new rural infrastructure facilities are built to adapt to the agricultural industrialization process, authorities must also face the dilemma of maintaining the infrastructure, which is a high cost to some authorities (Jacklin et al. 2021). Second, agricultural industrialization means vast initial financial investment and support; as the total annual budgets of the governments are fixed, increasing subsidies for agricultural industrialization from the local authorities may lead to decreasing devotion to rural infrastructure in specific years (Bai et al. 2022; Geng et al. 2022). Thirdly, agricultural industrialization may decrease the earnings and efficiency of rural infrastructure in some aspects. For instance, studies have found that regardless of whether agricultural industry stakeholders are classified as agricultural consumers (who pay low electricity prices) or industrial consumers (who pay high electricity prices but use electricity frugally), it is difficult for rural power infrastructure to obtain sufficient profits, which further hinders the interest of social capital to invest in rural infrastructure (Kato and Fukumi, 2020); meanwhile, agricultural industrialization may cause a surplus of rural labor; villagers may migrate to cities for work, which leads to the insufficient and ineffective use of rural infrastructure (Azizi, 2020; Kan and Chen, 2022; Wang et al. 2021c). Fourth, the agricultural industrialization process may interact differently with local villagers; some interactions may hinder rural infrastructure. For instance, in agricultural industrialization, relevant enterprises may compensate local villagers directly rather than the local rural authorities; the authorities have no extra money for rural infrastructure, degrading villagers' quality of life (Tuan and Hegedus, 2022). Fifth, agricultural industrialization may increase the ecological vulnerability of rural infrastructure; its rapid development may lead to higher sewage discharge and heavy metal pollution, complicating environmental challenges and making maintenance more difficult and costly for rural infrastructure systems (Wen et al. 2025; Zhang et al. 2025).

Rural infrastructure also impacts agricultural industrialization negatively. Firstly, villagers near rural infrastructure may have the NIMBY effect (not-in-my-back-yard effect) and therefore hinder agricultural industrialization; in particular, villagers are concerned about the safety, environmental, and pollution issues of rural infrastructure, and their protests may hinder the construction of rural infrastructure facilities, which in turn affect the agricultural industrialization process (Le Goff et al. 2022). Secondly, some rural infrastructure-related activities may decrease the input of agricultural industrialization. Specifically, constructing more rural roads (rural infrastructure) makes transportation more accessible, resulting in villagers migrating to cities or towns for a better life and work, leading to insufficient rural labor (input needed by agricultural industrialization). Another example is that some villages now share advanced urban infrastructure and discard existing rural infrastructure, resulting in the abandoned rural infrastructure occupying much land, which could have been inputted into the agricultural industrialization process but now has to be wasted. Besides,

villages with advanced rural infrastructure may attract villagers in surrounding villages, which means that the "advanced" villages need more money to maintain the infrastructure operation and decrease the budget for agricultural industrialization update (Azizi, 2020; Izakovicova et al. 2022; Qin et al. 2020). Thirdly, some rules and regulations of rural infrastructure hinder the agricultural industrialization process. For instance, some rural infrastructure-related laws are introduced to regulate land use details specifically, and some clauses, in turn, restrict land available for agricultural industrialization; technical assistance acts as a helpful capital to support rural infrastructure; however, in some villages, private technology capital may lead to the privatization of agricultural enterprises and is not conducive to integrated planning of agricultural industrialization (Carrillo, 2021; Xie et al. 2022a). Additionally, rural infrastructure prioritization in some villages directly raises the costs of agricultural industrialization; some local governments prioritize leveling high-quality flat land for rural infrastructure while relegating industrial projects to sloped areas with inferior soil quality, which results in increased costs for rural industrial construction (Cheng et al. 2025; Pang et al. 2024). Finally, rural infrastructure itself may be the burden of agricultural industrialization. For example, broadband infrastructure may hinder the agricultural industrialization process if the internet access speed is low; education and healthcare services may occupy a lot of financial funds and hinder the growth of agricultural industrialization (Aldashev and Batkeyev, 2021; Mazunguny and Punt, 2022).

Their interactions. Agricultural industrialization and rural infrastructure interact positively and negatively, and exploring their interactions and main influencing factors is necessary. As a result of this, we introduce coupling coordination to evaluate such interactions; in other words, coupling coordination can measure whether and how these two interact harmoniously (Huang et al. 2024a). The coupling coordination model has been widely applied to measure the interactions among systems to see whether they achieve sustainable, harmonious coordination (Wang et al. 2025; Yin et al. 2024; Zhao and Han, 2025); the results based on the coupling coordination have been successfully applied to guide practice in various fields (Geng et al. 2022). For instance, previous studies have used coupling coordination to evaluate the interactions between education and science popularization, between electricity and economy, between rural revitalization and urbanization, and between economic and environmental sustainability, depicting the usefulness of achieving SDG (Geng et al. 2024a; Geng and Yan, 2021; Liang and Zhao, 2024; Ma et al. 2025).

Current research examines the coupling coordination mechanisms in agricultural industry development, rural infrastructure construction, and related systems. Regarding the "agricultural industry" system, studies have explored the coupling coordination relationship between cropland and livestock, which reveals that urbanized areas are more likely to experience the decoupling of cropland from livestock; thus, it is crucial to prioritize coordinated development between cropland and livestock in the agriculture system (Chen et al. 2023). Another study highlights the importance of the coupling coordination among land resources, water resources, and food production in the agriculture system (Liu et al. 2025a). Additionally, some research has focused on the coordination between rural e-commerce and comprehensive rural development, emphasizing its significance in promoting rural economic growth (Zhu and Luo, 2024). Regarding "rural infrastructure," some studies explore the coupling coordination between China's "digital countryside strategy" (aiming to enhance digitalization in rural areas) and inclusive green growth,

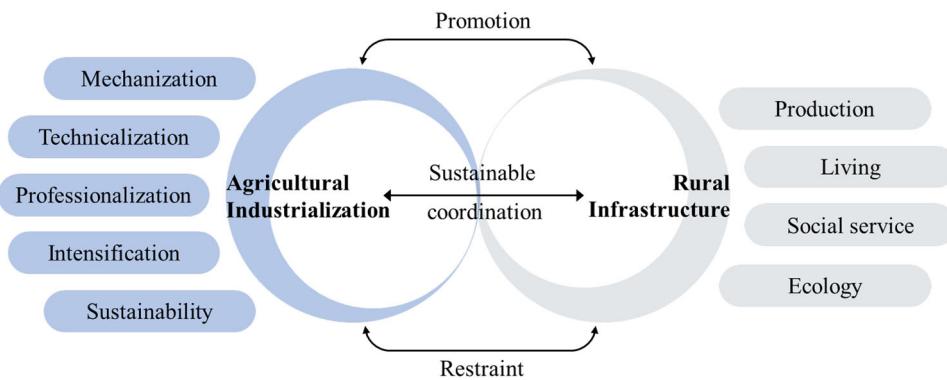


Fig. 1 Analytical framework of the coupling coordination mechanism.

suggesting that innovation, disaster reduction, and increased financial support can strengthen the coordination status (Zhang et al. 2024b). Besides, some research has explored the coordination between rural infrastructure digitization and rural tourism, noting that inadequate infrastructure hinders their benign synergetic development. (Liu et al. 2024). Additionally, some studies have examined the coordination relationship between digital rural construction and high-quality agricultural development, suggesting agricultural technology innovation, digital agricultural production bases, and digital skills training promote sustainable agriculture (Tian and Zhou, 2025).

We must admit that further studies exploring coupling coordination between AI and RI are mandatory because such coordination benefits achieving SDG (Kong and Liu, 2021; Li and Zhang, 2023). However, current studies focus only on the coupling coordination mechanisms between agricultural development, rural infrastructure, and other systems, failing to depict the direct interactions between AI and RI with proper and representative indicators, which makes it difficult to understand their interaction mechanisms theoretically. Besides, current studies primarily focus on the correlation between AI and RI, failing to connect their coupling coordination interactions to the SDG-9 goals (Li et al. 2024d). Additionally, they overlook these two systems' interactive dynamics from both spatial and temporal perspectives, making it challenging to fully understand how they actually interact to achieve SDG-9. Furthermore, current studies fail to discuss the main influencing factors in the coupling coordination mechanism, making the countermeasure less targeted and differentiated.

Based on that, we in this study would like to explore the coupling coordination mechanism of the two, assess the temporal dynamics and spatial variations of the coupling coordination status, depict the main affecting factors, and propose differentiated suggestions to enhance the coupling coordination between the two; by doing so, we can better achieve SDG-9.

Theoretical analysis

Coupling coordination mechanism. We now construct the coupling coordination mechanism between agricultural industrialization and rural infrastructure to explore how they interact to achieve SDG-9. Previous studies have shown their mutual effects; therefore, we can establish a coupling coordination mechanism; in this mechanism, these two can interact positively, leading to sustainable and benign status. The analytical framework of this coupling coordination mechanism is in Fig. 1. Specifically, agricultural industrialization (AI) follows the “mechanization, technicalization, professionalization, intensification, and sustainability” framework, and rural infrastructure (RI) follows the “production, living, social service, ecology” framework.

The analytical framework is applicable and representative because (1) they have been fully or partially used in previous studies and have been proven applicable; (2) they fully cover the specific targets of SDG-9 (sustainable industrialization and resilient infrastructure), depicting the essential elements of SDG-9 (Yan et al. 2024). Specifically, for industrialization, some studies have used the “technical, economic, environment, enterprise development, sustainable” framework and “economy, technological innovation, society, environmental resources” framework to evaluate the dimensions (Jin et al. 2022; Liu et al. 2017); the connotations of our framework to evaluate “agricultural industrialization” are similar to these existing ones; in addition, for rural infrastructure, some studies have used the “agricultural production, peasant living, rural social undertakings” framework and the “production, living, ecological, social” framework, which are similar to our framework in connotation (Li et al. 2023a; Zhou et al. 2023b). Furthermore, our frameworks highlight SDG-9, representing sustainability. In conclusion, the frameworks in the coupling coordination mechanism are justified by previous literature.

AI: (1) The “mechanization” dimension, demonstrating that the agricultural industry will use more efficient machines in production, positively impacts RI. A higher status of mechanization means more investment in agricultural production equipment, which requires more standardized working environments that match, such as standardized farmland, improved water conservancy facilities, and village roads, which drive RI development. (2) The “technicalization” dimension reflects technological inputs in the agriculture industry (such as chemicals, advanced agricultural facilities, and biotechnology), which promotes RI. Scientific and environmentally friendly technologies have brought convenience to the lives of villagers and improved the ecological and living environment of rural areas. (3) The “professionalization” dimension reflects the growth of professional agricultural industrialization companies and talents. These professional agricultural practitioners usually enjoy abundant and advanced industrialized equipment and technologies, which affect the efficiency of agricultural production; besides, some professional companies may provide affiliated rural health care and education services and accessible apartments to villages, enhancing RI in living status, social services, and environmental protection. (4) The “intensification” dimension directly evaluates the efficiency, namely the input-output ratio of AI: whether the materials, capitals, and resources are appropriately used. Higher intensification guarantees that extra money and resources can be devoted to RI to enhance living conditions, production infrastructure, social service, and ecology. (5) The “sustainability” dimension specifically demonstrates how AI meets the targets of SDG-9, which is also the novelty of this analytical framework of the coupling coordination mechanism. Achieving the targets of SDG-9, AI can create more jobs, get more funds, and grow continuously with

high quality, which is conducive to better RI in labor and money with sustainability.

RI: (1) The “production” dimension reflects the status of an infrastructure for production, such as transportation, water conservancy facilities, and energy usage. It is a prerequisite for agricultural mechanization and the attraction of AI talents who contribute to the technicalization and professionalization of AI. (2) The “living” dimension reflects villagers’ living status, an essential part of rural industrialization. It depicts household equipment infrastructure; satisfying living status brings convenience to residents, leaving them sufficient time to work and contributing to RI growth. (3) The “social services” dimension reflects the foundation for maintaining the orderly progress of villages (such as education, healthcare, and other public services). Rural social services guarantee better lives for villagers or professionals who are much more willing to participate in RI’s technicalization, professionalization, and intensification process. (4) The “ecology” dimension reveals rural areas’ ecological environment. Achieving rural sustainability requires ensuring friendly environmental conditions, which provides an ecological foundation for the professionalization and intensification of AI.

Notably, these dimensions’ connotations reflect the targets of SDG-9 (9.1–9.4), justifying that this analytical framework of the coupling coordination mechanism can reflect the requirement of SDG-9 and help achieve SDG-9.

Furthermore, a rigorous mathematical derivation of the coupling coordination mechanism, based on system dynamics theory and incorporating the Logistic growth model and Lotka-Volterra competition mechanism, can enhance the analytical foundation. The derivation is as follows.

(1) Assuming AI and RI exhibit resource-constrained Logistic growth without external interactions, then we can determine their natural growth over time NG_{AI} and NG_{RI} for AI and RI, respectively, with Eqs. (1) and (2). Natural growth depicts the growth potential of AI and RI. We want to highlight that, in the mathematical derivation process, AI and RI mean the development status of agricultural industrialization and rural infrastructure, respectively.

$$NG_{AI} = IGR_{AI} \times AI \times \left(1 - \frac{AI}{KC_{AI}}\right) \quad (1)$$

$$NG_{RI} = IGR_{RI} \times RI \times \left(1 - \frac{RI}{KC_{RI}}\right) \quad (2)$$

Here, IGR_{AI} and IGR_{RI} are the intrinsic growth rates, driven by AI’s or RI’s endogenous factors (such as using updated scientific and environmentally friendly technologies, resource input from stakeholders, and authorities’ policy supports). Besides, KC_{AI} and KC_{RI} are the upper limits of carrying capacity (limited by resources, such as land, market, and funding).

(2) Determine the promotion terms PT_{AI} and PT_{RI} . Here, we introduce their positive synergistic effects; PT_{AI} means AI obtains RI’s support, while PT_{RI} means that RI obtains support from AI.

$$PT_{AI} = \psi \times RI \quad (3)$$

$$PT_{RI} = \omega \times AI \quad (4)$$

ω is the positive affecting coefficient of AI on RI, while ψ is the positive affecting coefficient of RI on AI.

(3) Determine the restraint terms ST . AI and RI hinder each other because they may compete for limited resources (such as land, funding, and labor).

$$ST = \delta \times AI \times RI \quad (5)$$

δ is the negative affecting coefficient.

(4) Derivate the dynamic equations. $\frac{dAI}{dt}$ and $\frac{dRI}{dt}$ represent the growth rates in AI and RI over time, respectively; then, we can express AI and RI’s evolutions, respectively.

$$\begin{aligned} \frac{dAI}{dt} = NG_{AI} + PT_{AI} - ST &= IGR_{AI} \times AI \times \left(1 - \frac{AI}{KC_{AI}}\right) \\ &\quad + \psi \times RI - \delta \times AI \times RI \end{aligned} \quad (6)$$

$$\begin{aligned} \frac{dRI}{dt} = NG_{RI} + PT_{RI} - ST &= IGR_{RI} \times RI \times \left(1 - \frac{RI}{KC_{RI}}\right) \\ &\quad + \omega \times AI - \delta \times AI \times RI \end{aligned} \quad (7)$$

(5) Derivate the dynamic equilibrium. The coupling coordination mechanism is stable when AI and RI’s growth rates are 0. We can derive the Eqs. (8) and (9).

$$\begin{aligned} \frac{dAI}{dt} = IGR_{AI} \times AI \times \left(1 - \frac{AI}{KC_{AI}}\right) + \psi \times RI - \delta \times AI \times RI &= 0 \\ (8) \end{aligned}$$

$$\begin{aligned} \frac{dRI}{dt} = IGR_{RI} \times RI \times \left(1 - \frac{RI}{KC_{RI}}\right) + \omega \times AI - \delta \times AI \times RI &= 0 \\ (9) \end{aligned}$$

(6) Assuming $AI \neq 0$ and $RI \neq 0$; then Eqs. (8) and (9) can be expressed as the Eqs. (10) and (11).

$$\delta \times AI \times RI = IGR_{AI} \times AI \times \left(1 - \frac{AI}{KC_{AI}}\right) + \psi \times RI \quad (10)$$

$$\delta \times AI \times RI = IGR_{RI} \times RI \times \left(1 - \frac{RI}{KC_{RI}}\right) + \omega \times AI \quad (11)$$

(7) Simplify the equations. Assuming the Eqs. (10) and (11) are equal, $AI \ll KC_{AI}$, $RI \ll KC_{RI}$, and ignoring the high-order terms, then we can simplify the equation to $IGR_{AI} \times AI + \psi \times RI = IGR_{RI} \times RI + \omega \times AI$, which can be further simplified to the Eq. (12).

$$(IGR_{AI} - \omega) \times AI = (IGR_{RI} - \psi) \times RI \quad (12)$$

The above equation can be further derived into $AI = \frac{(IGR_{RI} - \psi)}{(IGR_{AI} - \omega)} \times RI$ and $RI = \frac{(IGR_{AI} - \omega)}{(IGR_{RI} - \psi)} \times AI$.

(7) Obtain the equilibrium values (EQ_{AI} and EQ_{RI}) at the stable state using the above derivations. Substitute Eq. (12) into Eqs. (10) and (11), respectively, then we can get the Eqs. (13) and (14).

$$EQ_{AI} = \frac{IGR_{AI} \times KC_{AI} \times (\psi KC_{RI} + IGR_{RI})}{IGR_{AI} \times IGR_{RI} + \delta^2 \times KC_{AI} \times KC_{RI}} \quad (13)$$

$$EQ_{RI} = \frac{IGR_{RI} \times KC_{RI} \times (\omega KC_{AI} + IGR_{AI})}{IGR_{AI} \times IGR_{RI} + \delta^2 \times KC_{AI} \times KC_{RI}} \quad (14)$$

Now, the two systems interact positively within the coupling coordination mechanism. Besides, changing specific values can alter these interactions; for example, increasing AI’s intrinsic growth rate (IGR_{AI}) through more efficient production machinery, upgraded technologies, enhanced talent, proper resource use, and supportive SGD policies or investments will boost RI. Conversely, raising RI’s intrinsic growth rate (IGR_{RI}) by improving the effectiveness and efficiency of rural transportation, energy, household equipment usage, healthcare access, education quality, and environmental governance will enhance AI. These mutual promotions foster positive interactions in the coupling coordination mechanism. In contrast, decreasing the negative affecting coefficient δ reduces mutual restraints between the two systems and improves their interactions. In conclusion, the mathematical derivation of this coupling coordination

Table 1 Evaluation system.

System	Dimension	Indicator *	Type	Source
Agricultural industrialization (AI)	Mechanization (M1)	Machinery power efficiency (M11)	+	(Daum et al. 2024; Murphy et al. 2011)
		Mechanical input scope (M12)	+	
		Mechanical input efficiency (M13)	+	
		Mechanical output efficiency (M14)	+	
	Technicalization (M2)	Technical research investment (M21)	+	(Baumhardt et al. 2015; Wang et al. 2024)
		Fertilizer use coverage (M22)	+	
		Pesticide use coverage (M23)	+	
		Plastic film use coverage (M24)	+	
	Professionalization (M3)	Human resource input (M31)	+	(He et al. 2022; Yang et al. 2023a)
		Input scope (M32)	+	
		Labor productivity (M33)	+	
	Intensification (M4)	Agricultural production efficiency (M41)	+	(Oliveira and Hecht, 2016; Song et al. 2022)
		Capital investment efficiency (M42)	+	
		Production factor investment efficiency (M43)	+	
	Sustainability (M5)	Financing ratio (M51)	+	(LaRota-Aguilera et al. 2024; Li et al. 2023d)
		Importance to employment (M52)	+	
		Importance to output value (M53)	+	
Rural infrastructure (RI)	Production (N1)	Reservoir use efficiency (N11)	+	(Du and Jiao, 2023; Jiang et al. 2023a)
		Power generation efficiency (N12)	+	
		Road use efficiency (N13)	+	
	Living (N2)	Household water supply quality (N21)	+	(Han et al. 2024; Zhou et al. 2023a)
		Household gas supply quality (N22)	+	
		Household clean energy supply efficiency (N23)	+	
	Social service (N3)	Public facilities investment coverage (N31)	+	(Shen et al. 2011; Wu et al. 2024; Zhou et al. 2023a)
		Basic education quality (N32)	+	
		Medical service coverage (N33)	+	
		Minimum social security service coverage (N34)	+	
	Ecology (N4)	Domestic sewage treatment coverage (N41)	+	(Du and Jiao, 2023; Jiang et al. 2023a; Zhang et al. 2022)
		Domestic waste disposal coverage (N42)	+	
		Green investment coverage (N43)	+	

*M11: total power of agricultural machinery/tractor numbers; M12: machine cultivated area per cultivated area; M13: agricultural diesel usage per cultivated area; M14: mechanically processed agricultural products per cultivated area; M21: research investment as a proportion of financial investment; M22: agricultural fertilizer usage per cultivated area; M23: pesticide usage per cultivated area; M24: plastic film coverage area per cultivated area; M31: employees in state-owned professionalized farms as a percentage of rural population; M32: land area of state-owned professionalized farms per cultivated area; M33: total agricultural output value of state-owned farms per capita; M41: agricultural output per capita; M42: rural fixed asset investment per capita; M43: construction area of productive buildings per capita; M51: value of production equipment as a proportion of investment; M52: number of people engaged in agri-food manufacturing as a proportion of the population; M53: income from agri-food manufacturing as a share of gross regional product; N11: soil erosion control area per reservoir capacity; N12: electricity generation in village per capita; N13: road length per capita; N21: household water supply coverage; N22: household gas penetration rate; N23: proportion of household solar heater coverage area to non-arable area; N31: proportion of investment in rural public facilities in total construction investment; N32: proportion of rural teachers with at least bachelor degrees in basic education institutions; N33: rural health workers per capita; N34: proportion of villagers living on subsistence allowances; N41: proportion of villages dealing with domestic sewage; N42: proportion of villages dealing with domestic waste; N43: proportion of landscaping public facilities to public facilities.

mechanism is grounded in system dynamics theory and strengthens this mechanism's analytical foundation.

Evaluation system. We construct an integrated evaluation system based on the above mechanism to evaluate the coupling coordination status of the two. The principles when selecting indicators are as follows:

- (1) These indicators could reflect AI and RI's core connotations and relations.
- (2) They can receive widespread consensus and be easily applied worldwide.
- (3) The indicators should not have multiple co-linear issues.
- (4) The indicators' data are accessible and usable.
- (5) The indicators reflect "per capita" or "efficiency" to enhance alternative comparability and minimize errors or bias from absolute regional differences.

We selected the indicators through literature screening, qualitative analysis, correlation coefficients, and significance tests

and thus constructed the comprehensive evaluation system (Table 1). AI has five dimensions with 17 indicators, and RI has four dimensions with 13 indicators. Some indicators are obtained after calculation; the equations and detailed explanations are attached in Table 1.

Specifically, we use mechanization, technicalization, professionalization, intensification, and sustainability as the main dimensions of AI. "Mechanization" represents the overall use performances of agricultural machinery and equipment, composed of 4 specific indicators: machinery power efficiency, mechanical input scope, mechanical input efficiency, and mechanical output efficiency. "Technicalization" evaluates technological use in the agricultural industrialization process, composed of 4 specific indicators: technical research investment, fertilizer use coverage, pesticide use coverage, and plastic film use coverage. "Professionalization" demonstrates the performances of professional practitioners in the agricultural industrialization process. Specifically, we explore the performances of agricultural professional companies, which includes 3 indicators: human resource input, input scope, and labor productivity.

“Intensification” demonstrates input-out efficiency from the means of production perspective, which includes 3 specific indicators: agricultural production efficiency, capital investment efficiency, and production factor investment efficiency. “Sustainability” demonstrates whether agricultural industrialization meets the specific sustainability targets, which include 3 specific indicators: financing ratio, importance to employment, and importance to output value.

RI has four dimensions: production, living, social service, and ecology. “Production” represents the upgradation of production-related infrastructure. Three indicators are selected: reservoir use efficiency, power generation efficiency, and road use efficiency. “Living” measures the villagers’ living conditions, which includes three indicators: household water supply quality, household gas supply quality, and household clean energy supply efficiency. “Social service” reflects RI’s public facilities, composed of 4 indicators: public facilities investment coverage, basic education quality, medical service coverage, and minimum social security service coverage. “Ecological” reflects RI’s ecological environment conditions and protection countermeasures, composed of 3 indicators: domestic sewage treatment coverage, domestic waste disposal coverage, and green investment coverage.

The positive indicators (+) mean that the larger the value is, the better the performance of the indicator and the more contributions to the system.

We want to highlight some indicator details. Firstly, the specific indicator selection is based on the accessibility of data to make calculation and multi-regional comparisons possible. For instance, for indicators M31-M33, we select state-owned farms rather than private-owned farms mainly because the latter’s data are not counted, making calculations and comparisons impossible. Therefore, scholars should adjust the indicators slightly based on the specific scenarios in future research. Secondly, whether the indicators are positive or negative should be considered in particular scenarios. The indicator should be positive if it contributes to “agricultural industrialization” or “rural infrastructure.” For instance, for M52 and M53, the more significant proportion of agri-food manufacturing in the total population or gross regional product can positively depict the status of “agricultural industrialization”; therefore, they are positive indicators, even though in some studies, they are negative indicators as we sometimes acknowledge that the more developed of a region, the less values of M52 and M53.

Methods

Research area and data. We select the case of 30 provincial regions in China (Fig. 2). Due to the lack of official statistics on Hong Kong, Macao, Taiwan, and Tibet, we will not include the above areas in this study to ensure comparability among alternatives. China has endeavored to achieve sustainable AI and RI, but the regional differences are still apparent. For instance, regions in eastern China have achieved sustainable agricultural industrialization due to their developed economy and transportation, while regions in the west are relatively lagging because of insufficient fiscal investment and mountainous terrain; besides, villages in the northeast regions face apparent population loss, which affects future rural infrastructure’s operation costs, while villages in Xinjiang in the northwest receive abundant and continuous financial aids from governments, accelerating sustainable rural infrastructure process. In addition, China is initiating the rural revitalization strategy, making villages and agricultural industries different from previous periods. Therefore, it is necessary to make temporal and spatial comparisons among these regions and propose related policies to achieve coupling coordination between AI and RI in China, which is beneficial to achieve SDG-9.

The data mainly come from the China Statistical Yearbook, China Rural Statistical Yearbook, China Urban-Rural Construction Statistical Yearbook, Educational Statistics Yearbook of China, China Agricultural Machinery Industry Yearbook, and China Health Statistical Yearbook. These publications are from 2010 to 2022, presenting data from 2009 to 2021. These data are from the national authority, which shares high accuracy and reliability, making the results more convincing (Geng et al. 2021).

We want to clarify why we take provincial areas as the research scale. From the appropriateness perspective, “province” is an appropriate scale because the agricultural industrialization status and the rural infrastructure process are sometimes similar within a province, making comparisons appropriate. From the statistics perspective, we need to guarantee that indicator data can be obtained and compared; however, current statistical sources mainly cover the provincial scale, lacking sufficient and comparable data at the cross-city, town, or village scale. Therefore, the cross-provincial scale is appropriate, practical, and applicable to evaluate the coupling coordination status between AI and RI and reflect the diversity of reality.

We employ the exponential smoothing method to estimate specific missing data. This method is distinguished by its high stability and reliability, leading to its extensive use in estimating absent values within time series datasets.

Calculation procedures. We use the analytic hierarchy process-information entropy weight (AHP-IEW) and the technique for order preference by similarity to ideal solution (TOPSIS) to calculate indicators’ weights, development status (D), and the coupling coordination status (CCS); we use gray correlation degree (GCD) to evaluate indicators’ correlations to find primary influencing factors. Specifically, we use the coupling coordination model to evaluate CCS; this model has been widely used to assess the coupling coordination status among systems in previous studies and has proved effective.

AHP is a multi-criteria decision analysis approach, which depends on evaluators’ professionalism and makes multi-level analysis composed of abundant factors convenient (Zhang and Liang, 2021); however, the results may be biased because of evaluators’ subjectivity. Besides, IEW is based on information entropy, which can avoid the inconsistency, instability, and subjectivity that may exist in some other methods (such as analytic hierarchy process, principal component analysis, and Delphi method) when we determine indicators’ weights (Chanthakhot and Ransikarbum, 2021); however, such objective approach may introduce potential validity concerns regarding indicator prioritization (extreme values in some indicators can make the weight of that indicator very large). Therefore, we incorporate both AHP and IEW to yield more robust weight evaluation outcomes. The integration has been widely applied in evaluating weights and proved effective and stable (Qin et al. 2024).

TOPSIS is commonly used to rank alternatives by detecting the distance between the evaluated alternative and the best/worst solutions. The results are obtained via calculation, making results and interpretation more convincing and objective. Besides, it depicts the relative performances of alternatives and describes how far an alternative is from the best, making it widely used in accurate comparisons (Chen, 2021).

GCD compares the similarity between the comparison and the referential data columns and determines the correlations among indicators. The non-correlations between indicators make GCD closer to 0, and the correlations make GCD closer to 1, meaning the corresponding indicators influence more. The primary influencing factors are obtained after quantitative analysis,



Fig. 2 Research area.

making results and analysis more objective and convincing (Yu and Yu, 2023). The process is in Fig. 3.

We want to highlight the interpretation of the values D, CCS, and influencing factors. The values emphasize “relative” performances rather than “absolute” performances. We use the coupling coordination model and the IEW, TOPSIS, and GCD methods, which measure relative differences among alternatives. We believe they are proper in this study, as we aim to evaluate how agricultural industrialization and rural infrastructure interact to achieve SDG-9, which emphasizes relative and long-term progress. Suppose we provide an observable phenomenon corresponding to specific mathematical values. $D = 1$ means this region performs outstandingly in every aspect in the observed period, and $CCS = 1$ means the interaction between agricultural industrialization and rural infrastructure of this region outperforms any other region in every dimension in every single year. However, value 1 does not mean this region has achieved “absolute” excellence: it has just achieved “relatively” excellence compared to others, and there is still a way to go to achieve better SDG-9. The “relative” results illustrate the essence of SDG: do not stop pursuing more excellence and a better future for human beings.

In the AHP process, 7 experts were asked to fill in the weight determination form. They have solid theoretical or practical expertise in agricultural industrialization, rural infrastructure, and rural revitalization, making the AHP results much more convincing. The Ethics Committee of the school approved the expert interview on March 4th, 2025 (reference number 2025030401). The AHP steps were added at a reviewer’s request during manuscript revision, and the committee was aware that consent was obtained after the manuscript’s initial submission. We conducted face-to-face interviews, clarifying the content and purpose in advance to ensure validity. Professionals were

informed that the interview form was anonymous and data would be used solely for research purposes and stored confidentially on a computer. Professionals gave oral consent before participating.

Weight determination with AHP. (1) Based on the expertise, experts conduct pairwise comparisons for elements in each hierarchy level (dimension and indicator in Table 1, respectively), assigning relative preferences using a 1/9 to 9 scale (Table 2) (Chen et al. 2014). After these comparisons, a pairwise comparison matrix is created. These comparisons are illustrated in the following matrix A , the positive definite reciprocal matrix, where $a_{i'i''}$ means the relative importance of the element i' over the element i'' . There are m elements (indicator or dimension) in total in the comparison matrix of the corresponding hierarchy.

$$A = [a_{i'i''}]_{m \times m} \quad (15)$$

(2) Use the geometric mean to evaluate priority vector (elements’ weight).

$$w_{i'} = \frac{\left(\prod_{i''=1}^m a_{i'i''} \right)^{\frac{1}{m}}}{\sum_{i''=1}^m \left(\prod_{i''=1}^m a_{i'i''} \right)^{\frac{1}{m}}}, i' = 1, 2, \dots, m \quad (16)$$

(3) Proceed the consistency test of the judgment matrix to determine whether experts’ evaluations are valid. When comparing scales, the number of evaluation factors should not exceed 9 to avoid logical errors; therefore, consistency test is necessary (Zhang and Liang, 2021). Calculate the consistency ratio CR with

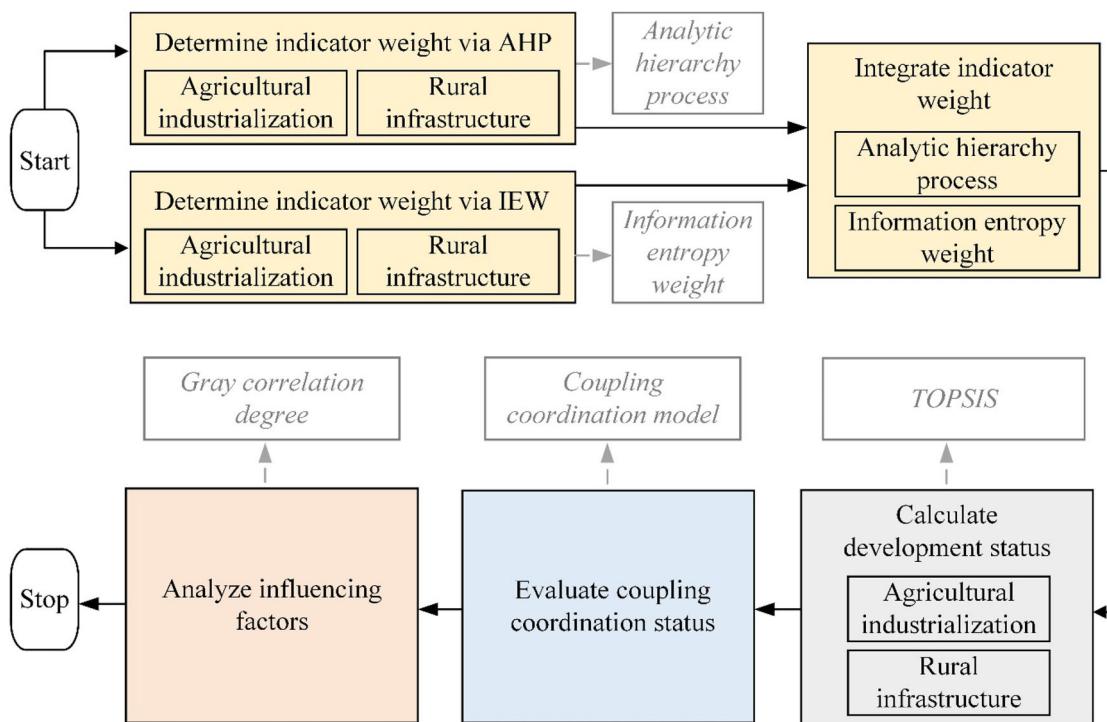


Fig. 3 Calculation process.

Table 2 Preference scale.

Value	Importance	Value	Importance
3	i' is slightly more important than i''	1/3	i' is slightly less important than i''
5	i' is more important than i''	1/5	i' is less important than i''
7	i' is apparently more important than i''	1/7	i' is apparently less important than i''
9	i' is definitely more important than i''	1/9	i' is definitely less important than i''
1	i' is as important as i''		

formula (17).

$$CR = \frac{CI}{RI} \quad (17)$$

CI is the consistency index, where $CI = \frac{\lambda_{\max} - m}{m - 1}$; the maximum eigenvalue $\lambda_{\max} = \frac{1}{m} \sum_{i=1}^m \frac{(Aw)_i}{w_i}$; RI is the random index (pre-defined), shown in Table 3. CR is acceptable and AHP process is valid if CR is less than 0.10 (Qin et al. 2024).

(4) Integrate each hierarchy level's weight and obtain the final indicator's weight wa_j .

$$wa_j = w_d \times w_j \quad (18)$$

Here w_j is the weight of the indicator j ($j = 1, 2, \dots, n$); w_d is the weight of the dimension where the indicator j is located. All indicators' weights sum up to 1.

Weight determination with IEW. (1) Standardize data. x_{ij} is the collected raw data, where i is the alternative under the indicator j of all the years. Here $i = 1, 2, \dots, m; j = 1, 2, \dots, n$. Then mark the new standardized value as x'_{ij} . Formula (19) is for the positive indicator (the larger, the better), while the formula (20) is for the negative indicator (Geng and Huang, 2022). This study's indicators are positive ones, and we list the formula (20) for

readers' future reference.

$$x'_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (19)$$

$$x'_{ij} = 1 - \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (20)$$

(2) Calculate lnf_{ij} to eliminate insignificance (Geng et al. 2020); this study introduces $1 + x'_{ij}$ to keep it positive.

$$f_{ij} = \frac{1 + x'_{ij}}{\sum_{i=1}^m (1 + x'_{ij})} \quad (21)$$

(3) Calculate the entropy value IE_j of indicator j . IEW is an objective method driven by data and independent of expert experience. Specifically, the smaller the indicator's entropy value, the greater its containing information and weight (Ju et al. 2024).

$$IE_j = - \left(\sum_{i=1}^m f_{ij} \ln f_{ij} \right) \quad (22)$$

(3) Calculate the indicator j 's coefficient ef_j .

$$ef_j = 1 - IE_j \quad (23)$$

Table 3 Random index.

Matrix size	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 4 Grades of D.

Grade	Value	Grade	Value
Excellent	[0.9, 1]	Close to average	[0.4], (0.4999)
Close to excellent	[0.8, 0.8999]	Acceptable	[0.3], (0.3999)
Advanced	[0.7, 0.7999]	Close to acceptable	[0.2], (0.2999)
Close to advanced	[0.6, 0.6999]	Poor	[0.1], (0.1999)
Average	[0.5, 0.5999]	Close to poor	[0], (0.0999)

(4) Calculate the weight w_{ij} .

$$w_{ij} = \frac{ef_j}{\sum_{j=1}^n ef_j} = \frac{1 - IE_j}{n - \sum_{j=1}^n IE_j} \quad (24)$$

(4) Integrate the weight of AHP and IEW; obtain indicator's combined final weight w_i .

$$w_i = h \times wa_j + (1 - h) \times wi_j \quad (25)$$

wa_j and wi_j are indicator's weight from AHP and IEW, respectively. h is the coefficient; both approaches are equally important in this study (to maintain objectivity and prevent excessive index weight from extreme values), thus, $h = 0.5$ (Geng and Tan, 2020).

Calculate D with TOPSIS. (1) Calculate AI's and RI's development status (D). x_j^+ and x_j^- represent the indicator j 's most significant and minor values in the year z ; i is the alternative under the indicator j (Geng and Zhang, 2021).

$$x_j^+ = \left(\max_{1 \leq z \leq u} x_{iz}, \max_{1 \leq z \leq u} x_{iz}, \dots, \max_{1 \leq z \leq u} x_{iz} \right) \quad (26)$$

$$x_j^- = \left(\min_{1 \leq z \leq u} x_{iz}, \min_{1 \leq z \leq u} x_{iz}, \dots, \min_{1 \leq z \leq u} x_{iz} \right) \quad (27)$$

(2) Calculate the optimal solution d_z^+ and the worst solution d_z^- of AI and RI, respectively. d_z^+ indicates the distance from the alternative to the positive ideal solution x_j^+ in the year z . d_z^- represents the distance from the alternative to the negative ideal solution x_j^- in the year z . Using these distances, we can calculate how far the alternative is from the optimal solution (Chen et al. 2024).

$$d_z^+ = \sqrt{\sum_{j=1}^k W_j (x_{zj} - x_j^+)^2}, z = 1, 2, \dots, u; 0 \leq d_z^+ \leq 1 \quad (28)$$

$$d_z^- = \sqrt{\sum_{j=1}^k W_j (x_{zj} - x_j^-)^2}, z = 1, 2, \dots, u; 0 \leq d_z^- \leq 1 \quad (29)$$

(3) Calculate D of AI and RI, respectively (AI-D, RI-D). AI-D and RI-D represent their relative proximity to the ideal solutions (Jiao et al. 2022). D's value ranges from 0 to 1, with higher values indicating better development status (Chen et al. 2024).

$$D = \frac{d_z^-}{(d_z^+ + d_z^-)}, z = 1, 2, \dots, u; 0 \leq D \leq 1 \quad (30)$$

(4) Based on previous studies, this paper divides D into ten grades at equal intervals, as shown in Table 4 (Deng et al. 2020).

(5) We define $m(x)$ and $n(x)$ are the D of AI and RI, respectively. To compare which one is relatively lagging, we

introduce the relative development type: development with RI lagging ($m(x) - n(x) > 0.1$), concurrent development ($-0.1 < m(x) - n(x) < 0.1$), and development with AI lagging ($n(x) - m(x) > 0.1$).

Calculate CCS. (1) Calculate the coupling degree (C) between AI and RI. The coupling degree quantifies the interaction between systems. A higher C value indicates a stronger relationship between systems (AI and RI in this study) (Wan et al. 2024). $m(x)$ and $n(x)$ denote AI-D and RI-D, respectively.

$$C = \sqrt{\frac{m(x) \times n(x)}{\left(\frac{(m(x) + n(x))}{2}\right)^2}} \quad (31)$$

(2) Calculate the comprehensive evaluation index of AI and RI T . λ and μ are coefficients. Here, the two objects interact and are equally important, so we set $\lambda = \mu = 0.5$ (Geng and Yan, 2021).

$$T = \lambda m(x) + \mu n(x) \quad (32)$$

(3) Calculate the coupling coordination status (CCS) between AI and RI. CCS overcomes the shortcomings of traditional coupling degrees, which may indicate high coupling despite low overall evaluation values. It offers a more explicit representation of a system's coupling coordination level (Li et al. 2024c).

$$CCS = \sqrt{C \times T} \quad (33)$$

(4) The grades of CCS are shown in Table 5; the grades are divided with equal intervals based on previous studies (Yuan et al. 2024).

Influencing factor analysis. (1) Determine the reference sequence and comparison sequence. This step aims to calculate the gray correlation between AI and RI, so we set the indicators of AI as the comparison sequences S_j ; we also set the indicators of RI as the reference sequences $S_{j''}$.

$$S_j = (S_j(1), S_j(2), S_j(3), \dots, S_j(n)). j' = 1, 2, 3, \dots, n \quad (34)$$

$$S_{j''} = (S_{j''}(1), S_{j''}(2), S_{j''}(3), \dots, S_{j''}(n)). j'' = 1, 2, 3, \dots, n \quad (35)$$

(2) Calculate the correlation degree $\varsigma_{j''j}(z)$ of the two sequences. The γ is defined as 0.5.

$$\varsigma_{j''j}(z) = \frac{\min \min |S_{j''}(z) - S_j(z)| + \gamma \max \max |S_{j''}(z) - S_j(z)|}{|S_{j''}(z) - S_j(z)| + \gamma \max \max |S_{j''}(z) - S_j(z)|} \quad (36)$$

(3) Define the new sequences by integrating the correlations of observed values to better depict the correlation between the

Table 5 Grades of CCS.

Grade	Value	Grade	Value
Extremely coordinated	[0.9, 1]	Transitional uncoordinated	[0.4, 0.4999]
Preferred coordinated	[0.8, 0.8999]	Less uncoordinated	[0.3, 0.3999]
Satisfying coordinated	[0.7, 0.7999]	Dissatisfying uncoordinated	[0.2, 0.2999]
Less coordinated	[0.6, 0.6999]	Non-preferred uncoordinated	[0.1, 0.1999]
Transitional coordinated	[0.5, 0.5999]	Extremely uncoordinated	[0, 0.0999]

sequences.

$$b^{(1)}(z) = \frac{b^{(1)}(z) + b^{(1)}(z-1)}{2}, z = 2, 3, \dots, u \quad (37)$$

(4) Calculate the GCD of the two sequences $(r_{j''j'})$.

$$r_{j''j'} = \frac{\sum_{z=1}^u \zeta_{j''j'}(z)}{u} \quad (38)$$

(5) Use each GCD value as a new element to form a matrix R arranged between S_j and $S_{j''}$.

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1j'} \\ r_{21} & r_{22} & \dots & r_{2j'} \\ \dots & \dots & \dots & \dots \\ r_{j''1} & r_{j''2} & \dots & r_{j''j'} \end{bmatrix} \quad (39)$$

Results

Temporal changes of D. The AI-D's temporal changes are in Fig. 4. The new law we find is that the development statuses of agricultural industrialization may fluctuate dramatically. Specifically, AI-Ds in most regions have witnessed apparent fluctuations since 2018, though the fluctuation tendencies (up or down) varied. Some examples support that: (1) In 2018, some regions declined in AI-D. Specifically, some regions have experienced significant declines (two grades down), as shown in Fig. 3a; some regions saw minor declines (one grade down), illustrated in Fig. 3b; in some regions, the AI-D decreased slightly with value differences less than 0.1, as depicted in Fig. 3c. Notably, Xinjiang shows the most pronounced decline, whose AI-D suddenly dropped to "close to acceptable" from "average," though still higher than most regions. (2) Some regions experienced a decline in 2018 but rebounded in the following two years, demonstrating volatility, as shown in Fig. 3(d). For instance, Shanghai dropped from "Close to average" in 2017 to "Acceptable" in 2018, returned to its original grade in 2019, and fluctuated between the two grades from 2019 to 2021. (3) Some regions experienced apparent increases in 2018, though the subsequent trends varied, as shown in Fig. 3e. Specifically, the D of Guangdong suddenly rose to the "close to advanced" level from "acceptable," far ahead of other regions; besides, the D of Shandong suddenly increased around 2018 from almost "close to acceptable" to almost "average" and then continuously decreased to normal, demonstrating the deteriorating sustainability. The key highlighted points are Xinjiang in 2018, Guangdong in 2018, and Shandong in 2018.

The dramatic fluctuations are caused by different reasons, demonstrating that the sudden changes in factors may cause huge fluctuations in agricultural industrialization. For instance, Xinjiang outperformed before 2018 because of the integrated effects of sufficient investment into the professionalized companies to increase their input scope and labor productivity (M32 and M33); the companies also obtained satisfying financing services, leading to better AI; however, since 2018, its mechanization dimension has faced apparent and dramatic decline (especially in mechanical input scope and mechanical input efficiency), leading to an apparent decrease in AI-D. We assume the decline is because more human labor participated in AI,

replacing particular machinery use. Besides, Guangdong has significantly increased its "mechanization" and "technicalization" dimensions (especially in mechanical input efficiency, technical research investment, and fertilizer use coverage) since 2018. Guangdong is an essential node of the "Belt and Road" Initiative and has solid fiscal and policy support, which has recently guaranteed AI. Furthermore, Shandong has witnessed worsening performances in the sustainability dimension since 2019 (decrease in importance to employment and importance to output value), mainly because of population loss and aging and the shifting focus on other industries (such as equipment manufacturing) in recent years.

The fluctuation of AI-D in 2018 examines various factors' interactions in AI, such as machinery, technology, human capital, production efficiency, and sustainability. This synergy raises rural socioeconomic ramifications differently across regions. For example, AI's performance in Xinjiang was mainly influenced by mechanization, though professionalization and technicalization also contributed; in 2018, insufficient investment in AI professionals led to weak mechanization and reduced application of pesticides and films, adversely affecting overall AI-D and forming a synergy interaction chain: "weak personnel professionalization - impact mechanization and technicalization—decline in AI-D." As a result, Xinjiang's rural areas faced increased challenges in achieving SDG-9 through the pathway of "mechanization reduction—agricultural industrialization decline—decreased income for rural communities and villagers—rural unsustainability." Besides, in 2018, Guangdong's AI-D was significantly impacted by "mechanization" and "technicalization," with professionalization, intensification, and sustainability having synergistic effects. These five dimensions increased more or less in 2018 in Guangdong; the factors synergy fostered a cycle of "more professional personnel—more efficient technological investment—better machinery use—more effective capital utilization—overall greater sustainability in AI." As a result, local rural areas have the socioeconomic ramifications of achieving high-quality development by "enhancing agricultural technical efficiency - increasing agricultural product value - raising villagers' income - ensuring rural sustainability." Conversely, Shandong's rural areas saw notable advancements in 2018 in terms of sustainability, professionalization, and technicalization interaction; agricultural industrialization positively influenced villagers' employment and incomes, which enabled local governments to allocate more funds for research and offer higher professional salaries while developing AI through "AI income promotion – AI investment promotion." However, this virtuous cycle did not continue; thus, Shandong's AI-D declined in subsequent years. Consequently, Shandong's rural regions faced socioeconomic challenges in achieving SDG-9 due to "unsustainable AI - inability to retain labor - rural decline."

The above results advance the understanding of SDG-9: the changes and fluctuations affect achieving SDG-9. For instance, Guangdong's increase in "mechanization" and "technicalization" dimensions helps achieve SDG-9.5 (enhancing research and upgrading industrial technologies) and SDG-9.b (supporting domestic technology development). In conclusion, the critical

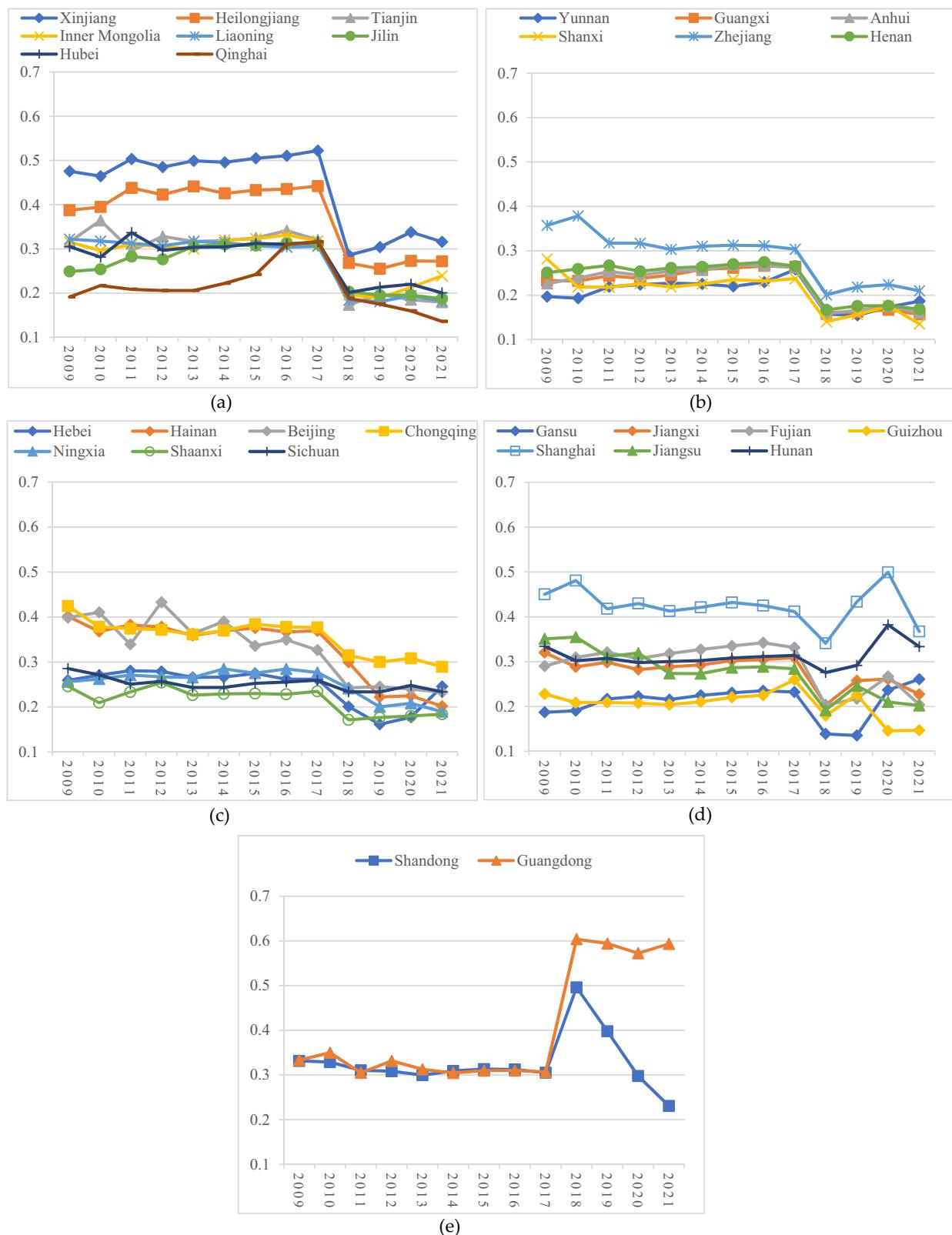


Fig. 4 AI-D's Temporal Changes. **a** Regions with Notable Decline in 2018 (2017's D-2018's D 0.1); **b** Regions with Slight Decline in 2018 (2017's D = 0.1); **c** Regions with Minimal Decline in 2018 (2017's D-2018's D 0.1); **d** Regions with Decline in 2018 followed by Rebounds in 2019-2020; **e** Regions with Notable Increase in 2018 (2018's D-2017's D 0.1).

point to highlight is that AI-D may fluctuate dramatically because some factors may suddenly change, leading to unstable AI performances.

Figure 5 shows the temporal changes of RI-D. The new law is that rural infrastructure may mildly develop annually. Specifically, RI-Ds have mild upward trends with decreasing gaps gradually. (1) Even if some regions had slight declines, others were growing, narrowing the gap between them. Specifically, the decline was minimal, with relatively stable fluctuations, in regions with decreasing RI-D values. Meanwhile, even regions with the lowest RI-D values gradually increased, making inter-regional differences in RI-D less pronounced. Some examples support this. The RI-D of Hainan was almost the highest among all the regions, maintaining the “close to average” every year (as shown in Fig. 4a), whereas Liaoning was relatively lagging in RI (almost the lowest in many years) at the “close to acceptable” grade (as shown in Fig. 4b); however, their gaps are gradually decreasing. (2) Many regions have seen significant RI-D growth. Some achieved numerical increases within their grades (Fig. 4b); others slightly increased from “Close to acceptable” to “Acceptable” (Fig. 4c), while some had a more notable rise from “Close to acceptable” to “Acceptable” (Fig. 4d). Additionally, certain regions upgraded from “Acceptable” to “Close to average” (Fig. 4e). Notably, we would like to highlight Ningxia; it showed an apparent increase from the “acceptable” at the beginning to the “close to average” recently, showing an encouraging sustainable growth trend; such growing trends could be found in many other regions. There are no apparent key turning points to highlight.

The mildly increasing trends depict the benefit of the continuous and accumulative input to rural infrastructure. For example, the rural living infrastructure in Hainan is much higher than in other areas; Hainan’s relatively simple administrative system allows the provincial government to input rural infrastructure more directly and conveniently; besides being rich in tourism resources, Hainan has promoted rural living infrastructure upgradation through tourism prosperity. Comparatively, Liaoning is low in RI because of the relatively low input to improve domestic sewage treatment coverage and domestic waste disposal coverage; problems such as population outflow, cold climate, and an underdeveloped economy have also profoundly impacted the input amount and efficiency of RI-D. In addition, Ningxia has vigorously promoted the rural revitalization strategy in recent years, and the local government encourages social capital to invest in RI, leading to an integrated increase in all dimensions. Specifically, benefiting from social capital investment, Ningxia increased its indicators in reservoir use efficiency, household water supply quality, minimum social security service coverage, and green investment coverage.

The continuous rise of RI-D in many regions reflects the interactions among factors, including production, livelihood, social services, and ecological infrastructures; their synergy has caused socioeconomic impacts on villages. For example, Hainan and Ningxia have effectively coordinated their rural infrastructure interactions in four dimensions. Hainan enhanced its ecological environment and tourist experience to boost rural tourism, creating a positive interaction chain that “better ecological infrastructure leads to improved environments - better living infrastructure enhances tourist experiences—funds are generated for agricultural production and social service infrastructure.” Meanwhile, Ningxia’s rural revitalization strategy focused on developing characteristic agriculture based on local rural conditions, resulting in an interaction chain where “improved production infrastructure generates more funds for living, social services and ecological improvements.” Therefore, by “enhancing the competitiveness of rural industries—improving villagers’ living standards—achieving rural sustainable development,” the

RI in Hainan and Ningxia positively impacted local economy and society over the long term. In contrast, although Liaoning’s RI increased annually, its overall value remained relatively low, with weak performance across these four aspects. That led to an interactive chain: “no dominant factors - weak overall RI.” Consequently, Liaoning’s rural regions faced socioeconomic challenges in achieving rural sustainability due to “slow development of rural infrastructure—lower rural attraction—slow rural economic and social growth.”

The above results promote the understanding of achieving SDG-9. The continuous and accumulative input to rural infrastructure matches SDG-9.1 (developing sustainable, resilient, and inclusive infrastructures), contributing to villages’ comprehensive growth (matching SDG-9.a: facilitating sustainable infrastructure development for developing countries). In conclusion, the critical point is that RI-D may go up mildly because the continuous input may have accumulative benefits to RI.

A comparison between AI-D and RI-D is in Fig. 6. The new law is that agricultural industrialization and rural infrastructure may not constantly develop concurrently. Specifically, before 2017, the AI-D and RI-D were concurrent in most areas, but after 2018, the AI-D generally lagged behind RI-D in many regions. One of the crucial reasons for the overall trend change is that China has been promoting rural revitalization since 2018, continuously improving RI-D. Besides, let us look at the mean value within the observed period. 30% regions (9 out of 30) were relatively weak in agricultural industrialization, demonstrating the inconsistency between AI and RI and depicting a long way for RI.

Different factors in different regions cause relatively imbalanced development statuses between agricultural industrialization and rural infrastructure. For instance, Xinjiang and Heilongjiang were relatively lagging in RI, demonstrating that the local RI could not support AI. For Xinjiang, insufficient water resources are a crucial constraint on its rural infrastructure development process. Although large-scale construction of water conservancy facilities has been carried out, they still need to be improved to meet the stable and high-quality supply of water resources for better agricultural production, living, and the environment. In addition, due to the vast territory, Xinjiang’s rural infrastructure, such as transportation and advanced medical services, is difficult and costly to upgrade. For Heilongjiang, the situation is different; although there are relatively abundant water resources, soil salinization is the problem. Meanwhile, the extended cold weather and frozen earth make it difficult to maintain infrastructure, such as reservoirs, drainage pipelines, irrigation facilities, and roads, which are not conducive to the efficient growth of RI. On the contrary, in western China, Gansu, Shaanxi, and Yunnan were relatively weak in AI. In the observed period, their AI was continuously lagging. There are some possible reasons. Firstly, they are limited by natural conditions, with complex terrain, mountainous areas, and deserts, making it challenging to form large-scale and intensive production that matches agricultural industrialization. Secondly, their local fiscal capacity is limited, resulting in insufficient investment in AI, especially in technological research, mechanized equipment upgradation, and the construction of deep processing industrial chains for farm products.

The above analysis indicates that different factors of AI and RI interact in various regions, leading to diverse outcomes in consistency (AI lagging or RI lagging). These differentiated results have apparent socio-economic impacts on local rural sustainable development. For example, regions with RI lagging may encounter the dilemma: “RI cannot support AI - AI cannot create jobs for villagers—villages’ weak endogenous development capacity—challenging sustainable development of rural economy

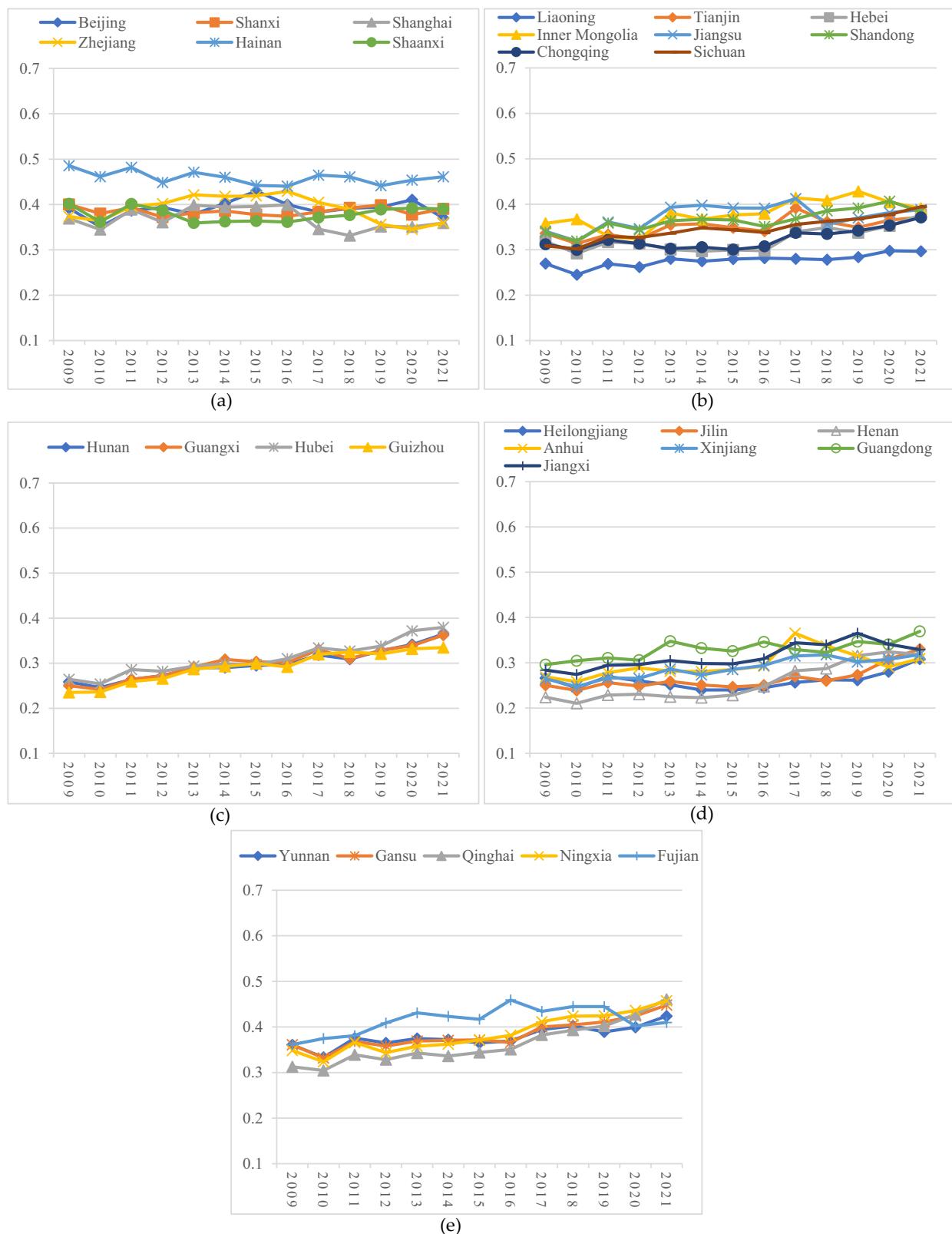


Fig. 5 RI-D's temporal changes. **a** Regions with Minimal Decline (2021's D-2009's D 0.1); **b** Regions Fluctuating within the Same Grades (Comparing 2021's D with 2009's D); **c** Regions with Minimal Increase from "Close to Acceptable" to "Acceptable" (2021's D-2009's D 0.1); **d** Regions with Notable Increase from "Close to Acceptable" to "Acceptable" (2021's D-2009's D 0.1); **e** Regions with Increase from "Acceptable" to "Close to Average".

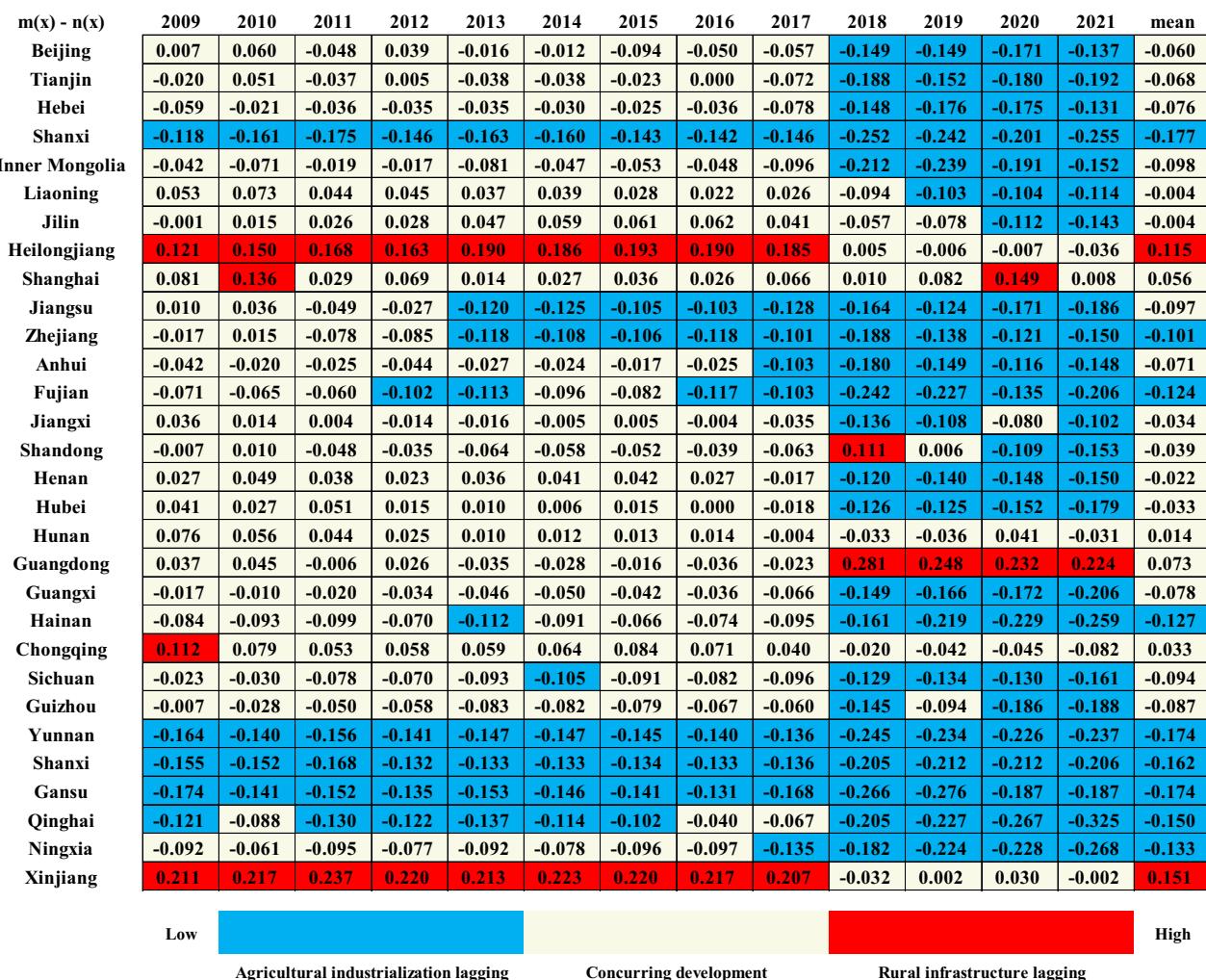


Fig. 6 Comparison between AI-D and RI-D.

and society.” Similarly, regions with AI lagging may face the issue: “AI cannot support RI - RI fails to ensure a decent life for villagers—weak rural attractiveness and resilience—difficult sustainable development of rural economy and society.” That implies that achieving SDG-9 is complicated and differentiated. Therefore, it is essential to propose targeted countermeasures for different regions (such as those lagging in AI or RI), which will be further discussed in section 6.1 Countermeasures.

In conclusion, the critical point is that AI and RI may not develop at the same pace; some regions may be high in AI, and some are high in RI, which is caused by different reasons or factors.

Spatial variations of D. Figures 7, 8 show the spatial mean distributions of the AI-D and RI-D from 2009 to 2021. The new law is that agricultural industrialization and rural infrastructure usually have different spatial distributions; simultaneously, they are similar: the coastal regions were relatively higher than others. The coastal regions were relatively higher mainly because of their vast plains and advanced economy, conducive to the wide use of agricultural machinery, attracting relevant talents and capital, and upgrading rural infrastructure.

The specific pattern of the spatial variations is that AI-D is dotted, whereas RI-D is connected. In detail, the spatial distributions were like “better regions were dotted” for AI-D;

differently, the spatial distributions were like “better-performing regions were connected” for RI-D. For example, for AI-D, Xinjiang, Beijing, Shanghai, Heilongjiang, Guangdong Chongqing, Shandong and Hunan were much higher (above “acceptable”) and dispersed in different geographical locations. Meanwhile, for RI-D, Xinjiang in the northwest, northeast China, central China, and some regions in south China showed relatively weak RI-D (“close to acceptable”), and better RI-D regions surrounded them.

Another law is that different reasons usually cause spatial variations. Specifically, the dotted regions advanced in AI-D had different factors. For example, Xinjiang has vast flat land suitable for growing crops harvested by machinery and enjoys many professional agricultural reclamation groups, which promotes AI-D. Beijing and Shanghai have limited arable land, but their developed economy contributes to more technical products or equipment and agricultural industry investments. Heilongjiang has abundant high-quality farmland resources with relatively small populations, making agricultural industrialization necessary. Guangdong and Chongqing have limited vast-and-flat land, but they have supportive encouragement to develop AI; villagers in Guangdong are so rich to buy machines for agricultural machines and to develop agri-food manufacturing; villagers in Chongqing enjoy supportive policies from the local government to the agri-food manufacturing industry. On the contrary, the weak RI-D regions also have various reasons. For instance,

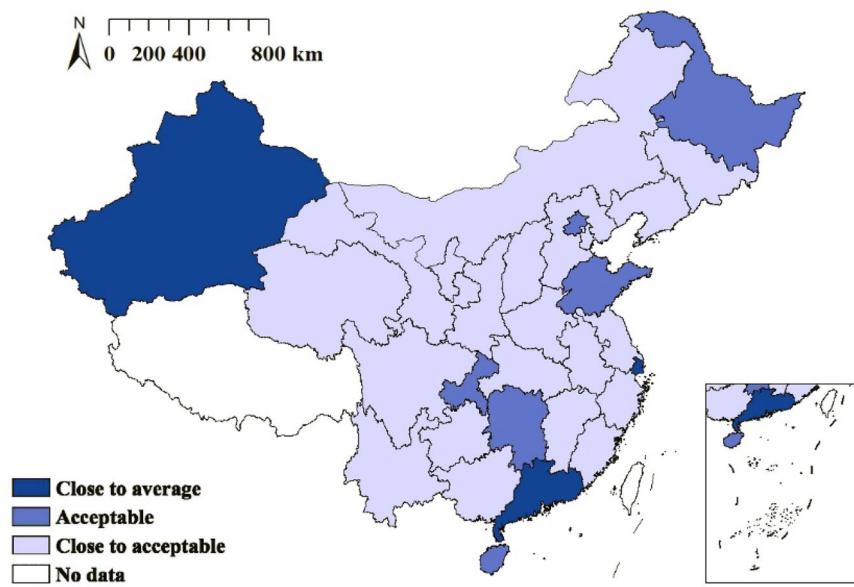


Fig. 7 AI-D's spatial mean distributions.

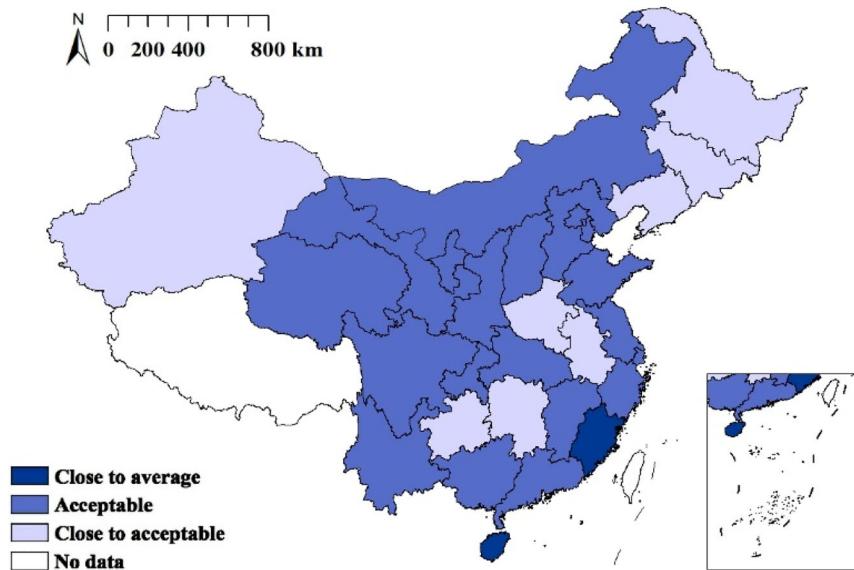


Fig. 8 RI-D's spatial mean distributions.

Xinjiang is weak in the social service dimension, especially regarding public facilities investment coverage and basic education quality. Though Xinjiang has initiated volunteer teaching projects and attracted temporary high-quality teachers, these teachers cannot solve the problem of weak essential education in rural areas from the root. Regions in the northeast are weak in the living dimension, especially in household water supply and household gas supply quality, showcasing the relatively weak living conditions there. Regions in central China (such as Anhui and Henan) are relatively poor in basic education quality and road use efficiency. Usually, these regions have advanced basic education quality and road use efficiency in cities; however, these indicators are weak in villages, demonstrating their urban-rural gaps and the long way to achieve better RI-D. Regions in the south (such as Guizhou and Hunan) are commonly weak regarding household clean energy supply efficiency. Some villages of these regions are poor in sunshine (especially in Guizhou), making household solar energy production relatively weak.

Another law is that sometimes facts differ from what we think. For instance, it is noteworthy that Henan performed weakly in both AI-D and RI-D, demonstrating that there is a long way to go before fulfilling SDG. That is a new finding, as Henan is traditionally believed to be a “big agricultural province” with large rural areas. Our finding is much more convincing and representative because we select indicators of “efficiency” and “per capita.” Its seemingly developed agricultural industry and infrastructure are based on a large rural population; hence, its agricultural mechanization rate, agricultural efficiency, and sustainability are relatively low, and rural public facilities are limited for each person. Specifically, Henan was low in labor productivity in the professionalization dimension (M3), power generation efficiency and road use efficiency in the production dimension (N1), and medical service coverage in the social service dimension (N3); the low values of these “per capita” indicators prove that huge population hinders sustainable coordination between AI and RI. Henan’s condition is opposite to the targets of

SDG-9, and stakeholders should take corresponding countermeasures to enhance AI-D and RI-D.

We want to highlight that the synergy between AI and RI factors significantly impacts rural economic and social sustainable development. For instance, Xinjiang has followed an interactive path of “adopting large agricultural machinery - increasing storage needs for RI - upgrading RI - further enhancing agricultural mechanization efficiency,” while Shanghai’s interactive trajectory involves “agricultural high-technology boosting production efficiency - more demand for efficient RI services - upgrading RI - further supporting AI.” In the rural economy, this interaction leads to “AI and RI input - increased agricultural output - higher villager income - rural sustainable economic growth;” for rural society, it results in “AI and RI input - improved rural infrastructure - enhanced rural sustainable social development.” The synergy affects achieving SDG-9, especially SDG-9.2 (inclusive industrialization) and SDG-9.1 (inclusive infrastructures). Regions with better AI-D imply that they are easier to achieve SDG-9.2, and the ones with better RI-D imply that they are relatively more straightforward to achieve SDG-9.1.

In conclusion, the critical point to highlight is that the development statuses of AI and RI have different spatial variations caused by different reasons; these reasons are not singular; instead, they are multiple synergistic interactions that lead to the final results. Besides, the factual results may differ from our stereotypes.

Temporal changes of CCS. The temporal changes of CCS are in Fig. 9. The general rule is that CCS may witness dramatic fluctuations due to the relative regional differences. For example, before 2017, CCS fluctuated mildly at the “transitional coordinated” status in most regions, whereas 2018 was a watershed year for CCS when some regions faced an apparent grade decline. If we explore further, such apparent changes were due to the out-performance of Guangdong (from the “transitional coordinated” to the “less coordinated”), making other regions relatively weak.

As we used TOPSIS to evaluate CCS, we could not say that these regions decreased, but we can confirm that they were “less hardworking” than Guangdong. Guangdong has outperformed since 2018 in many dimensions, such as mechanization, technicization, professionalization, and sustainability in AI and living and ecology dimensions in RI. They have formed positive interactions: “RI living infrastructures are improved—AI-related personnel are more professional—AI is increasingly mechanized and technical, with higher sustainability standards - RI ecological facilities are upgraded.” That has a derivative impact on local rural sustainable social and economic development that “better interaction between RI and AI - comprehensive agricultural development—increased villager satisfaction—overall rural sustainable development.” In conclusion, such a burst highlights that comprehensive sustainable coordination between AI and RI is applicable and needed.

Another law is that CCS gaps can gradually be diminished if we take appropriate countermeasures. For example, some regions upgraded from the “transitional uncoordinated” status to the “transitional coordinated” status from 2019, showing that regions minimized such gaps and endeavored to achieve much benign coupling coordination between agricultural industrialization and rural infrastructure. For instance, Hebei endeavored to enhance RI performances from the four dimensions by implementing the Rural Revitalization Strategy; Yunnan enhanced AI for better CCS by encouraging more advanced technology and investing in agriculture-related industries efficiently. These two regions demonstrate that “promoting AI through RI” and “promoting RI through AI” can enhance the “comprehensive interaction between AI and RI,” ultimately driving further rural sustainable socio-economic development. The results enhance our understanding of achieving SDG-9: the specific SDG-9 goals can achieve coordination; our efforts can facilitate the simultaneous achievement of various specific goals.

In conclusion, the critical point to highlight is that TOPSIS is applicable to evaluate CCS because we can easily find the relative

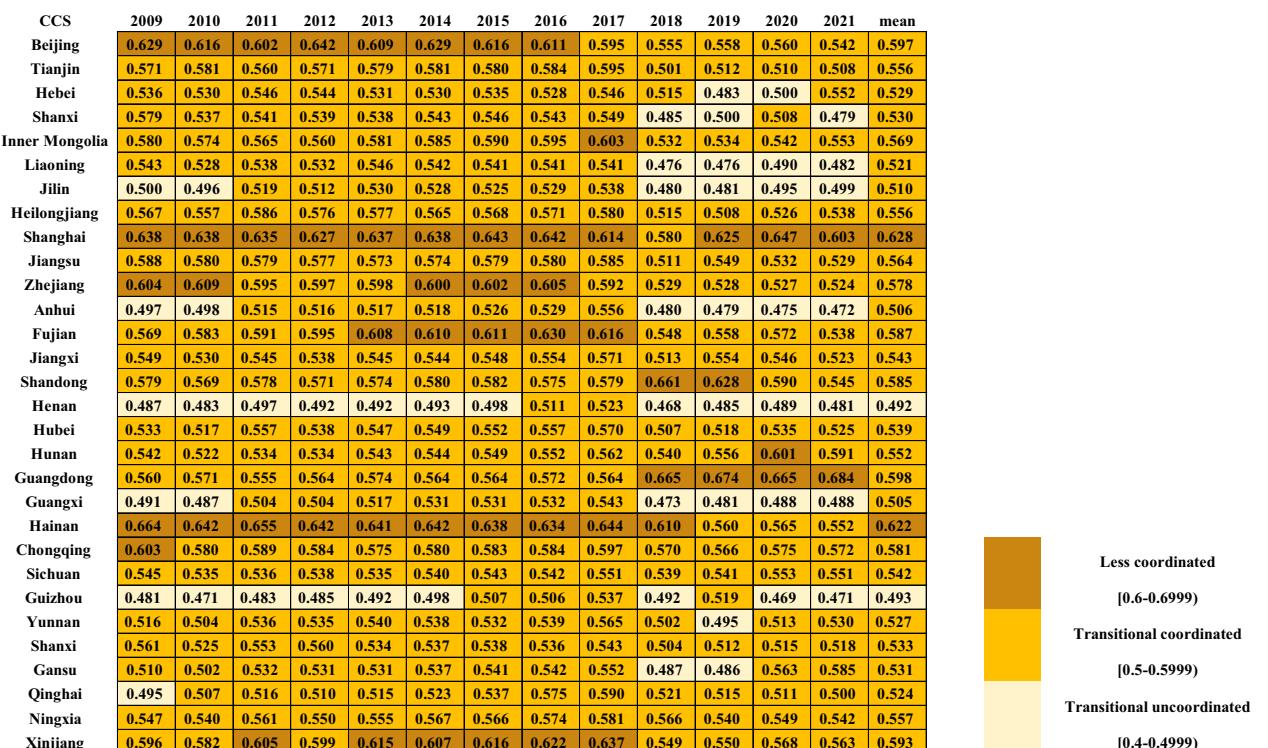


Fig. 9 CCS temporal changes.

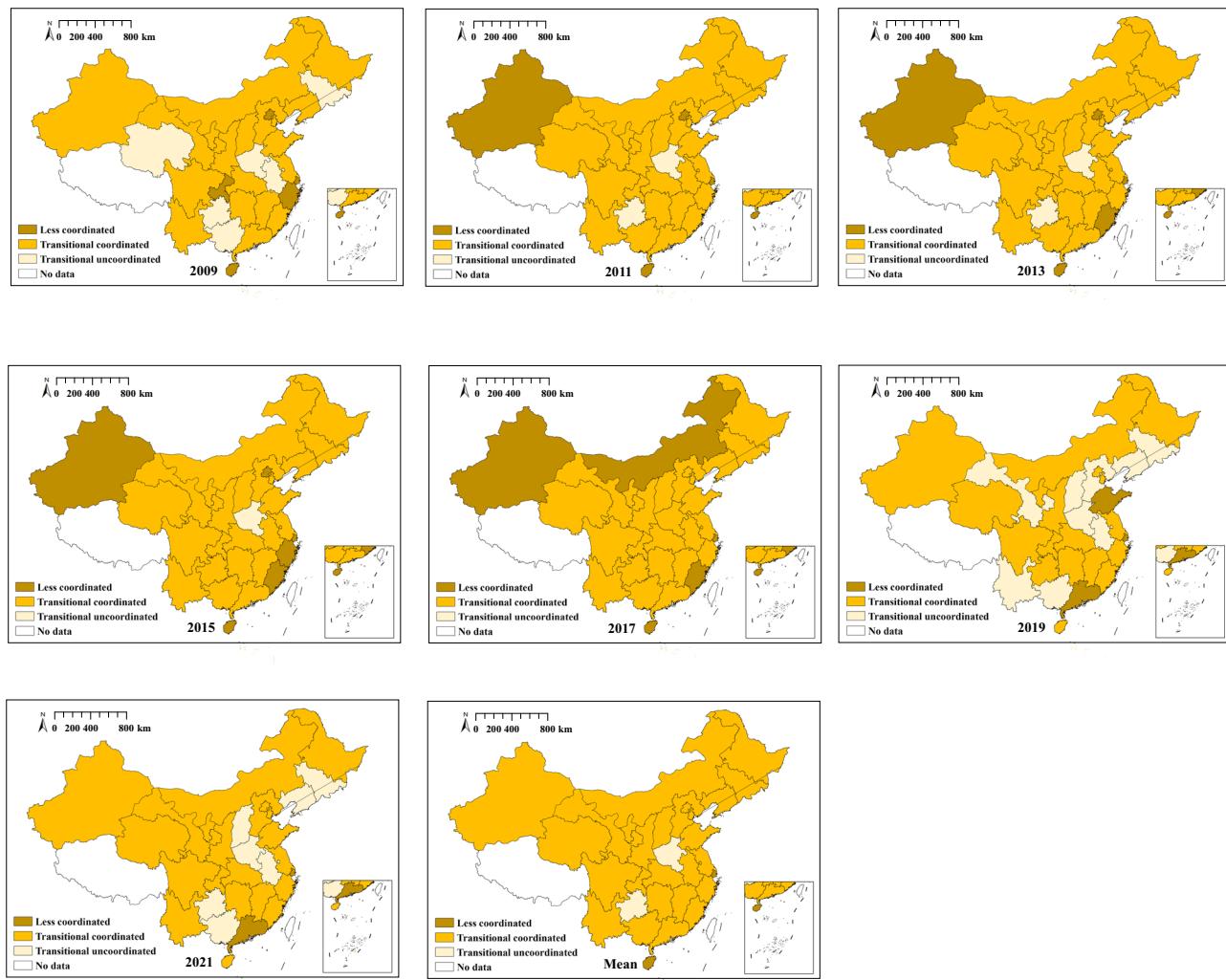


Fig. 10 CCS spatial distributions.

differences among regions, pushing those “relatively less hard-working” ones to be more hardworking to achieve better CCS.

Spatial variations of CCS. Figure 10 shows the spatial variations of CCS. An exciting law is that CCS is spatially correlated. Specifically, specific regions in central China, southwestern China, and northeastern China were relatively low in CCS, though the overall CCS was balanced nationally spatially. For instance, coastal regions performed relatively better; Shanghai and Hainan were more prominent in the “less coordinated” status, showing that their agricultural industrialization and rural infrastructure achieved relatively coupling coordination statuses. At the same time, some inland regions (Guizhou in the south, Henan and Anhui in the center, and Jilin and Liaoning in the northeast) had consistently relatively low CCS (“transitional uncoordinated”), showing weak performance in achieving coupling coordination statuses.

Another law is that outperforming regions have similarities while lagging regions have their own shortcomings. For example, Hainan and Shanghai outperformed in almost all dimensions. They enjoy convenient shipping transportation, making agricultural machine import and agricultural products export quickly and cheaply; besides, they initiate agricultural research and innovation resource exchange and sharing programs, increasing AI and RI competitiveness; in addition, the local governments

provide allowances and soft loans for upgrading agricultural equipment, productive infrastructure, and living infrastructure, enhancing coordination between AI and RI and achieving SDG-9. On the contrary, situations vary in other regions. For instance, Guizhou, in southwest China, is located in a mountainous area with complicated terrain, which brings significant challenges to agricultural industrialization and rural infrastructure construction; besides, although the local government has issued many policies in AI and RI, the practical guidance is insufficient; also, Guizhou is relatively insufficient in capital and technology investment, which restricts the integrated improvement of CCS. Anhui, in the central part, has lagged behind the adjustment of the agricultural structure and failed to meet the market demand effectively, which hinders AI promotion and RI upgradation; at the same time, villagers have become urban migrant workers, and villages are less populated, leading to “agriculture” and “rural areas” less developed; furthermore, Anhui lacks effective investment channels and mechanisms for social capital in AI and RI, which decreases social capital’s willingness to invest in AI and RI, restricting better CCS.

The interaction of the above factors significantly impacts rural areas’ sustainable economic and social development. For instance, in Hainan and Shanghai, the positive synergy between AI and RI fosters more coordinated and comprehensive rural development, aiding in achieving SDG-9. Conversely, in Guizhou and Anhui, investment and personnel professionalization shortcomings

2009	M1				M2				M3				M4				M5			Mean	Mean
	M11	M12	M13	M14	M21	M22	M23	M24	M31	M32	M33	M41	M42	M43	M51	M52	M53				
N1	N11	0.901	0.898	0.892	0.898	0.899	0.901	0.894	0.904	0.884	0.843	0.889	0.857	0.893	0.894	0.902	0.892	0.900	0.838	0.818	
	N12	0.759	0.761	0.758	0.759	0.759	0.759	0.759	0.760	0.756	0.757	0.759	0.757	0.757	0.762	0.757	0.762	0.714			
	N13	0.984	0.950	0.978	0.987	0.977	0.985	0.975	0.966	0.971	0.884	0.986	0.822	0.991	0.989	0.927	0.991	0.939	0.904		
N2	N21	0.981	0.956	0.982	0.983	0.976	0.988	0.976	0.971	0.965	0.885	0.981	0.826	0.987	0.990	0.932	0.987	0.944	0.904	0.902	
	N22	0.977	0.959	0.982	0.982	0.978	0.988	0.984	0.968	0.961	0.887	0.976	0.830	0.984	0.987	0.934	0.983	0.946	0.904		
	N23	0.973	0.947	0.974	0.975	0.974	0.979	0.974	0.963	0.968	0.888	0.977	0.822	0.982	0.983	0.922	0.982	0.934	0.899		
N3	N31	0.985	0.952	0.979	0.989	0.978	0.986	0.977	0.970	0.969	0.884	0.983	0.823	0.991	0.990	0.929	0.991	0.940	0.904	0.897	
	N32	0.985	0.949	0.978	0.988	0.976	0.984	0.974	0.966	0.970	0.883	0.987	0.821	0.993	0.992	0.927	0.993	0.937	0.904		
	N33	0.986	0.952	0.980	0.987	0.977	0.987	0.976	0.969	0.970	0.884	0.985	0.822	0.991	0.991	0.929	0.992	0.940	0.904		
N4	N41	0.982	0.946	0.976	0.984	0.975	0.979	0.974	0.963	0.969	0.881	0.987	0.818	0.996	0.994	0.923	0.994	0.933	0.902	0.903	
	N42	0.984	0.946	0.975	0.986	0.977	0.982	0.974	0.964	0.968	0.881	0.988	0.820	0.998	0.994	0.924	0.994	0.935	0.903		
	N43	0.984	0.946	0.974	0.987	0.979	0.980	0.972	0.964	0.970	0.882	0.988	0.819	0.994	0.991	0.924	0.994	0.935	0.903		
Mean	0.955	0.932	0.951	0.957	0.951	0.957	0.950	0.944	0.943	0.870	0.955	0.823	0.961	0.960	0.914	0.960	0.923				
Mean	0.949				0.951				0.923			0.915			0.932						
Low																					High

(a)																					
2021	M1				M2				M3				M4				M5			Mean	Mean
	M11	M12	M13	M14	M21	M22	M23	M24	M31	M32	M33	M41	M42	M43	M51	M52	M53				
N1	N11	0.999	0.999	0.999	0.999	0.997	0.999	0.999	0.999	0.998	0.999	0.977	0.999	0.683	0.995	0.999	0.998	0.920	0.896		
	N12	0.915	0.916	0.916	0.915	0.917	0.915	0.915	0.915	0.915	0.915	0.911	0.911	0.694	0.917	0.915	0.916	0.848			
	N13	0.999	0.999	0.999	0.999	0.997	1.000	0.999	0.999	0.998	0.999	0.976	0.999	0.682	0.995	0.999	0.999	0.920			
N2	N21	0.999	0.999	0.999	0.999	0.997	1.000	1.000	0.999	0.999	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920	0.920	
	N22	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	0.999	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
	N23	0.999	0.999	0.999	0.999	0.997	1.000	1.000	0.999	0.999	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
N3	N31	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920	0.920	
	N32	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
	N33	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
N4	N41	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920	0.920	
	N42	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
	N43	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	1.000	0.976	1.000	0.682	0.995	1.000	0.998	0.920		
Mean	0.993	0.993	0.993	0.993	0.991	0.993	0.993	0.993	0.993	0.992	0.992	0.993	0.971	0.993	0.683	0.989	0.993	0.992			
Mean	0.993				0.992				0.992			0.882			0.991						
Low																					High

(b)																					
2021	M1				M2				M3				M4				M5			Mean	Mean
	M11	M12	M13	M14	M21	M22	M23	M24	M31	M32	M33	M41	M42	M43	M51	M52	M53				
N1	N11	0.999	0.999	0.999	0.999	0.997	0.999	0.999	0.999	0.998	0.999	0.977	0.999	0.683	0.995	0.999	0.998	0.920	0.896		
	N12	0.915	0.916	0.916	0.915	0.917	0.915	0.915	0.915	0.915	0.915	0.911	0.911	0.694	0.917	0.915	0.916	0.848			
	N13	0.999	0.999	0.999	0.999	0.997	1.000	0.999	0.999	0.998	0.999	0.976	0.999	0.682	0.995	0.999	0.999	0.920			
N2	N21	0.999	0.999	0.999	0.999	0.997	1.000	1.000	0.999	0.999	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920	0.920	
	N22	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
	N23	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
N3	N31	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920	0.920	
	N32	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
	N33	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
N4	N41	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920	0.920	
	N42	0.999	0.999	0.999	1.000	0.997	1.000	1.000	0.999	1.000	0.998	0.999	0.976	1.000	0.682	0.995	1.000	0.999	0.920		
	N43	0.999	0.999																		

stakeholders (M32, from 0.870 to 0.992), importance to output value (M53, from 0.923 to 0.992), and mechanical input scope (M12, from 0.932 to 0.993) increased significantly. Although they were still not the most important factors, their increase highlighted that local governments could enhance AI by optimizing financing, expanding input scope and areas, and increasing the income from the agri-food manufacturing industry, stimulating RI effectively.

RI's Influencing Factors on AI. The first law is that rural life quality and social services are critical for AI. Specifically, in 2009, from the dimension perspective, the impacts of "living" (N2), "social service" (N3), and "ecology" (N4) on AI were roughly equal and significantly higher than that of "production" (N1), showing that improving rural life quality and rural social services were essential to promote AI. From the indicator perspective, except for reservoir use efficiency (N11) and power generation efficiency (N12), the influences of other indicators on AI were much more significant; among them, public facilities investment coverage (N31), basic education quality (N32), medical service coverage (N33), road use efficiency (N13), household water supply quality (N21), and household gas supply quality (N22) were the most important influencing factors, demonstrating that enhancing rural public facilities from these aspects was conducive to AI and thus contributed to more benign coupling coordination statuses between AI and RI.

Another exciting law is that RI is increasingly affecting AI comprehensively. Specifically, in 2021, all dimensions and indicators of RI had increasing impacts on AI, showing that RI is comprehensively affecting AI. Such comprehensive impacts were similar to the impacts of AI on RI, proving that the two were positively and sustainably coordinating. From the dimension perspective, "living" (N2), "social service" (N3) and "ecology" (N4) and were still the most influential dimensions for AI (rising from 0.902, 0.897, and 0.903 to 0.920, respectively), indicating that villagers' living conditions, rural services and environment have been profoundly affecting AI. Besides, "production" (N1) had the apparent increase (from 0.818 to 0.896), indicating that rural production infrastructure has recently been increasingly affecting AI performances. From the indicator perspective, all indicators had more significant impacts on AI than in 2009, and most of the indicators showed similar influence (about 0.920), which implied that these indicators may have integrated and coordinated influence on AI. Specifically, power generation efficiency (N12) and reservoir use efficiency (N11) increased apparently (from 0.714 to 0.848 and from 0.838 to 0.920, respectively), demonstrating their importance in enhancing AI. As an essential part of rural infrastructure, power facilities provide villagers with lighting and heating and are also the energy source of agricultural production, thus affecting AI; the efficient use of water conservancy infrastructure can reduce water damage to crops and thus provide the basis for agricultural industrialization.

In conclusion, AI and RI are two crucial components of rural development that mutually influence and interact; the indicators exhibit an evident coupling coordination status effect, which strengthens over time. Enhancing RI facilitates agricultural production and promotes the process of AI; simultaneously, AI supports the development of RI by accelerating agricultural production efficiency and generating more significant economic benefits. The increasing mutual impacts between agricultural industrialization and rural infrastructure prove that they can achieve benign coupling coordination and realize the targets of SDG-9. These results have enhanced our understanding of SDG-9: the specific goals of SDG-9 can interact and collaborate, ultimately promoting the overall achievement of SDG-9.

Discussions and conclusions

Countermeasures. Based on the previous analysis results, laws, and details, we find that different regions face different problems and scenarios; thus, we must take differentiated countermeasures based on the actual conditions and influencing factors to achieve coupling coordination status between AI and RI. The countermeasures, following the AI and RI dimensions and indicators, are also valuable references for countries or regions encountering similar scenarios who want to realize SDG-9 by achieving benign coupling coordination status. We admit that different countries or regions face different political and economic conditions, resources, histories, and values; thus, our suggestions need to be adjusted slightly by the facts. The countermeasures are for four types of regions categorized by the above CCS findings.

In some countries or regions, RI may lag behind AI (the typical examples in China are Xinjiang and Heilongjiang). These regions may be advanced in agricultural industrialization, but the benefits cannot affect rural infrastructure, making villages seemingly "less civilized." For these countries or regions, it is necessary to determine the characteristics of the natural environment and develop sustainable rural infrastructure that matches the corresponding agricultural production mode. (1) Make customized rural infrastructure plans; based on regional characteristics, local governments should promote different infrastructure construction plans, such as water-saving facilities in arid areas and thermal insulation facilities in cold areas. (2) Introduce policies to encourage the research and application of rural infrastructure technologies and equipment adapted to unique environments; for instance, domestic sewage treatment and waste disposal recycling equipment in remote or cold villages can be considered; they should be aware that AI and RI can jointly efficiently use the new equipment. (3) Enhance social service quality and rural living quality; regional governments can provide high-quality teachers and doctors with attractive allowances if they provide services in rural areas for specific years; local schools can provide courses regarding local, sustainable rural and agricultural development; use more efficient facilities to enhance the water and electricity use efficiency.

In some countries or regions, AI may lag behind RI (the typical examples in China are Shaanxi, Gansu, and Yunnan). Countries or regions may enjoy good rural construction and living standards because they enjoy preferential supportive policies or strategies. However, these villages cannot support their agricultural industrialization process; their AI may lag behind RI and other regions' AI with time. We suggest that these countries or regions carefully consider their positioning in AI and develop particular niche and differentiated agricultural industries. (1) Construct necessary AI facilities; based on the characteristics of rural areas, prioritize the construction of facilities closely related to agricultural industrialization, such as water conservancy, transportation, electricity, and internet. (2) Encourage technological innovation and promote intelligent agricultural machinery technologies adapted to local environments; install drones and robot assembly lines to enhance agri-food production efficiency. (3) Invite professional consulting companies to accelerate effective industry positioning. The consulting and marketing companies will carefully analyze strengths, weaknesses, opportunities, and threats to propose targeted professional strategies and detailed AI promotion solutions, enhance brand images, and improve the competitiveness of the local agricultural industries in specific niche markets. Proper positioning has been proved helpful in stimulating industry growth (Geng et al. 2024b).

Some countries or regions may have relatively benign coupling coordination statuses (the typical examples in China are Shanghai and Hainan). Countries or regions in this category have enjoyed the benefits of CCS between AI and RI, and some of them may

have been the representative example of achieving SDG-9; what they need to consider is how to surpass the current CCS status and become better ones so they can achieve SDG-9 more effectively and efficiently. We suggest that these countries or regions optimize their industrial structure and use new methods to achieve multi-dimensional growth in AI and RI. (1) Upgrade AI and RI and make them more intelligent; integrate them with advanced technologies such as the Internet of Things, big data, and artificial intelligence to empower efficient AI and RI. Bear in mind that technological innovation plays a vital role in the CCS. (2) Accelerate cooperation among various stakeholders; universities and agriculture-related companies can cooperate to apply the latest research into AI and RI practice, and villagers and investment corporations can collaborate in constructing facilities and equipment. Different stakeholders' cooperation can effectively expand involvement scopes and optimize AI and RI processes from all dimensions. (3) Attract more social capital to participate in AI and RI upgradation and optimization; laws should be implemented to guarantee the income mechanism of social capital; allow-lists and encouragement policies should be publicly announced to attract social capital.

Some countries or regions have relatively weak coupling coordination statuses (the typical example in China is Henan). Some countries or regions may face the dilemma that they lack sufficient funds while having surplus labor resources; it is difficult for them to initiate AI and RI quickly; therefore, we suggest that they should allocate limited resources wisely to improve resource utilization efficiency; of course, these countries or regions can "borrow" resources, funds, or help from countries with advanced AI and RI prudently. (1) Use population wisely and develop highly efficient labor-intensive agricultural industries; rural handicraft industry and agricultural and sideline food processing industry with machinery assistance can be considered. Bear in mind that human capital and machinery are essential in the CCS. (2) Provide professional skill training programs to villagers; the course can cover agricultural machine and technology products use and maintenance, introduction to financial planning, and household clean energy equipment use, aiming to enhance AI and RI simultaneously. We should remember that professional talents are vital in CCS. (3) Construct integrated multifunctional facilities to enhance rural service efficiency; such facilities provide supportive services to agricultural industrialization production and villager living; for instance, they can provide sharing machines and instruments of production, sharing business services such as tax and legal advice, and sharing learning centers.

Discussions. This paper constructs the coupling coordination mechanism between AI and RI, depicting how AI and RI interact positively to achieve SDG-9. Besides, we evaluate the temporal and spatial development status and the coupling coordination status between AI and RI, proposing the primary influential factors to enhance AI and RI performances. Detailed discussions are as follows.

Firstly, the coupling coordination mechanism can be used to evaluate the interactions between agricultural industrialization and rural infrastructure. We expand the scope of CCS to AI and RI, which is innovative. There are few studies about the CCS between AI and RI, though there are studies about the CCS of similar systems. For instance, with China and Poland as cases, some studies explored the CCS between industrialization and agricultural green development, between agricultural ecological environment and rural economic development, and between rural socio-economic-infrastructure development (Guo et al. 2021; Liu et al. 2022; Tomal, 2021). These studies depicted the coupling coordination mechanism among similar systems, proving the

effectiveness of the coupling coordination mechanism; however, they failed to depict the CCS between AI and RI explicitly. We successfully expanded the application scope of CCS to AI and RI, proving this study's novelty.

Secondly, the coupling coordination mechanism helps achieve SDG-9 targets. The coupling coordination mechanism incorporates AI and RI, consisting of "mechanization, technicalization, professionalization, intensification, and sustainability" and "production, living, social service, and ecology," respectively. The dimensions promote each other, achieving SDG-9. Other studies also prove that the coupling coordination mechanism contributes to SDG. For instance, the coupling coordination mechanism between socio-economic development and water security lays a scientific foundation for Lancang-Mekong River Basin countries in Southeast Asia to achieve SDG (Zheng et al. 2023). Besides, the coupling coordination mechanism can measure the interactions between SDG and other systems (such as carbon emission and digital economy), directly contributing to SDG globally (Cheng and Yang, 2023; Yang et al. 2023b). We focus on the coupling coordination interactions between AI and RI to achieve SDG-9, which further realizes the theoretical innovation of CCS.

Thirdly, coupling coordination helps propose more targeted and differentiated countermeasures. The analysis results, laws, and details show that regions face different problems and scenarios; therefore, regions should have differentiated solutions. We proposed specific countermeasures for four types of regions (lagging in AI, lagging in RI, high in CCS, and weak in CCS) based on AI and RI dimensions and indicators, which is conducive to SDG-9 and significant reference to rural development and governance in the globe. Other studies support the significance of coupling coordination in helping differentiated countermeasures. For instance, some studies propose that coupling coordination helps clarify specific ecological situations, making biodiversity conservation countermeasures possible; some propose that coupling coordination is helpful for different urban agglomerations to achieve differentiated low-carbon growth (Lian et al. 2023; Xie et al. 2022b). Studies also prove that the differentiated countermeasures contribute to more efficient achievement of SDG (Geng et al. 2024d). We propose that coupling coordination contributes to differentiated countermeasures, which effectively guide AI and RI practice to achieve SDG-9, which is insightful for global practice.

Results comparisons. By comparing our findings with previous ones, we may discover similarities or differences, which will contribute to society in theory and practice and justify some conclusions.

(1) Compare the development status D. We find that AI-D fluctuated dramatically in 2018; RI-D showed decreasing gaps among regions. Besides, both are similar in that the coastal regions were relatively higher. In contrast, limited studies explore AI-D and RI-D but explore similar systems. For instance, one study explores green agriculture development in China, proposing that D is increasing and regional differences are declining; the distributions show "high in the east and low in the west" (Huang et al. 2023). The similarity is that the coastal regions were much higher, while the difference is that AI-D had apparent fluctuations. The above comparisons justify that the eastern regions in China are better in rural development. Besides, let us compare the development status of systems between China and other countries. The example is from Lithuania; one study proposed that the financial autonomy statuses of the rural regions have spatial distributions: the insufficient economic development villages were usually in the south and the west (Skaurone et al. 2023), proving that spatial variations exist for different systems in

different countries. Compared with the above results, we contribute a new idea that the growth status of agricultural industrialization is distinctive; thus, differentiated and sustainable countermeasures should be proposed.

(2) Compare CCS with similar systems. We explore the coupling coordination statuses between agricultural industrialization and rural infrastructure. The overall CCS was relatively balanced, with the coastal regions relatively better and some inland regions relatively weaker. In contrast, one study explores the CCS between industrialization and agricultural green development in China, proposing that CCS varies apparently: the eastern, central, and western regions successively decrease CCS (Guo et al. 2021). We agree that the coastal regions are better in CCS because of the abundant flat land, developed economy, and efficient policies. However, we are different because we propose that the spatial distributions are much more balanced. As we use more “efficiency” and “per capita” data, we avoid absolute quantity bias, which may lead to the illusion that “there is strength in numbers.” Our results, obtained via “efficiency” and “per capita” indicators, demonstrate the achievement of the High-quality Development Mission in China, which emphasizes efficiency and sustainability. Now, let us compare the results from an international perspective. One paper discussed the coordination status between the rural mining industry and rural tourism in Spain, proposing that the mining industry and rural tourism affect each other positively and negatively. For instance, rural tourism enhances the local image, which is favorable to the rural mining industry; the mining industry provides valuable mining heritage, which is a helpful resource for rural tourism; however, the reopening of the mine may occupy local resources and make rural tourism the secondary economic role (Bahamonde-Rodríguez et al. 2024). The results are similar to ours: AI and RI have complicated interactions, so we should endeavor to achieve their coupling coordination to enjoy better SDG-9 outcomes.

(3) Compare CCS with different systems. We find that Henan in central China was relatively weak in CCS. In contrast, some studies obtain opposite results. For instance, one study explores CCS between economic development and university technological innovation in China, depicting that Henan is similar to surrounding regions (Yang and Cheng, 2023); one study explores CCS between new infrastructure construction and regional sustainability in China, depicting Henan’s average or even better coordination status (Yi et al. 2023). The results are different from ours because firstly, we measure different systems: agricultural industrialization and rural infrastructure are not the same as other systems such as university innovation and new infrastructure, making the difference reasonable; secondly, we use “per capita” indicators to evaluate: Henan has a considerable population; thus, its values are easy to be decreased. On the contrary, previous studies use absolute quantity indicators, increasing Henan’s CCS. We believe that “per capita” indicators are more proper for evaluating sustainability, focusing on an individual’s long-term well-being and actual benefits. Let us now compare this study with international studies. We propose that CCS has temporal and spatial differences, and better coupling coordination among systems helps achieve sustainable development goals. That has also been proved by studies focusing on other countries. For instance, one study explored the CCS of energy, water, and food in India, claiming that CCS was improving in the past ten years; however, as there still were temporal and spatial differences among different Indian states and union territories, it is promising that different stakeholders were collaborating to solve the disparities. Besides, CCS among systems helps achieve SDG (Mondal et al. 2023). The results are mostly consistent with our results, highlighting our claim that we

should endeavor to achieve benign coupling coordination between AI and RI to realize SDG-9.

Conclusions. To comprehensively discover the coupling coordination statuses between agricultural industrialization and rural infrastructure, we first construct the coupling coordination mechanism to discuss their mutual relations theoretically; secondly, we construct the evaluation system based on the mechanism to evaluate the development status and the coupling coordination statuses temporally and spatially with the case of China; thirdly we analyze the main influencing factors and propose specific, differentiated and applicable countermeasures to enhance the coupling coordination statuses. The results advance understanding and implementation of SDG-9 (such as SDG-9.1 promoting sustainable industrialization and SDG-9.4 upgrading industries and infrastructures for sustainability).

There are some new and innovative findings in this study.

From the D perspective, firstly, the development statuses of agricultural industrialization may fluctuate dramatically temporally because specific factors may suddenly change; AI-Ds in most regions have witnessed apparent fluctuations since 2018. Secondly, rural infrastructure may mildly develop temporally with upward trends and decreasing gaps, showcasing the benefit of the continuous and accumulative input to rural infrastructure. Thirdly, agricultural industrialization and rural infrastructure may not constantly develop concurrently due to different reasons in different regions. Fourthly, spatially, agricultural industrialization and rural infrastructure usually have different spatial distributions, while they are similar in that the coastal regions were relatively higher than others. The spatial variations are that AI-D is dotted, whereas RI-D is connected. The differences imply that achieving SDG-9 is relatively complicated and differentiated.

From the CCS perspective, firstly, temporally, CCS may witness dramatic fluctuations due to the relative regional differences; CCS gaps can gradually be diminished if we take appropriate countermeasures. Secondly, CCS is spatially correlated; specific regions in central China, southwestern China, and northeastern China were relatively low in CCS. Specifically, outperforming regions have similarities, while lagging regions have their own shortcomings. The results enhance our understanding of achieving SDG-9: the specific SDG-9 goals can achieve coordination; our countermeasures can facilitate the simultaneous achievement of various specific goals; besides, achieving SDG-9 is quite complex; regions with high and low CCS need to have differentiated paths or emphasis in achieving SDG-9.

From the perspective of influencing factors, firstly, for AI’s influencing factors on RI, “technologicalization” and “mechanization” are critical dimensions that affect RI, and the influential factors may change temporally. Secondly, for RI’s influencing factors on AI, rural life quality, social services, and rural ecological environment are critical to affect AI, and RI is increasingly affecting AI comprehensively. These results have enhanced our understanding of SDG-9: the specific goals of SDG-9 can interact and collaborate, ultimately promoting the overall achievement of SDG-9.

Contributions, novelties, and limitations. This study has the following contributions. Firstly, we contribute to the coupling coordination theory. We establish the coupling coordination mechanism between agricultural industrialization and rural infrastructure; it depicts how these two interact, enriching coupling coordination theory. Secondly, we contribute to the understanding of SDG. We propose that we can further understand and explore SDG from the coupling coordination perspective and can use the coupling coordination mechanism

between AI and RI to achieve SDG-9; by depicting the temporal and spatial dynamics of the coupling coordination statuses between AI and RI, we can understand how to achieve SDG-9. Thirdly, we contribute to sustainability practice. After analyzing the lagging systems and primary influencing factors, we propose differentiated and replicable countermeasures to realize SDG-9; the categorized solutions tell us “what to do specifically” and are helpful references to enhance AI and RI and further achieve SDG-9. In addition, this study has the following innovations. Firstly, from the theoretical innovation perspective, the theoretical coupling coordination mechanism between AI and RI is new, as we incorporate the “sustainability” dimension and emphasize the goal of SDG in the mechanism. Secondly, from the viewpoint innovation perspective, the expression of “sustainability” is new; we propose that sustainability should focus on individual well-being, namely “per capita” and “efficiency,” which can be reflected in indicator selection and calculation: indicators should be more about “per capita” than about “absolute amount.” Thirdly, from the practice innovation perspective, the differentiated countermeasures are new, emphasizing that different regions facing different scenarios should take differentiated actions to enhance coupling coordination statuses and achieve SDG-9. Besides, the countermeasures should be replicated in other regions facing similar conditions.

This study has the following limitations. The first is the data availability issue; we have to exclude some critical indicators because we cannot obtain data; for instance, we have to exclude the indicator of “rural entertainment facility coverage” as there is no data for this indicator, though it is representative in evaluating rural infrastructure. Besides, we have to ignore evaluation from the city, town, or village scales because data from those scales is difficult to obtain and compare. The second is the in-depth analysis issue; we have to exclude more in-depth analysis, such as CCS predictions and CCS configuration path analysis, due to word limit; they are valuable in deepening our understanding of how the two achieve coupling coordination statuses and take more specific countermeasures. The third is the time update issue; we have to exclude exploring CCS in recent years as the statistical yearbooks documenting data for 2022 and 2023 have yet to be published. The latest data will provide more details, correct research errors, and valuable references for more targeted and accurate countermeasures. Based on the above limitations, we aim to deepen our future research in the following aspects. Firstly, we will look for data alternatives; specifically, we will look for more statistical yearbooks to include more indicators. Besides, we may use similar indicators to replace the ones for which there is no data. Furthermore, we may look for other effective channels to get data with more detailed scales and observe the results from a micro perspective. Secondly, we will deepen our future research based on this study; precisely, we may predict CCS with various approaches to see whether our countermeasures are effective and practical; we may explore the differentiated paths to achieve CCS to propose more specific countermeasures. Thirdly, we will include the latest data; specifically, the data in 2022 and 2023 will be included in future research to obtain a more comprehensive understanding of CCS between agricultural industrialization and rural infrastructure.

Data availability

Statistics data cannot be shared publicly because the data are from national statistical yearbooks published by the National Statistical Bureau, which means authors do not have rights to publicly distribute data without permissions. Data are available from the official websites (contact via the National Statistical Bureau, info@stats.gov.cn), or from the published national statistical

yearbooks for researchers who meet the criteria for access to data. Besides, data about experts’ AHP evaluations are within the supplementary file.

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Author contributions

Conceptualization, YG; methodology, YG; software, QX; validation, QX; data processing, QX; data analysis, QX; data curation, QX; writing—original draft preparation, QX, NZ, XY; writing—review and editing, GY, YY, XJ; visualization, QX; supervision, YG; project administration, YG; funding acquisition, YG.

Competing interests

YG was a member of the Editorial Board of this journal at the time of acceptance for publication. The manuscript was assessed in line with the journal's standard editorial processes, including its policy on competing interests.

Ethical approval

The Ethics Committee of the School of Business, Shanghai Dianji University approved the expert interview on March 4th, 2025 (reference number 2025030401). The process follows the guidelines of the Declaration of Helsinki (2013). A new analysis (analytic hierarchy process) was done due to referee comments; thus, the ethical approval was obtained after the paper's initial submission. The committee was aware that this study needs human participants at a reviewer's request during manuscript revision, and the discussion was after this paper's initial submission and before the revision.

Informed consent

The informed consent statement was obtained on March 4th, 2025; the informed consent statement was obtained on the same day when the ethical approval was obtained, but the informed consent statement was obtained after the ethical approval was obtained.

Authors read out the informed consent statement to the participants orally; participants were informed that the interview form was anonymous and data would be used solely for research purposes and stored confidentially on a computer. The participants gave oral consent before participating.

Additional information

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