

Achieving synergistic benefits through integrated governance of cultivated cadmium contamination via multistakeholder collaboration

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Rice serves as a vital staple food, but its accumulation of cadmium (Cd) has sparked widespread concerns regarding food safety and ecosystem security. Here, we conducted a seven-year systematic field experiment in the Xiangjiang River Basin of China, where an integrated governance framework (IGF) was established to ensure rice safety. The IGF, tailored to geographical zoning and pollution gradation, includes targeted soil treatments, crop management strategies, and stakeholder engagement. The quality of both the soil and the crop was improved, with a reduction in soil Cd availability of 36%, and a decrease in Cd in rice grain of 57–78%. This framework not only addresses multiple challenges but also supports sustainable development goals (SDGs 2, 3, 6, 9) by fostering comprehensive synergies among science, policy, and local community participation. Our findings provide empirical guidance for safe rice production in Cd-contaminated areas and provide solid scientific-driven decision support globally.

Rice serves as the primary staple food globally, sustaining more than half of the world's population and accounting for 11% of global cropland^{1–3}. However, with the growth of the world population, the global food security situation is still grim, as it suffers from the superimposed impact of extreme climate change⁴, resource degradation^{5,6}, yield stagnation⁷, water stress^{8,9}, and limited room for cropland expansion¹⁰. The intake of Cadmium (Cd) from rice causes Itai-itai disease, which was first reported in the Jinzu River Basin of Toyama Prefecture, Japan¹¹. Cd has high mobility in the soil–plant system, is easily absorbed by crops and accumulates in their edible parts^{12,13}, posing significant health risks through the food chain^{14,15}. High Cd levels represent a global issue extensively distributed across Japan, Bangladesh, Thailand, Pakistan, Iran, Malaysia and China^{16,17}, with millions of hectares of cultivated soil becoming sterile and

ceasing agricultural production. In 2023, the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations jointly released the “Safety Assessment Report on Specific Pollutants in Food”, highlighting rice (contributing 38–56%) as a primary source of Cd exposure in diets^{18,19}. Therefore, the successful remediation of Cd-contaminated arable land and the cultivation of low-Cd rice are of paramount importance. They are directly linked to global food security and align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 1 (no poverty), SDG 2 (zero hunger), and SDG 3 (good health and well-being)^{20–22}.

Previous studies have focused on the mechanism of Cd pollution in paddy soil and migration pathways within soil–rice–human^{12,13,23,24}. Advances have been made in the development of low-Cd accumulating varieties²⁵, Cd-hyperaccumulating plants^{12,26}, gene regulation¹⁵, and

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agronomic²⁷ and process optimization techniques²⁸. Nevertheless, laboratory technical studies cannot satisfy all the requirements for the advancement, availability, adaptability, and stability of safe rice production technology. The promotion and application of technology are restricted due to doubts regarding defects in certain aspects of the technologies²⁹. In other words, the innovation of technology and policy must undergo practical tests, scientific evaluation, and technical optimization in the implementation process.

To address the Cd pollution in paddies, the most urgent task is to establish an efficient management strategy and maintain its effectiveness and stability. The governance of farmland pollution is a complicated system involving multiple stakeholders, multilevel policy objectives, and various technologies^{30,31}. In the past few decades, widespread conflict has developed among various stakeholders (government, farmers, enterprises, and third-party evaluators) in terms of science, society, and politics (see Supplementary Note 1 and Supplementary Fig. 1). An integrated governance framework (IGF) should be constructed to address multiple challenges and bottlenecks, such as a trade-off among multiple stakeholders; multidimensional goal achievement (soil health, food security, and ecological security); and the applicability and stability of technical patterns.

China has achieved remarkable success by using only 7% of the world's cultivated land (1.83 billion hectares) to feed 18% of the world's population (7.89 billion); rice plays a pivotal role in the success^{32,33}. In recent decades, the problem of heavy metal pollution in farmlands has gradually received increasing attention. A recent study indicated that approximately 10 million hectares of farmland in China are affected by contamination³⁴. The Chinese government has implemented a series of measures to mitigate heavy metal pollution in cultivated soil (see Supplementary Fig. 2). To address this issue, an ambitious project was proposed by the Chinese central government with unprecedented determination, aiming at solving the practical problems of Cd pollution in paddy soil (see Supplementary Note 2 for the background of proposing this ambitious project). The project lasted seven years from 2014 to 2020, with a total investment of approximately 7.33 billion yuan, covering a cultivated land area of 180,000 hectares and benefiting over 3 million farmers in 26 county-level administrative regions. From 2021 to 2023, additional funding was received from the Asian Investment and Development Bank to promote the application of technological achievement (see Supplementary Fig. 3). Given the success of the project which is acknowledged as the largest heavy metal pollution control project for cultivated land worldwide, we think it is time to systematically assess the effectiveness of the implemented strategies and technological patterns.

Here, we report the outcomes of concerted efforts in engaging multiple stakeholders (the government, enterprises, farmers, and researchers) over seven years of field work. The IGF for the control of Cd-contaminated paddy governance is established on the basis of a chain of “science-management-evidence-feedback”. We have tested the applicability and effectiveness of IGF implementation across South-Central China over seven years. The key characteristics of pattern success are identified to coordinate actions and optimize strategies for governance. Finally, we demonstrate that IGF can simultaneously address multidimensional sustainability challenges and yield cobenefits (soil health, food security, and ecological security). Our findings provide empirical evidence for safe rice production in Cd-contaminated soils, contributing to solid scientific-driven decision support for other regions facing similar issues.

Results

Establishment of the integrated governance framework

We established an IGF for heavy metal pollution in farmland that integrates with a normalized workflow (Fig. 1), following the principles of local adaptation, government leadership, farmer engagement, and profitability. The primary management priorities could be delineated

through a consensus-driven approach that aligns the interests of diverse stakeholders, including governmental entities, farmers, and enterprises. This consensus facilitates the implementation of coordinated and cohesive actions. From the perspective of the governing mechanism, a tripartite organizational system comprising the government, implementors (farmers and remediation enterprises), and supervisory evaluators was constructed, with the aim of enhancing the scientific basis and transparency of government decision-making. By engaging large-scale farmers, we achieved a paradigm shift from individual to collective co-governance. From a policy perspective, a closed-loop decision-making chain encompassing supervision, implementation, evaluation, feedback, and optimization was established, fostering seamless integration of science, policy, and societal engagement. On the one hand, decision support is underpinned by scientific-based evidence; on the other hand, technology and policy optimization are refined through feedback evaluation.

The primary duties of the main stakeholders are enumerated below. The government takes a dominant role, as it is responsible for providing major financial support, setting implementation goals and priorities, providing supervision and administration, mobilizing and coordinating all parties to collaborative participation, and implementing with a bottom-up initiatives. The implementors, predominantly farmers and remediation enterprises, are tasked with the rigorous enforcement of sustainable governance practices, the reporting of field challenges, and proactive adaptation to policy or program modifications. Research institutions provide scientific and comprehensive guidance to policymakers and implementors in executing action plans. Furthermore, these institutions should refine governance strategies in response to field feedback to attain collaborative objectives. The role of the evaluator involves objective assessments of the scientific rigor and effectiveness of the plan, oversight of the implementors' process, and monitoring of governance outcomes. Evaluators provide scientific evidence through prompt, precise evaluations and feedback, which informs the refinement of technical approaches and management protocols.

To achieve effective governance and maintain profitability, we further detail the technical importance of determining the cultivation of low-Cd-accumulating rice varieties, augmented by targeted agronomic practices (Fig. 2). Here, the strategy is to formulate a context that acknowledges regional geographic distinctions and varying levels of soil contamination. This process can harmonize rice production with the concurrent remediation of polluted soils, thereby enhancing both crop yields and environmental recovery (see Supplementary Note 3 for the implementation of comprehensive utilization and management patterns).

Evaluation of governance effectiveness

Our seven-year field experiment demonstrated that the IGF significantly enhanced soil and crop quality, offering a viable solution for safe rice production in Cd-contaminated farmland (Fig. 3). The spatiotemporal distribution pattern of Cd in rice revealed a diminishing pattern in which the number of rice cultivation spots exceeded the safety threshold over the years (Fig. 3a). Despite a stable total Cd level in the soil (the average value is 0.423 mg kg⁻¹), there was a marked 36% decline in the available Cd content (Fig. 3b). Most encouragingly, a yearly steady decline in Cd within rice grains was evident, with early rice showing a 57% decrease and late rice showing a 78% decrease. From 2018 to 2020, the Cd levels in all rice crops cultivated within the study areas consistently fell below the maximum permissible limits set by both the European Union (EU) and China for Cd in foodstuffs intended for human consumption. The limites are <0.2 mg Cd kg⁻¹ for both regulatory bodies. Furthermore, these concentrations were significantly lower than the safety threshold established by the FAO of <0.4 mg Cd kg⁻¹. The effectiveness of governance in the different management zones is shown in

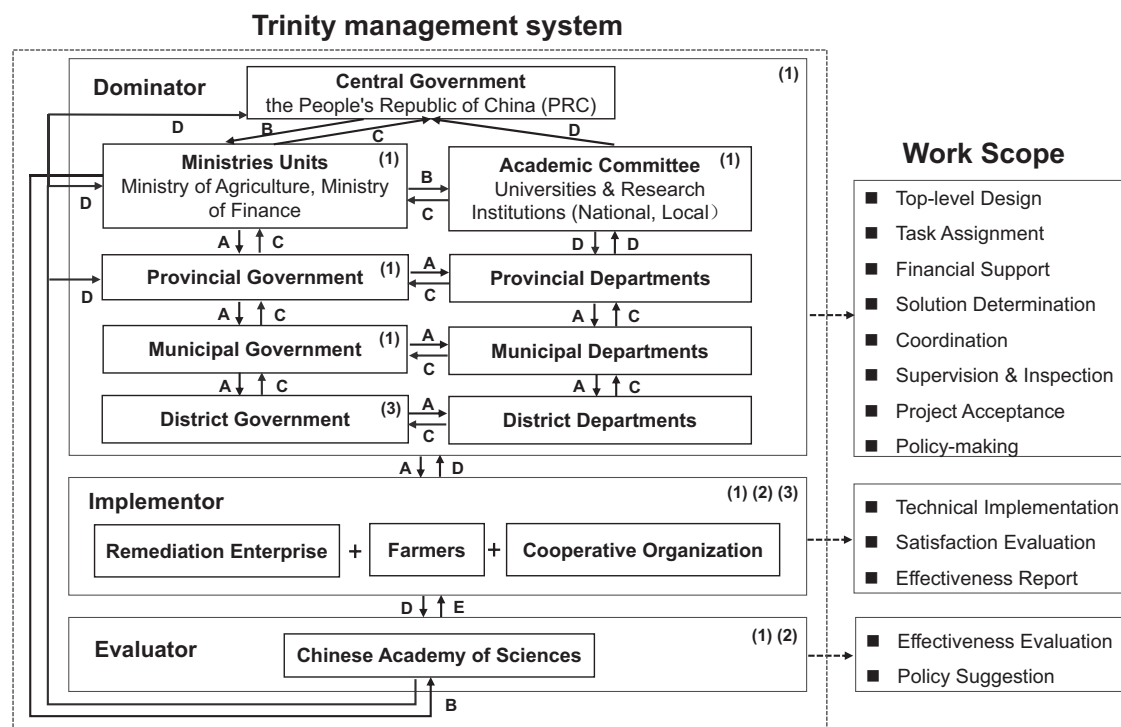


Fig. 1 | Workflow and responsibilities of the IGF for the governance of Cd-contaminated paddy. (1) Technical Support from Academic Committee; (2) Propaganda & Report by Social Media; (3) Additional Financial Support from World Bank. **A** Govern & Supervision; **B** Delegate; **C** Report; **D** Feedback; **E** Effectiveness Evaluation. Here, the advantages of the IGF are summarized. Explicit objectives: Clearly defined objectives that orient the decision-making process, ensuring the alignment of all actions with desired outcomes. Accountability: Defining responsibilities and instituting evaluations of performance and enforcement mechanisms. Collaboration: Facilitating partnerships and cooperation across governing farmers, entities, sectors, and governmental levels to harness collective capabilities.

Inclusivity: Engaging a broad spectrum of stakeholders in the governance process to encompass diverse perspectives and needs. Transparency: Ensuring open and accessible decision-making to cultivate trust and accountability among stakeholders. Adaptability: The capacity to modify strategies and approaches in response to evolving needs, new data, or unexpected challenges. Efficiency: Optimizing resource utilization to achieve outcomes, reduce waste and maximize output. Innovation: Promotion of the generation and application of novel ideas, technologies, and practices to enhance governance outcomes. By focusing on these attributes, governing entities can enhance their effectiveness, ensure the success of their initiatives, and better serve the public interest.

Supplementary Fig. 4. Moreover, we tracked the soil pH progression over the management phase (see Supplementary Fig. 5), indicating a consistent increase from 5.32 in 2014 to 6.12 in 2020, under a broad range of agronomic interventions.

Mechanism analysis for optimizing governance

Here, we identified the key mechanisms for successful implementation, aiming to support the optimization of action strategies (Fig. 4). A total of 16 variables that affect Cd accumulation in rice were quantified, including soil conditions, governance practices, and climate conditions (Fig. 4a, b). In the random forest regression model, the 16 variables accounted for approximately two-thirds (65%) of the spatial variation in the Cd content within rice, with a root mean square error (RMSE) of 0.05 mg kg^{-1} . Among these factors, soil pH, (total and available) Cd levels in soils, average temperature during the rice season, average light duration during rice season and soil organic matter (SOM) were identified as the primary influencing factors. Surprisingly, we discovered that SOM also played a significant role, contributing approximately 12% to the Cd content in late rice, which is approximately four-fifths of the impact of soil pH on average.

We elucidated the complex interactions between Cd levels in rice and the critical determinants by analysing partial dependence plots. This analysis has the potential to pinpoint the thresholds or inflection points for key parameters, thereby providing essential insights for the formulation of targeted regulatory strategies (Fig. 4c, d). We observed a significant negative correlation between the Cd content (inclusive of both total and bioavailable fractions) in rice grains and the soil pH. This pH-related response was consistent across both early and late-

maturing rice varieties. As the soil pH ranged from 5 to 7, the Cd content in both early and late rice grains tended to decrease. However, beyond a soil pH of 7, continuous increases had a minimal impact on further reducing Cd levels. In contrast, the concentration of Cd in rice grains was closely associated with the total and available soil Cd, indicating a significant positive correlation. Generally, the Cd content in rice grains increased alongside rising total or available Cd content in the soil, and it stabilized near the threshold level (indicated by the vertical dashed line). Thus, we validated the existence of an optimal Cd concentration in soil. Beyond this threshold, an increase in the amount of Cd in soil does not substantially increase the Cd content in rice grains. The results suggest that heightened focus on the critical factors and their respective thresholds is imperative to facilitate decision-making optimization for subsequent regulatory interventions. Notably, both temperature and precipitation exhibit significant threshold effects, which can lead to changes in soil conditions. These climate-driven shifts, coupled with persistent soil acidification, synergistically enhance the cadmium bioavailability in rice. Consequently, when strategies to prevent and control Cd contamination in rice are formulated, it is imperative to comprehensively consider the threshold effects of these factors and their complex interactions.

Evaluation of synergistic benefits

Finally, we evaluated the economic benefits (Fig. 4a), which are crucial for measuring the effectiveness of governance and its sustainability over time³⁵. The analysis demonstrated that the IGF we adopted generated a cumulative economic surplus totalling 1.23 billion yuan, which equates to an average annual increase in societal benefits of 176 million

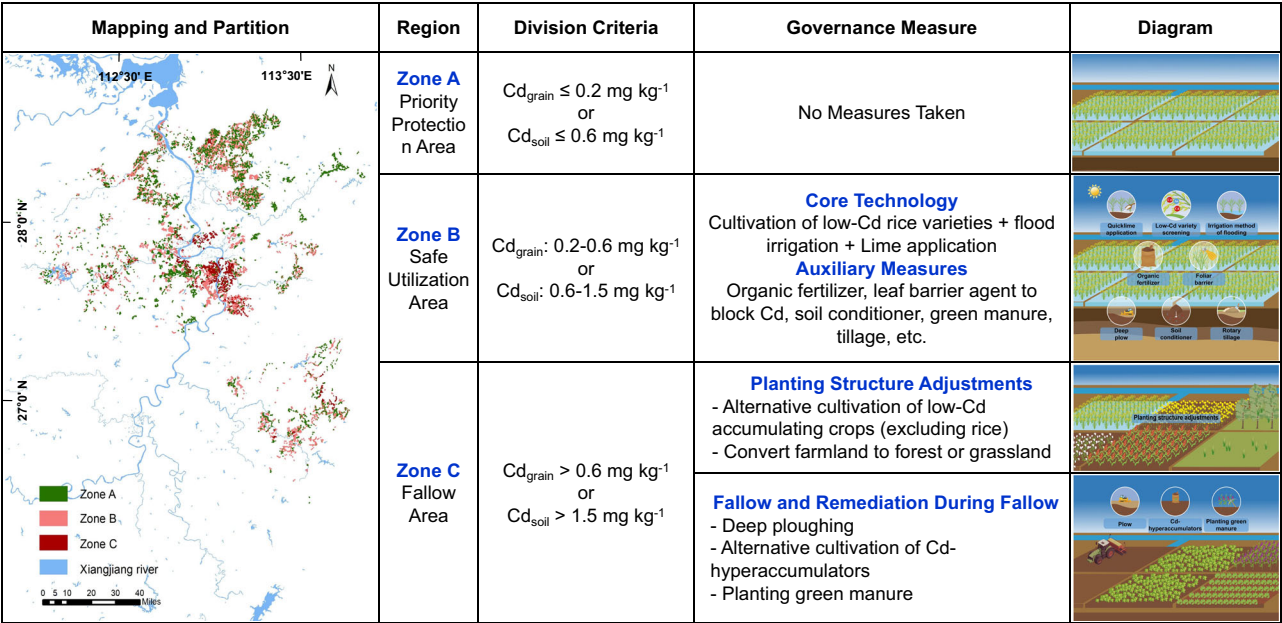


Fig. 2 | Comprehensive utilization and management patterns based on geographical partitioning and pollution classification. Planting structure adjustments: Alternative cultivation of low-Cd-accumulating crops (excluding rice): Non-food economic crops including oilseeds, cotton, ornamental seedlings and facility-grown crops. Fallow and remediation during fallow: (1) Deep ploughing: Ideally scheduled during the autumn or winter to allow the soil to regenerate adequately before the next planting cycle or a period of fallow. The frequency of deep ploughing is not annual but is instead determined by the soil's health and the specific needs of the crops, often occurring every few years. (2) Alternative cultivation of Cd-hyperaccumulators: *Sorghum biomass*. Demonstration of plant removal technology testing: These plants are harvested upon maturation, and the

sections containing pollutants are disposed of properly. The duration required to significantly decrease soil contamination can range from months to years, a time-frame that is influenced by the initial contamination levels and the plant species' capacity for pollutant accumulation. (3) Planting green manure: Green manure is flexible, occurring yearly or seasonally, and is tailored to the nutritional profile of the soil and the crop rotation scheme. Upon maturation, green manure is incorporated into the soil, followed by cultivation as necessary to enhance decomposition. These strategies are effective in mitigating soil degradation, reducing the incidence of pests and diseases, and managing Cd stress. Concurrently, they could improve soil health, food security, and ecological security, thereby reinforcing sustainable agricultural systems.

yuan. Notably, as the model implementation progressed, the share of grain in overall economic benefits increased steadily, whereas the feed proportion decreased dramatically. The shift is attributable to enhanced rice quality and signifies the revitalization of the land's capacity for food production.

Farmers are the primary stakeholders in agricultural activities, and their satisfaction is a crucial determinant of cooperation, the adoption of technical innovations, and the successful implementation of agricultural policies³⁶. On this basis, we gauged farmer satisfaction with the utilization of various types of polluted arable land and the efficacy of diverse remediation strategies. (Supplementary Tables 1–3). The survey reveals that farmers exhibit a positive, optimistic, and supportive stance towards integrated governance measures, giving governance measures a satisfaction rate of 99.33% (Fig. 5b). Certain farmers expressed a preference for enhanced subsidies and more favour policy incentives, which led to a relatively low satisfaction (95.79%) with the plant structural adjustment.

We discovered that the IGF substantially contributed to the realization of sustainable goals (Fig. 5c). This approach is applicable to the sustainable development goals of this study, which include SDGs 1, 2, 3, 6, 9, and 15. These goals cover social (SDG 2, SDG 3), economic (SDG 1, SDG 9), and environmental (SDG 6, SDG 15) aspects. Over the seven-year duration of the project implementation, food security indices in the study area rose substantially in Hunan Province and at the national level, with the study area showing particularly notable improvements. In 2021, SDGs 2, 3, 6, and 9 registered marked improvements in scores compared with those in 2014, indicating a significant positive correlation among SDG 2, 3, 6 and 9 ($p < 0.05$) (see Supplementary Fig. 6). While SDG 1 and SDG 15 experienced less growth than did the other four sustainable development goals during this period, SDG 2 increased at the national and provincial levels.

Discussion

Efficient governance of Cd pollution in cultivated land is crucial for ensuring safe rice production and achieving the SDGs^{22,32,37}, however, requiring empirical validation of its effectiveness, adaptability, and stability via experimental trials and onsite monitoring^{35,38,39} is needed. In this study, we carried out a seven-year practice and developed an IGF for managing Cd stress in cultivated land, which addresses for the concerns of a diversity of stakeholders^{40–42}, thereby facilitating the coalescence of benefits spanning soil health, food security, and ecological security. We then identified some key characteristics of successful implementation, established thresholds and inflection points, and defined 'Safe Minimum Standards' to offer an early warning indicator for subsequent governance and regulation⁴³. The integrated mechanisms and framework were pivotal to the successful execution of our project, as they significantly promoted the seamless integration of science, policy, and social participation. Therefore, the IGF is up to date, as it is underpinned by scientifically driven decision support throughout its implementation process.

The governance practices are striking, particularly when we consider the strengthened means of implementation via collaboration and coordination. China has achieved multiple successes in handling complex issues through integrated policy and governance strategies, which are exemplified by advancements in land system sustainability³⁸, elimination of extreme poverty⁴⁴, and sustainable smallholder farming²⁹. These approaches have produced some valid models for achieving regional sustainable development. Therefore, we place greater emphasis on bottom-up initiatives and collaborative involvement throughout the programme. Some studies have indicated that an ambitious and well-designed management policy with well-defined objectives, stringent enforcement, and inclusive collaboration substantially increases the probability of successful

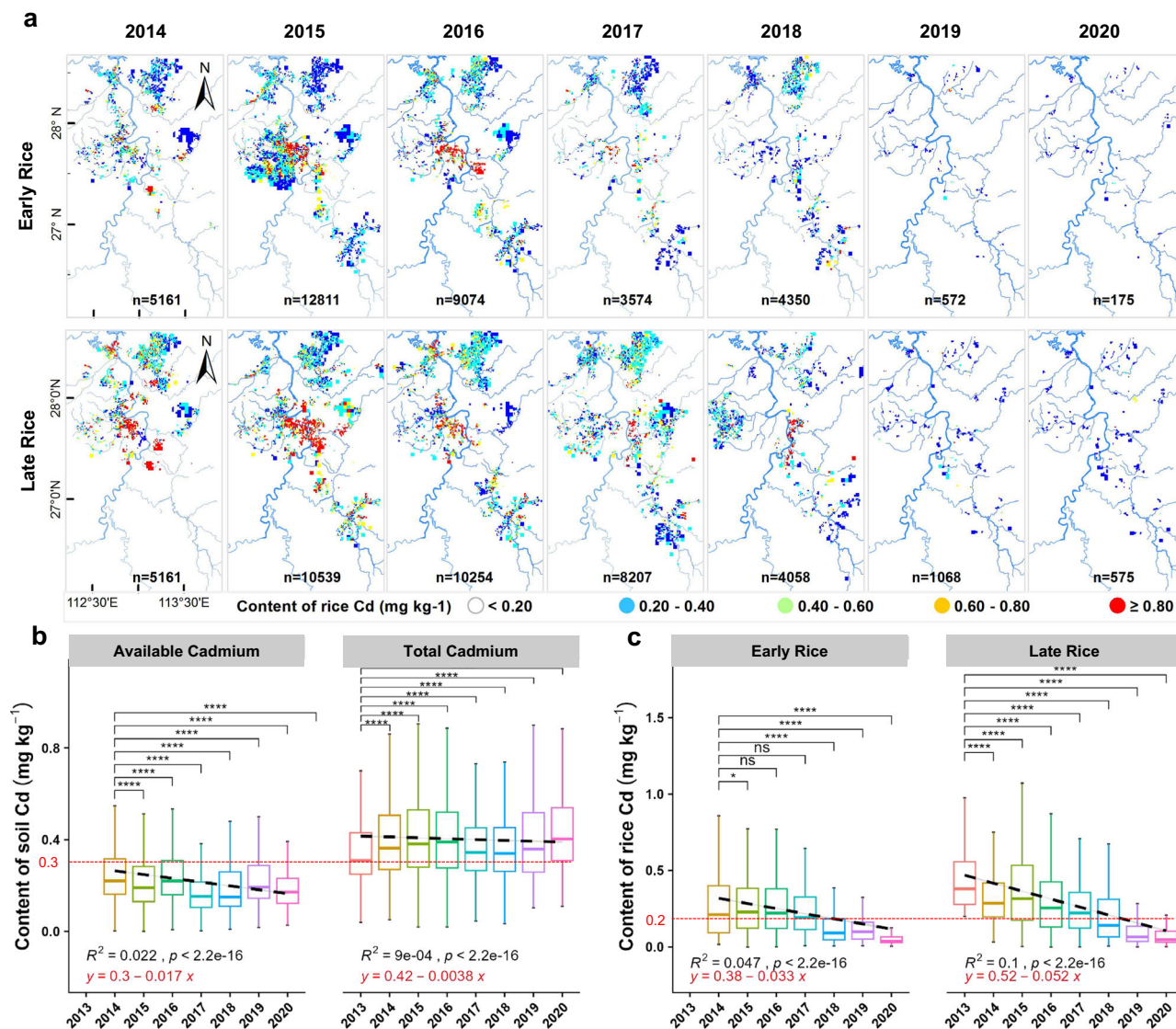


Fig. 3 | Comprehensive utilization and management mode. **a** The spatial distribution of cadmium in grain from 2014 to 2020; **b** the variation in soil available cadmium and total cadmium from 2013 to 2020; **c** the variation in cadmium in early rice and late rice from 2013 to 2020. In **a**, the cadmium content in rice grains is classified into five levels. In **b** and **c**, the bar within the box plots shows the 25th and 75th percentiles, the whiskers beyond the bar represent the 95th and 5th percentiles, and the inner line indicates the median. The black dashed lines in **b** and **c** reveal the trend of cadmium content in the soil and rice grains. A Wilcoxon rank-sum test was used to compare the Cd in the soil or rice grains across different years.

The *p*-values for multiple comparisons were adjusted via the Bonferroni method. In **b** and **c**, * indicates a *p*-value less than 0.05; ** indicates a *p*-value less than 0.01; *** indicates a *p*-value less than 0.001; **** indicates a *p*-value less than 0.0001. The red dashed line in **b** represents the maximum permissible limit for Cd in soil, as established by China, which is set at 0.3 mg kg⁻¹. The red dashed line in **c** represents the maximum permissible limits set by both the European Union (EU) and China for Cd in foodstuffs intended for human consumption, which are 0.2 mg kg⁻¹ for both regulatory bodies. Cd reduction (%) = [(Initial Cd concentration in 2013 – Final Cd concentration in 2020)/Initial Cd concentration in 2013] × 100%.

action plans^{5,41,45}. Furthermore, China's sustainability initiative incorporated the collaborative engagement of a diverse array of stakeholders, ensuring a balanced reconciliation of interests among all parties. This approach facilitated the development of a robust operational guarantee mechanism, an adept feedback and response system, and a stringent scientific evaluation framework^{46,47}. On the basis of these findings, we constructed an integrated governance and evaluation strategy for managing Cd stress in low-Cd-accumulating rice cultivars, accompanied by various agronomic measures. All the technologies were implemented through cooperation with the government, scientific researchers, enterprises, and farmers. A responsive and inclusive interface among science, society and policy was constructed via the engagement of various stakeholders, accompanied by urgent political action and technological innovation.

Previous studies of pollution prevention have focused on the effectiveness and neglected the potential of technology optimization and management improvement⁴⁸. Thompson et al. noted that strengthening empirical research on timely, accurate, and scientific evaluations for action plans had profound meaning for policy innovation and technical innovation⁴⁹. Here, we highlighted a close coupling relationship between scientific observation and governance services, advocating for a balanced approach that addresses the interests and specific needs of diverse stakeholders. We proposed the framework and identified priorities for environmental management by mobilizing and organizing stakeholders to implement sustainable development interventions across large-scale farmland, thereby achieving comprehensive benefits. This framework exemplifies scientific and systematic governance and advances successful implementation through policy and scientific support.

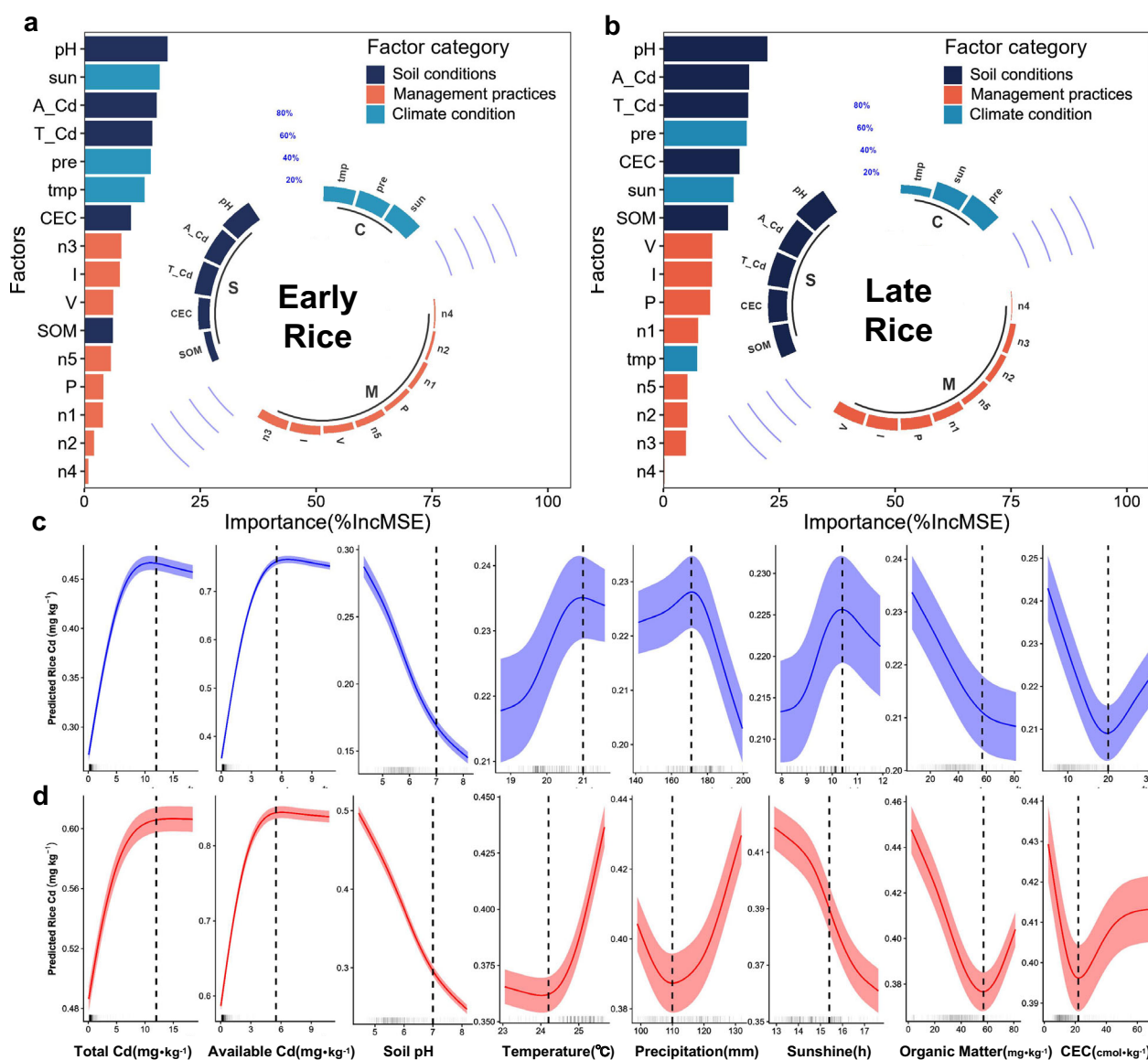


Fig. 4 | Drivers and their responses to Cd in rice. In panels **a** and **b**, bar charts illustrate the hierarchical significance of influential factors as determined by the random forest regression model, and pie charts further classify these factors into distinct categories. The soil environment factors include SOM, cation exchange capacity (CEC), total soil cadmium (T_Cd), and available soil cadmium (A_Cd); field management factors include rice variety (V), irrigation (I), pH conditioner (P), and a series of numerals representing specific agronomic practices such as foliar inhibitors (n1), soil conditioners (n2), green manures (n3), ploughing (n4), and organic fertilizers (n5); and climate conditions include sunshine (sun), temperature (tmp),

and precipitation (pre). Panels **c** and **d** feature partial dependence plots that elucidate the relationship between each factor and the cadmium content in rice. The regSmooth function is applied to smooth these curves, providing a more precise representation of the linkage between the influential factors and rice cadmium levels. In panels **c** and **d**, the solid lines signify the mean partial dependence of the dominant factors on the rice cadmium content, with dashed lines indicating the inflection points for each factor. The shaded ribbons encompass 95% confidence intervals, thereby quantifying the uncertainty in the predictions and reinforcing the reliability of the findings.

Although China has taken urgent action and initiated pilot projects to combat heavy metal contamination in cultivated land in Hunan, the impacts and contributions to the regional environment remain to be fully realized. Hence, we focused on a multidimensional evaluation, including a socioeconomic investigation, a governance effectiveness evaluation, and a public awareness assessment. This holistic approach is instrumental in addressing Cd pollution in regional cultivated land and promoting the harmonious development of the economy, society, and environment³⁸. We conducted a comprehensive evaluation of progress, effectiveness, and contributions to both local and national SDGs. Public concerns about acceptability were solved via policy guidance, scientific-driven decision support, and outcome contributions. Farmers are essential to the development and

protection of cultivated land, and their pivotal role must be maintained. They typically prefer land use that obtains the highest economic benefit, which highlights the profound impact of individual economic benefits on their preferences for cropland use and governance strategies³⁵. Our research signifies a major transformation from individual to collective management. The enhanced outcomes are attributed mainly to the IGF and thus promote the inclusivity and sustainability of strategies to combat Cd pollution in cultivated land. This approach allows farmers to access multidimensional benefits from crop quality, monetary subsidies, environmental benefits, and other aspects. However, integrated management requires additional inputs and expertise, making it challenging for farmers to adopt⁴⁸. Here, remediation enterprises played an indispensable role in

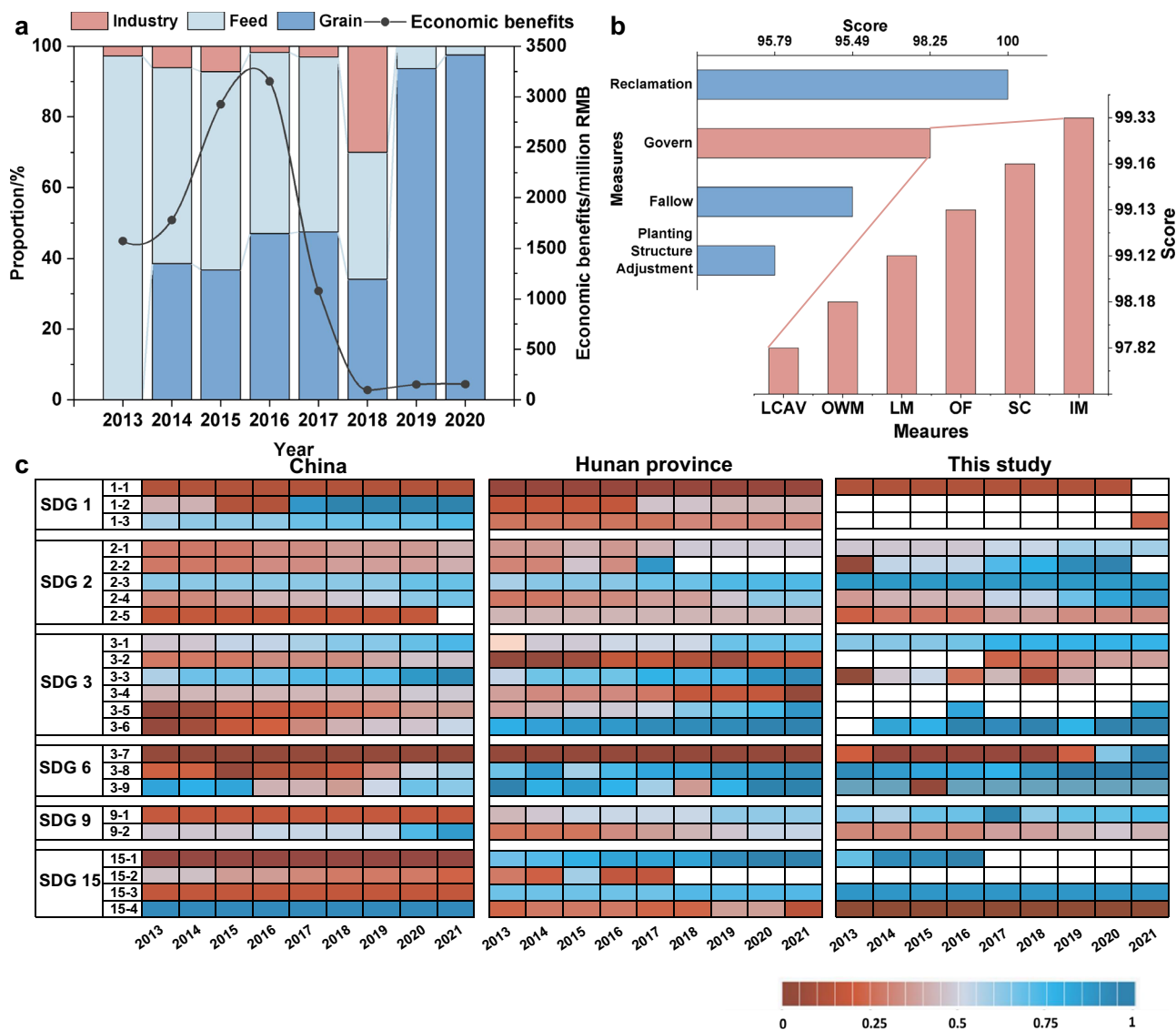


Fig. 5 | Economic benefits and contributions to the SDGs. In **a**, grain usage proportions and economic benefits are accounted for from 2013 to 2020. The stacked bars represent the proportion of grain used for industry, feed, and direct consumption. The line graph represents the total economic benefits from these three grain disposal methods per million yuan. In **b**, scores of different measures for cadmium pollution control in rice. LCAV low-Cd accumulation varieties, OWM optimized water management, LM lime, OF organic fertilizer, SC soil conditioner, and IM integrated measures. The blue bars represent the effectiveness score, whereas the red line represents the cost score for each governance measure. In **c**, contributions to the SDGs in China and Hunan Province are analysed. The heatmap shows the contribution levels to various SDG targets, with darker blue

indicating greater contributions and darker red indicating lower contributions. SDG indicators: 1-1: Unemployment insurance coverage; 1-2: medical insurance coverage; 1-3: endowment insurance coverage; 2-1: grain yield per unit area; 2-2: food security rate; 2-3: reduced child malnutrition; 2-4: agro-forestry output per capita; 2-5: cultivated land area per capita; 3-1: health worker density; 3-2: tuberculosis incidence; 3-3: malaria incidence; 3-4: viral hepatitis incidence; 3-5: maternal mortality ratio; 3-6: Neonatal mortality rate; 6-1: domestic water usage per capita; 6-2: surface water quality; 6-3: drinking water quality; 9-1: mechanized farming area ratio; 9-2: ratio of R&D expenditure to GDP; 15-1: soil erosion control index; 15-2: ratio of environmental investment to GDP; 15-3: forest coverage rate; and 15-4: habitat protection.

facilitating the adoption and application of the technical model. Furthermore, we evaluated these interactions via a blend of scientific evidence and expert judgement. Our study is of great interest because it accounts for regional sustainable development quantitatively. We confirmed that ambitious targets of SDG 2 (Zero Hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), and SDG 9 (industry, innovation and infrastructure) were advanced, thereby expediting progress towards sustainable development goals.

In summary, we demonstrated that it is feasible for the ambitious commitment to achieve the SDG agenda through integrated governance. We welcome stakeholders to validate the defined thresholds and inflection points in practice to promote parameter

optimization, for the sake of precise pollution control and sustainable agriculture. Additionally, scientists and stakeholders are encouraged to explore the applicability of the integrated governance strategy across various climatic zones and soil types, to further refine it on the basis of new insights and expertise. Given the background of global climate change, we emphasize the need to investigate the impact of extreme weather and climate events, such as heavy rain, drought, and floods, on rice production safety and productivity stability. Interdisciplinary discussions should be fostered to better evaluate and predict the threats to human health and regional conductivity effects associated with the safe utilization of Cd-contaminated cultivated land.

Methods

Description of the data strategy

The survey datasets we collected consisted of two categories: large-scale soil-rice paired sampling survey data from multiple locations over eight years from 2013 to 2020 (including data on soil physico-chemical properties and heavy metal content) and records of comprehensive remediation measures; and satisfaction survey questionnaire data from the implementing bodies, i.e., the farmers. Our study covers the period from 2013 to 2020, with 2013 serving as the pre-implementation baseline. Annual data collection was conducted for all variables.

Our sampling protocol for soil and rice was as follows: soil samples were collected from the top 0–20 cm layer via a stainless steel auger. Rice samples were collected at the maturity stage. Sampling was conducted twice a year, coinciding with the early and late rice seasons. The spatial distribution of the sampling points was designed to cover the entire study area, with a grid-based approach ensuring representative coverage. The study encompasses 26 county-level administrative regions involving over 3 million farmers. Field experiments were conducted on a total area of 113,333 hectares, with soil sampling performed at a density of one sample point per hectare.

During the 7-year implementation period (2014–2020), we regularly conducted coordinated monitoring and evaluation of soil and rice. Furthermore, through technical guidance and training for farmers, farmers' professional cooperatives, and other agricultural production and management entities, we collected a total of 1,617,366 coordinated monitoring sampling points in the first phase (Stage 1, 2014–2017) and 147,294 points in the second phase (Stage 2, 2018–2020).

Our field experimental design included plot sizes of 100 m², with each treatment replicated three times in a randomized complete block design. The treatments included various remediation measures, such as lime application, organic amendments, and water management strategies. Additionally, we collected data from both the control and treatment groups in 2015 to calculate the drivers of rice Cd uptake.

To ensure the quality of the soil-rice coordinated monitoring data after the implementation of comprehensive remediation measures, the demonstration and promotion work of the measures were designed and managed by local agricultural experts and extension personnel and implemented in the field of demonstration points according to a series of remediation operation standards and specifications. All field implementations were carried out during the early and late rice planting seasons of the year. Local agricultural experts and extension personnel provided direct and consistent onsite guidance and suggestions during critical periods of agronomic measures to address weed and pest control, variety selection, tillage, sowing date and density, irrigation (in the irrigation system, all rice experiments used flood irrigation) and harvesting. This advice minimized the impact of field management differences other than comprehensive remediation measures on variations in rice Cd content.

The environmental parameters were measured at each sampling point. The soil pH was determined via a 1:2.5 soil:water suspension. The organic matter content was measured via the Walkley–Black method. The soil Cd content was analysed via atomic absorption spectrophotometry after acid digestion.

The design of the regional demonstration point remediation measure implementation plan maximized the reduction in rice Cd, avoiding changes in rice Cd content caused by noncomprehensive remediation control measures. On the basis of the coordinated monitoring points for soil and rice, in 2015, we obtained 451 early rice measuring points and 535 nonmeasuring points via random sampling, 532 late rice measuring points, and 532 nonmeasure points. The spatial distributions of the field trials for the IGF and control groups in 2015 can be found in Supplementary Fig. 7.

To understand the work situation of government department staff, township (town) staff, and agricultural technicians in the project area

and to assess the satisfaction of farmers and the public in the project area, we formulated an interview plan and survey questionnaire form for personnel. The indicators of the survey questionnaire involve the organization of work, effects of implementation, and the use of funds. Included were the adjustment of planting structure, remedial fallow, the implementation of remediation technology measures, crop growth, industrial chain construction, maintenance of field infrastructure, implementation effects, implementation specifications, impact on the environment, and violations.

Our data collection method for questionnaire indicators involved face-to-face interviews conducted by trained surveyors. In the last three years of project implementation from 2018 to 2020, we collected a total of 1066 questionnaires on planting structure adjustment, 321 on remedial fallow, 334 on remediation measures, and 25 on recultivation. A total of 128 counties, cities, districts, 378 villages, and 1746 questionnaires were covered. The specific design of the questionnaire is shown in Supplementary Tables 1–3.

We also collected different types of geospatial raster datasets and statistical yearbook data of SDG indicators, including the interpolation results of rainfall, temperature, and sunlight duration and DEM elevation data (all from the National Earth System Science Data Center: <http://loess.geodata.cn/index.html>). On the basis of the random sampling of rice field measurements and nonmeasure points, spatial connections were used to add variables from different geospatial raster datasets to the points. Our study adheres strictly to the ethical standards of scientific research and has received approval from the Ethics Committee of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences.

Background and process of IGF construction

In response to the challenges of sustainable agricultural development and environmental protection, the IGF was conceptualized as a comprehensive approach to manage and remediate farmland pollution. This framework, developed through a collaborative effort between the government and scientific researchers, has undergone a systematic evolution since its inception in 2013. The IGF is grounded in scientific principles and tailored to the specific geographical and pollution characteristics of agricultural regions, ensuring its effectiveness and scalability. The following paragraphs outline the stepwise development and implementation of the IGF, highlighting its scientific foundation and adaptive approach to integrated governance.

In 2013, the government and scientific researchers jointly established the first version of the work guidance framework, designating 120,000 hectares (approximately 1.8 million mu) of farmland as pilot sites. The 'mu' is a traditional Chinese unit of area, approximately equal to 1/15 of a hectare or about 666.67 square metres.

In 2014, following expert review, the primary organizational management and implementation model was formulated. Specifically, the government took the lead, with scientific researchers providing technical support, and the implementation was conducted by local agricultural departments and individual farmers. The effect testing was led by the government with farmer involvement, and the pilot area was expanded to 180,000 hectares (approximately 2.7 million mu).

Between 2015 and 2017, we observed that measures were not fully implemented when relying solely on farm households for implementation. Consequently, the government introduced third-party remediation and management enterprises as joint implementation entities while establishing demonstration areas of tens to hundreds of hectares.

Between 2018 and 2020, the IGF was established in accordance with geographical zoning and pollution gradation, yielding significant economic benefits through the cultivation of alternative crop varieties.

Factor importance assessment and optimal pathway calculation

To explore the relationships between the aforementioned 16 variables and the concentration of Cd in rice, we employed a random forest

model utilizing a 5-fold cross-validation method to verify the training outcomes. This involved randomly partitioning the dataset into five segments, with one segment used as the test set and the remaining segment used as the training set in rotation, to assess the model's stability and reliability. The random forest algorithm was implemented via the nested R package “randomForest” (V 3.1), with the “mtry” parameter set automatically, and 5-fold cross-validation was performed via the R package “caret” (v6.0-86).

The random forest analysis determined the importance and marginal effects of each variable in three categories—climate, the soil environment, and management measures—on the concentration of Cd in rice. We measured the relative importance of each variable in the concentration of Cd in rice via the mean decrease in accuracy (%IncMSE), which quantifies the specific contribution of each variable to the overall model performance. This method is based on the change in the mean squared error (MSE) across all trees in the model; if the inclusion of a variable significantly reduces the overall MSE, then the variable makes a substantial contribution to improving the model's predictive accuracy.

The ‘pdp’ R package was leveraged to compute the partial dependence, which was then smoothed via Tikhonov regularization (ridge regression). To fine-tune the regularization parameter utilized for smoothing the partial dependence curves, a leave-one-out cross-validation approach was employed. The partial dependence variance and standard error of the model predictions were computed via bootstrap sampling. Partial dependence plots reflect the dependency between variables and model predictions by showing how the predicted average change in Cd concentration in rice is associated with the numerical change in a variable. Additionally, to quantify the uncertainty of the predictive results, the range of predictive outcomes at different variable values is indicated by shaded areas.

Accounting of economic benefits from the disposal of contaminated rice

Categorized disposal of rice contaminated by heavy metals is conducted to improve the compliance rate and sales revenue of rice, thus ensuring the income of farmers and the safety of grain and enhancing the comprehensive benefits of Cd-contaminated arable land. On the basis of the relevant data obtained from the assessment work, the following values were utilized:

From 2013 to 2020, the selling prices for rice used for food, feed, and industrial purposes were set at 3.55, 2.3, and 1.5 yuan kg⁻¹, respectively. The average yield for 2013–2020 was set at 6670.05 kg ha⁻¹. The remediation and management areas for 2013–2020 were 10.40, 10.40, 17.33, 17.33, 5.97, 0.67, 0.67, and 0.67 million mu, respectively. The specific calculation process for the economic benefits of the disposal of Cd-contaminated rice is shown in [Supplementary Table 2]; the calculation formula is shown in Eq. (1):

$$E_{i,j} = \alpha_{i,j} \times P_{i,j} \times Y_{i,j} \times A_{i,j} \quad (1)$$

Where:

i represents the year of implementation; 2013–2020. j represents the disposal category of rice, which includes food use (rice with Cd content less than 0.2), feed use (rice with Cd content greater than 0.2 and less than 1), and industrial use (rice with Cd content greater than 1). where $E_{i,j}$ represents the economic benefits, indicating the economic losses or remediation costs due to Cd pollution for rice of a specific use in year i , with the unit being yuan. $\alpha_{i,j}$ is the proportion of rice, indicating the proportion of rice of a specific use in total rice in year i . $P_{i,j}$ is the sales unit price, i.e., the market selling price per unit of rice for a specific use in year i , with the unit being yuan kg⁻¹. $Y_{i,j}$ is the average yield, i.e., the average output of rice per unit area for a specific use in year i , with the unit being kg ha⁻¹. $A_{i,j}$ is the remediation and management area, i.e., the area of land producing rice for a specific use in year i that requires remediation or management to reduce the impact

of Cd pollution, with the unit being ha, as shown in Eq. (2):

$$E_i = \sum_{j=1}^n E_{i,j} \quad (2)$$

Where: i represents the year of implementation, 2013–2020, and j represents the disposal category of rice. E_i represents the economic benefits for all uses of rice in year i , indicating the economic losses or remediation costs due to Cd pollution, with the unit being yuan ha⁻¹.

Agricultural household satisfaction survey questionnaire

The questionnaire design adheres to relevant ethical principles as follows: first, the principle of informed consent, where surveyed farmers are provided with comprehensive information regarding the purpose, procedures, risks, and benefits of the investigation; second, the principle of confidentiality, with researchers entering into confidentiality agreements with government departments; third, the principle of impartiality, where researchers have accounted for the random selection of farmers within the survey area, differentiating by gender, age, and educational level; fourth, the principle of harmlessness and benefit, where the survey results can fully reflect the effectiveness of remediation measures and collect opinions and suggestions for improvement from farmers regarding issues encountered during the implementation process, facilitating timely resolution of problems; and fifth, the principle of responsibility, where researchers are accountable for the welfare of the subjects and the accuracy of the research findings.

The design of the questionnaire is based on the effectiveness of adjusting the planting structure in polluted farmland, remediation and fallow management measures, accounting for issues of widespread concern to both the government and farmers. A total of three questionnaires were designed, each containing 10 questions with 5 options labelled A, B, C, D, and E, corresponding to scores of 100, 90, 80, 70, and 60, respectively.

The planting structure adjustment survey questionnaire (see Supplementary Table 1) includes topics such as the completion of adjusted areas, crop (aquatic product) growth, responsibility of grassroots units, negative impacts of adjustments on life and economic income, adequacy of related publicity work, scientific rationality of the adjustment process, satisfaction with adjustment policies and measures (such as subsidies and preferences), negative impacts of adjustments on farmland quality, attitudes towards adjustment work, and any violations in the supporting field facilities.

The remediation survey questionnaire (see Supplementary Table 2) includes topics such as the impact of remediation measures on improving farmland pollution, the standardization of operations by third-party implementation units, the responsibility of grassroots units, the negative impacts of remediation on life and economic income, the adequacy of publicity work on remediation, the scientific rationality of the remediation execution process, satisfaction with remediation policies and measures (such as subsidies and preferences), the negative impacts of remediation on farmland quality, attitudes towards remediation work, and any violations by the implementing party. Additionally, a third-party supervision questionnaire for remediation was designed. It required detailed records of the implementation rate of 7 measures, including implementation time, quantity, area, and quality.

The fallow management survey questionnaire (see Supplementary Table 3) includes topics such as the improvements in farmland pollution via various technical measures of fallow management, the quality of implementation of various fallow measures, the rate of water management, responsibilities of grassroots units, negative impacts of fallow on life and economic income, adequacy of publicity work on fallow, scientific rationality of the fallow execution process, satisfaction with fallow policies and measures (such as subsidies and preferences), negative impacts of pollution control on farmland quality, and attitudes towards the effectiveness of fallow work.

From 2018 to 2020, surveys on the adjustment of planting structures and fallow and remediation measures were conducted in the Xiangjiang River area. During the field inspections from March to May and November to December each year, farmers were randomly selected for interviews and questionnaire completion. The scope of the random checks covered the implementation areas of the three measures, with the area for each questionnaire distribution not overlapping to ensure comprehensive coverage of the survey. The number of questionnaires for the adjustment of planting structures, fallow management, and remediation were 1066 (covering 180 villages in 21 counties), 346 (covering 99 villages in 13 counties), and 334 (covering 99 villages in 10 counties), respectively. After the questionnaires were collected, the survey personnel statistically grouped and calculated the satisfaction of each measure, taking the average value as the survey result for that measure.

Selection and calculation of sustainability indicators

We tracked progress towards the SDGs by quantifying (scoring) the indicators in target areas. The sustainability indicators were selected primarily by referencing the global indicator framework for the SDGs and targets of the 2030 Agenda, the United Nations' official list of global SDG indicators, and published studies assessing the sustainability of environmental strategies³². The SDGs applicable to the target areas include 1, 2, 3, 6, 9, and 15 and represent economic (1, 9), social (2, 3), and environmental (6, 15) contributions (see the data shared link for the selection of SDG indicators). On the basis of the accessibility of the data, especially in the case area, we collected as many SDG indicators as possible during the project (2014–2021).

Data for the selected indicators in this study were gathered from the following authoritative sources: the China Statistical Yearbook, China Statistical Yearbook of Environment, China Health Statistical Yearbook, China Population & Employment Statistics Yearbook, China Water Resources Bulletin, China Forestry Statistical Yearbook, China Statistical Yearbook on Science and Technology, China Rural Statistical Yearbook, Yearbook of China's Insurance, Report on the State of the Ecology and Environment in China, Hunan Statistical Yearbook on Environment, Hunan Health Statistical Yearbook, Hunan Rural Statistical Yearbook, Hunan Forestry Statistical Yearbook, Report on the State of the Ecology and Environment in Hunan, Hunan Water Resources Bulletin, and Hunan Statistical Yearbook on Science and Technology (see Supplementary Table 1).

We used two methods to select the upper bound for each indicator. One type of upper bound used the absolute threshold, for which the indicator had a clear upper bound, such as the proportion of excellent water quality. Under these conditions, the optimal value of the index is 100%. The second type had no clear thresholds or standards; that is, there was no clear upper bound for the indicator, such as arable land productivity. In this study, the average number of top performers was leveraged as the upper threshold. Moreover, to mitigate the influence of outliers, the authoritative SDG Index and Dashboards report were used to establish the lower limit as the bottom 2.5% of the data in the country evaluation. In this work, the lower limit was set as the average of the data at the bottom 5% of the acquired data.

To enable cross-SDG comparability, the indicator values for each SDG were normalized to a standardized scale ranging from 0 (denoting the poorest performance) to 1 (signifying the optimal performance). Normalized values exceeding the upper threshold were assigned a score of 1, whereas those falling below the lower bound were awarded a score of 0. Other indicators were normalized and standardized by calculating their position in all values for each single indicator. The data were normalized across the case area and at the provincial and national levels together and were thus comparable across three different levels.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data necessary for replication will be available via figshare (<https://doi.org/10.6084/m9.figshare.26172871>).

Code availability

All computer codes necessary for replication will be available via figshare (<https://doi.org/10.6084/m9.figshare.26172871>).

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Author contributions

X.L. conceived and designed the research. X.L., Y.L., H.T., H.C. and X.W. conducted the results analysis. Y.L. and H.T. drafted the first version of the manuscript. X.L., Y.L., H.T., H.C., and X.W. contributed to the interpretation of the results, critical revision of the manuscript, and approval of the final version of the manuscript. Y.L. and H.T. contributed equally to the work.

Competing interests

The authors declare no competing interests.

Additional information

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