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Assessing coupling coordination between human-animal-environmental health for advancing uniform progress in One Health

Ya Tian [a,b,*,1], Zonghan Li [b,1], Xueyi Luo [b], Zheng Hu [b], Tong Xu [b], Kai Wu [b], Min Cao [b], Prajal Pradhan [c,d], Min Chen [b], Hui Lin [a,**]

[a] School of Geography and Environment, Jiangxi Normal University, Nanchang 330022, China
[b] Key Laboratory of Virtual Geographic Environment, Ministry of Education of PRC, Nanjing Normal University, Nanjing 210023, China
[c] Integrated Research on Energy, Environment and Society (IREES), Energy and Sustainability Research Institute Groningen (ESRIG), University of Groningen, Groningen 9747 AG, the Netherlands
[d] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 601203, 14412 Potsdam, Germany

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ABSTRACT

The One Health (OH) approach aims to sustainably balance and optimise the health of people, animals, and ecosystems. However, there is a lack of robustly quantified insights into its spatiotemporal coupling and coordination. This study employs the OH index, which incorporates Sustainable Development Goals (SDGs), to examine the coupling and coordination relationships among three health subsystems, elucidate their four spatiotemporal patterns, and identify key driving factors. Our results indicate that the degree of OH coupling coordination is improving, despite spatial unevenness across SDG regions. Countries with varying economic levels often exhibit similar coupling coordination patterns, suggesting the potential for policy coherence to foster regionally uniform development. Key factors for breaking the cycle of poverty include increased health spending, improved education, and better dietary balance. In regions facing significant economic and environmental pressures, promoting animal and environmental health through biodiversity conservation and habitat preservation is essential for achieving OH coupling coordination. Nevertheless, the absence of governance mechanisms, along with factors such as climate change, military conflicts, and fragile alliances, poses serious obstacles to achieving uniform OH. Therefore, this study underscores the necessity of targeted policy interventions, interdisciplinary collaboration, and comprehensive governance to address this unevenness, promote coordination, and advance global health governance.

1. Introduction

In recent decades, our planet has frequently experienced deadly global pandemics, including Ebola, highly pathogenic avian influenza, and Coronavirus Disease 2019 (COVID-19) [1]. The emergence of infectious diseases is driven by a complex interplay of factors, such as population growth, urban and agricultural expansion, and intensive livestock production [2–4]. The current fragmented framework of health governance is inadequate for tackling complex health challenges [5].

The One Health (OH) approach is a unifying strategy that aims to sustainably balance and optimise the health of people, animals, and ecosystems [6]. It offers essential tools for effective prevention, preparedness, and response to pandemics [7]. The World Health Organisation (WHO) Pandemic Agreement has integrated the OH approach and established its key criteria [8]. This highlights the OH concept as a crucial tool for transforming the global health security governance paradigm. It shifts the focus from a traditional emphasis on control rather than prevention and an overemphasis on national interests to a deeper preventive approach, fostering a new global health security paradigm based on unity and collaboration [9].

Since the introduction of OH, considerable efforts have been dedicated to developing its conceptual and assessment frameworks. Richard Coker [10] and J. Lebov [11] proposed evaluation frameworks to guide

* Corresponding author at: School of Geography and Environment, Jiangxi Normal University, Nanchang 330022, China.
** Corresponding author.
E-mail addresses: tianya@jxnu.edu.cn (Y. Tian), huilin@cuhk.edu.hk (H. Lin).

[1] Ya Tian and Zonghan Li contributed equally to this work

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OH policies and researchers, as demonstrated through case studies on infectious diseases. Zhang and colleagues [12] proposed a cell-like framework that adopts a holistic perspective, serving as an evaluation tool to measure OH performance. The utilisation of artificial intelligence (AI) and big data technologies for the digital implementation of the OH approach facilitates data-driven solutions to the challenges of inter-connected health domains [13].

Furthermore, the introduction of the Sustainable Development Goals (SDGs) has created opportunities for OH [5,14]. The One Health High-Level Expert Panel has developed an overarching Theory of Change in addition to the OH definition, providing a conceptual framework and theoretical foundation for the implementation of OH and SDGs [15]. Despite these advancements, there remain challenges, such as the overlapping and incomplete nature of OH assessment indicators, as well as difficulties in data acquisition [16]. Importantly, the lack of a comprehensive framework that systematically addresses the three health subsystems and integrates SDG indicators results in gaps that hinder the translation of these advancements into effective actions and policies.

A deep understanding of the complex relationships among three health subsystems is essential for advancing OH progress. Previous studies have shown that the advancement of human health often comes at the expense of animal and environmental health [3,4,17,18]. Anthropogenic factors, such as urban and agricultural expansion, the intensification of livestock production, and deforestation, have led to the loss of biodiversity and habitat destruction [1]. Importantly, all these impacts result in complex interactions, increasing the risk of disease spillover [19]. Research suggests that animals harbor approximately 1.7 million undescribed viruses, with an estimated half capable of infecting humans [20]. Areas with frequent land-use changes and high pressure on biodiversity are identified as hotspots for the emergence of infectious diseases [3,21]. Furthermore, climate change may exacerbate this process, leading to increasingly complex consequences [22]. Nevertheless, there is a lack of systematic analysis of the spatiotemporal relationships among the three health subsystems, particularly those driven by authoritative data.

To address these deficiencies, we innovatively introduce the coupling coordination degree (CCD) into the OH index [23] (Table S1) to examine the relationships among the three health systems globally and nationally [24]. The CCD model has been widely used to evaluate relationships and overall development levels among subsystems, particularly those involving trade-offs between environmental health, human health, and socio-economic development [25–27]. For example, the CCD model has been applied within the framework of safe and just operating space and SDGs to assess the interactions between environmental performance and human well-being in China, providing targeted policy recommendations to promote sustainable development [25]. This demonstrates the broad applicability of the CCD model in analyzing complex, interconnected systems. Therefore, we examine the CCD trends from 2000 to 2020 and the CCD magnitude in 2020 to elucidate coupling coordination patterns and identify key driving factors using Extreme Gradient Boosting (XGBoost) regression tree methods [28]. This study addresses the following questions: 1) What are the dynamic spatiotemporal characteristics of CCD among the various health subsystems? 2) What are the coupling coordination patterns among the different health subsystems? 3) What are the key drivers contributing to the various coupling coordination patterns?

2. Methods

2.1. Data source and processing

This study employs the three-level OH index framework [23], integrating various established indicators from the SDGs and the global One Health index to explore the dynamic spatiotemporal characteristics of CCD, identify coupling coordination patterns, and analyze the influence of key drivers (Fig. S1). The OH index framework is organized into human, animal, and environmental health systems, 17 OH targets, and 49 OH indicators (Table S1). We collected data spanning from 2000 to 2020 (Table S2), according to seven recognized principles (relevance, authoritative sources, open access, completeness, timeliness, comparability, and national-scale data) [12]. Random cross-checks and consistency tests were conducted during data collection to ensure its integrity and quality. Furthermore, only countries with less than 50 % data deficiency across the three health subsystems are included [12], yielding a dataset of 148 countries from the 193 United Nations member states.

We first calculate the OH index and the scores of three health systems using a four-step process: (1) selecting indicators, (2) setting target and baseline values, (3) normalisation, and (4) aggregation [29]. The detailed calculations are shown in Supplementary Note 1. Global, regional, and national scale scores are computed by arithmetic means for each target, the three health systems, and the OH index from 2000 to 2020. Initially, the OH indicator scores are aggregated to yield OH target scores, and then these are aggregated to obtain human, animal, and environmental health scores. The OH index is then calculated as the mean of the scores for the three health systems. To minimize subjectivity, all OH indicators are equally weighted and considered equally important [30].

2.2. Coupling coordination degree model

We investigate the coupling and coordination relationships among three health subsystems from 2000 to 2020 across countries worldwide using the CCD model. In detail, we first calculate the coupling degree using formula (1), then measure the overall development level and CCD using formulas (2) and (3) respectively. The formulas are as follows:

$$C = \sqrt[3]{\frac{f_{(X)} \times f_{(Y)} \times f_{(Z)}}{\left(\left(f_{(X)} + f_{(Y)} + f_{(Z)}\right)/3\right)^3}} \tag{1}$$

where C represents the coupling degree, $C \in [0, 1]$.The greater the coupling degree is, the stronger interaction between the subsystems would be, and vice versa; $f_{(X)}, f_{(Y)}$, and $f_{(Z)}$ represent the performance of human, animal, and environmental health, respectively.

$$T = \alpha f_{(X)} + \beta f_{(Y)} + \gamma f_{(Z)} \tag{2}$$

$$\mathrm{D} = \sqrt{C \times T} \tag{3}$$

where T represents the overall development level, and D represents the degree of coupling coordination, $D \in [0, 1]$. Higher values of D represent more synergies and a higher overall level of OH development. α, β and γ are the weights indicating the importance of each subsystem, respectively, and $\alpha + \beta + \gamma = 1$. In this study, we assume that three health subsystems are equally important. Thus, $\alpha = \beta = \gamma = 0.33$. Furthermore, we categorise the CCD values into four development stages concerning the experience of relative studies [31,32], as shown in Table 1.

Table 1
Classification of Coupling Coordination Degree (CCD) Levels.

Range of CCD	Level of CCD magnitude	Description
[0,0.4]	Uncoordinated	Progress in any health subsystem sacrifices others
(0.4,0.6]	Transitional	The transition state of uncoordinated and coordinated
(0.6,0.8]	Primary coordinated	Progress in any health subsystem promotes less to others
(0.8,1.0]	High coordinated	Progress in any health subsystem promotes more to others

2.3. Spatial coupling coordination patterns between human, animal, and environmental health

To explore the spatiotemporal changes in the coupling coordination relationships among three health subsystems, we categorise countries into four coupling coordination patterns based on two dimensions: the level of CCD (y-axis) and the level of development (x-axis) (Fig. 1) [25]. The CCD level is quantified by the CCD magnitude, while the development level is quantified by the changing trends of CCD, using Mann-Kendall trend test methods (Supplementary Note 2). Along the x-axis, regions can be classified as upward or downward trends. The upward trend regions indicate an increasing level of CCD, whereas the downward trend regions suggest a more trade-off direction. Along the y-axis, regions are classified as synergistic (CCD > 0.8) or trade-off (CCD ≤ 0.8) [25]. Consequently, these two dimensions delineate four coupling coordination patterns: the pilotage pattern (Quadrant I) shows synergy with an upward trend; the arrogance pattern (Quadrant II) shows synergy but a downward trend; the predicament pattern (Quadrant III) represents trade-offs with a downward trend; and the catch-up pattern (Quadrant IV) indicates trade-offs with an upward trend.

2.4. Identifying key drivers in various coupling coordination patterns

In this study, we employ the XGBoost regression tree method to identify the key drivers of coupling coordination patterns by analyzing the contributions of 49 OH indicators to the spatiotemporal variations in CCD. XGBoost is an advanced machine learning technique that effectively models complex nonlinear relationships, manages interactions between predictors, and evaluates the contribution of each feature to the model [33]. For various coupling coordination patterns, the average CCD magnitude of countries serves as the response variable, with the average scores of 49 OH indicators as predictors. We assess the importance of each indicator using feature importance metrics, quantified by the mean decrease in accuracy. Higher values indicate a greater contribution to the model, with a range from 0 % to 100 % [34]. Detailed calculations, parameter selections, and model accuracy assessments are provided in Supplementary Note 3, along with Fig. S2, Tables S3 and S4.

3. Results

3.1. Global spatiotemporal dynamics of the coupling coordination relationships in One Health

Our findings reveal spatial unevenness in the OH CCD across countries worldwide (Fig. 2A, B). Specifically, seventy countries with a high OH coordinated level (CCD > 0.8) are primarily located in member

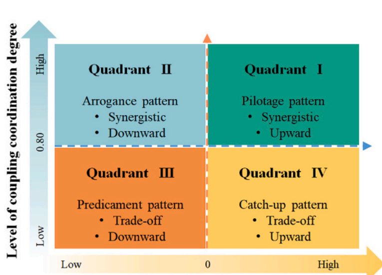

Fig. 1. Coupling coordination patterns among human, animal, and environmental health. Four patterns are divided into two dimensions: the level of coupling coordination degree (CCD) in 2020 (y-axis) and the level of development from 2000 to 2020 (x-axis). Regions located in quadrants away from the middle horizontal line exhibit greater synergies and a higher CCD of One Health, and vice versa. Regions in quadrants away from the middle vertical line are more developed, and vice versa.

countries of the Organisation for Economic Cooperation and Development (OECD), as well as in Eastern Europe and Central Asia, the Middle East and North Africa. Seventy-three countries ($0.6 < \text{CCD} \leq 0.8$) with a primary OH coordinated level are mainly found in Latin America, the Caribbean, Sub-Saharan Africa, and Eastern Europe. Five countries ($0.4 < \text{CCD} \leq 0.6$), including the Bahamas, Haiti, Timor-Leste, Somalia, and Seychelles, are in a transitional level. Only Vietnam, with a CCD ≤ 0.4, is considered uncoordinated. Notably, the magnitude of CCD varies across the three health coordination relationships (Fig. 2A and S3). In countries with high OH coordinated level, the CCD for human-animal health is the highest, while countries with primary OH coordinated level, such as those in Latin America and the Caribbean, exhibit the highest CCD for human-environment health. The CCD between animal and environmental health remains the lowest in most countries.

Furthermore, we observe remarkable progress in the globally averaged CCD magnitude of OH, which reached 0.78 in 2020 (Fig. 2C and D). However, spatial disparities in CCD trends exist across different countries (Fig. 2D and S3). For instance, 29 countries in Sub-Saharan Africa and East and South Asia show substantial increases, while 16 countries in the Middle East and North Africa experienced decreases. Moreover, the CCD among health subsystems indicates that human-animal health has seen the fastest growth (0.20 %), followed by human-environment (0.13 %) and animal-environment (0.06 %), from 2000 to 2020.

3.2. Global spatial coupling coordination patterns

Our study reveals spatial heterogeneity in the coupling coordination relationships among three health subsystems, resulting in four distinct spatial patterns. Most countries display synergies and an upward trend, including 53 countries from the OECD, Latin America and the Caribbean, Eastern Europe and Central Asia, which are categorised as the pilotage pattern (Fig. 3A and S4). In contrast, 12 countries, mainly in the Middle East and North Africa, fall into the arrogance pattern, showing synergies with a downward trend. Moreover, 29 countries, primarily from Latin America and the Caribbean, Oceania, and sub-Saharan Africa, face the predicament pattern, marked by trade-offs and a downward trend, representing the least favourable development pattern. Meanwhile, 55 countries, mainly located in sub-Saharan Africa, East and South Asia, are in the catch-up pattern, featuring trade-offs but with an upward trend.

However, some countries within the same region exhibit lower levels of CCD and display divergent trends (Fig. 3B). For example, while the majority of OECD countries follow the pilotage pattern, the United Kingdom, France, and Australia fall into the arrogance pattern, with the United Kingdom showing a significant downward trend ($Z = -2.57$). New Zealand is in the predicament pattern (CCD $= 0.76$, $Z = -2.32$), and Mexico and South Korea are in the catch-up pattern. Although the Middle East and North Africa predominantly align with the arrogance pattern, the United Arab Emirates shows a downward trend ($Z = -4.08$) within the predicament pattern. Latin America and the Caribbean, East and South Asia mainly follow the catch-up pattern, but 13 countries from these regions show synergies and an upward trend, placing them in the pilotage pattern.

3.3. Contribution of drivers to various coupling coordination patterns

Human drivers play a significant role in the CCD level of global OH (Fig. 4). Our findings reveal that human health drivers are crucial in the pilotage, arrogance, and predicament patterns, contributing 58.76 %, 61.59 %, and 56.20 %, respectively (Fig. 4A; 4B and 4C). In contrast, environmental health drivers primarily affect the catch-up patterns, with a cumulative contribution exceeding 57.58 % (Fig. 4D). Notably, environmental drivers also play a significant role in the pilotage pattern, contributing 31.15 % (Fig. 4A). While animal health drivers contribute the least (<3.59 %) to the catch-up pattern, they remain important in the pilotage and arrogance patterns, with contributions greater than 20.20

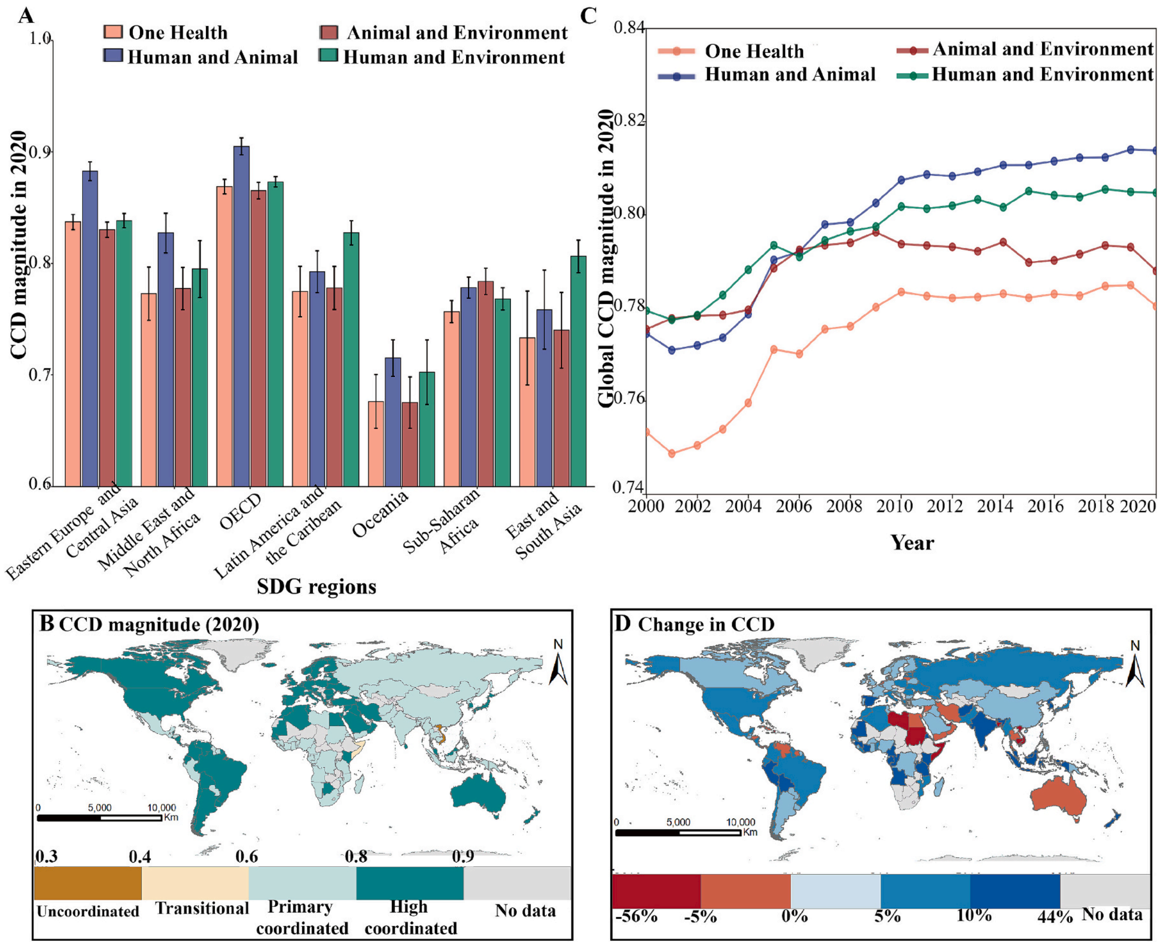

Fig. 2. Global One Health (OH) Coupling Coordination Degree (CCD) in 2020 and changes from 2000 to 2020. A) Average CCD of the three or two health subsystems across different sustainable development goal regions in 2020. B) Global spatial pattern of the OH CCD in 2020. C) Change in the global average CCD of the three or two health subsystems from 2000 to 2020. D) Global spatial pattern of the change rate of OH CCD from 2000 to 2020.

% (Fig. 4B).

Furthermore, the key drivers vary in terms of coupling coordination patterns. The dominant contributing drivers for the pilotage, arrogance, predicament, and catch-up patterns are domestic health expenditure, nutrition score, adolescent fertility, and species habitat, accounting for 34.57 %, 31.74 %, 51.96 %, and 49.36 % of all drivers, respectively (Fig. 4). Domestic health expenditures, nutrition scores, and species habitat exhibit positive impacts, suggesting that an increase in species habitat promotes CCD (Fig. S5). In contrast, adolescent fertility shows negative impacts, suggesting that increases in this driver hinder CCD (Fig. S5). Furthermore, significant human-driven factors include vaccination, contributing 19.98 % to the catch-up pattern. Key animal and environmental drivers are the red list index and controlled solid waste, with contributions of 18.21 % and 18.73 %, respectively, to the arrogance pattern (Fig. 4), all of which exhibit a positive impact (Fig. S5).

4. Discussion

The key to advancing uniform progress in global OH lies in promoting the CCD while mitigating trade-off effects [23]. In this study, we systematically explore the spatiotemporal dynamics of the CCD among these three health subsystems, employing an improved framework that incorporates health indicators related to SDGs. We also analyze the magnitude of the CCD and its development trends to identify various OH coupling coordination patterns across countries worldwide. More importantly, we identify the key driving factors for each health subsystem under different coupling coordination patterns and their influence on the CCD. These findings have crucial implications for policymaking and enhancing global health governance.

Although the CCD of OH has shown an upward trend, spatiotemporal unevenness among the three health dimensions impedes uniform progress. Regions with a high coordinated level typically exhibit advanced economic development and public health resources, enhancing human-animal health integration [35]. However, regions with a primary coordinated level struggle with severe environmental pollution and economic inequalities, hindering OH progress [36]. Addressing knowledge gaps and enhancing policy support are essential for improving coordinated health outcomes. For example, 70 countries, mainly in the OECD, Eastern Europe, and Central Asia, exhibit a high coordinated level (CCD > 0.8), which can be attributed to promoting health policymaking and practices through the OH approach [37]. In contrast, Vietnam has an uncoordinated level (CCD ≤ 0.4) due to inadequate disease surveillance and control systems [38,39] and environmental pollution from rapid industrialization [40].

Our findings reveal that over 60 % of countries worldwide exhibit incoordination or a downward trend, with substantial disparities across various coupling coordination patterns. For instance, 21 countries located in the Middle East and North Africa fall into the arrogance pattern, showing synergies but a downward trend, primarily due to persistent political instability and military conflict, leading to population displacement and health system collapse [41]. Climate change exacerbates water scarcity and air pollution, increasing the disease burden [42]. Latin America and the Caribbean, as well as Oceania, face the predicament patterns, being highly vulnerable to economic shocks,

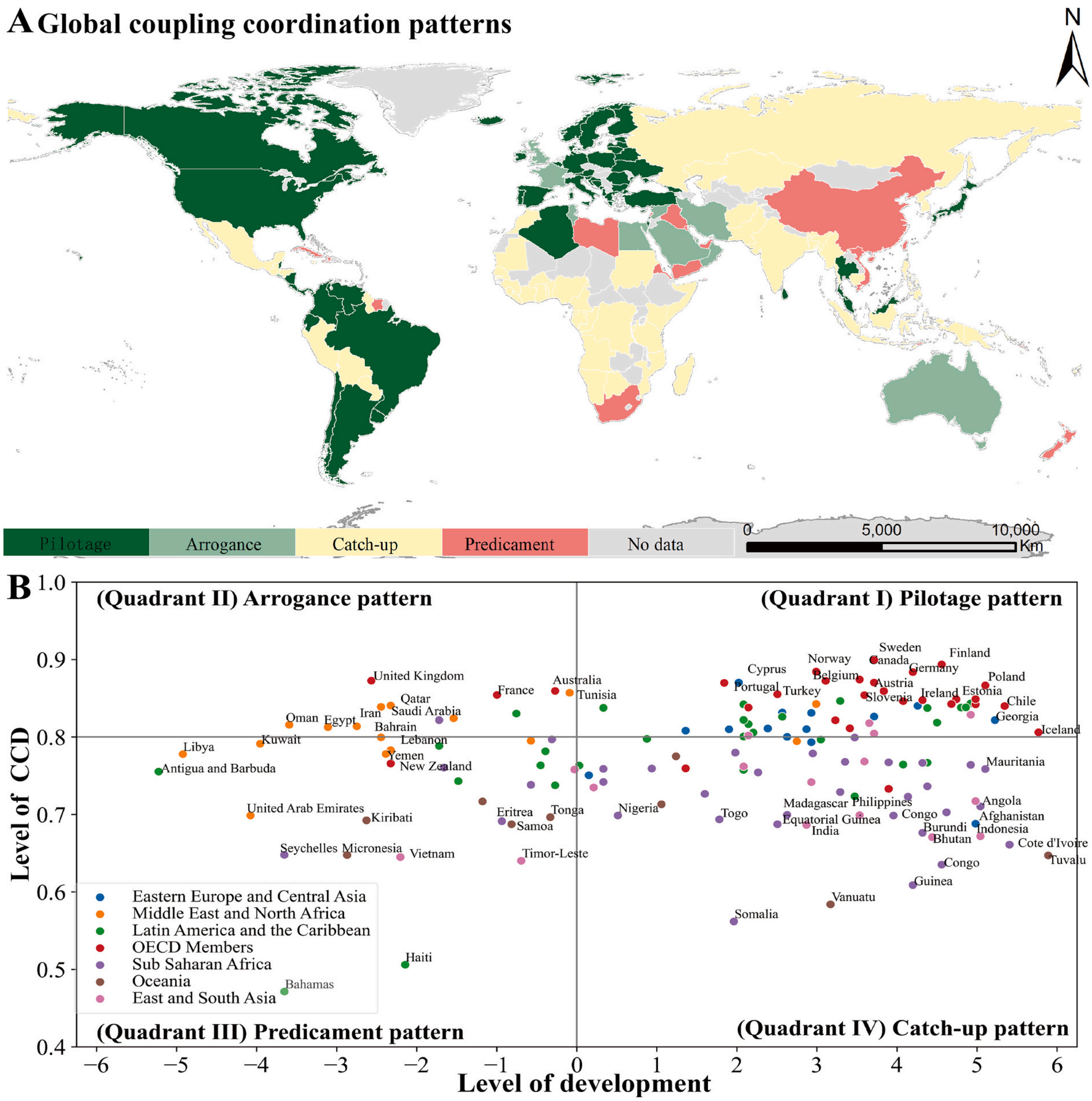

Fig. 3. Global One Health (OH) coupling coordination patterns. A) Spatial OH coupling coordination patterns. B) Performance relative to the levels of coupling coordination degree (y-axis) and development trends (x-axis) across countries worldwide. Corresponding to Fig. 1, pilotage, arrogance, predicament, and catch-up represent Synergistic and Upward, Synergistic and Downward, Trade-off and Downward, and Trade-off and Upward, respectively.

climate change, and disasters, which impede OH progress [43]. Conversely, the catch-up pattern, which includes 47 countries, shows an upward trend despite incoordination, attributed to OH initiatives [44]. These insights highlight the critical need for tailored strategies aligned with the challenges and strengths of countries in different patterns to foster coordinated OH development.

While different coupling coordination patterns have been identified across SDG regions, these patterns are not consistently observed across all countries in the same region. For example, while OECD member countries generally fall into the pilotage pattern, declines in animal and environmental health have led countries such as the UK, France, and Australia to shift to the arrogance pattern, with New Zealand even transitioning into the predicament pattern. This decline is partly due to unsustainable consumption patterns and negative international spillover effects [45,46]. However, countries with varying geographical and economic circumstances may share similar coupling coordination patterns. For example, 18 countries across East and South Asia, Latin America, and the Caribbean fall under the pilotage pattern. As shown in the Sustainable Development Report 2020, these countries have made considerable progress in health-related SDGs, particularly in no poverty (SDG1) and clean water and sanitation (SDG6) [30]. The improvement in SDG1 has significantly spurred progress in other goals and demonstrates the strongest synergy with good health and well-being (SDG3) [46]. Consequently, innovation and strengthened economic development, aimed at poverty reduction, remain crucial for improving health coupling coordination in resource-limited countries.

Understanding spatiotemporal variation mechanisms of CCD is crucial for supporting policy towards advancing the progress of OH. Our findings suggest that improving domestic health expenditure, nutrition scores, and health literacy are key to breaking the vicious cycle of poverty and poor health, thereby promoting CCD in OH. For example, countries in the pilotage pattern show that increased domestic health expenditure helps reduce mortality rates and enhance productivity [47]. Furthermore, countries in the arrogance pattern face challenges such as

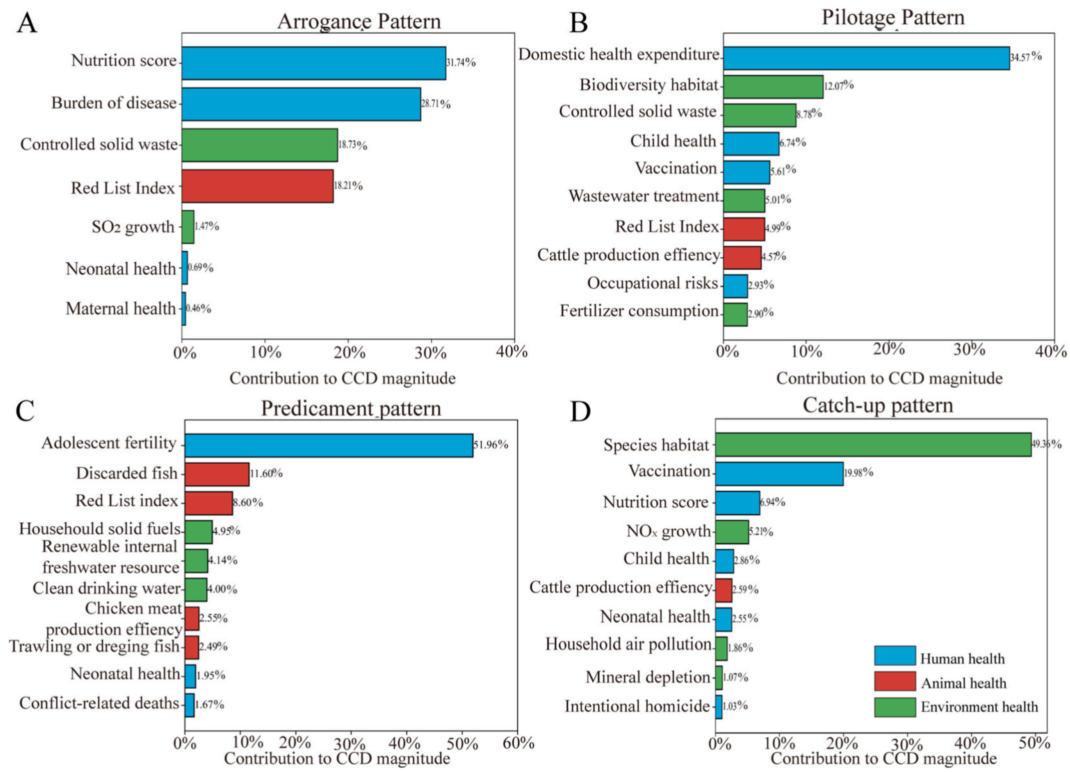

Fig. 4. Contribution of drivers to variations in One Health coupling coordination patterns. A) Arrogance pattern (Quadrant II). B) Pilotage pattern (Quadrant I). C) Predicament pattern (Quadrant III). D) Catch-up pattern (Quadrant IV). The relative contributions are presented as percentages (%). For each indicator, we illustrate the contribution of each of the three health subsystems to the changes in coupling coordination degree: human (blue), animal (red), and environmental (green) health indicators. All the drivers in each development pattern account for at least 90 % of the mean value of the coupling coordination degree from 2000 to 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the high prevalence of diabetes and obesity due to nutritional imbalances, hindering CCD progress [48]. Additionally, countries in the predicament pattern demonstrate that poverty-driven high adolescent birth rates impede CCD, particularly in Sub-Saharan Africa [49]. However, for countries in the catch-up pattern, protecting species habitats and biodiversity is critical for improving the CCD of global OH. Past studies indicate that agricultural expansion and climate change may lead to a loss of over 25 % of habitats by 2050, exacerbating biodiversity loss and increasing the risk of disease spillover [50,51]. This highlights the importance of environmental governance during periods of rapid economic development.

While our study yields worthwhile findings, it is nonetheless important to recognise its limitations. These include potential incomplete aspects in the OH indicator framework, largely due to challenges in data availability, particularly in animal health and emerging contaminants. Future research should focus on developing this framework and exploring the political, economic, and cultural factors that influence health relationships to enhance our understanding of the dynamics of CCD among three health subsystems [12]. Nevertheless, this study underscores the complexity of global health governance, as regions face distinct challenges and opportunities in advancing OH. Therefore, achieving coupled coordinated development among three health subsystems requires interdisciplinary collaboration and integrated governance.

5. Conclusions

This study examines the spatial-temporal coupling and coordination of three health subsystems across countries from 2000 to 2020. While global improvements in the CCD of global OH have been observed, spatial-temporal unevenness persists, particularly in regions with varying levels of economic development. However, countries with varying economic levels may fall into the same coupling coordination patterns, suggesting opportunities for shared strategies to enhance regional development. Key drivers for breaking the poverty cycle include increased health expenditures, economic growth, balanced diets, and reduced adolescent fertility rates. Additionally, protecting species habitats and biodiversity is vital, especially in regions facing economic and environmental pressures. However, the lack of robust governance mechanisms hinders uniform progress in OH. These challenges are further exacerbated by climate change, military conflicts, and fragile international partnerships. This study highlights the necessity of targeted efforts and interdisciplinary collaboration to promote coordinated development and improve global health governance.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Ya Tian: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zonghan Li:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xueyi Luo:** Writing – review &

editing, Methodology, Data curation. **Zheng Hu:** Writing – review & editing, Methodology, Data curation. **Tong Xu:** Writing – review & editing, Methodology, Data curation. **Kai Wu:** Writing – review & editing, Investigation. **Min Cao:** Writing – review & editing, Supervision. **Prajal Pradhan:** Writing – review & editing, Supervision. **Min Chen:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Hui Lin:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.onehlt.2025.101013.

Data availability

Our research data for One Health indicators came from authoritative databases (listed in Table S1). All data are for the years 2000 through 2020.

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