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Synergetic development assessment of transboundary watershed ecological compensation

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ABSTRACT

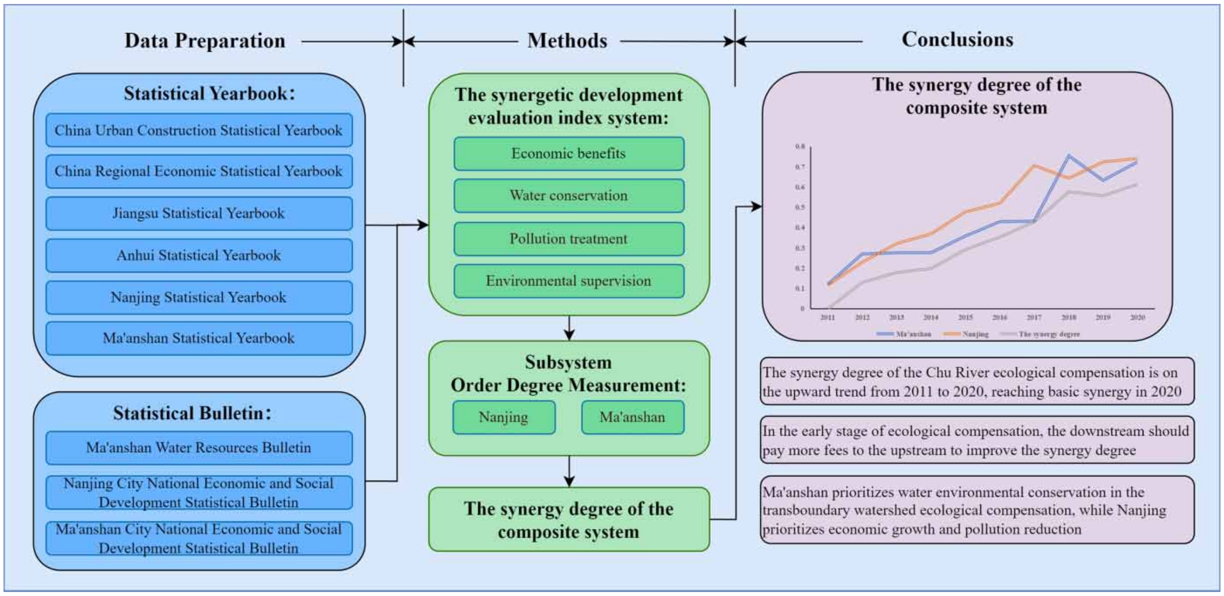
Ecological compensation (EC) is essential to promote the coordinated and sustainable development of the watershed. Firstly, the synergetic development index system of the watershed EC was proposed, which includes the economic benefits, water conservation, pollution treatment, and environmental supervision. Then, the order degree of subsystems was calculated. Finally, the synergetic development level of the watershed EC was evaluated. Taking the upstream (Ma'anshan) and the downstream (Nanjing) of the Chu River as the case study area, the results showed that: (1) From 2011 to 2020, the synergetic development level between Ma'anshan and Nanjing has showed an upward trend; (2) The synergetic development level of the watershed EC in the Chu River has reached basic synergy in 2020; (3) Ma'anshan concentrates on protecting the water ecological environment while Nanjing concentrates on economic growth and water pollution control will improve the synergy degree. This study can provide references for the optimization of watershed EC mechanism, and to promote watershed coordinated development.

Key words: composite system, ecological compensation, sustainable development of watershed, synergetic development assessment, synergy degree model

HIGHLIGHTS

- The watershed ecological compensation (EC) synergetic development index system is proposed.
- The synergy degree between upstream and downstream is analyzed.
- The upstream focuses on ecological environment protection while the downstream focuses on water pollution control will improve the efficiency of EC.

GRAPHICAL ABSTRACT



1. INTRODUCTION

With the rapid development of socio-economics, the ecological environment has suffered serious damage, especially the watershed ecology and environment. To promote green and sustainable development of socio-economic, scholars have taken a series of research (Burrichter *et al.* 2022; Hong & Van 2022; Mamani *et al.* 2022; Panyasing *et al.* 2022; Pimonratanakan 2022; Satria *et al.* 2022; Walter *et al.* 2022). Among them, ecological compensation (EC) is an effective solution to coordinate the protection of the ecological environment and the development of the economy (Zbinden & Lee 2005; Engel *et al.* 2008). Since the 1980s, the United States has piloted EC in the Catskill, Tennessee, and Mississippi River basins. It has improved the water use efficiency. Germany and the Czech Republic have promoted EC to address the pollution problem in the Elbe basin. Costa Rica has established the National Forest Fund to protect forested areas and water sources. China has taken EC in the Dong Jiang, Xiang Jiang, Xin'an Jiang, and other watersheds since the last century (Chen *et al.* 2021).

With the implementation of ecological compensation, how to improve the efficiency of ecological compensation has gradually become the research focus. Mayrand & Paquin (2009) proposed that the EC involves multi-agents, such as the beneficiaries of environment improvement, the protectors of the environment, and the government. Scholars proposed to encourage different stakeholders to participate in EC (Guan *et al.* 2021; Zhu *et al.* 2023). Li *et al.* (2021) suggested to establish the 'government guidance, market operation, social engagement, communication, system operation, and scientific management' mechanism to increase the effect of watershed EC. Generally, the downstream is the beneficiary and the upstream is the ecological environment protector, which are the most important stakeholders in watershed EC (Freeman 1984; Deng & Chen 2022; Fang *et al.* 2022). The collaboration of upstream and downstream can improve the efficiency of EC (Gregory & Brett 2018; Gao *et al.* 2019; Ding *et al.* 2022). Therefore, measuring the synergetic development degree of upstream and downstream is essential to the collaborative and sustainable development of the watershed. Due to the synergy degree model evaluating the synergetic development level (SDL) of the composite system effectively (Qiao *et al.* 2017; Kong & Gou 2019), this paper adopts it to assess the SDL of watershed EC.

In the influence analysis of EC, Guan *et al.* (2015) put forward that it is important to consider the ecological-economic value of water resources in the calculation of watershed EC standards. Zhang *et al.* (2019) proposed that it is important to promote the coordination development of economic, societal, and ecology in the implementation of EC. Also, scholars found that the coupling coordination development of water resources, economy, and ecological environment is important to the sustainability of a watershed (Wang *et al.* 2016, 2022; Koc 2022). Meanwhile, Guan *et al.* (2021) put forward that the ability of pollution control and environment supervision also play an important role in improving the effect of EC.

Therefore, this paper established the synergetic development index system of watershed EC from economic benefits, water conservation, pollution treatment, and environmental supervision. Then, the composite system and the synergy degree model were adopted to assess the synergetic development level of upstream and downstream regions. This study can provide references for the establishment and improvement of multi-agent EC.

2. STUDY AREA AND DATA SOURCES

Chuhe River originates from Liangyuan Town, Feidong County, Anhui Province, with a total length of approximately 260 km. It is a cross-border river between Jiangsu Province and Anhui Province. The Chuhe River mainly flows through Hefei, Chuzhou, Ma'anshan, and Nanjing, entering the Yangtze River from Liuhe District in Nanjing. To protect the ecological environment of the Chuhe River, the Anhui Province and the Jiangsu Province signed the 'Cooperation Agreement on Establishing a Horizontal Ecological Protection and Compensation Mechanism for the Yangtze River Basin' in 2018. The water quality of the Chu River basin has significantly improved after the EC agreement was signed. Thus, this paper took the upstream (Ma'anshan) and downstream (Nanjing) as the case study area to evaluate the synergetic development level of watershed EC.

The research data is from China Urban Construction Statistical Yearbook, Ma'anshan Statistical Yearbook, Anhui Statistical Yearbook, Nanjing Statistical Yearbook, Jiangsu Statistical Yearbook, Ma'anshan Water Resources Bulletin, Ma'anshan City National Economic and Social Development Statistical Bulletin, Nanjing City National Economic and Social Development Statistical Bulletin, and China Regional Economic Statistical Yearbook from 2011 to 2020.

3. METHODS

3.1. Synergetic development evaluation index system

This paper explores the synergetic development of transboundary watershed EC. Thus, the composite system includes two subsystems: the upstream and the downstream. The synergetic development of the subsystem should comprehensively consider the impact of ecological environmental protection and the development of society and economy. Meanwhile, the treatment of pollution and the supervision of the water ecological environment also play important roles in the synergetic development of upstream and downstream. Therefore, each subsystem includes four order parameters: economic benefits, water conservation, pollution treatment, and environmental supervision. The index system is shown in Table 1.

3.2. Subsystem order degree measurement

Suppose that S is a composite system, that has several subsystems and order parameters, i.e., $S = \{S_1, S_2, \ldots, S_n\}$. $S_i (i = 1, 2, \ldots, n)$ is a subsystem of S. In this study, $n = 2$, that is, the synergetic system has two subsystems: the upstream city Ma'anshan and the downstream city Nanjing. Assume $e_i = \{e_{i1}, e_{i2}, \ldots, e_{ij}\}$ is the order parameter of subsystems, where $\beta_{ij} \le e_{ij} \le \alpha_{ij}$ $(j = 1, 2, \ldots, m)$, α_{ij} and β_{ij} are the upper and lower bound of the order parameter component e_{ij}, respectively. e_{ij} has a positive or negative contribution to the system order degree. When e_{ij} is a positive indicator, the larger the value of it, the better the development of the system, and the higher order degree of the system. When e_{ij} is a negative indicator, the larger the value of e_{ij}, the lower the order degree of the system. The order degree model is:

$$U_i(e_{ij}) = \frac{e_{ij} - \beta_{ij}}{\alpha_{ij} - \beta_{ij}} \tag{1}$$

where $U_i(e_{ij}) \in [0, 1]$. Generally, the larger value of e_{ij}, the more it contributes to the system order degree. The contribution of the order parameter e_i to the order degree of the subsystem S_i is achieved through the integration of $U_i(e_{ij})$, which is determined by the magnitude of the order degree of the order parameter component and the form of the combination. $U_i(e_i)$ can be calculated as follows:

$$U_i(e_i) = \sum_{j=1}^{m} \omega_j U_i(e_{ij}) \tag{2}$$

where ω_j represents the effect of the jth order parameter in the subsystem. Due to the entropy weight method obtaining the weights of each indicator objectively based on the degree of dispersion of the data, this paper adopted it to calculate the effect of each order parameter.

Table 1 | The synergetic development evaluation index system

Composite system	Subsystem	Order parameter	Secondary indicators
The synergetic development of transboundary watershed ecological compensation	Upstream region and downstream region	Economic benefits	GDP growth rate
			Capita disposable income
			The proportion of ecotourism in GDP
		Water conservation	Forest coverage
			Improvement of soil erosion
			Per capita domestic water consumption
		Pollution treatment	Industrial wastewater treatment rate
			Town's life sewage centralized treatment rate
			Domestic waste treatment rate
		Environmental supervision	Proportion of ecological environment protection investment in GDP
			Number of water quality automatic monitoring station
			Laws and regulations of ecological environment protection

3.3. Composite system synergy degree model

The synergy degree of the composite system refers to the collaborative development state of the composite system through the interaction of subsystems. Taking t_0 as the initial value, the order degree of each subsystem is $U_i^0(e_i)$; when the system reaches the time t_1, subsystem order degree changes to $U_i^1(e_i)$. Assume that the composite system synergy degree is μ, the defining equation is given as follows:

$$\mu = \varphi \cdot \sqrt[n]{\left|\prod_{i=1}^{n}[U_i^1(e_i) - U_i^0(e_i)]\right|} \tag{3}$$

where $\varphi = \min[U_i^1(e_i) - U_i^0(e_i) \neq 0]/|\min[U_i^1(e_i) - U_i^0(e_i) \neq 0]|$, $\mu \in [-1, 1]$. t_0 and t_1 denote the base period and the reporting period, respectively; $U_i^0(e_i)$ and $U_i^1(e_i)$ denote the order degree of the base period and the order degree of the reporting period of the subsystem, respectively. There are two criteria for measuring the composite system synergy degree. One is using the same moment as the base period, and the results describe the long-term evolutionary dynamics of the composite system. The other is using adjacent moments as the base period, and the results describe the developmental stability of the composite system. In this paper, the former model is used to evaluate the synergy development degree of the composite system. The higher the value of the composite system synergy degree μ, the better the development of the composite system synergy. The classification of synergy degree for composite systems (Wang *et al.* 2019) is shown in Table 2.

Table 2 | Classification of the composite system synergy degree

Synergy degree	Synergy classification
[−1,0)	Severe non-synergy
[0,0.4)	No synergy
[0.4,0.6)	Mild non-synergy
[0.6,0.8)	Basic synergy
[0.8,0.9)	Good synergy
[0.9,1]	Quality synergy

4. RESULTS AND DISCUSSION

Ma'anshan and Nanjing are the subsystems of the synergetic development of transboundary watershed EC. The order degree of each subsystem was obtained according to formula (1) and formula (2). Then, the synergy degree of the composite system of transboundary watersheds was obtained according to formula (3).

4.1. The order degree of subsystems

The order parameters of Ma'anshan from 2011 to 2020 are shown in Figure 1.

As shown in Figure 1, water conservation, economic benefits, and environmental regulation are on the upward trend from 2011 to 2020. From environmental regulation, before the implementation of EC, it maintained stable fluctuations and small growth. After the EC has been taken, the Ma'anshan government has formulated a series of environmental protection laws and regulations, thus it has increased significantly, from 0.236 to 0.928. From economic benefits, the implementation of EC has some impact on the local economy. The attention is that the pollution control ability has increased significantly from 2017 to 2018. It indicated that the Ma'anshan government has taken much effort to improve the watershed ecological environment after Ma'anshan and Nanjing signed the EC agreement. However, when the water quality has been improved to a certain extent, it will take much greater effort to improve it. The order degrees of Ma'anshan from 2011 to 2020 are shown in Table 3.

As shown in Table 3, the order degrees of Ma'anshan were on an upward trend from 2011 to 2020. Especially from 2017 to 2018, it has increased significantly. It indicated that the Ma'anshan government has invested a large amount of funds to restore and protect the watershed ecological environment. However, due to historical reasons, the economic development, water resource protection, and pollution control were still at the non-synergy level. The main reason is that the restoration of the ecological environment is not overnight, and in the early stage of EC, the local government invested much in the environment protection, which impacted the development of the economy. As the improvement of ecological environment, the degree of synergy will improve.

The order parameters and order degrees of Nanjing from 2011 to 2020 are shown in Table 4.

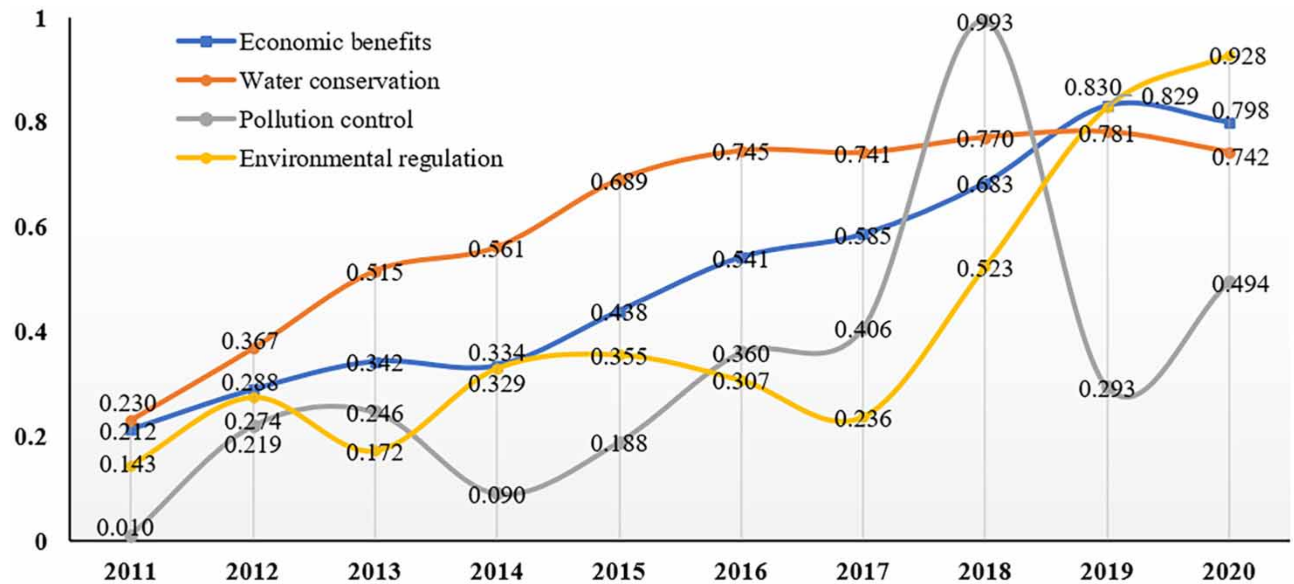


Figure 1 | The order parameters of Ma'anshan from 2011 to 2020.

Table 3 | The order degrees of Ma'anshan from 2011 to 2020

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Order degree	–	0.017	0.016	0.024	0.063	0.098	0.084	0.308	0.257	0.338

Table 4 | The order parameters and order degrees of the Nanjing synergy system from 2011 to 2020

Year	Economic benefits	Water conservation	Pollution treatment	Environmental supervision	Order degree
2011	0.233	0.117	0.085	0.059	–
2012	0.287	0.243	0.232	0.175	0.011
2013	0.360	0.485	0.231	0.217	0.033
2014	0.436	0.499	0.352	0.219	0.058
2015	0.478	0.701	0.519	0.247	0.108
2016	0.521	0.655	0.572	0.368	0.153
2017	0.620	0.738	0.698	0.743	0.317
2018	0.721	0.428	0.914	0.597	0.260
2019	0.808	0.465	0.951	0.741	0.344
2020	0.777	0.422	0.752	0.996	0.322

As shown in Table 4, the economic benefits, pollution treatment, and environmental supervision have improved much from 2011 to 2020. Meanwhile, the order degree has increased gradually from 2011 to 2020. The order degree improved much from 2016 to 2017, but with a decrease from 2017 to 2018. According to the order parameter, water conservation and environmental supervision decreased in 2018, resulting in a decrease in the order degree. In the early stage of EC, the government should make much effort to coordinate the development of the economy and the protection of the environment. It is worth that the order degree is on the upward trend as the implementation of EC. Thus, with the implementation of EC, the synergy will be improved.

4.2. The synergy degree of the composite system

The synergy degree of the Chu River (Ma'anshan–Nanjing) EC is shown in Table 5.

As shown in Table 5, the synergy of composite systems was on the upward trend. In 2020, it has achieved basic synergy, which indicated that the EC in the Chuhe River has achieved certain accomplishments. Although the synergy degree of Ma'anshan was smaller than that of Nanjing, the gap gradually narrowed after 2017. It indicates that the EC can improve the synergy degree of the watershed effectively. To improve the effect of EC and the synergy degree of the complex system, the downstream should pay more subsidy to the upstream in the early stage of EC. The dynamic development of the synergy degree in the Chu River EC is shown in Figure 2.

As shown in Figure 2, the synergy degree of subsystems and the composite system were on the upward trend from 2011 to 2020. The order degree of Nanjing is higher than that of Ma'anshan, which is mainly due to the higher economic benefits and

Table 5 | The synergy degree of the Ma'anshan–Nanjing composite system

Year	Ma'anshan	Nanjing	Synergy degree
2011	0.121	0.116	–
2012	0.270	0.229	0.130
2013	0.278	0.323	0.180
2014	0.278	0.369	0.199
2015	0.358	0.477	0.293
2016	0.430	0.522	0.354
2017	0.432	0.707	0.429
2018	0.754	0.644	0.578
2019	0.633	0.724	0.558
2020	0.724	0.741	0.614

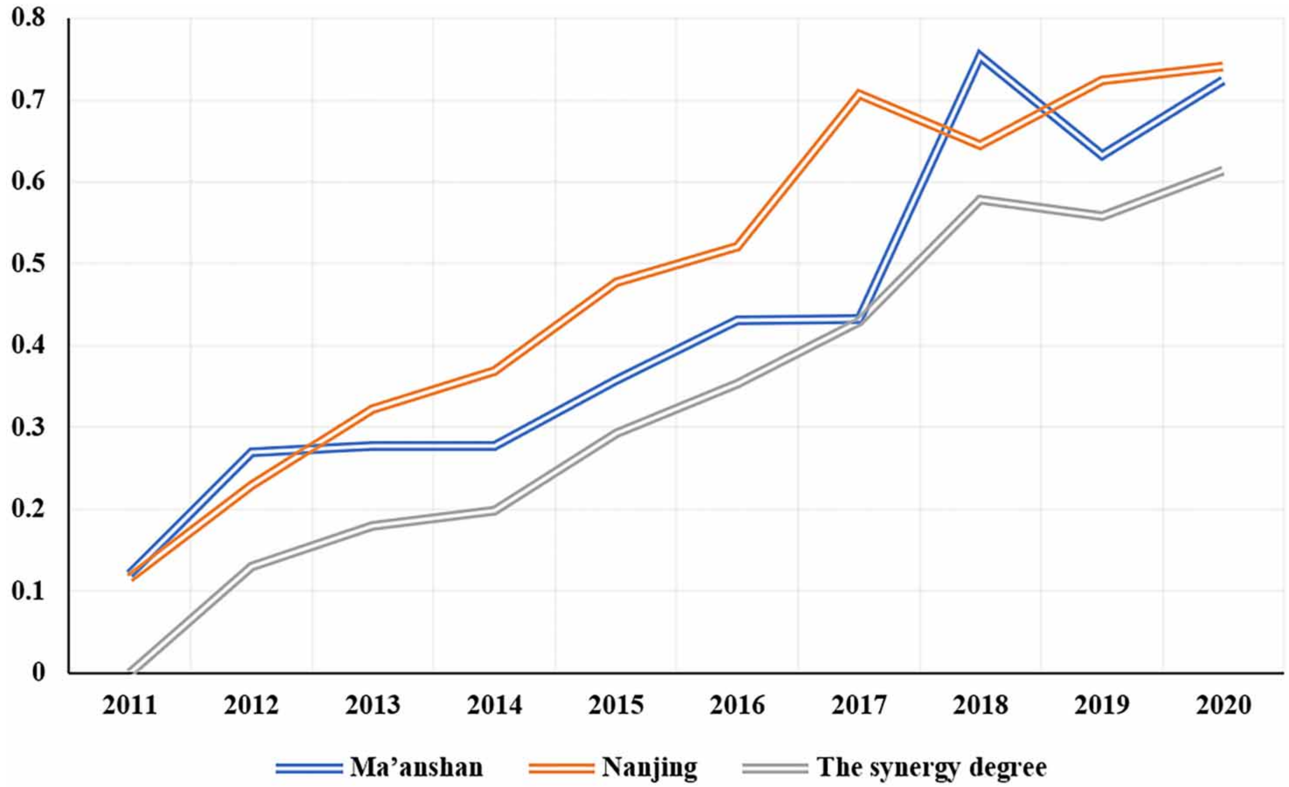


Figure 2 | The synergy degree of the composite system.

environmental supervision ability of Nanjing. From 2017 to 2018, the synergy degree of the composite system has improved much. It indicated that the watershed EC has promoted the sustainable development of the watershed.

5. CONCLUSIONS

The evaluation of watershed EC synergy is important to promoting the sustainable development of the watershed. Based on the synergy degree model of the composite system, this study investigates the synergetic development level of watershed EC in the Chu River. The conclusions are: (1) The synergy degree of the Chu River EC is on the upward trend from 2011 to 2020, and it has reached basic synergy in 2020; that is, the implementation of EC is beneficial for the coordinated development of watershed ecology and socio-economy (Chen *et al.* 2021; Deng & Chen 2022). (2) In the early stage of EC, the downstream should pay more funds to the upstream to improve the synergy degree; i.e., at the beginning pilot of EC, the upstream needs to sacrifice some economic benefits to protect the ecological environment (Gao *et al.* 2019). (3) The upstream (Ma'anshan) takes more effort on the protection of the ecological environment and the downstream (Nanjing) pays more attention to the control of pollution which will improve the synergy degree of the composite system.

This study proposes a method for the evaluation of the effect of watershed EC by assessing and analyzing the synergy development level of transboundary watershed EC between upstream and downstream. In the future study, to improve the effect and synergy degree of EC, the market-based trading of natural resources can be conducted. For example, adopting the digital twin technology to establish the biological resource trading platform; encouraging the public to participate in the watershed EC; and improving the supervision and management mechanisms of watershed ecological products.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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