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Abstract

The dynamic interplay between technological innovations, natural resources, and CO_2 emissions carries significant ecological consequences. Despite its importance, this field remains underexplored by environmentalists, yielding vague and inconclusive outcomes. Furthermore, these studies often lack a precise examination of natural resources' role in shaping environmental quality. Recognizing the imperative need for a more comprehensive and rigorous analysis of the complexities involved in studying CO_2, this research delves into the asymmetric impact of technological innovation and natural resources on CO_2. It does so while taking into account the symmetric influence of economic growth and trade openness over the period from 1980 to 2020. To unravel these connections, the study utilizes the Nonlinear Autoregressive Distributed Lag (NARDL) model and the dynamic multiplier technique. The findings stemming from the NARDL analysis and dynamic multiplier approach reveal that positive shifts in technological innovation and natural resources lead to a reduction in CO_2 emissions, while negative shifts result in an increase. Conversely, trade openness and economic growth are identified as factors that stimulate CO_2, potentially compromising ecological integrity. The empirical insights gleaned from this study pave the way for a range of policy recommendations that can benefit Japan in its pursuit of environmental sustainability**.**

Keywords: CO_2 emissions; Natural Resources; Technological Innovation; Trade Openness; Nonlinear

1. Introduction

Copious natural resources (NR) have long been recognized as a fundamental factor of production, even though their unchecked exploitation can result in long-term economic challenges, often referred to as the "resource curse" (Dogan et al., 2020; Humphreys et al., 2007). Developed countries such as Japan encounter ecological issues associated with carbon emissions (CO_2) at numerous phases, from the initial extraction of NR to their ultimate utilization. As a result, it becomes imperative to curb the rise in CO_2 stemming from resource exploitation. Economic progress drives industrialization, which, in turn, escalates the value of natural resources. Unsustainable exploitation of these resources has adverse ecological consequences, including impacts on deforestation, agriculture, and mining (Singh et al., 2023; Tang et al., 2022). Economic growth also accelerates the depletion of NR, thus, resulting to upsurge in waste generation (Onifade et al., 2022). Furthermore, the initial phase of economic progress fosters the production, consumption, and utilization of polluting goods (Awosusi et al., 2022; Ibrahim et al., 2023).

Ecological challenges, encompassing issues like water pollution, deforestation and global warming, pose a significant threat to the sustainable utilization of NR for future generations. Numerous international conferences have convened to explore alternative strategies for extenuating these ecological problems and realizing SDGs. Nevertheless, despite commitments made via initiatives like the Paris Climate Conference, aimed at plummeting emissions, CO_2 continue to ascend. Simultaneously, the relentless exploitation of NR driven by deforestation, industrialization, and mining contributes to ecological deprivation (Ağa et al., 2023). The exploitation of NR gives rise to profound ecological concerns, including deforestation and rising global temperatures (Irfan et al., 2022; Razzaq et al., 2022). By incorporating sustainable management practices into consumption and production processes, it becomes possible to regulate the rate of NR utilization, a concept recognized as resource rejuvenation (Akram et al., 2023; Ullah et al., 2023). Manufacturing processes in advanced nations predominantly depend on conventional energies. Moreover, these nations often resort to fossil fuels importation to fulfill their energy desires (Adebayo, 2022; Al-Faryan et al., 2023). The implementation of advanced technologies, the enforcement of rigorous ecological regulations, and the transition from industrial to service-oriented sectors within the economy can contribute to long-term contamination lessening, facilitated by robust economic expansion (Ozturk & Acaravci, 2016; Shahbaz et al., 2013). The discourse above naturally prompts an empirical inquiry aimed at comprehending the influence of natural resources on CO_2.

Various economic factors exert an influence on such emissions, with trade openness (TR) being one of the most prominent. TR impacts CO_2 through its effects on scale, composition, and technology. When the combined effects of composition and technology, particularly oriented toward cleaner goods, outweigh the scale effect, trade openness contributes to an enhancement in ecological excellence (Awokuse, 2008; Destek & Sinha, 2020). Conversely, if the composition of manufactured products leans toward more contaminating goods, it tends to have a detrimental impact on ecological excellence. Consequently, no definitive theoretical consensus has been reached on this matter. In light of this, several studies have delved into the empirical exploration of the interrelationship between trade openness and CO_2. However, due

to the diversity of results obtained, a definitive consensus remains elusive. For example, certain studies indicate that TR results in an upsurge in CO_2 and a deterioration of ecological excellence (Li & Haneklaus, 2022; Omri & Saadaoui, 2023). These investigations contend that stringent ecological regulations in advanced economies lead contamination-intensive industries to shift to emerging nations, effectively converting these emerging nations into "pollution havens" via a combination of scale and composition effects. On the contrary, research by Ibrahim & Ajide (2021), Pata & Caglar (2021) and Wang et al., (2022) argues that the positive impacts of TR, particularly in terms of technology and knowledge spillovers, bolster ecological integrity. Nevertheless, Udeagha & Breitenbach (2023) postulates that the influence of TR on CO_2 is contingent upon a nation's economic progress. Consequently, the interrelationship between TR and CO_2 is far from universal, prompting a need for additional examination into the intricate effects of TR on the environment. With this objective in mind, this study endeavors to assess the correlation between TI, NR, EG, TR, and CO_2 in Japan.

Japan has made substantial strides over the past decade in realizing its vision of an efficient, resilient, and sustainable energy system. The nation's robust foundation in innovation and technology is poised to play a pivotal role in the development of the necessary technologies to achieve its goal of attaining carbon-neutrality by 2050 (IEA, 2023). Japan's energy policy is firmly grounded in the principles of energy security, economic efficiency, environmental sustainability, and safety. In recent years, Japan has taken steps to diversify its energy sources, optimize the efficiency of fossil fuel usage, and curtail energy consumption. Although the country's greenhouse gas emissions reached a peak in 2013 due to the temporary closure of nuclear plants following the Fukushima incident, by 2018, they had decreased to levels last seen in 2009 (IEA, 2023). Reaching the target of achieving carbon-neutrality by 2050 will necessitate Japan significantly expediting the deployment of low-carbon technologies by 2030. This will require addressing regulatory and institutional barriers while further bolstering competition within its energy markets. It is also imperative to develop various decarbonization scenarios and prepare for the possibility that certain low-carbon technologies, like nuclear power, may not expand as rapidly as initially envisioned (IEA, 2023). Incorporating a greater reliance on market-driven mechanisms, such as carbon pricing, could be a viable policy option for Japan. This approach has the potential to cost-effectively reduce emissions, stimulate innovation, and reinforce the nation's already commendable energy efficiency levels.

This research contributes to the existing literature in several significant ways: (i) By scrutinizing the environmental impact of TI and NR, the study's model incorporates controls for EG and TR in the context of Japan. (ii) The research takes into account the asymmetric effects of both TI and NR on CO_2. (iii) Additionally, it marks the initial attempt to assess the roles of NR, TI, TR, and EG in shaping CO_2 while considering the asymmetric effects of NR and TI. (iv) Lastly, this study employs the innovative NARDL model and the dynamic multiplier technique to provide insights for policymaking, covering the period from 1980 to 2020. The NARDL, in particular, serves as a valuable time series approach for estimating both long and short-term dynamics, taking into consideration both positive and negative shifts in the regressors.

The subsequent sections of this study are outlined as follows: Section II presents the literature review, while Section III expounds on the data and model utilized in the study. Section IV presents the empirical analysis results. Finally, Section V encompasses policy recommendations and the study's conclusions

2. Literature Review

In addressing the factors influencing CO_2 and their associated economic and environmental implications, various policies have been set in motion, guided by recommendations from multiple intergovernmental organizations. The detrimental consequences arising from the release of CO_2 into the atmosphere have prompted numerous countries to reevaluate their policy frameworks. These climate change-induced effects encompass issues such as extreme weather conditions, droughts, encroachment of deserts, severe winters, and more. While these detrimental effects are well-recognized by many nations, their steadfast pursuit of pro-growth agendas often complicates their transition toward more sustainable practices. This increase in CO_2 can be attributed to several factors, including natural resources, trade openness, technological innovation, and economic growth.

Studies exploring the relationship between natural resources (NR) and CO_2 have been extensively documented in the literature, revealing a range of findings. For instance, in the case of NICs, (Onifade et al., 2022) delved into the drivers of CO_2 with a particular focus on NR as a determinant. Their study employed the MMQR approach, yielding results indicating a positive influence of NR on CO_2, thus potentially compromising ecological integrity. Conversely, when examining BRI nations, (Khan et al., 2021) took a distinct approach by investigating the drivers of CO_2 using panel estimators. Their findings pointed to NR as a primary contributor to ecological harm within the BRI nations. In a similar vein, in a study encompassing 31 advanced economies, (Muhammad & Khan, 2021) employed GMM estimators and data spanning from 1990 to 2018 to explore the drivers of CO_2, placing a particular emphasis on NR as a potential culprit. Their results suggested that the growth in CO_2 was attributable to an increase in NR. Similarly, in their research involving BRICS nations, (Caglar et al., 2022) aimed to align with the SDGs by utilizing a nonlinear approach to investigate the drivers of CO_2. Their findings underscored the significant role of NR in exacerbating CO_2.

Numerous studies have been conducted to examine the intricate relationship between economic growth (EG), technological innovation (TI), and CO_2. These investigations span the fields of energy and environmental literature, offering valuable insights. For instance, (Adebayo & Kirikkaleli, 2021) employed time-frequency techniques to propose SDGs for Japan. Their study delved into the drivers of CO_2 within the context of Japan, spanning the period from 1990 to 2015. The authors focused on the roles of EG and TI, and their results revealed that both EG and TI contribute to CO_2, potentially enhancing ecological integrity. Similarly, (Ojekemi et al., 2022) directed their attention to formulating SDGs initiatives for the BRICS nations as a whole. They investigated the determinants of CO2 emissions in this group of countries, covering the timeframe from 1990 to 2018. EG and TI were the focal points of their analysis, and the utilization of the AMG estimator unveiled a complex relationship. Their findings suggested that TI played a role in reducing CO_2, while the impact of GDP was detrimental to the ecosystem. In another study involving the OECD economies from 1990 to 2018, (Dong et al.,

2018) identified EG and TI as key drivers of CO_2. Their results indicated that TI had a role in mitigating CO_2, while EG emerged as a prominent contributor to CO_2. In the case of Portugal, (Adeshola et al., 2022) explored the adverse impact of CO_2 on the ecosystem. Their study, utilizing wavelet analysis, focused on EG and TI as the primary variables of interest. Their results underscored that both EG and TI played significant roles in causing ecological damage.

The literature has extensively examined the impact of trade openness on ecological quality, revealing a spectrum of findings. For instance, in their pursuit of SDGs, (Chhabra et al., 2022) utilized GMM estimators and data spanning from 1994 to 2018 to investigate the determinants of CO_2. Their study focused on the role of trade openness (TR), and their results indicated that an increase in TR amplified CO_2, particularly in the upper quantiles, with more pronounced effects compared to the lower and middle quantiles. In a different approach, (Udeagha & Breitenbach, 2023) employed the NARDL methodology to explore CO_2 drivers, including TR, in the context of the SADC. Their study covered the period from 1960 to 2020, and the results revealed that an increase (or decline) in TR intensified (or mitigated) CO_2 in the SADC nations. Similarly, within the framework of the EKC, (Li & Haneklaus, 2022) focused on the case of China to investigate CO_2 with TR as a central variable. Their analysis encompassed data from 1992 to 2022, and their findings indicated that an increase (or decline) in TR intensified (or mitigated) CO_2 in China. Additionally, (W. Wang et al., 2022) conducted an analysis that yielded similar results for the G7 nations. Their study, employing data from 1990 to 2020 and the CS-ARDL estimator, established the pivotal role of TR in exacerbating ecological deterioration within the G7 nations.

3. Data and Methods

3.1. Data

In this section, we provide an overview of the data used in the study, with a particular focus on the dependent variable (CO_2) and the independent regressors (EG, NR, TI, and TI). The dataset spans from 1980 to 2020, as the analysis commences in 1980 due to the absence of available TI data before that year. The sources of the data, as well as their measurement units and corresponding abbreviations, are presented in Table 1. Furthermore, following the approach advocated by (Korkut Pata et al., 2022) and (Adebayo & Alola, 2023), we applied a logarithmic transformation to the series, encompassing CO_2, EG, NR, TI, and TI. Furthermore, we illustrate the evolution of the utilized variables, as depicted in Figure 1.

Table 1: Descriptive Statistics

Sign	Variables	Measurement	Source
EG	Economic Growth	Per Capita 2015 US$ Constant	WB (2022)
NR	Natural resurces	% of GDP	WB (2022)
TI	Technological Innovation	Addition of patent resident and nonresident	WB (2022)
CO_2	Carbon emissions	Per Capita	OWD (2022)
TR	Trade Opnness	% of GDP	WB (2022)

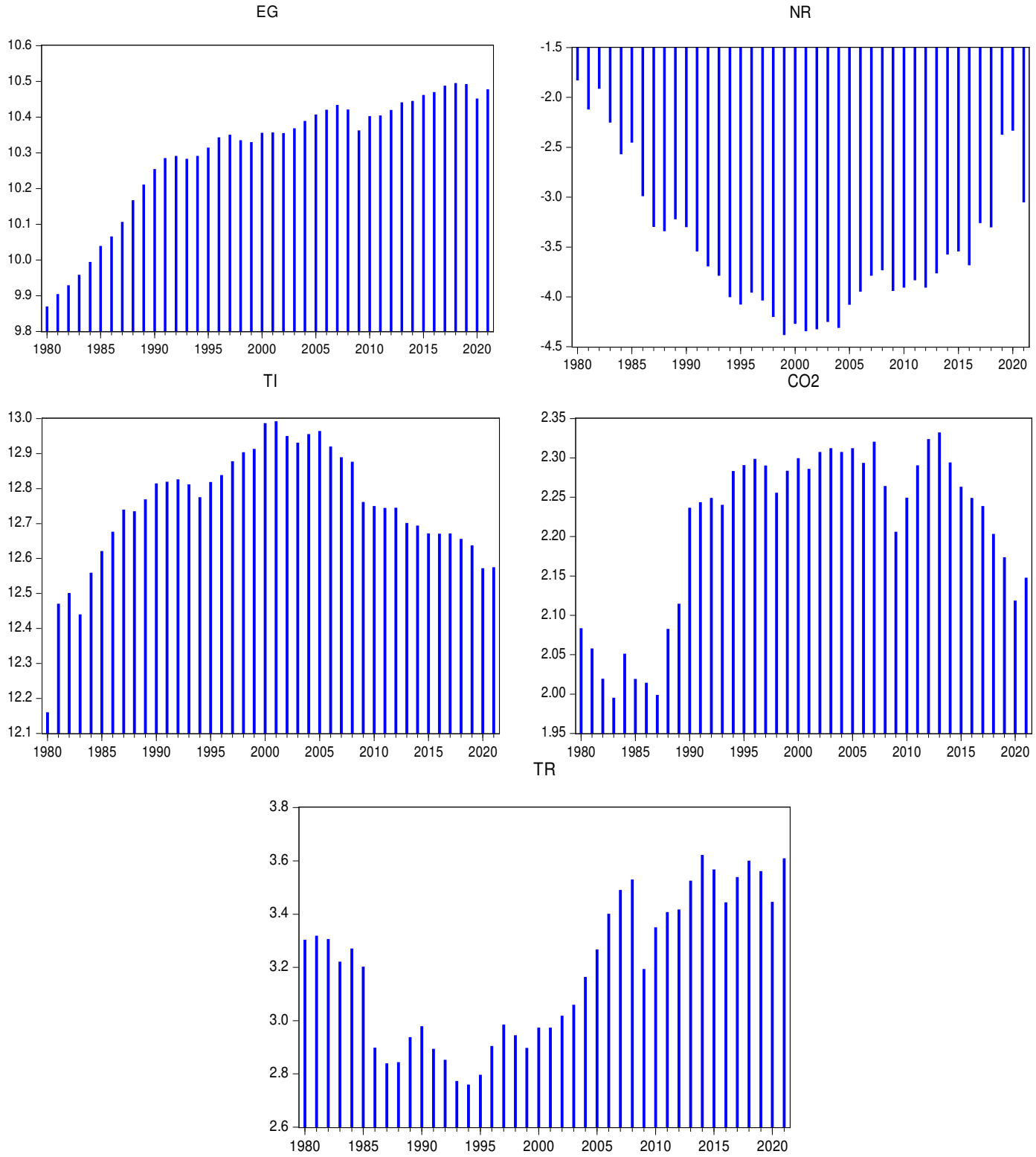


Figure 1: Trend of EG, NR, TI, TR and CO_2

3.2. Methods

To begin with the initial assessment, this study employed the widely recognized ADF and PP tests, which are the two most commonly utilized unit root tests. The primary objective of this initial step was to ascertain the stationary properties of the variables under investigation.

Subsequently, the study ventured into the realm of nonlinear autoregressive distributed lag (NARDL) analysis, as introduced by (Shin et al., 2014). The NARDL framework represents a significant advancement beyond traditional ARDL modeling. In this study, the NARDL approach was harnessed to unravel the intricate interrelationship between CO_2 and its determinants. When dealing with time series data that exhibit characteristics of order 1(0), 1(1), or a combination of both 1(0) and 1(1), the asymmetric ARDL method was deemed appropriate for analysis.

The NARDL methodology necessitated a judicious selection of lags to capture the dynamic relationships, while also addressing concerns related to endogeneity. An adept choice of lag periods was paramount in resolving the potential challenges stemming from multicollinearity within the NARDL framework. Additionally, the study segmented the variables based on their respective positive and negative shifts, employing the NARDL approach for this purpose. Consequently, our fundamental model dissects technological innovation (TI) and natural resources (NR) into opposing dynamics, encompassing negative and positive motions. The transformation of series into shocks was executed in the following manner: (TI^+, TI^+, NR^+, NR^+).

$$\Delta CO_{2t} = \sigma_0 + \sum_{i=1}^{t} \sigma_1 \Delta CO_{2t-1} + \sum_{i=1}^{t} \sigma_2 EG_{t-1} + \sum_{i=1}^{t} \sigma_3 \Delta TR_{t-1} + \sum_{i=1}^{t} \sigma_4 \Delta NR_{t-1} + \sum_{i=1}^{t} \sigma_5 \Delta TI_{t-1} + \varphi_1 CO_{2t-1} + \varphi_2 EG_{t-1} + \varphi_3 TR_{t-1} + \varphi_4 NR_{t-1} + \varphi_5 TI_{t-1} + \varpi_t \quad (1)$$

Equation 1 furnishes estimates for symmetric effects. Nonetheless, to scrutinize the asymmetric consequences of technological innovation (TI+ and TI−) and natural resources (NR+ and NR−) on carbon emissions, we employ the innovative nonlinear ARDL (NARDL) estimator.

$$NR^+ = \sum_{i=1}^{t} \Delta NR^+ \sum_{i=1}^{t} \max(NR_i, 0) \quad (2)$$

$$NR^- = \sum_{i=1}^{t} \Delta NR^- \sum_{i=1}^{t} \min(NR_i, 0) \quad (3)$$

$$TI^+ = \sum_{i=1}^{t} \Delta TI^+ \sum_{i=1}^{t} \max(TI_i, 0) \quad (4)$$

$$TI^- = \sum_{i=1}^{t} \Delta TI^- \sum_{i=1}^{t} \min(TI_i, 0) \quad (5)$$

In continuation of Equations 2–3, the NARDL model can be formulated in accordance with Equation 1, considering both their positive and negative shocks as depicted below:

$$\Delta CO_{2t} = \sigma_0 + \sum_{i=1}^{t} \sigma_1 \Delta CO_{2t-1} + \sum_{i=1}^{t} \sigma_2 EG_{t-1} + \sum_{i=1}^{t} \sigma_3 \Delta TR_{t-1} + \sum_{i=1}^{t} \sigma_4 \Delta NR_{t-1}$$
$$+ \sum_{i=1} \sigma_5 \Delta NR^{+}_{t-1} + \sum_{i=1} \sigma_6 \Delta NR^{-}_{t-1} + \sum_{i=1} \sigma_7 \Delta TI^{+}_{t-1} + \sum_{i=1} \sigma_8 \Delta TI^{-}_{t-1} + \varphi_1 CO_{2t-1}$$
$$+ \varphi_2 EG_{t-1} + \varphi_3 TR_{t-1} + \varphi_4 NR^{+}_{t-1} + \varphi_5 NR^{-}_{t-1} + \varphi_6 TI^{+}_{t-1} + \varphi_7 TI^{-}_{t-1}$$
$$+ \varpi_t \qquad (6)$$

The assessment of nonlinear cointegration is conducted through the Bounds test, following a rule of thumb which entails rejecting the null hypothesis in NARDL when the F-statistic exceeds the lower and upper bound critical values. Figure 2 unveiled the trend of the techniques employed.

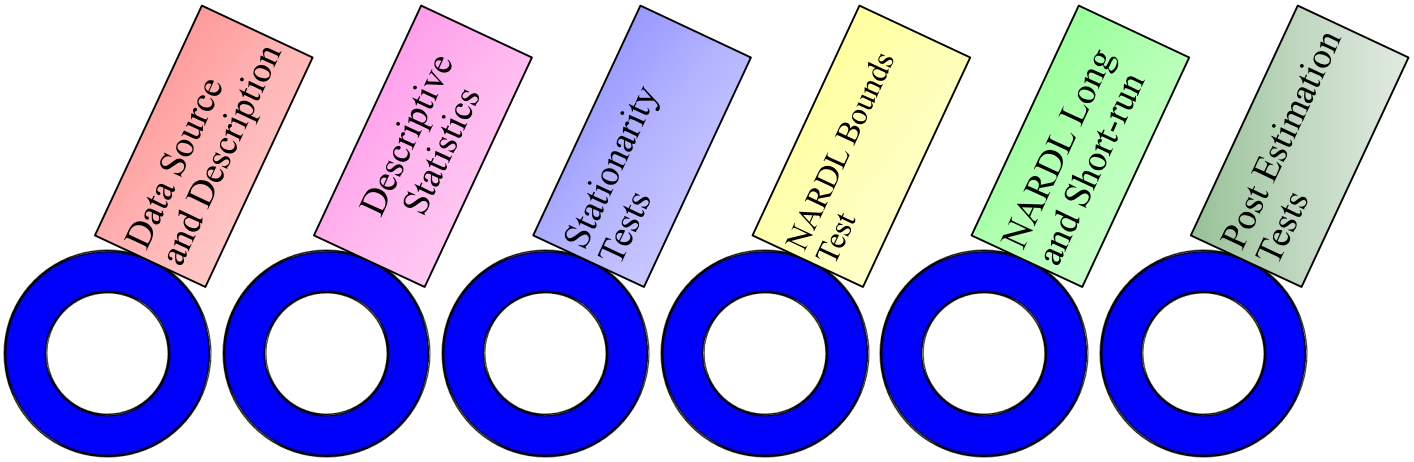


Figure 2. Analysis Process

4. Findings and Discussions

4.1. Descriptive Analysis

Table 2 provides an overview of the statistical characteristics of the variables under investigation. The mean values for CO_2, EG, NR, TI, and TR are 2.2120, 10.301, -3.4869, 12.74, and 3.1927, respectively. Notably, the standard deviation of NR indicates a relatively high level of volatility compared to the other series, whereas CO_2 exhibits lower volatility. Furthermore, CO_2, EG, and TI demonstrate negative skewness, while NR and TR display positive skewness. Additionally, TI exhibits leptokurtic behavior as its kurtosis value exceeds 3, while CO_2, EG, NR, and TR exhibit platykurtic tendencies, with kurtosis values below 3.

Table 2: Data statistical Properties

	CO_2	EG	NR	TI	TR
Mean	2.2120	10.301	-3.4869	12.747	3.1927
Median	2.2494	10.355	-3.7114	12.755	3.2119

Maximum	2.3325	10.495	-1.8269	12.992	3.6225
Minimum	1.9951	9.8696	-4.3829	12.160	2.7606
Std. Dev.	0.1067	0.1757	0.7194	0.1703	0.2779
Skewness	-0.8580	-1.1265	0.8567	-1.0246	0.0161
Kurtosis	2.2777	3.1428	2.6710	4.6991	1.5706
Jarque-Bera	6.0662	8.9199	5.3274	12.402	3.5776
Probability	0.0481	0.0115	0.0696	0.0020	0.1671

Next, we explore the data's stationarity features by resting on the PP and ADF tests which are reported in Table 3. The results as shown by these tests disclosed that at level, EG, TR, NR and CO_2 are nonstationary, while TI is stationary at level. Nonetheless, the series including EG, TR, CO_2 and NR becomes stationary after first difference; thus suggesting that the investigated series exhibit I(1) and I(0) but they do not exhibit I(2) behavior.

Table 3: Data Stationarity Results

	ADF	ΔADF	PP	ΔPP
EG	-2.1679	-5.2158***	-2.0531	-5.2188***
TR	-2.2352	-5.8381***	-2.1265	-5.8905***
NR	-1.6322	-5.0535***	-1.5044	-7.3139***
TI	-3.6125**		-3.6584**	
CO_2	-0.6180	-5.4839***	-0.7844	-5.4512***

Note: *** P<1% and **P<5%

4.2. NARDL Bounds Test

The bounds test which captures the long-run cointegration between variables is deployed in evaluating the long-run association between the indicators. The outcomes of the ANRDL bounds test as shown in Table 4 display that the investigated series are cointegrated; thus, suggesting long-run association. This discovery gives room for further analysis by exploring the regressor's impact on CO_2.

Table 4: Bounds Test

	Value	Signif.	I(0)	I(1)
F-statistic	5.9449***	10%	2.12	3.23
	6	5%	2.45	3.61
		2.5%	2.75	3.99
		1%	3.15	4.43

Note: ***P<0.01

4.3. NARDL Results

Once the confirmation of cointegration is established, the study takes a divergent approach, examining the nonlinear interrelationship between CO_2 and its drivers (EG, TR, NR, and TI) (see Table 5). Initially, the impact of EG on CO_2, observed from both a long-term and short-term perspective, is found to be positive. These findings underscore the fact that EG exerts a positive influence on CO_2, resulting in an increase in ecological squalor in Japan. This

revelation highlights a concerning trend in Japan, signaling unsustainable growth in both the short and long term. Consequently, there is a pressing need for Japan to realign its policies to steer toward ecological sustainability. Additionally, it is imperative for Japan to gradually reduce its heavy reliance on fossil fuel-based energy, primarily utilized in production. Transitioning from such polluting energy sources to cleaner alternatives would not only promote sustainable development but also benefit the environment. These findings align with similar conclusions drawn by (Awosusi et al., 2023), as well as (Destek & Sinha, 2020) and (Acheampong, 2018), all of whom have emphasized the unsustainable role of EG in ecological dilapidation.

Moreover, we discovered both in the short and long-term that growth in CO_2 is attributed to the expansion in TR in Japan. The discovery demonstrates that expansion in TR promote ecological deterioration. This perspective is also corroborated by prior studies including (Udeagha & Breitenbach, 2023), (Destek & Sinha, 2020) and (Chhabra et al., 2022). According to (Ibrahim et al., 2022), heightened trade activity has the potential to trigger greater resource extraction, especially in nations abundant in natural resources. This can have consequences such as the destruction of habitats, deforestation, and an upsurge in contamination, all of which have adverse effects on ecological excellence. Additionally, trade can incentivize the relocation of industries to nations with less stringent ecological guidelines. This can lead to an increase in contamination and the release of GHGs, further exacerbating issues linked to water and air contamination and adding to climate change, all of which have detrimental impacts on the ecosystem (Chhabra et al., 2022). Furthermore, the transport of goods over extended distances, are usually associated with trade intensification, as a result can result in higher CO_2 from the transport sector, which in turn adds to air contamination and the release of GHGs

Table 5: NARDL Results

	Long-run Results			Short-Run Results		
Variable	Coefficient	t-Statistic	Prob	Coefficient	t-Statistic	Prob
EG	0.3732**	2.2125	0.0342	0.5240*	2.0256	0.0532
TR	0.1252***	2.9271	0.0062	0.1121**	2.3406	0.0272
NR (+)	-0.0651***	-3.1993	0.0031	-0.0353	-1.5418	0.1352
NR (-)	-0.0077	-0.2324	0.8176	-0.0042	-0.1548	0.8781
TI (+)	-0.0608***	-3.4276	0.0000	-0.7319***	-2.8920	0.0076
TI (-)	-0.1151	-1.0025	0.3236	0.0754***	3.3074	0.0000
ECT(-1)	-	-	-	-0.5188***	-5.9847	0.0000
C	-2.7375	-1.7056	0.0978			
R^2	0.9524					
Adj R^2	0.9405					
S.E. of reg	0.0258					

Note: ***P<0.01, **P<0.05 and P<0.1

In the context of a positive shift in NR, its influence on CO_2 is negative, indicating that an increase in natural resources contributes to ecological improvement. Conversely, a negative shift in NR, while also having a negative impact, does not lead to an enhancement in ecological excellence in Japan. In essence, we can deduce that a long-term positive shift in NR benefits

the ecological integrity of Japan. This discovery aligns with the viewpoints of previous studies (e.g., Ali et al., 2022; Ampon-Wireko et al., 2022; Azam et al., 2023; Razzaq et al., 2022), which have likewise highlighted the constructive role of natural resources in mitigating ecological dilapidation. As emphasized by Wang et al., (2023), natural vegetation, comprising grasses and trees, plays a pivotal role in averting erosion and stabilizing soil, especially in regions prone to landslides. Furthermore, numerous natural environments offer habitats for pollinators such as butterflies and bees, which are indispensable wild plant pollination and for crop. The preservation of these environments guarantees the continued accessibility of pollination services (Ağa et al., 2023). Additionally, natural river systems and wetlands have the capacity to engross excess water during heavy rainwater, mitigating the risk of flooding. This flood regulation function holds paramount significance for the well-being of both human communities and environments. Furthermore, the sustainable harvesting of NR can yield essential commodities while safeguarding the long-term sustainability and vitality of environments.

Similarly, in Table 6 above, our findings provide significant negative evidence regarding the positive impact of TI on CO_2 in Japan. However, in the case of the negative shift in TI, although the effect is negative, we do not observe substantial support for its impact on CO_2. This underscores that an increase in TI in Japan contributes to the growth of ecological integrity in the country. In the short term, positive (negative) shifts in TI result in the reduction (increase) of CO_2. This suggests that TI is a sustainable driver in Japan, aligning with the country's progress towards achieving SDG 8. These results are in line with the findings of previous studies by (Abbasi et al., 2022) and (Acheampong et al., 2022), both of which underscore the effective role of TI in mitigating CO_2. Nonetheless, our discovery contrasts with the research by Adebayo & Kirikkaleli (2021) in the case of Japan, where they emphasized in their study that TI increases CO_2, potentially harming the ecosystem. In contrast, innovations in the industrial and transportation sectors have the potential to lessen GHGs and contaminants, thus playing a role in bolstering greener air and a healthier ecosystem. Additionally, the utilization of waste management and advanced recycling technologies can mitigate the ecological consequences associated with waste dumping. Furthermore, the adoption of precision agriculture technologies enables farmers to crop production optimization while plummeting reliance on fertilizers and pesticides, thereby lessening the impact on environments.

The ECT is anticipated to exhibit a negative and statistically significant value. As indicated by the outcomes presented in Table 6, the ECT value is indeed negative (-0.55) and statistically significant. This suggests that approximately 51% of short-term deviations can be corrected to reestablish equilibrium in the long term.

4.4. Post Estimation Results

Having established the connection between the variables through NARDL analysis, our model underwent a battery of post-estimation tests, encompassing serial correlation, heteroskedasticity, normality, and Ramsey tests. The results of these tests indicate the absence of serial correlation, the absence of heteroskedasticity, normal distribution of residuals, and the absence of model misspecification. Furthermore, the model exhibits stability, as demonstrated by the CUSUM and CUSUM of squares, as illustrated in Figure 3a and b.

Table 2: Diagnostic Tests

Tests	Pvalue	Decision
Serial Correlation	0.447	No issue of serial correlation
Heteroskesdascity	0.206	No sign of heteroskesdascity
Normality	0.366	Residuals are distributed normally
Ramsey	0.197	No mispecification

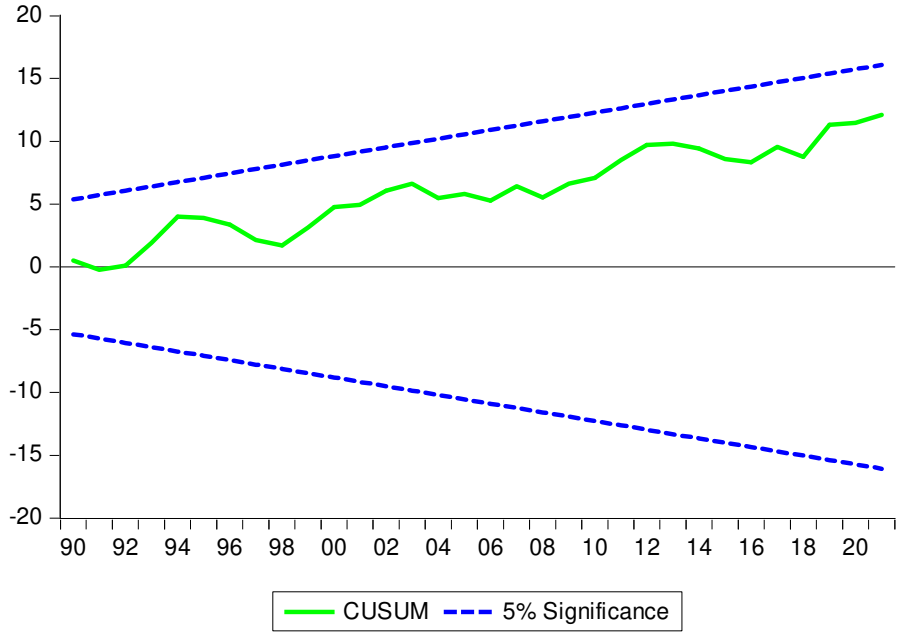


Figure 3a: CUSUM

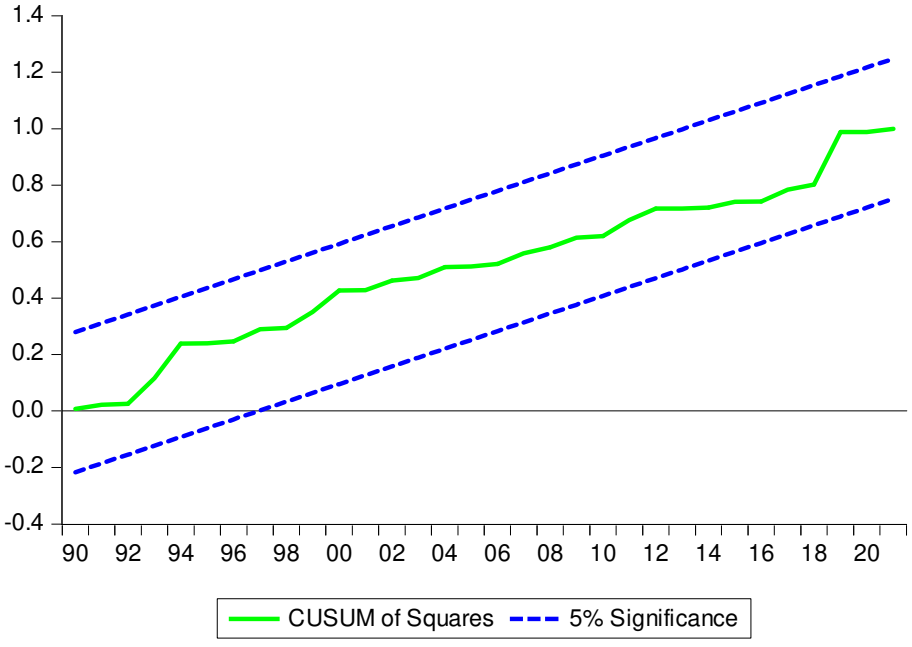


Figure 3b: CUSUM of Squares

4.5. Dynamic Asymmetric Multiplier

The results of the dynamic asymmetric multiplier analysis are visually represented in Figure 4, showcasing the dynamic adjustment process for NR and TI. Figure 4a and 4b provide an overview of CO_2 adjustment in response to NR and TI, considering various time lags and both unfavourable and favourable shifts. The blue-dotted lines in the figure illustrate the magnitude and variability of asymmetric alterations between favourable and unfavourable shifts, indicating their statistical significance. These findings contribute to our understanding of ecological integrity. In addition, the red-dotted and solid red lines represent negative and positive changes, with the vertical axis illustrating the magnitude of these changes and the horizontal axis denoting the time horizon. The dynamic multiplier results indicate the presence of both positive and negative shifts in NR and TI over time. Figure 4a and 4b offer a concise summary of these findings. Specifically, the results showcase that positive shift in TI lead to a mitigation in CO_2 over the time horizon, while negative shifts in TI result in increased CO_2. Similarly, positive shifts in NR are associated with a decrease in CO_2 across the time horizon, while negative shifts in NR lead to increased CO_2.

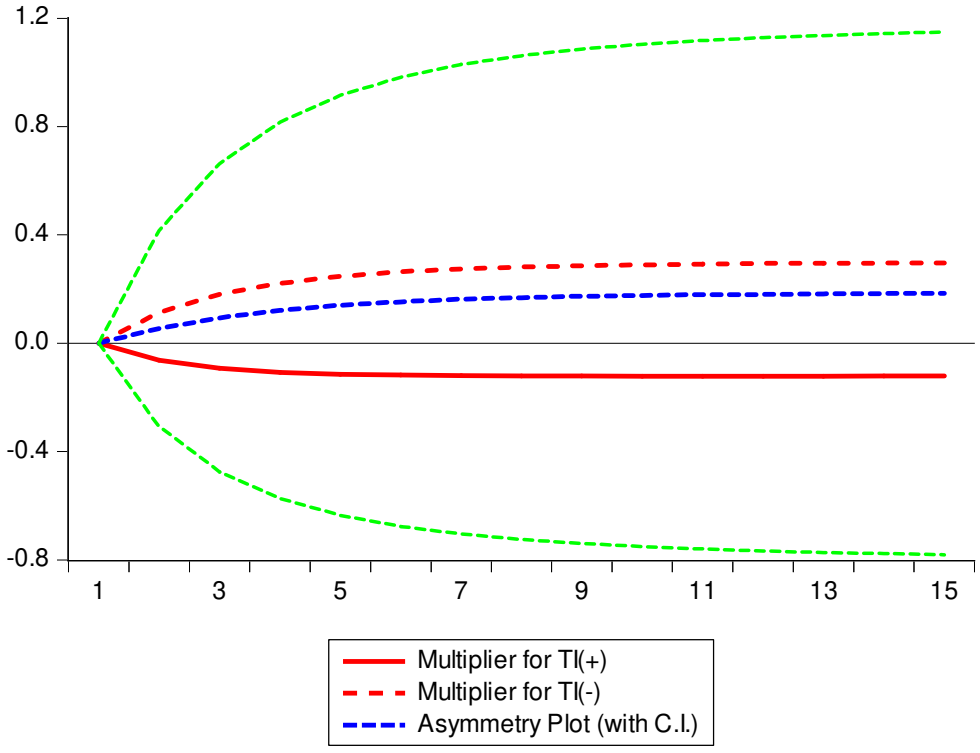


Figure 4a: multiplier for TI

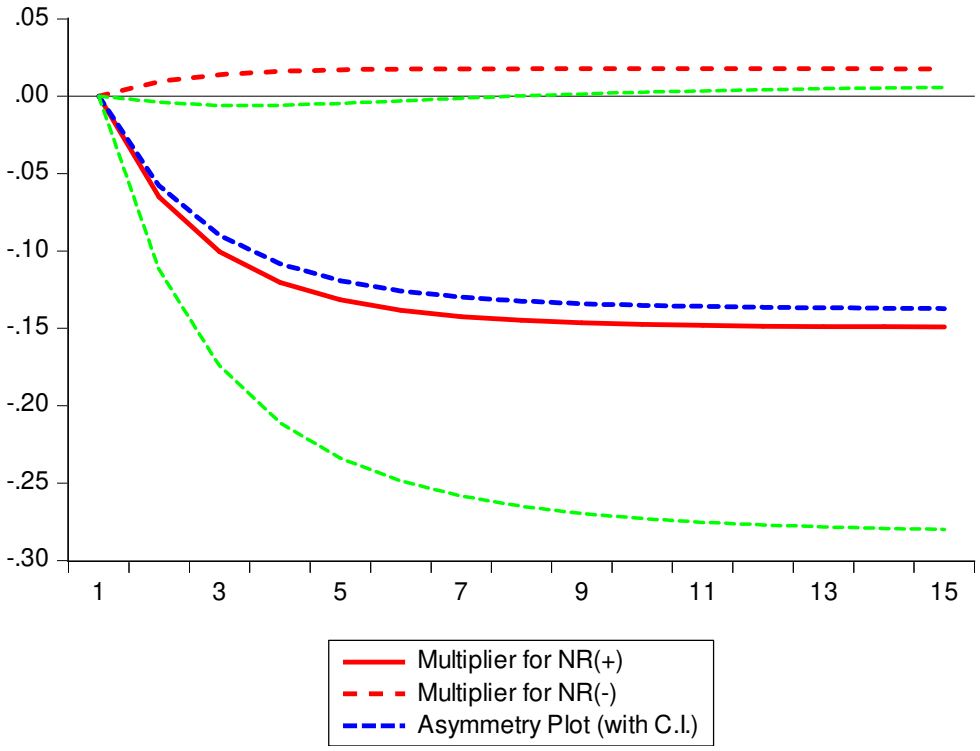


Figure 4b: multiplier for NR

5. Conclusion and Policy Directions

5.1. Conclusion

Our empirical investigation contributes significantly to enhancing our comprehension of the roles played by natural resources and technological innovation in mitigating CO2 and fostering ecological integrity in Japan. Furthermore, our investigation has yielded intriguing results, particularly concerning sustainability, which offers vital policy insights. The outcomes from our nonlinear ARDL analysis and dynamic multiplier approaches indicate that positive (negative) shifts in technological innovation and natural resources result in a reduction (increase) of CO_2. In contrast, trade openness and economic growth are found to stimulate CO_2 emissions, thus potentially undermining ecological integrity. In light of these compelling findings, it becomes imperative to recognize that during phases of economic growth in Japan, environmental pollution is likely to increase. As the Japanese economy continues to expand, there is an inherent risk of environmental degradation, particularly if there is increased reliance on inexpensive but environmentally harmful energy sources such as fossil fuels. Consequently, fostering advancements in technological innovation is crucial in reducing environmental emissions in Japan. Additionally, the adoption of alternative energy sources, notably renewables, is paramount to achieving the goal of carbon neutrality in Japan and curtailing CO_2.

5.2. Policy Directions

In light of the above, the following targeted suggestions will be valuable in addressing this matter:

Sustainable economic growth presents a multifaceted interrelationship with CO_2. Initially, economic growth tends to raise CO_2. However, as economies progress to higher levels of growth, a notable reduction in CO_2 becomes discernible. This phenomenon can be attributed to an increased focus on ecological concerns and a commitment to preserving the ecosystem. Consequently, the imperative lies in the pursuit of inclusive economic progress and developmental activities that prioritize ecological conservation. The acceptance of green growth measures, the integration of clean technologies, eco-friendly industrialization and sustainable urbanization all play instrumental roles in fostering sustainable EG. In this context, the implementation of well-conceived and effective policy initiatives becomes indispensable

Moreover, in order to mitigate the impact of NR exploration, it is imperative to integrate sustainable principles and frameworks into the process of resource exploration in Japan. These approaches should encompass the concept of "green exploration" and enhanced regulations concerning mineral water and soil management. This proactive stance will contribute to a lessening in CO_2 and the promotion of ecological excellence. Additionally, penalties should be imposed on those who violate these regulations to safeguard both the ecosystem and resources. Furthermore, policymakers in Japan should consider employing subsidies and tax incentives as motivators to encourage corporations to adopt "eco-friendly technologies" for their NR exploration endeavors.

Conversely, the liberalization of trade presents a viable approach to mitigating CO_2, as it facilitates the widespread expansion and exchange of sustainable energy products, technologies, and services on a global scale. Consequently, we propose that policymakers and governments in Japan consider a controlled and gradual opening of its economy to increased foreign trade. Simultaneously, Japan should prioritize the preservation of national well-being by actively pursuing energy efficiency through the transition to green energy sources.

The advancement of green technology and the adoption of green energy sources hold significant potential for curtailing CO_2. Positive stimuli from TI contribute to a lessening in CO_2, while negative shocks do not significantly affect CO_2. Consequently, substantial investments in green technology innovations, coupled with sound management of economic activities, can facilitate a noteworthy CO_2 mitigation Japan. To this end, Japanese governments should augment their investments in green TI. Furthermore, addressing the issue of ecological squalor necessitates the promotion of renewables at both household and commercial levels. This can be accomplished via the provision of incentives, such as price subsidies for renewables. Additionally, businesses should be mindful of the ecological impact of their operations by integrating renewables solutions and fostering the development of TI that foster ecological sustainability.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate This study follows all ethical practices during writing

Consent for publication

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Competing interests

The authors declare no competing interests

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