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Haoliang Fu, Pengyu Huang, Yang Xu & Zhukai Zhang

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Digital trade and environmental sustainability: the role of financial development and ecological innovation for a greener revolution in China

Haoliang Fu[a], Pengyu Huang[b], Yang Xu[c] and Zhukai Zhang[b]

[a]School of Finance, Guangdong University of Finance and Economics, Guangzhou, PR China; [b]School of Business, University of Chinese Academy of Social Sciences, Beijing, PR China; [c]School of Finance, Jilin University of Finance and Economics, Changchun, PR China

ABSTRACT

China's government has pledged to attain net-zero emissions by 2050 and aims to create the world's most resilient and forward-looking border by 2025. It has outlined a high-level vision for digital trade and a freeport plan and guarantees to implement new free trade agreements, develop infrastructure, and equalise the economy. Therefore, this study explores the dynamic impact of digital trade and financial development on ecological sustainability from 2000-Q1 to 2020-Q4. We apply the Bootstrap ARDL model for empirical analysis and found that digital trade in goods and services, financial development, and green innovation are conducive to long-term environmental sustainability. Similar results are also observed in the short run; however, the influence of short-run parameters is relatively lower. Moreover, the error correction term endorses convergence towards stable equilibrium with a 32.7% quarterly adjustment rate. Granger causality test report uni-direction casualty in all variables, except green innovation and carbon emissions. These findings recommend an inclusive policy for promoting digital trade, financial integration, and green innovation in China.

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1. Introduction

In the early 1990s, people had limited access to banks and financial institutions for investing their money and had a low tendency to push upwards from lower-income to higher class. Therefore, the derivation of financial services was a significant obstacle for the people. According to the report of global partnership on financial inclusion 2020, nearly 30% of the world's people still lack access to financial institutions since 2011. A strong, liberal, well-structured financial framework can only be a prerequisite for high-quality economic development (Irfan et al., 2022; Razzaq et al., 2022). China has adopted economic reform and sustainable development policies that serves banks and boosts environmental quality. The significance of banks' financial

CONTACT Yang Xu xuyangjilin@sina.com

system and its role in generating credit has been debated. It has greatly influenced economic progress over several decades (Gheisari et al., 2021). The critical function of banks is the production of credit or deposits. Banks, like other businesses, want to make money due to accepting demand deposits and making consumer credit advances to make this determination. Financial development is essential in fostering Gross Domestic Product (GDP) by boosting industry investments (Pham & Huynh, 2020). It also stated that fading economies must expand their capital markets (Gao et al., 2022; Razzaq, An, et al., 2021).

A well-organised financial institute facilitates the smooth operation of channelling funds from investors to debtors and transparently lubricates financial prudence. It promotes the affordable provision of financial services to society (Ahmad et al., 2021). Banks and financial institutes provide consumers funds to purchase energy-intensive products like air conditioning cars, freezers, and microwaves, which can significantly increase the consumption of non-renewable energy, causing carbon emissions (CO_2). Furthermore, a solid financial system improves the GDP, which relies heavily on fossil fuels and causes environmental degradation (Emara and El Said, 2021). In this situation, the digital economy substantially impacted global economies, particularly in/after COVID-19, when digital education and virtual business operations grew and provided assistance for trade activities with lower ecological footprints. China's digital economy is progressing under resources, policy, and technology conditions. It also provides fertile ground for digital trade (DTRD). The meaning of DTRD is evolving due to a better understanding of the notion of the digital economy (Zhang, Wei, et al., 2021). According to the China Academy of Information and Communications Technology, 'DTRD' is 'a trade form in which digital technology plays a key role', comprising the digitalisation of trade products and processes. Research on DTRD began very late in China than in other countries (Chen et al., 2021). DTRD plays an essential personification in the rapid expansion of the digital economy and improves environmental quality. The cost of DTRD is lower than conventional trade, attributable to the ease of data collection and communication (Huang et al., 2022). Video conferencing augmented reality and virtual reality can assist in actualising globally backbreaking work commuting and reduce expenses for DTRD in the context of the digital economy.

Furthermore, China's increasing adoption of 5G communication and blockchain technology contributes to a secure and dynamic scaffolding for development (Guo et al., 2020). DTRD has revolutionised how financial transactions are handled for maximum efficiency. DTRD makes a company further persuasive, efficient, and responsive to customer requirements. Manufacturing, design, sales, and distribution are all areas that DTRD can support. Distribution is the overall output, revenue, or wealth distribution among persons or production components (such as labour, land, and capital). Although digitalisation has been unequal across the European Union, it remains the primary driver of budgetary and social evolution (McKinsey Report, 2016).

The Covid-19 epidemic has altered perceptions of the relationship between digitisation and several environmental challenges. For global economies and cultures, the epidemic has turned into a catastrophic disaster (OECD, 2021; Xuefeng et al., 2021).

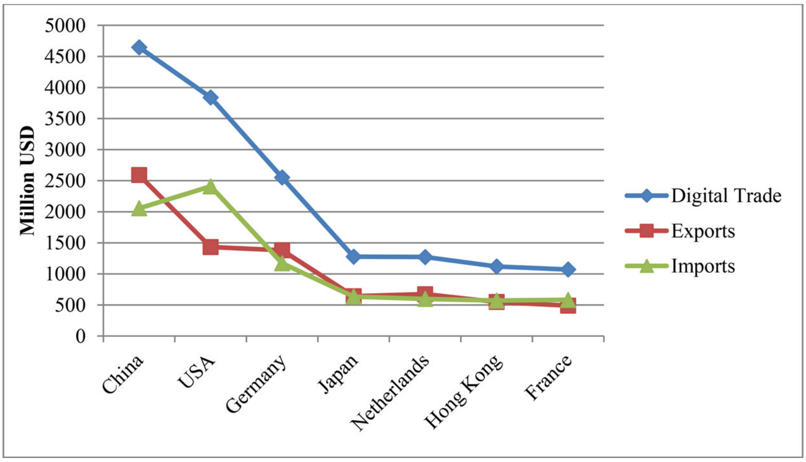

Figure 1. Digital trade trends in advanced economies.
Source: WTO Press/876 https://www.wto.org/english/res_e/statis_e/wts2021_e/wts21_toc_e.htm (accessed on 16 December 2021).

However, restrictions on movement and initiatives to reduce person-to-person contact have significantly enhanced environmental quality (Dobson et al., 2020). In addition, pandemic precautions, including social isolation and lockdowns, have spurred an increase in the use of digital technologies (Pandey & Pal, 2020). However, new electronic devices have been used to replace existing equipment at home, increasing e-waste (Freitas et al., 2020). These are regarded as Covid-19's direct environmental implications in the condition of devastation mainframe (UNEP, 2021). The advantages of digitalisation including to resolve major environmental issues like solid waste, e-waste, and agricultural waste (Du et al., 2022). Digital technology improves biodiversity and the quality of the environment, which is an optimistic viewpoint. Technology in digital trade improves the effectiveness of governmental policies and citizens' views by visualising and developing usable digital business models that prevent biodiversity damage (Ran et al., 2022).

Digitalisation also helps with environmental management, sustainable production, and sustainable urbanisation. In the chemical and heavy industries, digital technology improves their ability to foresee band expands the production and company, resulting in long-term growth. Through digitalisation, companies can achieve more innovative and imperishable manufacturing in green energy (Ran et al., 2022). China has prioritised developing the digital economy during the last decade, implementing numerous supportive policies. Meanwhile, China lagged behind Europe and the United States, dominating the DTRD business. Digital services exports by establishing, developing, and transitioning countries were 243.2 billion, 720.38 billion, and 41.19 billion dollars, respectively (in US dollars). The United States, China, Ireland, Germany, and the Netherlands contributed half of the total, with the United States alone accounting for 16.7%. With the rise of DTRD, there is still a global imbalance.

According to United Nations Conference on Trade and Development (UNCTAD), China's DTRD scale expanded by 11.4 percent annually from 2015 to 2019, from 179.44 billion US dollars to 271.81 billion US dollars. The ratio of trade services among them climbed from 27.4% to 34.7%. Developing DTRD is a critical component of China's long-term economic development. DTRD has various aspects distinct from traditional trading forms, owing to the technical qualities and evolution of the digital economy. Figure 1 presents the volume of digital trade in advanced economics, indicating a higher trend in China, followed by U.S.A. and Germany. China's DTRD tranquility confronts some challenges, including the containment of China's core technology and uneven regional growth. In light of these dangers, this paper intends to examine the influence of digital trade, ecological innovation, and financial development on ecological sustainability. This study applies the Bootstrap ARDL model and finds that digital trade, ecological innovation, and financial development significantly reduce ecological degradation in the long run, while economic growth is the main contributor.

The rest of the study comprises a literature review of section two, discussing previous studies finding and establishing a theoretical framework in section three. Section four discusses the proposed methodology and data summary, whereas the details discuss the empirical findings in section five. Conclusion and policy recommendations are presented in the last section.

2. Literature review

2.1. Digital trade and environmental quality

The literature shows the expanding concerns for DTRD to transact digitally without transportation, increase economic growth, and reduce pollution by encouraging technological innovation (Zugravu-Soilita, 2018). DTRD replaces conventional methods of selling goods and services without incurring transport expenditure. Many facets of human existence have altered due to access to information technology applications, and digitalisation has gradually modified information delivery techniques. However, if the properties of digitalisation are not adequately recognised, various concerns arise from its misuse and abuse (Dasgupta, 2022). Digitisation refers to automated procedures and operations, such as transforming data from one format to another. Digital platforms have low-cost features that help the digital economy and trade thrive. The gravity model in classical trade theory states that transportation expands the trade among people; however, DTRD has resolved transport problems (Jiang et al., 2022). In terms of product qualities, digital products have a considerably low cost due to their great replicability and low marginal cost (Jiang et al., 2022). González and Jouanjean (2017) argued that digital trading reduces knowledge asymmetry, expedites supply-demand matching, and lower prices. A wide range of economic operations can be transferred via digital payment technologies. As a result, information technology platforms are efficient instruments and approaches for economic growth. Prevailing methods of payment would not be conceivable without advanced technologies.

Current methods attempt to boost financial inclusion, removing those obstacles the public faces. Stakeholder involvement and connection can be strengthened by aligning the objectives and merging existing ideas with new thoughts to generate unique solutions, which helps to strengthen connections and collaborations. As a result, creative methods and tactics to enhance financial inclusion can be tailored to the country's needs (Liu et al., 2022). Well information flows, more adaptability, flexibility and productivity in investment projects are all made possible by digital technology. New digital technology business models have emerged in recent years, owing to China's infrastructure, R&D capacity, and industry vitality (Neligan et al., 2022).

According to the National Industrial Information Security Development Research Center's 'Analysis of Digital Economy Situation in 2020–2021', China's 5G deployment has significantly accelerated, with China leading the world scope. (Zhang, Zuo, et al., 2021) demonstrated that China is the world leader in artificial intelligence; as a result, China continued to place a premium on digital technology, encourage international commerce, and establish new DTRD models (Jiang & Lau, 2021). Digitalisation can resolve major environmental issues like solid waste, e-waste, food waste, and agricultural waste (Wen et al., 2022). It also helps with environmental management, sustainable production, and sustainable urbanisation. In the chemical and heavy industries, digital technology plays a key role in resolving environmental issues (Feroz et al., 2021). Shkarlet et al. (2020) claimed that digital enterprises adopt environmentally friendly technology. As a result, promotion, computing, and partner interactions help improve environmental quality. Production variables, organisational structure, job location, payment systems with other enterprises, and employee communication tactics are all considered.

2.2. Financial development and environmental quality

The incredible economic growth over the last 40 years following the reform and opening-up strategy in 1978, coupled with severe ecological deterioration. As the world's biggest carbon emitter, China is under an enormous burden to lessen carbon emissions. China's capacity and compliance with cutting emissions significantly impact the worldwide low-carbon transition (Tan et al., 2022). It intends to cut emissions per unit of GDP by 65 percent by 2030, compared to 2005, and promote renewable energy. Therefore, the Chinese government has set a '3060' carbon reduction objective. The low-carbon economy necessitates a massive investment to move from traditional fossil fuels to clean energy (Niu et al., 2020). The financial sector is crucial to credit allocation, and its growth certainly greatly impacts the low-carbon transition. China's carbon emissions have been the subject of many studies. Angadi (2003) exhibits that the financial sector is the backbone of economic growth since it is active, robust, and efficient. According to Bhattacharya and Wolde (2010), it is the fundamental factor for the MENA region's low economic development compared to other regions. Donou-Adonsou and Sylwester (2016) revealed some surprising results, confirming that microfinance institutions reduce developing nations' poverty levels. Therefore, fintech companies make financial services more accessible to the general public. Financial inclusion becomes the strategy for minimising and reducing poverty. The state can intervene directly and indirectly through approaches to poverty alleviation.

Increased financial inclusion can help the public and private sectors eliminate poverty, and financial institutions should collaborate. DTRD is a solution for financial inclusion offered by the financial sector (Boute et al., 2022). Financial technology enterprises in the finance industry provide digital banking goods and services to low and excluded populations. Consumers can attach their bank accounts to digital payment channels to undertake commercial activities through login credentials. Online or automated transactions between organisations and persons are sometimes digital transactions (Gawusu et al., 2022). The actions of the financial technology industry impact financial inclusion and stability. Working with fintech companies has the advantage of lower expenses; these financial technology companies can help low-income people handle their finances regularly. Financial institutions that do not handle deposits lowering compliance costs, allowing them to serve their customers better and collaborate with traditional financial institutions to cut operational costs and improve the quality of their intermediation services. An operational expenditure (Opex) is money spent daily by a corporation to run a business or system. Fintech start-ups can become more financially viable by collaborating with traditional financial institutions (Najaf et al., 2022).

3. Material and methods

3.1. Theoretical framework

According to the ecological modernisation theory, eco-friendly concerns are neutralised by developing resource abundance through green innovation, which simultaneously enhances a firm's ecological and financial pursuance (Ferronato et al., 2019). Economic volatility and poor social asset management affect trade and foreign loans (Li et al., 2020). Digitalisation refers to the embodiment of digital mechanisms into goods or services. In contrast, digital transformation refers to the general adoption of new business models; green goods should focus on digital platforms (Feroz et al., 2021). Furthermore, applying digitalisation to catastrophic ecological undertaking saves operational costs and increases the safety of workers while decreasing resource use and degradation (Singh et al., 2017). Digitalisation may be used to alleviate problems like resource scarcity, transportation congestion, and air pollution (Ha et al., 2022).

Due to the digital revolution, financial inclusion has been less confined by geography and time. The digital financial inclusion ecosystem is created and assessed thoroughly in this study. The research on DTRD focuses on environmental quality and financial stability. This study looks at digital financial inclusion and local ties. The leading causes of the economic downturn have been financial industry disruptions and obligations aroused by systemically essential credence associations. This led to a loss of faith in the financial organisation's capability to come across reimbursement obligations and an increase in financial, pecuniary, and social hazards, all of which were unstable at the time (Searing et al., 2021). These hazards have warped economic growth, resulting in an unsettling economy. Cash, credit, and bartering are the three most basic payment methods.

This study follows Akinsola et al. (2022) and Langnel et al. (2021) to draw the empirical link between DTRD, Financial development (FD), green innovation (GI), GDP, and carbon emissions as:

Table 1. Descriptive Statistics.

Variables	Mean	Minimum	Maximum	Std. Dev.
CO_2	1.876	2.473	3.756	0.035
DTRD	3.149	3.628	4.346	0.072
FD	2.362	4.159	5.202	0.049
GI	1.993	2.501	3.281	0.044
GDP	2.702	3.463	4.196	0.057

Source: Author estimation.

$$CO2_{it} = (DTRD_{it},\ FD_{it},\ GI_{it},\ GDP_{it}) \quad (1)$$

In Equation (1), CO2 stands for total carbon dioxide emissions, DTRD for DTRD, FD for financial development, GI for green innovation, and GDP for per capita economic growth, respectively, for the Chinese economy from 1990 to 2020. It forms the following testable econometric equation.

$$CO2_{it} = \beta_1 DTRD_{it} + \beta_2 FD_{it} + \beta_3 GI_{it} + \beta_4 GDP_{it} + a_i \ + \varepsilon_{it} \quad (2)$$

3.2. Data

This study uses time-series data from China from 2000 to 2020, including carbon emissions in metric tonnes per capita, digital trade percentage of total trade in digital deliverables and services, financial development index, green innovation/technologies as a percentage of total technologies, and GDP in constant dollar per capita taken from World Bank, OECD. Statistics, UNCTAD, and IMF databases. The data is transformed into quarters following recent literature (Razzaq et al., 2021; Suki et al., 2021).We take the logarithm of all variables for a standard measurement and offer magnitude in the form of elasticities as output (Shahbaz et al., 2020). The descriptive statistics are presented in Table 1. Notably, all the variables have a positive mean value. The description revealed that DTRD has the highest mean value, with 3.149, while CO_2 has the lowest mean value, with 1.876. DTRD has a higher standard deviation than financial development and technology innovation.

3.3. Empirical model

3.3.1. The bootstrap-ARDL

To check the long-term cointegration link among the variables, this study uses a recently developed bootstrap auto-regressive distributive lag (BARDL) bound testing approach McNown et al. (2018). This method effectively addresses the low size problem, which (Pesaran et al., 1999) did not address. Furthermore, BARDL is expanding the traditional ARDL approach, incorporating a new cointegration test to boost the power of T and F tests. This test has two conditions. First, the coefficient value of Error Corrections Terms (ECTs) is statistically significant. Second, significant coefficients are required for the lagged independent variables. According to (Pesaran et al., 2001), lower and upper bounds are evaluated for the second condition. The test can only investigate the first condition, where ECTs are statistically significant if the

Table 2. Correlation table.

Correlation	CO_2	DTRD	FD	GI	GDP
CO2	1				
DTRD	−0.325**	1			
FD	−0.250**	0.148	1		
GI	−0.439*	0.332	0.068	1	
GDP	0.591**	0.180	0.012	0.274***	1

Note: ***, ** and, * represents level of significance at 1%, 5% & 10%.
Source: Authors.

model comprises I (1) integrated of order one variables. As a result, the traditional ARDL technique has poor explanatory and power properties (McNown et al., 2018).

$$X_t = \sum_{i=1}^{p} \alpha_i X_{t-i} + \sum_{j=0}^{q} \beta_j Y_{t-j} + \sum_{k=0}^{r} \gamma_k Z_{t-k} + \sum_{i=1}^{u} \hat{\tau}_i D_{t,1} + u_t \quad (3)$$

where i, j, k, and l represent the lags I = 1, 2 … .p; j = 0, 1, 2, … ., q; k = 0, 1, 2, … ., r; l = 0, 1, 2, … ., s), t denotes time, yt is the dependent variable, y_t and z_t are the independent variables, D_t, is a break year dummy based on Kim and Perron (2009) unit-root Following is the model's error-correction procedure:

$$\Delta X_t = \psi X_{t-1} + \varphi Y_{t-1} + \gamma Z_{t-1} + \sum_{i=1}^{p-1} \pi_i X_{t-i} + \sum_{j=1}^{q-1} \lambda_j Y_{t-j} + \sum_{k=1}^{r-1} \delta_k Z_{t-k} + \sum_{i=1}^{u} \hat{\rho}_i D_{t,1} + u_t \quad (4)$$

The above equation's parameters yield the following function: = p i = 1ai, = q i = 0i, and = r i = 0i. Similarly, the corresponding functions from the first equation are represented by j, k, and i. Equation (2) is obtained using constant-term (c) in the following unconditional model:

$$\Delta X_t = c + \psi X_{t-1} + \varphi Y_{t-1} + \gamma Z_{t-1} + \sum_{i=1}^{p-1} \pi_i X_{t-i} + \sum_{j=1}^{q-1} \lambda_j Y_{t-j} + \sum_{k=1}^{r-1} \delta_k Z_{t-k} + \sum_{i=1}^{u} \hat{\rho}_i D_{t,1} + u_t \quad (5)$$

This capability is enabled by the bootstrap-ARDL system, which concurrently supplies critical values for all tests while producing robust estimates (McNown et al., 2018).

4. Results and discussions

4.1. Correlation matrix

Table 2 presents the correlation matrix results, indicating that environmental degradation has a negative link with DTRD, financial development, and green innovation, while a positive correlation is observed with economic growth. The high partial correlation between the independent variables is one cause of bias in the estimators. However, results show that the correlation among regressors is lower, indicating that the model is free from multicollinearity.

Table 3. Results of unit root test.

Variables	ADF (Level)	ADF (Δ)	ZA (Level)	Break year	ZA (Δ)	Break year
CO2	−0.568	−6.105***	0.684	2010 Q1	−7.953***	2011 Q1
DTRD	−0.429	−3.827***	−1.321	2004 Q1	−9.463***	2015 Q2
FD	−1.057	−4.169***	−0.593	2006 Q1	−8.720***	2015 Q4
GI	−0.834	−3.640***	−1.401	2010 Q2	−10.874***	2018 Q4
GDP	−1.065	−6.093***	−1.816	2017 Q2	−8.528***	2007 Q1

Note: *** represent level of significance at 1%.
Source: Authors.

4.2. Unit root tests

Establishing the order of integration is critical before estimating the BARDL model. As a result, we apply the Zivot and Andrews (2002) and augmented Dickey-Fuller (ADF) unit root tests, and the results are shown in Table 3. ZA test has the advantage of considering the structural break in data. Both ZA and ADF tests show that all variables are stationary at I(1); thus, rejecting the null hypothesis at a 1% significance level.

Table 3 presents the outcome of the ZA unit root test that offered five key findings. First, CO2 displays a structural break at the difference and level series in Q1-2010 and Q1-2011, reflecting the repeal of a 25-year-old environmental law in 2010 and its subsequent revision in the 12th Five-Year Plan (Gov, 2015) from 2011 to 2015. Second, DTRD displays a structural break at the level and difference series in Q1-2004 and Q2-2015. Due to DTRD, access to the global market becomes easy for the customers, facilitating them and reducing the transaction cost. It also boosts productivity and creates new channels for business enterprises. Third, FD began to decline in China's industrial manufacturing sector due to the business's bad performance and high rates of non-performing loans since 2006. Therefore it is needed to boost the resource allocation efficiency.

Fourth, due to the implementation of the 'Mass Entrepreneurship and Innovation (WEF, 2020)' initiative in 2015 and the construction of 5G and 4G infrastructure in 2017, there has been a fundamental change in technology innovation (NDRC, 2017). So, technology innovation indicates a structural break at the level (2010 Q2) and difference series (2018, Q4). This demonstrates the importance of technology in all sectors, which reduces deforestation, fossil fuel consumption, and carbon emissions. China GDP grew by 14% in five years, reaching $1.3 trillion after joining the world trade organisation. However, following the global financial crisis in 2007, China's GDP growth fell to 9.6% in 2008 (WDI, 2020), which relates to almost identical shocks.

4.3. The bootstrap ARDL bound testing framework

Following the validation of variable stationarity, this research looks at the cointegration link between model variables. This research uses BARDL to verify the presence of long-term cointegration among the variables. The choice of the optimal lag length is required when using the BARDL model to estimate the cointegration relationship because the wrong lag order alters empirical data. As a result, the best lag duration is determined using the Akaike Information Criteria (AIC), which is extensively used because of its sophisticated power (Lütkepohl, 2006). The second column in Table 4 lists the lag lengths of all variables from both models in chronological order.

Table 4. Results of bootstrapped ARDL cointegration analysis.

Bootstrapped ARDL cointegration analysis						Diagnostic tests			
Estimated models	Lag length	Break year	F_{PSS}	T_{DV}	T_{IV}	$\bar{R}^2$	Q-stat	LM(2)	JB
Model-1	1, 1, 1, 2, 1	2010 Q1	28.548***	−9.578***	−8.321***	0.927	4.979	1.084	0.561

Model-1: $CO2_t = f\,(DTRD_t, FD_t, GI_t, GDP_t)$.
Note: The asterisks *** show significance at 1%.
Source: Authors.

Empirical findings show that the null hypothesis is rejected based on the F-test and t-test on the lagged level of the dependent variable. The diagnostic test 'Q-stat' accepts the null hypothesis, indicating that all relevant variables have a standard variance that confirms the data distribution's normality. Jarque-Bera statistics support these findings as well. Furthermore, the findings show that the variables in the model have no serial association (Pesaran et al., 2001).

We can evaluate long-term and short-term elasticities after confirming the cointegration relationship among the variables. The long-term estimates are presented in Table 5. Results indicate that a 1% increase in DTRD, financial development, and green innovation decreases carbon emissions by 0.289 percent, 0.175 percent, and 0.255 percent, respectively; however economic growth boosts environmental degradation by 0.394 percent in China. There is theoretical plausibility because these findings are supported by recent empirical literature (Fu et al., 2022; Wang et al., 2022). China's digital economy strengthens the digital infrastructure and the continual emergence of new models under resources, policy, technology, and talents. China's digital economy provided fertile ground for DTRD. China's mobile technology has advanced from 2G to 5G, which is very helpful in decreasing the environmental pollution.

Based on the international balance of payments, China's income from international trade was 3,241.9 billion RMB in January and February 2021; trade-in products generated 2,951.6 billion RMB in revenue, 2,303.9 billion RMB in expenditure, and a surplus of 647.7 billion RMB; trade in services generated 290.4 billion RMB in revenue, 378.6 billion RMB in expenditure, and an 88.3 billion RMB deficit. China has a significant trade deficit with the United States, particularly in service exports. There is still significant space for improvement in China's service trade business. According to financial development, increased competitiveness or more access to greener industrial technology could improve resource competencies. Financial sector changes promoting innovation and improving total factor productivity could boost GDP while simultaneously improving environmental quality (Soytas & Sari, 2009). Financial development also can boost the banking system's flexibility and the development of the stock market. As a result, more investment will be available, increasing market and energy efficiency (Rani et al., 2022; Solà et al., 2021).

Green innovation helps to reduce emissions. Environmental and technological developments have reduced the cost of some material items (aluminium, polyester, and silicon) while increasing their efficiency and consuming less material. As a result, material consumption is reduced, positively impacting the environment's quality. Furthermore, the climate issue and lowering human ecological footprint alter lifestyle and consumption patterns. Green technology and environmentally friendly policies were developed to support smart growth (with efficient resources and reduced material use), low

Table 5. Results BARDL cointegration analysis (long run).

Variable	Coeff.	T-Stats	*p* Value
Constant	0.155	1.258	0.259
$DTRD_t$	−0.289***	−5.364	0.000
FD_t	−0.175***	−3.127	0.000
GI_t	−0.255***	−5.374	0.000
GDP_t	0.394***	6.057	0.000
D_{2008}	0.195***	5.514	0.000
R^2	0.881		
Adj − R^2	0.876		
Durbin Watson	2.054		
Stability analysis			
Test		F-Stats	*p* Value
χ^2_{NORMAL}		0.659	0.439
χ^2_{SERIAL}		0.723	0.361
χ^2_{ARCH}		0.854	0.292
χ^2_{HETERO}		0.426	0.865
χ^2_{RESET}		0.652	0.465
CUSUM		–	Stable
CUSUMsq		–	Stable

Note: *** represent level of significance at 1%.
Source: Authors.

carbon emissions, low carbon cities, and green agriculture (Guan et al., 2022; Wang et al., 2022). Likewise, higher economic expansion necessitates using more fossil energy for goods manufacturing, resulting in increased carbon emissions. It suggests that China is not prioritising environmentally friendly growth and development. Statistics also demonstrate that conventional fossil fuel-based energy sources, such as oil, coal, and natural gas, account for a large portion of the region's energy consumption and emissions. The results coincide with recent studies (Razzaq, Wang, et al., 2021; Sun et al., 2022).

The dummy variables have a positive impact on carbon emissions. The international market experienced an oil glut in 2008, with the United States playing a key role. Excess supply was spurred by receding geopolitical fears and OPEC policies, resulting in lower oil prices and the United States' increasing oil output. As a result, the dependent variable, carbon emissions, has been captured by the chosen dummy. The global economic crisis that began in 2008 caused a slowdown in economic development and exacerbated China's structural imbalances. Furthermore, the effectiveness of these confines is based on the stability study, which shows that error terms are stable from the model and normally distributed. The model has no serial correlation and heteroscedasticity. The model has no autocorrelation, which is supported by Durbin-Watson test statistics. Finally, the CUSUM and CUSUMsq tests confirm that all estimates are stable and reliable.

Table 6 reports the short-run outcomes and indicates that a 1% increase in DTRD, financial development, and technology innovation reduces carbon emissions by 0.021, 0.053, and 0.058 percent. However, a 1% increase in economic growth increases environmental degradation by 0.194%. The dummy variable affirms that the chosen year significantly impacts pollution. ECT is negative and significant at the 1% level, confirming the rapid convergence towards long-term equilibrium in a short-term shock or disequilibrium. The negative ECM value confirms that variables have a long-term association (Banerjee, 1999). Unlike prior studies, which drew a direct

Table 6. Results BARDL cointegration analysis (short run).

Variable	Coeff.	T-Stats	*p* Value
Constant	0.365*	2.357	0.040
$DTRD_t$	−0.021**	−2.085	0.043
FD_t	−0.053*	−1.759	0.050
GI_t	−0.058**	−2.529	0.037
GDP_t	0.194**	2.630	0.032
D_{2008}	0.355***	5.369	0.000
ECM (−1)	−0.327***	−6.821	0.000
R^2	0.852		
Adj − R^2	0.795		
Durbin Watson	2.214		

Note: ***, ** and * represent level of significance at 1%, 5% and 10% respectively.
Source: Authors.

causal link without considering the previous year's effect, distorting the true parameters of the current year. The current year's DTRD and financial development in time series models undeniably depend on the prior year's performance. As a result, time lag effects must provide accurate estimations; otherwise, model parameters will overstate elasticities.

The results of the Granger-causality test are presented in Table 7. This study examines the causality between variables based on the F-stat and probability values, implying the null hypothesis of no Granger causality. The outcomes support a bi-directional causality between green innovation and CO2 emissions and a uni-directional causality between DTRD, FD, and GDP. It implies that DTRD promotes GDP and significantly impacts emission levels.

DTRD helps to increase technical efficiency, but the current state of important core technological links in China and the siphoning effect of talents and finances brought by digital industrialisation make it challenging to contribute to sustainable growth (Walter, 2022). China's development has grown rapidly due to interactions between human capital and technical R&D (Ren et al., 2021). The rapid growth of DTRD volume is expected to negatively influence green gases when there is an insufficient linkage between digital technology and the original manufacturing method. Increased technology investment has led to an extension of the scale of DTRD (Auboin et al., 2021). According to (Shabani & Shahnazi, 2019), there is no systematic planning for DTRD. Similar findings have been obtained in previous studies (Shehzad et al., 2021). Digital products and services can help businesses improve their energy utilisation efficiency and pollutant treatment levels while also fulfilling the influence of DTRD on energy consumption and emission reduction (Lange et al., 2020).

Digital payments facilitate the buying and selling of goods and services over the internet. The widely used digital economy has witnessed substantial development and perfection, and it may be applied to various financial sectors. As a result, organisations that have previously overlooked the economic opportunities continually expanded. Small firms and corporations can now participate in global product and service acquiring and selling to digitisation. It is a distinguished fact that digital transformation has increased the country's economic potential. Millions of jobs have been created globally due to the advancement of mobile applications. E-commerce

Table 7. Results of Granger causality.

Null hypothesis:	F-Statistic	Prob.
DTRD does not Granger Cause CO_2	15.683	0.000
CO_2 does not Granger Cause DTRD	0.185	0.830
FD does not Granger Cause CO_2	12.490	0.000
CO_2 does not Granger Cause FD	1.088	0.530
GI does not Granger Cause CO_2	8.995	0.000
CO2 does not Granger Cause GI	13.578	0.000
GDP does not Granger Cause CO_2	12.623	0.000
CO_2 does not Granger Cause GDP	1.856	0.412

Source: Authors.

transactions have increased dramatically during the previous few years. And credit for digitalisation activity made producing and distributing products and services far easier, more competitive, and more profitable. As a result of digitisation, a significant shift in the way products and services are delivered has occurred. People may readily access the items and services they require online, ranging from funds transfer, entertainment, education, and security to hotel reservations. In the digital economy, most business transactions are conducted electronically, minimising the need for financial transactions, increasing participation, and decreasing corruption.

5. Conclusion and implications

DTRD is an essential economic function of digital technology emerging as a tool for global economic resumption. This study uses data on China's DTRD volume from 2000-Q1 to 2020-Q4 to investigate the plausible association between DTRD, financial development, green innovation, and economic growth. Using bootstrap ARDL, this study explored that DTRD, financial development, and green innovation significantly and negatively influence long-term carbon emissions. These findings suggest that DTRD can help coordinate regional growth, offer new economic development opportunities for underdeveloped areas, and ensure appropriate resource allocation. By integrating these efforts, China could boost digital technology output, encourage conventional businesses to switch to digital, and generate more digital products. Furthermore, China would resolutely promote industries with delayed DTRD development so that these areas can participate in global digital commerce. The legislature should emphasise the new generation of informative communication technology's penetration and connection effect and strengthen enterprise informatisation. Promoting equipment technology and integrating infrastructure develop eco-products and address climate vulnerabilities. Improving manufacturing sector technology innovation and creating a modern industrial system are also imperative for green growth. The primary tool for green transformation is to promote energy-saving and emission-reduction technologies and clean manufacturing processes across the board, industrial technology greening, and advancing green technology in diverse regions.

Moreover, increase DTRD openness and the scope of technical collaboration. Expedite the transition from traditional to DTRD, and minimise reliance on low-value-added, high-pollution industries in trade exports by implementing rigorous environmental protection and energy-use norms. Furthermore, China would encourage the DTRD imports of new technologies, improving businesses' ability to ingest, assimilate, and employ green and clean technology. China's digital sector is developing rapidly, indicating that traditional Chinese companies are quickly converting into digital businesses. As a result, more optimisation of the digital industrial structure is required to support financial growth enhancement. China should implement the 'digital technology plus' development model to help conventional industries modernise and upgrade. China should actively encourage the software and information sector and the internet and digital communication industries, which are strongly tied to DTRD. Future studies can examine the influence of digital trade on growth and their possible channels at regional or country levels.

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