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Industrialization, globalization, ICT, and environmental degradation in Malaysia: A frequency domain analysis

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ABSTRACT

This paper examines the causal relationship between industrialization, globalization, information communication technology (ICT) and environmental degradation in Malaysia during 1970–2019. It uses two indicators of environmental degradation (carbon emissions and ecological footprint), three dimensions of globalization (political, social, and economic) and three indicators of ICT (users of internet, mobile cellular, and fixed telephone subscriptions). It utilizes Granger causality technique in frequency domain which differentiates between permanent and temporary causality, Vector Error Correction approach as well as Variance Decompositions. The bound test shows that the variables have cointegration relationship. It reveals joint long-run and short-run causality from industrialization, globalization, and ICT to carbon emissions, albeit the causality to ecological footprint is tenuous. It indicates that industrialization, globalization, and ICT significantly predict carbon emissions at high frequency than at low frequency. A substantial percentage of the forecast error variance in environmental degradation are explained by industrialization, globalization, and ICT. The robustness of the empirical outcomes is confirmed by the alternative proxies of the variables. Our study implies that industrialization, globalization, and ICT are determinants of environmental degradation. Therefore, policies to mitigate environmental problem should prioritize these variables to attain green economy.

1. Introduction

The industrial sector is considered as one of the significant drivers of Gross Domestic Product (GDP) because it provides goods and services (exports), income and employment opportunities [1,2]. Besides, some studies have showed that globalization and information communication technology (ICT) contribute to economic prosperity [3,4]. However, industrialization, globalization and ICT could accentuate energy consumption, and influence environmental quality [5,6]. The soaring degree of environmental degradation engendered by high greenhouse gases or carbon emissions [2,7] requires an investigation into the causal relationship between industrialization, globalization, ICT, and environmental degradation. The deterioration of the environment can pose serious threats to

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global warming, climate change, and have adverse consequences on human lives [7]. Hence, concerted efforts are required to mitigate the environmental impacts of human activities (production, consumption, and transportation) otherwise, the menace will continue to soar and endanger the ecosystem. Thus, the recognition of the causal link between industrialization, globalization, ICT, and environmental degradation is crucial to formulate the requisite policies to attain sustainable economic development.

The theoretical literature posits that industrial development or activities can generate carbon emissions and other greenhouse gases which are detrimental to environmental quality especially at the early stage of industrialization [6,8]. However, as the society develops, the environmental consequences of the industrial sector could diminish due to technological advancement or innovations, urbanization and changes in the composition or structure of the economic sectors [8]. Besides, the globalization-led growth hypothesis contends that globalization enhances economic expansion by improving the flow of capital, innovation, trade, knowledge, foreign direct investment, labour, and technological diffusion [9]. However, globalization could stimulate growth at the cost of pollution especially in nations that have weak institutional quality and environmental standards [10]. Conversely, globalization may not aggravate environmental degradation if it enhances global information and shared knowledge that can increase awareness about ecological and environmental issues. It can mitigate environmental degradation if it boosts foreign direct investment and the transfer of innovative, green technology and environmental-friendly production techniques from developed to developing countries [10]. Moreover, the link between ICT and environmental degradation has been posited by the theoretical literature which argues that the usage and disposal of ICT could generate pollution and influence environmental degradation [11]. However, ICT applications could enhance environmental quality by providing opportunities for smarter cities, transport systems, industrial processes, and electrical grids [12].

The motivation for this study stems from the dearth of empirical studies on the causal relationship between industrialization, globalization, ICT, and environmental degradation in Malaysia. Though some studies have shown the causal link between environmental degradation and some variables in certain countries or regions [13], the subject matter has yet been empirically explored within a framework that accounted for industrialization, globalization, and ICT in Malaysia. It is fundamental to empirically investigate this issue in Malaysia because of the high degree of environmental degradation in the country. For instance, the available statistics[1] show that CO2 emissions increased from 1.35 to 8.09 metric tons per capita while ecological footprint rose from 1.7 to 3.99 global hectares per person during the 1970–2019 period. The real GDP per capita increased from USD1915.8 to USD12486.7 while energy consumption soared from 547.1 to 3003.5 kg of oil equivalent per capita. Though industry value added relative to GDP marginally declined from 41.8 % to 38.3 %, globalization index rose from 42.6 to 82.5 while ICT (fixed telephone subscriptions per 100 people) increased from 0.96 to 20.2. Consequently, it is essential to conduct an econometric analysis to determine the causality between the variables with a view to enhancing policy decisions making.

Hence, the specific objective of this study is to determine the direction of the causal relationship between industrialization, globalization, ICT, and environmental degradation in Malaysia. Essentially, this study makes some contributions to the extant literature in the following areas: Firstly, it represents an innovative idea that exposes the causal relationship between industrialization, globalization, ICT, and environmental degradation in a single framework. It conducts both bivariate and multivariate analyses to appropriately capture the relationship between the variables. It uses the empirical strategies that unravels joint long run and short run causality; temporary and permanent causal relationships; as well as the degree of the forecast error variance (reaction) in environmental degradation that are explained by exogenous (standard deviation) shocks to industrialization, globalization, and ICT over time. The use of these multiple strategies provides robust empirical outcomes that are fundamental for policy formulations.

Secondly, unlike previous studies that typically used one indicator of environmental degradation, this study employs two indicators of environmental degradation (i.e., CO2 emissions and ecological footprint) to suitably capture different dimensions of environmental degradation. This is essential because CO2 emissions are considered as the main drivers of greenhouse gases which deteriorate environmental quality, climate change, and global warming [13,14] whereas ecological footprint is a reliable index that evaluates the pressure which individuals exert on ecosystem because of waste absorption and consumption [15,16].

Thirdly, unlike previous studies, this study uses overall globalization as well as the three dimensions of globalization (i.e., political, social, and economic dimensions) to aptly capture the causal relationship between globalization and environmental degradation. The original globalization index developed by Dreher [9] disaggregated globalization into economic, social, and political dimensions. The economic dimension consists of long-distance flow of goods, income, investment, services, capital, and market exchange perceptions while the social dimension comprises the diffusion of information, personal contacts, images, and cultural proximity. The political dimension involves the tools used by the government to distribute policies worldwide such as embassies, involvement in international organizations and United Nations peace keeping missions [7]. Moreover, Gygli et al. [17] revised the globalization dimensions to distinguish between the de facto and the de jure indices. Precisely, the de facto index measure actual international flows in activities (e.g., trade in goods and services, investment, migration, information, embassies) while the de jure index measures policies and conditions (e.g., tariffs, trade agreements, investment regulations, international airports, international treaties) that affect the flows and activities [17,18]. Hence, this study also uses the de facto and the de jure indices of economic, social, and political dimensions for greater insights.

Finally, unlike previous studies that usually focused on one proxy of ICT, this study uses three indicators of ICT (i.e., users of internet, mobile cellular, and fixed telephone subscriptions) to comprehensively capture different aspects of ICT development. It also

[1] Data on CO2 emissions, real GDP per capita, energy consumption, industrialization, and ICT were obtained from the World Development Indicators [74]. Data on ecological footprint were collected from the Global Footprint Network [75] while data on globalization index were gathered from the KOF Globalisation Index [76].

uses industry value added relative to GDP and the manufacturing value added relative to GDP as indicators of industrialization. The empirical outcomes on the causal relationship between industrialization, globalization, ICT, and environmental degradation could assist policy makers to make informed decisions on environmental, sectoral, and energy policies to achieve environmental sustainability.

Apart from this introduction, this paper has four sections; The second section reviews the related studies; the third section shows the methodology; The fourth section contains the results; the fifth section analyses the policy implications/options.

2. Theoretical framework and literature review

2.1. Theoretical framework

The underpinning theoretical framework of this study is the Environment-Energy-Output (EEO) model which contends that energy consumption and output growth are the main drivers of environmental degradation [19–21]. The rationale for using the EEO model is to account for the impact of energy consumption and output growth on environmental degradation. Some previous studies have employed the EEO model to determine the factors that influence environmental degradation [21–24]. Specifically, output growth requires energy consumption, which could have adverse consequences on environmental degradation especially if the energy is sourced from fossils fuels (coal, gas, oil) that produce carbon emissions [2]. However, energy consumption will not worsen environmental degradation if there is a high proportion of renewable or clean energy (which is environmentally friendly) in the total energy mix [25]. Besides, some economic activities associated with output growth (e.g., agricultural, transport, commercial, residential activities) produces carbon emissions. Essentially, a pollution-intensive method of production will aggravate environmental degradation while a clean method of production will not degrade the environment [1].

For instance, Ang [19] revealed that output growth exerts a causal influence on energy consumption and environmental degradation in France while Ehigiamusoe [26] revealed that energy consumption and output growth are detrimental to environmental degradation in 25 African nations. In a panel data of 122 countries, Ehigiamusoe and Lean [2] noted that energy consumption and output growth increase environmental degradation. But after splitting the sample, the analysis showed that output growth alleviates environmental degradation in countries with high-income but worsens environmental degradation in countries with middle- and low-income.

This study augments the EEO model with industrialization, globalization, and ICT. The theoretical literature posits that industrial development could influence environmental degradation. The theory of ecological modernization indicates that industrial activities represent a social transformation process that boosts modernization and generates environmental problems. But the adverse environmental consequences of industrial development could diminish due to technological growth, urbanization, and movement from manufacturing-based economy to service-based economy [8]. Similarly, the urban environmental transition theory opines that though expansion in manufacturing activities make a society wealthier, it could deepen environmental pollution. However, as a society gets richer, pollution could decrease because of technological development or modifications in the composition or structure of the economic sectors [21]. Ehigiamusoe [13] posited that industrial activities can release carbon emissions and other greenhouse gases into the environment while Wen et al. [27] noted that industrial development may not exacerbate carbon emissions if there is environmental awareness as well as the adoption of energy-efficient technologies.

Moreover, the theoretical literature opines that globalization has the capacity to intensify environmental degradation if it encourages the movement or relocation of pollution-intensive firms from the developed countries (with stringent environmental regulations) to developing nations that have weak institutional quality and environmental standards [10]. Globalization can affect environmental degradation since it boosts economic activities, international knowledge spillovers, innovation, technological diffusion, international trade, foreign direct investment, and capital flows that have implications on environmental sustainability [17]. It also promotes mutual interdependence and networks among stakeholders at multinational distances, as well as integrates countries, technologies, and culture [9]. However, globalization may not intensify environmental degradation if it promotes global information and shared knowledge that improve awareness about environmental protection. It can boost foreign direct investment and the transfer of innovative, green technology and environmental-friendly production techniques from developed to developing countries [10]. Though globalization offers opportunities for economic expansion, it involves a complex process of economic, social, and political integration which may pose severe environmental challenges to countries if not properly managed [28].

Finally, the theoretical literature posits that ICT can influence environmental degradation [4]. The rapid growth in ICT facilities and infrastructure could exert pressure on energy consumption and ultimately aggravates CO2 emissions [29]. ICT services and products can increase electricity usage, boost economic activities, and constitute electronic waste which could have ramifications for environmental sustainability [3]. ICT applications and penetrations (e.g., smart grids, buildings) can influuence environmental degradation. It can also enhance technological transfer, innovation, economic competitivess which promote investment activities [3]. ICT development will not increase CO2 emissions if it enhances energy efficiency and productivity in various economic sectors [5]. ICT-enabled technologies that integrates renewable energy, power grid optimization, intelligent transport systems, building smart homes as well as smart cities will not intensify environmental degradation [29].

2.2. Literature review

2.2.1. Industrialization and environmental degradation

Some scholars have provided empirical evidence on the nexus between industrialization and environmental degradation in different countries though the conclusions are mixed. For instance, Poumanyvong and Kaneko [30] investigated the link between industrialization and CO2 emissions in 99 countries (divided into high-, middle-, and low-income panels) and disclosed that industrialization aggravates CO2 emissions in all panels. Using the panel data of 76 nations, Li and Lin [31] showed that industrialization has a detrimental impact on CO2 emissions. Sohag et al. [6] also explored the nexus between industrialization and CO2 emissions in 86 nations and reported that industrialization exacerbates CO2 emissions. Zhang and Lin [32] noted that industrial development worsens CO2 emissions in China. However, when the sample was split, the study reported that industrial development increases CO2 emissions in Eastern region, reduces CO2 emissions in Western region, while the effect is insignificant in the Central region. Voumik and Sultana [33] also reported that industrialization contributes to CO2 emissions in BRICS (Brazil, Russia, India, China, South Africa). Opoku and Aluko [34] used the quantile regression approach to determine the impact of industrialization on ecological footprint in 37 African countries and found heterogeneous effects. Precisely, industrialization increases ecological footprint in the 10–30th quantiles but decreases ecological footprint in the 40–90th quantiles.

Kahouli et al. [35] also analyzed the link between industrialization and CO2 emissions and showed a long-run unidirectional causal relationship from industrialization to CO2 emissions while a bidirectional causality exists between the variables in the short-run in Saudi Arabia. Nasir et al. [36] explored the nexus between industrialization and CO2 emissions in Australia and revealed a unidirectional causality from industrialization to CO2 emissions. In a related study, Rahman and Alam [37] revealed that industrialization intensifies CO2 emissions, while the Granger causality test indicated a bidirectional causal relationship between the variables in Australia. Usman and Balsalobre-Lorente [38] reported that industrialization contributes to ecological footprint in 10 newly industrialized nations. The Granger causality test showed a unidirectional causal relationship from industrialization to ecological footprint.

Conversely, Naude [39] noted that industrialization can lower the emissions associated with agricultural activities (e.g., deforestation, livestock farming) by transferring labour from harmful environmental agricultural activities to the industrial sector. Besides, industrialization will not aggravate environmental problems if the sector is energy efficient and uses clean production technologies. In a study of different income groups, Rafiq et al. [40] found that industrialization lessens CO2 emissions in countries with high-income while the effect is insignificant in countries with low- and middle-income. Zhou et al. [41] also explored the link between industrial transformation and CO2 emissions in China and revealed that the first-order lag of industrial adjustment mitigates CO2 emissions. Lin et al. [42] studied the connection between industrialization and CO2 emissions in Nigeria and found that industrialization does not aggravate CO2 emissions. Ehigiamusoe [13] analyzed the link between industrialization and CO2 emissions n in ASEAN + China and disclosed that industrialization diminishes CO2 emissions.

2.2.2. Globalization and environmental degradation

Some empirical works have explored the relationship between globalization and environmental degradation, albeit the outcomes are mixed. One strand of the literature concluded that globalization aggravates environmental degradation because it encourages the relocation of pollution-intensive industries from the developed nations (with strict environmental laws) to the developing countries with lenient environmental regulations [21,32,43,44]. For instance, Sethi et al. [45] explored the connection between globalization, economic growth, and CO2 emissions in India. The evidence indicated that though globalization boosts economic expansion, it has a harmful impact on environmental degradation. Khan et al. [46] investigated the nexus between globalization and CO2 emissions and showed that economic, social, and political globalization have harmful effects on CO2 emissions in Pakistan. Using the data of G7 countries, Wang et al. [47] revealed that economic dimension of globalization aggravates CO2 emissions while Shahbaz et al. [48] found support for the globalization-driven CO2 emissions hypothesis in 25 developed countries.

In a related study, Shahbaz et al. [44] reported that overall, social, and political globalization increase CO2 emissions in India. Ehigiamusoe et al. [21] revealed that globalization has a harmful impact on CO2 emissions in 31 African countries. Zaidi et al. [10] showed a causal relationship from globalization to CO2 emissions in 17 Asia Pacific Economic Cooperation countries. Rudolph and Figge [49] investigated the link between globalization and ecological footprint in 146 economies and reported that globalization has a harmful relationship with ecological footprint. Evidence from the dimensions of globalization indicated that economic globalization has a positive relationship with ecological footprint; social globalization is negatively correlated with ecological footprint; and political globalization has no relationship with ecological footprint.

Another strand of the literature posits that globalization can mitigate environmental degradation if it promotes environmental awareness, enhances the importation of clean technologies, removes trade barriers, and boost technological innovations [33,50]. Precisely, Ahmed, Zhang, and Cary [51] showed that variations in economic globalization lessens ecological footprint in Japan. Ahmad et al. [50] revealed that economic globalization diminishes CO2 emissions at the aggregate and sectoral levels in India. They noted that economic globalization can help to control the carbon emissions from the agricultural, industrial and services sectors. Bilgili et al. [52] examined the nexus between globalization and ecological footprint in Turkey and reported that globalization (political, trade, and interpersonal dimensions) mitigates ecological footprint. Shahbaz et al. [53] also examined the association between globalization and CO2 emissions in 19 African nations. The findings showed that globalization decreases CO2 emissions in 8 countries; globalization aggravates CO2 emissions in 5 nations; and there is no connection between globalization and CO2 emissions in the remaining countries.

Moreover, the impact of globalization on CO2 emissions may be contingent upon the level of economic development of the countries. In this regard, Leal et al. [43] investigated the role of globalization on CO2 emissions in 58 countries (divided into 26 developing and 32 developed nations). Evidence from the study revealed that globalization aggravates CO2 emissions in developing countries but mitigates CO2 emissions in developed countries. Similarly, Le and Le [54] analyzed the nexus between globalization and environmental degradation in 128 countries (divided into high-, middle-, and low-income countries) and reported that overall, economic, and social globalization mitigate environmental degradation while political globalization worsens it in the whole panel. It further showed that overall, economic, and social globalization mitigate environmental degradation in middle income countries but aggravate it in low-income countries. But in high-income countries, the effect of overall, economic, and social globalization on environmental degradation is tenuous. The study also revealed that political globalization intensifies environmental degradation in the whole panel and middle-income countries; mitigate it in high-income countries; and have weak effect in low-income countries. Finally, some studies have showed that globalization and environmental degradation have insignificant relationship [35,36]. Ahmed et al. [22] showed that globalization has insignificant relationship with ecological footprint while Xu et al. [55] reported an insignificant relationship between globalization and CO2 emissions in Saudi Arabia.

2.2.3. ICT and environmental degradation

The relationship between ICT and environmental degradation has also been investigated in some studies. Lee and Brahmasrene [56] studied the nexus between ICT, economic growth, and CO2 emissions in 9 ASEAN, and found that ICT increases both economic growth and CO2 emissions. Park et al. [4] showed that ICT aggravates CO2 emissions in 23 European countries, and the Granger causality test showed a unidirectional association from ICT to CO2 emissions. Danish et al. [57] reported that ICT increases CO2 emissions in 11 emerging economies while Arshad et al. [58] showed that ICT has a detrimental impact on CO2 emissions in 14 countries. Haseeb et al. [3] revealed that ICT contributes to CO2 emissions in BRICS while the causality approach detected a bidirectional association between ICT and CO2 emissions. Raheem et al. [59] analyzed the impact of ICT on CO2 emissions in G7 economies and found that ICT has a harmful impact on CO2 emissions. Ahmed and Le [5] also showed a causal relationship from ICT to CO2 emissions in 6 ASEAN while Baris-Tuzemen et al. [12] revealed a significant connection between ICT and CO2 emissions in Turkey. Atsu et al. [60] showed that ICT has a detrimental impact on CO2 emissions in South Africa. Avom et al. [61] examined the nexus between ICT and CO2 emissions in 21 African countries and reported that ICT has a direct harmful impact on CO2 emissions. They added that ICT indirectly exacerbates CO2 emissions through energy consumption and financial development.

However, some scholars have indicated that ICT can alleviate environmental degradation [11,62,63]. Godil et al. [62] studied the nexus between ICT and CO2 emissions in Pakistan and reported that ICT reduces CO2 emissions. Using the panel data of 58 countries, N'dri et al. [11] indicated that ICT mitigates CO2 emissions in countries with relatively low-income, whereas ICT has insignificant relationship with CO2 emissions in nations with high-income. They opined that efforts to attain environmental sustainability should embrace ICT policies that can alleviate environmental issues in developing economies. Similarly, Caglar et al. [63] investigated the relationship between ICT and ecological footprint in 10 nations with the worst environmental quality (China, India, Brazil, Russia, Germany, Japan, Indonesia, Mexico, USA, United Kingdom) and found that ICT improves environmental quality. Dogan and Pata [64] examined the relationship between ICT and environmental quality in G7 nations and showed that ICT improves environmental quality. They advised countries to integrate green ICT infrastructure into their environmental policies with a view to attaining environmental sustainability. Huang et al. [65] also showed that ICT mitigates ecological footprint in G7 (advanced) nations but degrades ecological footprint in E7 (developing) nations. The Granger causality test indicated a bidirectional causality between ICT and ecological footprint in both G7 and E7 countries. Balsalobre-Lorente et al. [66] also revealed that ICT reduces CO2 emissions in 36 OECD countries. Albaity and Awad [67] explored the impact of ICT on ecological footprint (divided into low-, medium- and high-levels of ecological footprint) in 50 high-income 49 upper-middle-income, and 72 low-income nations. Evidence from the study revealed that, irrespective of the income level, ICT improves environmental quality in countries with high level of ecological footprint but deteriorates environmental quality in nations with low level of ecological footprint.

Some studies have also found that ICT and environmental degradation have insignificant relationship [68,69]. Asongu et al. [68] revealed that ICT has insignificant impact on CO2 emissions in 44 African countries. Ramzan et al. [69] used linear and non-linear causality techniques to examine the nexus between ICT and ecological footprint in Pakistan. Evidence from the linear causality test showed that ICT has insignificant relationship with ecological footprint albeit the non-linear causality test suggests that ICT can predict ecological footprint.

The literature review above indicates that the relationship between industrialization, globalization, ICT, and environmental degradation have been explored in some countries or regions (though with mixed conclusion) but the issue has yet been empirically determined in Malaysia. The lack of consensus in previous studies necessitates more investigation, particularly in a country where the literature is still scanty. Besides, most previous studies focused on one proxy of environmental degradation, industrialization, globalization, and ICT. But this study differs from previous studies because it uses different indicators of environmental degradation (i.e., CO2 emissions and ecological footprint), industrialization (i.e., industry value added relative to GDP and manufacturing value added relative to GDP), ICT (i.e., fixed telephone subscriptions, mobile cellular subscriptions, and internet users). It also uses the de facto and de jure indices of overall, economic, social, and political globalization. To obtain robust empirical outcomes that can assist policy decision-making, this study conducts both bivariate and multivariate analyses to aptly capture the nexus between the variables. The empirical strategies unravel joint long run and short run causality, temporary and permanent causal relationships, as well as the degree of forecast error variance in environmental degradation that are explained by exogenous shocks to industrialization, globalization, and ICT over time.

3. Methodology

3.1. Model specification

This study employs the Environment-Energy-Output (EEO) model which posits that environmental degradation is a function of energy consumption and output growth [19,20]. In line with the extant literature, this study augments the EEO model with industrialization, globalization, and ICT [42,70]. The model can be written in form of Error Correction Model as presented in Equation (1) below:

$$\Delta ENV_t = \varphi_0 + \sum_{k=1}^{m}\varphi_1 \Delta ENV_{t-k} + \sum_{k=0}^{n}\varphi_2 \Delta ENC_{t-k} + \sum_{k=0}^{o}\varphi_3 \Delta GDP_{t-k} + \sum_{k=0}^{p}\varphi_4 \Delta IND_{t-k} + \sum_{k=0}^{q}\varphi_5 \Delta GLO_{t-k} + \sum_{k=0}^{r}\varphi_6 \Delta ICT_{t-k} + \varpi ECT_{t-1} + \mu_t \tag{1}$$

where ENV = environmental degradation proxy by CO2 emissions (metric ton per capita) and alternatively by ecological footprint of consumption (global hectares per person), ENC = energy consumption (kg of oil equivalent per capita), GDP = real GDP per capita (2010 constant price in dollars), IND = industrialization (proxy by industry value added/GDP, and alternatively by manufacturing value added/GDP), GLO = overall globalization index, and ICT = information and communication technology (proxy by fixed telephone subscriptions per 100 people, and alternatively by mobile cellular subscriptions per 100 people, as well as internet users as percentage of population), ECT = error correction term, μ = error term, t = time index, Δ = first difference operator, k = lag length optimally chosen with a step-down process restricted to 4 lags.

This study tests the null hypothesis that there is no joint short-run causality against the alternative hypothesis: $H_0 : \varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \varphi_5 = \varphi_6 = 0$, $H_1 : \varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \varphi_5 = \varphi_6 \neq 0$.

It rejects the null hypothesis if the coefficient of the F-statistic (derived from the VEC Granger causality/block exogeneity Wald tests) is significant at 5 % level, implying that a joint short-run causal relationship runs from the independent variables to CO2 emissions. Similarly, this study tests the null hypothesis that there is no joint long-run causality against the alternative hypothesis: $H_0 : \varpi = 0$; $H_1 : \varpi \neq 0$. The null hypothesis is rejected if the coefficients of the lagged ECT is negative and significant at 5 % level, suggesting that a joint long-run causality runs from the independent variables to CO2 emissions. Moreover, the error correction term represents the convergence coefficient that indicates the speed of adjustment from short-run deviation to long-run equilibrium [44,50,54].

This study also specifies the ECT models for all the variables as presented in Equations (2)–(6) below:

$$\Delta ENC_t = \varphi_0 + \sum_{k=1}^{m}\varphi_1 \Delta ENC_{t-k} + \sum_{k=0}^{n}\varphi_2 \Delta ENV_{t-k} + \sum_{k=0}^{o}\varphi_3 \Delta GDP_{t-k} + \sum_{k=0}^{p}\varphi_4 \Delta IND_{t-k} + \sum_{k=0}^{q}\varphi_5 \Delta GLO_{t-k} + \sum_{k=0}^{r}\varphi_6 \Delta ICT_{t-k} + \varpi ECT_{t-1} + \mu_t \tag{2}$$

$$\Delta GDP_t = \varphi_0 + \sum_{k=1}^{m}\varphi_1 \Delta GDP_{t-k} + \sum_{k=0}^{n}\varphi_2 \Delta ENV_{t-k} + \sum_{k=0}^{o}\varphi_3 \Delta ENC_{t-k} + \sum_{k=0}^{p}\varphi_4 \Delta IND_{t-k} + \sum_{k=0}^{q}\varphi_5 \Delta GLO_{t-k} + \sum_{k=0}^{r}\varphi_6 \Delta ICT_{t-k} + \varpi ECT_{t-1} + \mu_t \tag{3}$$

$$\Delta IND_t = \varphi_0 + \sum_{k=1}^{m}\varphi_1 \Delta IND_{t-k} + \sum_{k=0}^{n}\varphi_2 \Delta ENV_{t-k} + \sum_{k=0}^{o}\varphi_3 \Delta ENC_{t-k} + \sum_{k=0}^{p}\varphi_4 \Delta GDP_{t-k} + \sum_{k=0}^{q}\varphi_5 \Delta GLO_{t-k} + \sum_{k=0}^{r}\varphi_6 \Delta ICT_{t-k} + \varpi ECT_{t-1} + \mu_t \tag{4}$$

$$\Delta GLO_t = \varphi_0 + \sum_{k=1}^{m}\varphi_1 \Delta GLO_{t-k} + \sum_{k=0}^{n}\varphi_2 \Delta ENV_{t-k} + \sum_{k=0}^{o}\varphi_3 \Delta ENC_{t-k} + \sum_{k=0}^{p}\varphi_4 \Delta GDP_{t-k} + \sum_{k=0}^{q}\varphi_5 \Delta IND_{t-k} + \sum_{k=0}^{r}\varphi_6 \Delta ICT_{t-k} + \varpi ECT_{t-1} + \mu_t \tag{5}$$

$$\Delta ICT_t = \varphi_0 + \sum_{k=1}^{m}\varphi_1 \Delta ICT_{t-k} + \sum_{k=0}^{n}\varphi_2 \Delta ENV_{t-k} + \sum_{k=0}^{o}\varphi_3 \Delta ENC_{t-k} + \sum_{k=0}^{p}\varphi_4 \Delta GDP_{t-k} + \sum_{k=0}^{q}\varphi_5 \Delta IND_{t-k} + \sum_{k=0}^{r}\varphi_6 \Delta GLO_{t-k} + \varpi ECT_{t-1} + \mu_t \tag{6}$$

3.2. Justification of variables

This study uses two indicators of environmental degradation (i.e., CO2 emissions and ecological footprint) to effectively capture the causal relationship between industrialization, globalization, ICT, and environmental degradation. It uses CO2 emissions since it is considered as the main driver of greenhouse gases which deteriorate environmental quality, global warming as well as climate change [13,14]. Besides, it uses ecological footprint which is a reliable index that evaluates the pressure which human actions exert on the ecosystem because of absorption of waste and consumption [15,16]. It is usually calculated by quantifying the effects of human actions on six bio-productive land utilization types (such as grazing land, cropland, forest land, fishing grounds, build-up land, as well as carbon sequestration ground). Industrialization is proxy by industry value added relative to GDP [31], while the manufacturing value added relative to GDP is used as an alternative proxy [34,49].

Regarding globalization and ICT, this study uses globalization index which agreed with the literature [46,51,52]. It also employs the three dimensions of globalization (political, social, economic) in line with some studies [43,46,54]. It also uses the de facto and de jure indices of political, social, and economic globalization. The de facto index measure actual international flows in activities (e.g., trade in goods and services, investment, migration, information, embassies) while the de jure index measures policies and conditions (e.g., tariffs, trade agreements, investment regulations, international airports, international treaties) that affect the flows and activities [17,18]. In the extant literature, the proxies often used for ICT are the fixed telephone subscriptions, mobile cellular subscriptions, internet users, and fixed broadband subscriptions [11,70]. However, in the case of Malaysia, data on fixed broadband subscriptions is not long enough to conduct time series analysis, while data on mobile cellular subscriptions and internet users are only available for 1986–2019 and 1992–2019 respectively. Therefore, we use fixed telephone subscriptions as our main proxy since data are available for the 1970–2019 period. However, for robustness checks, we use mobile cellular subscriptions and internet users as alternative proxies.

3.3. Empirical strategies

The empirical strategies employed in this study proceed as follows: First, this study conducts the unit root test to ascertain the level of integration of the variables using ADF and PP tests. Second, it employs the Autoregressive Distributed Lag (ARDL) bound test to determine the existence of a cointegration relationship between the variables. The unit root and cointegration tests are essential because they enable us to choose the appropriate Granger causality technique. For instance, the Vector Error Correction Model (VECM) Granger causality approach is more appropriate for a model that have cointegration relationship while the Vector Autoregressive (VAR) Granger causality approach is more suitable for a model which is not cointegrated [71]. Third, since the Bound test shows that the variables are cointegrated, this study determines the joint causal relationship between the variables in a multivariate framework using the Vector Error Correction Model (VECM) approach. This approach is chosen because it can reveal the joint short run and long run causal relationships. It is also suitable even for relatively small sample. Nevertheless, the VECM approach cannot reveal causality in frequency domain (temporary and permanent periods).

Consequently, this study employs the Granger causality technique in frequency domain recommended by Breitung and Candelon [72] to ascertain the causality between the variables in a bivariate framework at certain frequency domains. This technique can evaluate the predictive power of industrialization at some given frequencies on environmental degradation. It uses bivariate vector autoregressive model (albeit it can be generalized to test for causality in three-dimensional systems. The framework can be utilized to unravel the short-run and long-run predictability, since it can reveal causality over diverse frequencies (ω) such as temporary and permanent periods. Hence, this study evaluates the temporary and permanent causal associations between the variables as well as calculates the test statistics at low ($\omega = 2.5$) and high ($\omega = 0.5$) frequencies [73]. It tests the null hypothesis (e.g., industrialization does not Granger cause environmental degradation at specific frequency) against alternative hypothesis. The temporary and permanent causal associations show that the individual causation is valid in short and long periods. The optimal lag length was chosen based on Bayesian Information Criteria. Breitung and Candelon [72] posited that frequency domain test is robust and is applicable regardless of the integration and cointegration properties of the variables.

Finally, this study utilizes the Variance Decompositions (VDs) to ascertain the percentages of the forecast error variance in environmental degradation that are explained by industrialization, globalization, and ICT. It also utilizes the Impulse Response Functions (IRFs) to determine the response of environmental degradation to shocks in industrialization, globalization, and ICT [70].

3.4. Data

This study employs time series annual data of Malaysia covering the 1970–2019 period. Data on CO2 emissions, energy

Table 1
Descriptive statistics and correlations.

	CO2	EFP	ENC	GDP	IND	GLO	ICT
Mean	4.654	3.036	1712.1	6147.5	40.367	64.971	11.348
Maximum	8.125	4.450	3003	12486.6	48.530	81.555	21.148
Minimum	1.351	1.700	523.5	1915.8	30.318	42.623	0.962
Standard Dev..	2.459	0.884	851.7	3038.5	4.255	12.966	7.094
CO2	1						
EFP	0.955***	1					
ENC	0.989***	0.955***	1				
GDP	0.970***	0.913***	0.973***	1			
IND	0.484***	0.624***	0.513***	0.383***	1		
GLO	0.982***	0.961***	0.989***	0.962***	0.581***	1	
ICT	0.897***	0.925***	0.896***	0.857***	0.675***	0.925***	1

Notes: *** indicates statistical significance at 1 % levels. CO2 = carbon dioxide emissions, EFP = ecological footprint, ENC = energy consumption, GDP = real GDP per capita, IND = industry value added relative to GDP, GLO = globalization index, ICT = information communication technology.

consumption, real GDP per capita, industrialization, and ICT were collected from the World Development Indicators [74]. Data on ecological footprint were collected from the Global Footprint Network [75], while data on globalization were collected from the KOF Globalisation Index [76], a publication of the KOF Swiss Economic Institute. Availability of data dictated the scope of our research.

4. Empirical results

4.1. Preliminary analysis

Table 1 displays the variables' descriptive statistics as well as correlation. It indicates widespread disparities among ecological footprint, CO2 emissions, GDP, energy consumption, industrialization, globalization, and ICT in Malaysia. During the 1970–2019 period, the average ecological footprint, CO2 emissions, GDP, energy consumption, industry valued added relative to GDP, globalization index and ICT were 3.03 global hectares per person, 4.65 metric ton per capita, USD6147.5, 1712 kg of oil equivalent per capita, 40.36 %, 64.97 and 11.34 per 100 people respectively. The corresponding standard deviations suggest relatively spread-out data points round averages. Figs. 1–4 show that all the variables (except industry value added) experienced rising trends during the period. Moreover, the correlation show that the variables are positively related to ecological footprint and CO2 emissions.

Furthermore, the panel unit root test (Table 2) indicate that globalization is stationary at level [I(0)] whereas the remaining variables are stationary after first differenced [I(1)] at 5 % level. Therefore, we proceed to ascertain whether the variables have cointegration relationship.

Therefore, ARDL bound test shown in Table 3 indicate a cointegration relationship since the calculated F-statistic is larger than upper bound critical value in the model. Though the cointegration test discloses the existence of a long-run association between the variables, it cannot indicate the causal relationship between them. If two variables have cointegration, it implies that a causal association exists between them in at least one direction. Therefore, we ascertain the direction of causality using the techniques which is appropriate for a cointegrated model.

4.2. VECM granger causality

The VECM estimations reported in Table 3 indicate joint long-run and short-run causal relationships from GDP, energy consumption, industrialization, globalization, and ICT to CO2 emissions in Malaysia. The long-run causality is confirmed by the negative sign and significance of the coefficient of the lagged error correction term (ECT). The ECT also shows the speed of adjustment from short-run disequilibrium to long-run equilibrium. For instance, in the CO2 emissions model, the estimated speed of adjustment is 25.3 % per year, suggesting that the economy will take approximately 4 years to converge to long-run equilibrium from short-run disequilibrium. Moreover, the joint short-run causality is confirmed by the significance of the F-statistic (derived from the VEC Granger causality/block exogeneity Wald tests). Moreover, there are evidence of individual short-run causal relationships from the independent variables to CO2 emissions (see Appendix 1). Hence, variations in GDP, energy consumption, industrialization, globalization, and ICT can cause variations in CO2 emissions in Malaysia.[2] This outcome agreed with [5] who reported that GDP, globalization, and ICT are significant determinants of CO2 emissions in 6 ASEAN. Sohag et al. [6] showed that energy consumption and industrialization drives CO2 emissions in 86 nations whereas [2] noted that energy consumption and GDP raise CO2 emissions in 122 nations. Kahouli et al. [35] revealed a long-run unidirectional causal relationship from GDP, energy consumption, industrialization, and urbanization to CO2 emissions in Saudi Arabia. Nasir et al. [36] also found a unidirectional causal relationship from GDP, energy consumption, industrialization, and trade to CO2 emissions in Australia.

However, when ecological footprint was utilized as an alternative proxy of environmental degradation, the outcomes displayed in Table 3 show no significant evidence to support any joint long-run or short-run causality from the independent variables to ecological footprint in Malaysia. This finding is consistent with [77] who found insignificant causality from energy consumption, trade, and GDP to ecological footprint in Thailand, albeit [78] documented causality from energy consumption, globalization, and GDP to ecological footprint in Turkey.

Second, the VECM estimations discloses a joint long-run causality from energy consumption, GDP, globalization, ICT, and CO2 emissions to industrialization in Malaysia. The ECT coefficient is significance with a negative sign. This suggests that energy consumption, GDP, globalization, ICT, and CO2 emissions are significant determinants of industrialization. This outcome is in consonant with [46] who stated that energy consumption enhances industrialization in Pakistan.

Third, we find a joint long-run and short-run causal relationships from energy consumption, GDP, globalization, industrialization, and CO2 emissions to ICT in Malaysia. The ECT coefficient is negative and significant (long-run causality), and the F-statistic (derived from the VEC Granger causality/block exogeneity Wald tests) is significant (short-run causality). This implies that energy consumption, GDP, industrialization, and globalization are significant determinants of ICT in Malaysia. This evidence agreed with [3] who showed that GDP, globalization, and energy consumption cause ICT in BRICS, while [58] noted that GDP and energy consumption

[2] We thank the anonymous referee for this suggestion. To control for trend in the models, this study added trend to the bound cointegration test and the VECM Granger causality models and redo the analysis. The results reported in Appendix 2 are similar to the empirical outcomes displayed in Table 3 (without trend). Precisely, the bound test shows that the variables have cointegration relationships while the VECM Granger causality test indicates joint long-run and short-run causal relationships from GDP, energy consumption, industrialization, globalization, and ICT to CO2 emissions in Malaysia.

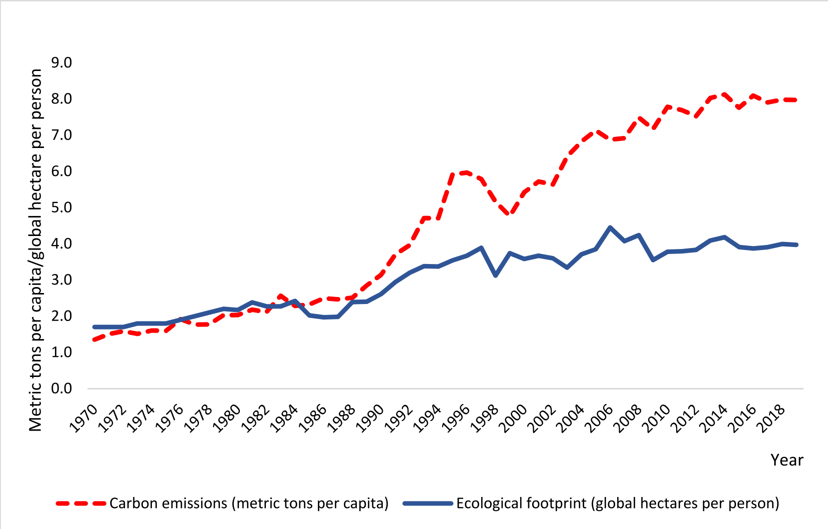

Fig. 1. Environmental degradation.
Source: Drawn by the authors with data from World Development Indicators [46] and Global Footprint Network [47].

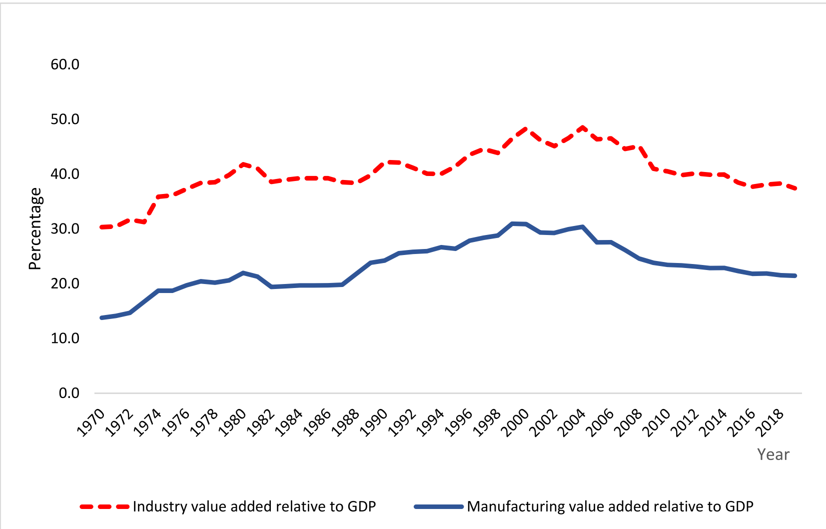

Fig. 2. Industrialization.
Source: Drawn by the authors with data from World Development Indicators [46]

Granger causes ICT in 14 countries.

Fourth, we find a joint short run causality from GDP, industrialization, globalization, ICT and CO2 emissions to energy consumption in Malaysia. A joint short run Granger causality from energy consumption, GDP, industrialization, ICT and CO2 emissions to globalization in Malaysia. Ahmed et al. [79,80] documented that GDP and globalization drive energy consumption. Finally, the VECM indicates a joint short-run and long-run causal relationships from GDP, industrialization, globalization, ICT, and ecological footprint to energy consumption; a joint long run causality from GDP, energy consumption, globalization, ICT, and ecological footprint to

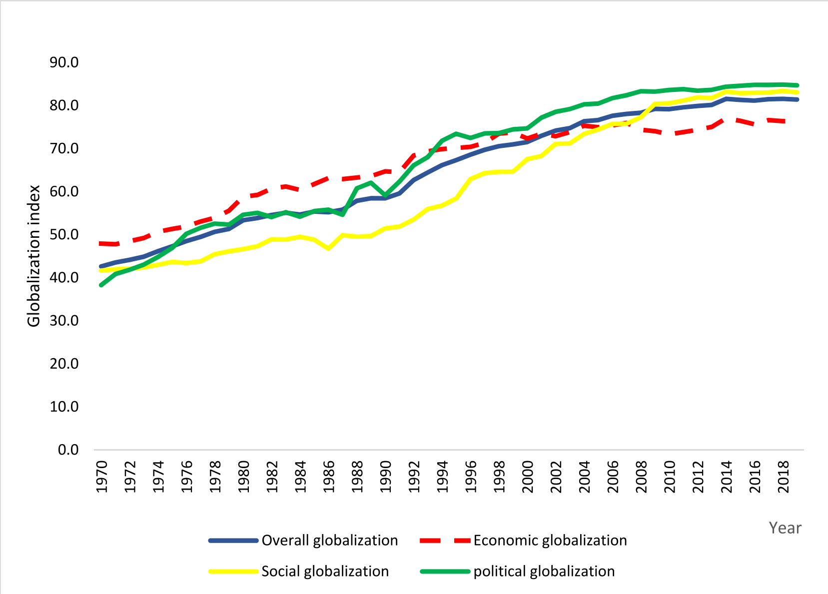

Fig. 3. Globalization index.
Source: Drawn by the authors with data from KOF Globalization Index [48] published by KOF Swiss Economic Institute.

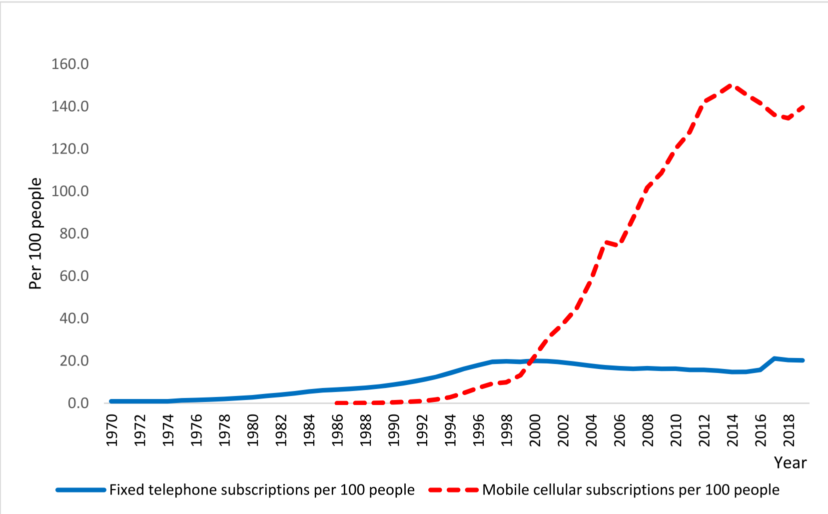

Fig. 4. Information and communication technology.
Source: Drawn by the authors with data from World Development Indicators [46]

Table 2
Unit root tests.

	Augmented Dickey Fuller		Phillips-Perron	
Variables	I(0)	I(1)	I(0)	I(1)
CO2	−1.437	−8.066***	−1.437	−8.012***
EFP	−1.436	−9.033***	−1.408	−8.915***
ENC	−1.425	−6.933***	−1.648	−6.978***
GDP	−1.773	−5.992***	−1.737	−5.991***
IND	−2.667*	−6.282***	−2.659*	−6.282***
GLO	−3.621***	−4.524***	−3.062**	−4.580***
ICT	−2.820	−3.919***	−2.544	−3.911***

Notes: ***, ** and * indicate statistical significance at 1 %,5 % and 10 % levels respectively, and a rejection of the null hypothesis of no unit root.

Table 3
Bound cointegration tests and VECM Granger causality estimations.

Causal Flow	Bound test	F-statistic	ECM statistic
$CO2 \leftarrow (ENC, GDP, IND, GLO, ICT)$	3.509**	35.371*** (0.000)	−0.253*** [-2.649]
$ENC \leftarrow (CO2, GDP, IND, GLO, ICT)$	7.304***	30.957** (0.050)	−0.027 [-0.375]
$GDP \leftarrow (CO2, ENC, IND, GLO, ICT)$	6.238***	21.921 (0.344)	−0.039 [-0.864]
$IND \leftarrow (CO2, ENC, GDP, GLO, ICT)$	5.167***	48.362*** (0.000)	−0.135*** [-4.171]
$GLO \leftarrow (CO2, ENC, GDP, IND, ICT)$	17.375***	29.976* (0.070)	0.016 [-1.171]
$ICT \leftarrow (CO2, ENC, GDP, IND, GLO)$	4.196***	37.522*** (0.010)	−0.217*** [-2.359]
$EFP \leftarrow (ENC, GDP, IND, GLO, ICT)$	6.130***	3.338 (1.000)	−0.208 [-0.906]
$ENC \leftarrow (EFP, GDP, IND, GLO, ICT)$	8.394***	48.436*** (0.000)	−0.186** [-1.815]
$GDP \leftarrow (EFP, ENC, IND, GLO, ICT)$	9.409***	10.709 (0.953)	−0.088 [-1.081]
$IND \leftarrow (EFP, ENC, GDP, GLO, ICT)$	2.612*	24.819 (0.208)	−0.101* [-1.587]
$GLO \leftarrow (EFP, ENC, GDP, IND, ICT)$	16.831***	15.652 (0.738)	0.022 [1.039]
$ICT \leftarrow (EFP, ENC, GDP, IND, GLO)$	4.037**	43.355*** (0.001)	0.495*** [3.587]

Notes: ***, ** and * indicate statistically significance at 1 %, 5 % and 10 % levels, respectively. The upper bound critical values of the bound test are 3.90, 3.21 and 2.89 at the 1 %, 5 % and 10 % levels, respectively. *P*-values of F-statistics are reported in parenthesis, while the values in squared brackets are t-statistics of the coefficients of the ECT.

industrialization; and a joint short run causality from GDP, energy consumption, industrialization, globalization, and ecological footprint to ICT in Malaysia.[3] The outcomes agreed with some prior studies [63,79].

4.3. Granger causality test in frequency domain

To ascertain causality in bivariate framework, as well as show whether the causal relationship is permanent or temporary, this study employs the frequency domain Granger causality approach. The results shown in Table 4 indicate a permanent causality from energy consumption to CO2 emissions; permanent causality from GDP to CO2 emissions; permanent causality from industrialization to CO2 emissions; and permanent causality from ICT to CO2 emissions in Malaysia. The results show both temporary and permanent bidirectional causal relationships between CO2 emissions and globalization. The implication is that GDP, energy consumption, industrialization, globalization, and ICT significantly predict CO2 emissions at high frequency than at low frequency. The outcomes agreed with [4] who showed unidirectional causality from GDP and ICT to CO2 emissions in 23 nations. Haseeb et al. [3] found that GDP, energy consumption, and ICT Granger cause CO2 emissions in BRICS, while [5] reported a causal relationship from GDP, energy consumption, globalization, and ICT to CO2 emissions in 6 ASEAN. N'dri et al. [11] noted that ICT drives CO2 emissions in 58 countries while Alkhathlan and Javid [81] reported that GDP and energy consumption Granger cause CO2 emissions in Saudi Arabia. Avom et al. [61] also revealed that GDP, energy consumption and ICT contribute to CO2 emissions in 21 African nations.

As for ecological footprint, the results indicate permanent causality from energy consumption to ecological footprint; permanent causal relationship from GDP to ecological footprint; permanent causal relationship from industrialization to ecological footprint; permanent causal bidirectional relationship between globalization and ecological footprint. These imply that GDP, industrialization, and globalization predict ecological footprint at high frequency than at low frequency in Malaysia. In conclusion, the temporary and permanent causality suggest that the causal relationships are valid for short and long durations, respectively. The outcomes are in consonant with [63] who reported that GDP, energy consumption and ICT significantly drive ecological footprint in 10 nations. Usman and Balsalobre-Lorente [38] also revealed that industrialization Granger causes ecological footprint in 10 newly industrialized nations. Sharif et al. [82] revealed that a bidirectional causal relationship between globalization and ecological footprint in 8 countries.

4.4. Alternative proxies

To establish the robustness of the estimations, this study utilizes alternative proxies of industrialization (i.e., manufacturing value added relative to GDP), three globalization dimensions (political, social, and economic) and two alternative proxies of ICT (internet users and mobile cellular subscriptions). The outcomes of the frequency domain Granger causality test displayed in Table 5 are comparable to the empirical outcomes shown in Table 4 regarding the significance of the coefficients.

A summary of the results reveals a permanent causality from manufacturing value added to CO2 emissions in Malaysia. The results show temporary and permanent causal relationship from economic dimension of globalization to CO2 emissions; bidirectional permanent causality between social globalization and CO2 emissions; and bidirectional permanent causality between political globalization and CO2 emissions. Besides, there are evidence of bidirectional permanent causal relationship between mobile cellular subscriptions and CO2 emissions, as well as a bidirectional permanent causality between internet users and CO2 emissions in Malaysia.

[3] We thank the anonymous referee for this suggestion. To ascertain whether multicollinearity exist in the VECM Granger causality model, this study conducts multicollinearity test using Variance Inflation Factors (VIF) and found that energy consumption is highly correlated with carbon emissions and ecological footprint. To tackle this issue, this study dropped energy consumption from the VECM model and redo the analysis. The results reported in Appendix 3 are similar to the results displayed in Table 3. It shows joint long-run and short-run causal relationships from GDP, industrialization, globalization, and ICT to environmental degradation in Malaysia.

Table 4
Results of causality tests at low and high frequencies
Notes: ***, ** and * indicate statistically significance at 1 %, 5 % and 10 % levels respectively, and a rejection of null hypothesis (No Granger-causality). *P*-values are in parenthesis.

Causal flow	Permanent ($\omega = 0.5$)	Temporary ($\omega = 2.5$)
$ENC \nrightarrow CO2$	8.442**	1.587
	(0.014)	(0.452)
$CO2 \nrightarrow ENC$	2.687	0.292
	(0.260)	(0.864)
$GDP \nrightarrow CO2$	5.653**	3.852
	(0.050)	(0.145)
$CO2 \nrightarrow GDP$	0.644	1.061
	(0.724)	(0.588)
$IND \nrightarrow CO2$	7.802**	2.105
	(0.020)	(0.349)
$CO2 \nrightarrow IND$	1.304	0.185
	(0.520)	(0.911)
$GLO \nrightarrow CO2$	6.336**	6.769**
	(0.042)	(0.033)
$CO2 \nrightarrow GLO$	10.375***	7.727**
	(0.005)	(0.021)
$ICT \nrightarrow CO2$	4.448*	3.245
	(0.100)	(0.197)
$CO2 \nrightarrow ICT$	3.145	0.559
	(0.207)	(0.755)
$ENC \nrightarrow EFP$	2.113	2.257
	(0.347)	(0.323)
$EFP \nrightarrow ENC$	4.606*	0.620
	(0.100)	(0.733)
$GDP \nrightarrow EFP$	11.465***	0.474
	(0.003)	(0.788)
$EFP \nrightarrow GDP$	5.282*	0.937
	(0.071)	(0.625)
$IND \nrightarrow EFP$	5.071*	0.233
	(0.079)	(0.889)
$EFP \nrightarrow IND$	4.106	1.081
	(0.128)	(0.582)
$GLO \nrightarrow EFP$	6.008**	4.557
	(0.049)	(0.102)
$EFP \nrightarrow GLO$	5.512*	5.567*
	(0.063)	(0.061)
$ICT \nrightarrow EFP$	2.481	0.268
	(0.289)	(0.874)
$EFP \nrightarrow ICT$	6.186**	0.387
	(0.045)	(0.823)

Opoku and Aluko [78] showed that manufacturing value added contributes to environmental degradation in 37 African nations. Rudolph and Figge [49] noted that economic globalization aggravates ecological footprint, while social and political globalization do not intensify ecological footprint in 146 economies. Balsalobre-Lorente1 et al. [1] found a bidirectional causality between mobile cellular subscriptions and CO2 emissions in BRICS while Haseeb et al. [3] reported a bidirectional causality between internet users and CO2 emissions in BRICS.

For further robustness checks, this study employs the de facto and the de jure indices of overall, economic, social, and political globalization and redo the analysis. The empirical outcomes shown in Appendix 4 are similar to the results displayed in Table 5. More precisely, there is a permanent causality from the de facto and the de jure overall globalization to CO2 emissions; permanent causality from the de facto economic globalization to CO2 emissions; permanent causality from the de facto social globalization to CO2 emissions; as well as a permanent causality from the de facto political globalization to CO2 emissions in Malaysia. However, the causality from the de jure economic, social, and political globalization are weak. This is not surprising because the de facto index measures actual international flows in activities (e.g., trade in goods and services, investment, migration, information, embassies) while the de jure index measures policies and conditions (e.g., tariffs, trade agreements, investment regulations, international airports, international treaties) that affect the flows and activities [17,18]. Some previous studies have argued that de facto and de jure indices of economic, social, and political globalization could have different effects on economic or environmental sustainability [17,43].

Table 5
Robustness checks of causality tests at low and high frequencies (Alternative proxies)
Notes: ***, ** and * indicate statistically significance at 1 %, 5 % and 10 % levels respectively, and a rejection of null hypothesis (No Granger-causality). *P*-values are in parenthesis. MAN = manufacturing value added relative to GDP, EGLO = economic globalization index, SGLO = social globalization index, PGLO = political globalization index, MCS = mobile cellular subscriptions (per 100 people), INT = individuals using the Internet (% of population).

Causal flow	Permanent ($\omega = 0.5$)	Temporary ($\omega = 2.5$)
$MAN \nrightarrow CO2$	6.371**	2.401
	(0.041)	(0.301)
$CO2 \nrightarrow MAN$	2.925	0.137
	(0.231)	(0.933)
$EGLO \nrightarrow CO2$	14.04***	6.295**
	(0.000)	(0.043)
$CO2 \nrightarrow EGLO$	3.026	5.584*
	(0.220)	(0.061)
$SGLO \nrightarrow CO2$	6.651**	3.758
	(0.036)	(0.152)
$CO2 \nrightarrow SGLO$	11.948***	0.426
	(0.002)	(0.807)
$PGLO \nrightarrow CO2$	7.147**	0.147
	(0.028)	(0.928)
$CO2 \nrightarrow PGLO$	6.569**	0.670
	(0.037)	(0.715)
$MCS \nrightarrow CO2$	4.627*	4.816*
	(0.098)	(0.090)
$CO2 \nrightarrow MCS$	6.203**	0.305
	(0.045)	(0.045)
$INT \nrightarrow CO2$	5.749**	5.571*
	(0.050)	(0.061)
$CO2 \nrightarrow INT$	7.719**	2.323
	(0.021)	(0.313)

4.5. Variance Decompositions

The Variance Decompositions (VDs) reported in Table 6 indicate the proportion of the forecast error variance in the variables at the first ten period due to a shock on each variable. It shows that certain degree of the forecast error variance in CO2 emissions are caused by exogenous shocks to GDP, energy consumption, industrialization, globalization, and ICT in Malaysia. In the tenth period, for instance, a given exogenous shock to GDP, industrialization, globalization, ICT and energy consumption can respectively explain 30.8 %, 10.8 %, 8.3 %, 4.8 % and 1.5 % of the forecast error variance in CO2 emissions in Malaysia. This suggests that GDP, industrialization, globalization, ICT and energy drive CO2 emissions in Malaysia. These findings agreed with our VECM and frequency domain results, and are consistent with some previous studies [1,46,56,59,83,84].

However, when we utilize ecological footprint, the VDs presented in Table 6 (Panel B) indicate that a given exogenous shock to industrialization, globalization, energy consumption and GDP can respectively explain 10.7 %, 9.4 %, 3.7 % and 2.5 % of the variance in ecological footprint in Malaysia. This suggests that industrialization, globalization, energy consumption and GDP are significant determinants of ecological footprint in Malaysia albeit the impact of ICT is tenuous. These findings agreed with our VECM results, and some previous studies [16,79].

Second, the VDs show that some degree of the forecast error variance in GDP are caused by exogenous shocks to energy consumption, globalization, industrialization, and ICT in Malaysia. In the tenth period, for instance, a certain exogenous shock to energy consumption, globalization, industrialization, and ICT can respectively explain 16.1 %, 5.2 %, 4.2 %, and 3.5 % of the variance in GDP in Malaysia. This suggests that energy consumption, globalization, industrialization, and ICT are significant determinants of GDP in Malaysia.

Third, the VDs discloses that certain degree of the forecast error variance in energy consumption are caused by exogenous shocks to GDP, globalization, ICT, and industrialization in Malaysia. In the tenth period, for instance, a given exogenous shock to GDP, globalization, ICT, and industrialization can respectively explain 22.3 %, 15.3 %, 6.7 % and 5.6 % of the variance in energy consumption in Malaysia. This suggests that GDP, globalization, ICT, and industrialization significantly drive energy consumption in Malaysia.

Fourth, the VDs show that certain degree of the variance in industrialization are caused by exogenous shocks to globalization, energy consumption, GDP, and ICT in Malaysia. In the tenth period, a specific exogenous shock to globalization, energy consumption, GDP and ICT can respectively explain 36.1 %, 12.6 %, 3.9 % and 1.7 % of the variance in industrialization in Malaysia. This suggests that globalization, energy consumption, GDP and ICT are significant drivers of industrialization in Malaysia.

Fifth, the VDs show that certain degree of the variance in globalization are caused by exogenous shocks to GDP, energy consumption, ICT, and industrialization in Malaysia. In the tenth period, for instance, a specific exogenous shock to GDP, energy

Table 6
Variance decompositions.

Variance Decomposition of CO2							
Period	S.E.	CO2	ENC	GDP	IND	GLO	ICT
1	0.069	100.00	0.000	0.000	0.000	0.000	0.000
2	0.111	68.295	0.391	8.952	6.394	15.041	0.924
3	0.138	68.398	0.413	11.208	4.566	12.028	3.384
4	0.167	60.615	0.288	15.580	4.987	13.984	4.543
5	0.192	60.461	0.219	16.269	5.088	13.470	4.490
6	0.209	59.946	0.309	18.013	5.280	11.488	4.960
7	0.220	55.889	1.161	20.968	5.622	10.422	5.934
8	0.226	53.043	1.612	22.981	6.801	9.922	5.639
9	0.236	48.706	1.585	25.965	9.382	9.176	5.183
10	0.250	43.723	1.455	30.831	10.846	8.343	4.805
Variance Decomposition of ENC							
Period	S.E.	CO2	ENC	GDP	IND	GLO	ICT
1	0.052	56.146	43.853	0.000	0.000	0.000	0.000
2	0.079	45.650	49.129	4.493	0.081	0.647	0.000
3	0.089	44.863	42.422	5.947	1.476	2.534	2.755
4	0.094	41.308	42.214	5.357	1.330	6.507	4.280
5	0.103	38.090	34.378	4.466	2.228	16.945	3.891
6	0.144	37.323	28.685	9.914	2.579	15.462	6.034
7	0.122	33.769	26.430	14.624	2.341	15.626	7.207
8	0.126	31.753	26.976	14.689	2.230	16.917	7.431
9	0.132	29.239	25.459	16.745	4.882	16.614	7.059
10	0.138	26.968	23.080	22.323	5.657	15.261	6.709
Variance Decomposition of GDP							
Period	S.E.	CO2	ENC	GDP	IND	GLO	ICT
1	0.033	1.505	63.978	34.515	0.000	0.000	0.000
2	0.052	6.501	41.745	45.066	2.288	4.105	0.293
3	0.066	9.261	29.893	48.063	3.129	8.597	1.055
4	0.082	9.177	24.849	50.522	3.475	9.748	2.226
5	0.098	10.880	21.905	52.424	2.722	8.972	3.094
6	0.110	10.849	20.378	54.358	2.695	7.702	4.016
7	0.118	9.752	19.709	56.856	2.754	6.929	3.996
8	0.124	8.871	18.122	59.607	3.090	6.298	4.089
9	0.131	7.916	16.949	61.875	3.695	5.733	3.829
10	0.139	7.267	16.144	63.589	4.289	5.228	3.479
Variance Decomposition of IND							
Period	S.E.	CO2	ENC	GDP	IND	GLO	ICT
1	0.023	0.560	31.995	0.067	67.376	0.000	0.000
2	0.029	18.146	22.432	0.196	54.819	1.795	2.619
3	0.039	35.430	14.521	1.998	38.724	7.818	1.507
4	0.049	35.927	14.747	2.755	28.455	16.479	1.634
5	0.057	28.770	14.506	2.052	24.818	28.153	1.699
6	0.065	26.107	16.424	1.770	20.591	33.341	1.764
7	0.074	28.084	15.507	1.415	17.314	36.045	1.632
8	0.082	31.600	14.504	1.940	13.983	36.015	1.954
9	0.089	32.882	13.437	3.297	12.276	36.111	1.995
10	0.096	35.257	12.625	3.936	10.425	36.059	1.694
Variance Decomposition of GLO							
Period	S.E.	CO2	ENC	GDP	IND	GLO	ICT
1	0.010	0.390	0.879	2.084	0.324	96.320	0.000
2	0.016	9.614	3.198	3.210	1.559	82.417	0.000
3	0.023	20.733	3.811	6.431	0.826	66.247	1.949
4	0.027	20.538	2.629	6.820	0.677	65.822	3.511
5	0.031	17.797	2.054	6.843	0.524	69.227	3.553
6	0.036	15.046	2.055	6.740	0.950	72.111	3.095
7	0.040	13.034	3.843	7.504	1.191	70.413	4.011
8	0.044	10.977	4.006	9.470	1.324	69.881	4.338
9	0.048	9.643	3.922	10.866	1.607	70.056	3.903
10	0.051	9.072	3.776	13.265	2.764	67.570	3.550
Variance Decomposition of ICT							
Period	S.E.	CO2	ENC	GDP	IND	GLO	ICT
1	0.067	17.574	3.827	3.818	10.080	5.974	58.724

(*continued on next page*)

Table 6 (*continued*)

Variance Decomposition of GLO							
Period	S.E.	CO2	ENC	GDP	IND	GLO	ICT
2	0.101	18.396	6.454	3.374	16.045	10.262	45.466
3	0.149	17.039	9.226	23.251	17.602	8.145	24.734
4	0.210	16.839	13.152	34.025	13.489	8.161	14.331
5	0.279	16.464	16.824	35.433	12.136	7.636	11.506
6	0.348	16.288	16.521	40.621	12.234	5.916	8.417
7	0.420	17.930	15.654	44.745	11.155	4.257	6.255
8	0.500	20.567	15.520	45.358	10.034	3.308	5.255
9	0.585	22.230	15.331	45.187	9.878	2.569	4.803
10	0.669	23.340	14.765	46.009	9.769	1.964	4.151
Panel B							
Variance Decomposition of EFP							
Period	S.E.	EFP	ENC	GDP	IND	GLO	ICT
1	0.106	100.00	0.000	0.000	0.000	0.000	0.000
2	0.133	95.155	0.988	0.042	1.636	2.007	0.169
3	0.164	93.155	1.032	0.289	2.727	2.662	0.132
4	0.182	87.402	2.031	0.664	4.773	5.017	0.110
5	0.203	82.885	2.654	0.920	6.910	6.536	0.091
6	0.221	79.654	3.295	1.573	7.756	7.613	0.106
7	0.239	76.660	3.529	1.968	9.220	8.529	0.091
8	0.258	75.324	3.522	2.411	9.811	8.848	0.081
9	0.276	74.404	3.596	2.506	10.318	9.099	0.074
10	0.293	73.542	3.783	2.475	10.707	9.423	0.066

Notes: Cholesky Ordering: CO2, ENC, GDP, IND, GLO, ICT.
Notes: Cholesky Ordering: EFP, ENC, GDP, IND, GLO, ICT.

consumption, ICT and industrialization can respectively explain 13.2 %, 3.7 %, 3.5 % and 2.7 % of the variance in globalization in Malaysia. This suggests that GDP, energy consumption, ICT and industrialization are significant determinants of globalization in Malaysia.

Finally, the VDs show that certain degree of the variance in ICT are caused by exogenous shocks to GDP, energy consumption, industrialization, and globalization in Malaysia. In the tenth period for instance, a specific exogenous shock to GDP, energy consumption, industrialization and globalization can respectively explain 46 %, 14.7 %, 9.7 % and 1.9 % of the variance in ICT in Malaysia. This suggests that GDP, energy consumption, industrialization and globalization are significant drivers of ICT in Malaysia.

4.6. Impulse Response Functions

The Impulse Response Functions (IRFs) shown in Fig. 5 indicate the reactions of CO2 emissions to shocks on GDP, energy consumption, industrialization, globalization, and ICT (extent of effect). First, the IRFs show that the reaction of CO2 emissions to a standard deviation shock on GDP, energy consumption, industrialization and globalization is positive with a stable power over time. However, Fig. 6 indicates that the reaction of ecological footprint to a standard deviation shock in energy consumption, industrialization and globalization is positive with a stable power over time.

Second, the IRFs provide evidence to show that the reaction of energy consumption to a standard deviation shock on GDP, industrialization, globalization, and ICT is positive. Third, the reaction of GDP to a standard deviation shock on energy consumption, industrialization and globalization is positive with a stable power over time. Fourth, the reaction of industrialization to a standard deviation shock on GDP, globalization and ICT is positive. Fifth, the reaction of globalization to a standard deviation shock on GDP and industrialization is positive. Finally, the reaction of ICT to a standard deviation shock on GDP, energy consumption and globalization is positive. These findings are consistent with our VDs results.

5. Discussion, policy implications and conclusion

The aim of this study is to determine the direction of the causal relationship between industrialization, globalization, ICT, and environmental degradation in Malaysia during the 1970–2019 period. It uses two indicators of environmental degradation (i.e., ecological footprint and CO2 emissions), two indicators of industrialization (i.e., industry value added relative to GDP and manufacturing value added relative to GDP), and three indicators of ICT (i.e., fixed telephone subscriptions, mobile cellular subscriptions, and internet users). It also uses the de facto and de jure indices of overall, economic, social, and political globalization. The empirical strategies utilized in this study are the VECM Granger causality, Frequency domain Granger causality approach, Variance Decompositions (VDs) and Impulse Response Functions (IRFs).

The empirical evidence of this study indicates that the variables have cointegration relationship. It reveals joint long-run and short-run causality from industrialization, globalization, and ICT to CO2 emissions, albeit the causality from the variables to ecological footprint is tenuous. It also reveals that industrialization, globalization, and ICT can predict CO2 emissions at high frequency than at

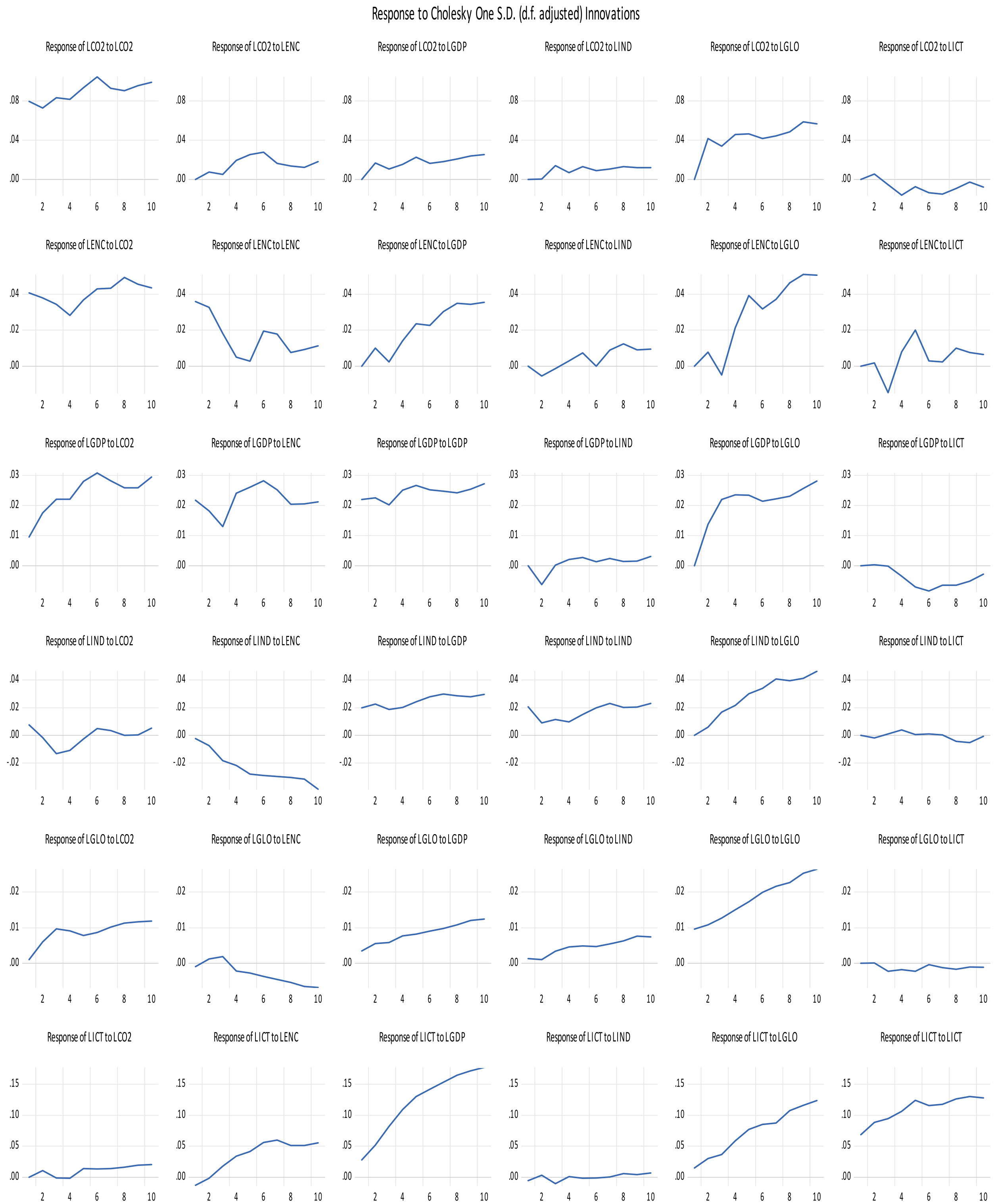

Fig. 5. Impulse Response Functions (CO2 emissions)
Notes: The vertical axis of the IRFs measures the impulse response of the dependent variable (in standard deviation) to shocks in the independent variables while the horizontal axis measures the time period (in years).

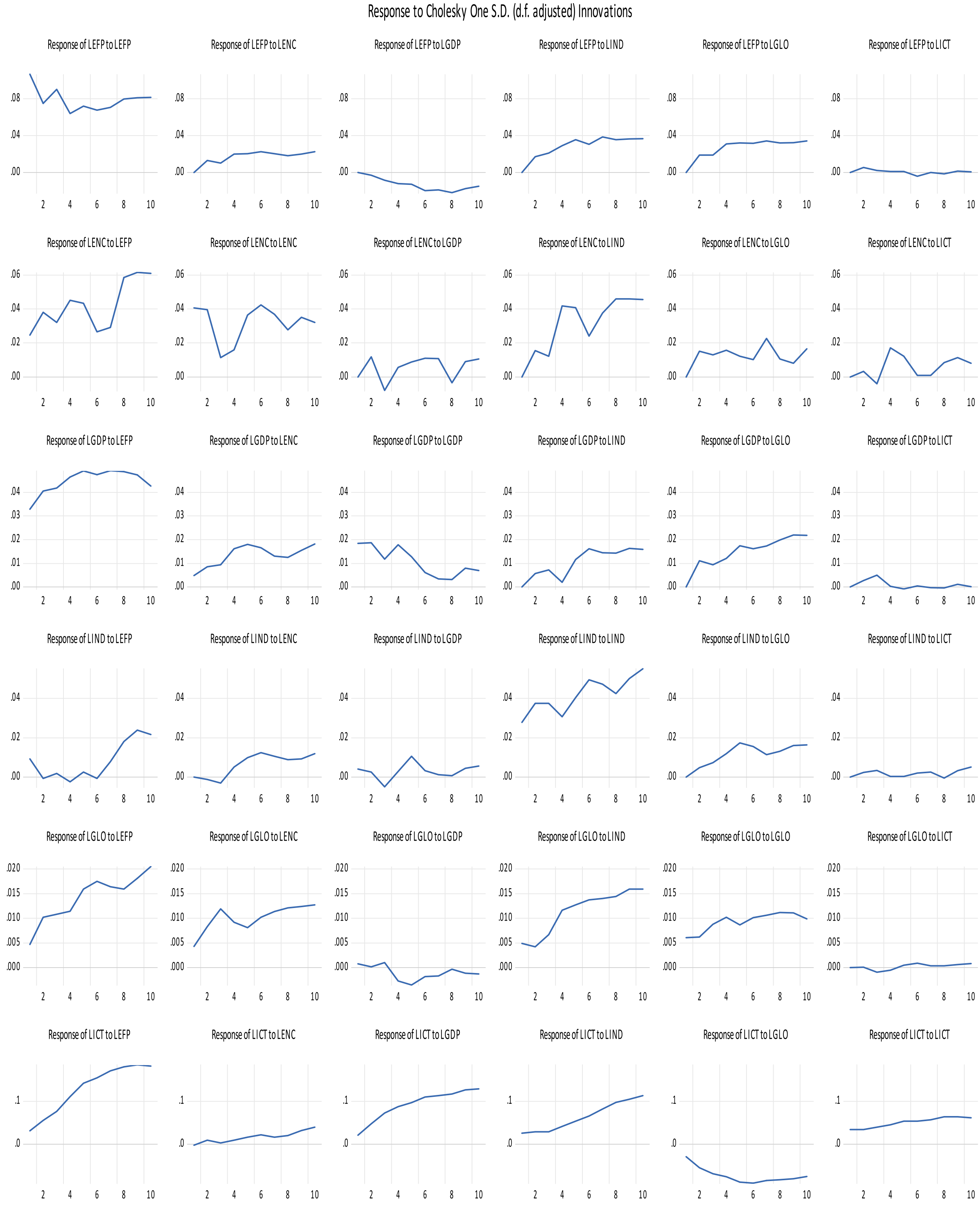

Fig. 6. Impulse Response Functions (Ecological footprint)
Notes: The vertical axis of the IRFs measures the impulse response of the dependent variable (in standard deviation) to shocks in the independent variables while the horizontal axis measures the time period (in years).

low frequency. It shows the percentage of the forecast error variance in environmental degradation that are explained by exogenous shocks to industrialization, globalization, and ICT over time. The plausible justification why industrialization contributes to CO2 emissions in Malaysia is probably because most of the energy required for industrial activities are obtained from fossil fuels that emit intensive pollution. For instance, more than 90 % of the total energy consumption in Malaysia are obtained from fossil fuels while less than 10 % of the energy are obtained from clean or renewable resources [74]. The policy implication of this finding is that industrialization causes environmental degradation in Malaysia. To tackle the detrimental environmental consequences of industrialization in Malaysia, it is essential to formulate industrial and environmental policies that can encourage the sector to embrace clean production technologies and environmental-friendly projects. Incentives should be provided to industries that practice environmental protection while high-pollution industries should be penalized (e.g., carbon tax). It may be required to formulate and implement environmental laws and regulations that can ensure environmental sustainability. It may be necessary for the country to invest in the production of renewable energy technologies, Research and Development into clean energy as well as technological innovations on energy efficiency.

Globalization Granger causes environmental degradation in Malaysia probably because it encourages the movement of capital flows, trade, labour, foreign direct investment, goods and services. These activities could have detrimental environmental consequences if the firms use obsolete or dirty technologies that emit pollution. Hence, it is necessary to create the strategies that can appraise the environmental sustainability of globalization and its dimensions. It is fundamental to encourage energy efficiency and environmental-friendly technologies in economic dimension of globalization (e.g., flow of income, capital, investment, goods/services), social globalization dimension (e.g., diffusion of information, people, images, cultural proximity, personal contact) and political globalization dimension (e.g., embassies in nations, international organizations membership). Since, this study revealed that de facto indices of globalization have detrimental effects on environmental degradation, it may be necessary to consider the environmental consequences of globalization in the country's quest for sustainable development. The government should emphasize the need for environmental protection to foreign investors and associates since globalization erodes national borders, integrates national culture, technologies and create mutual interdependence and relations.

ICT Granger causes environmental degradation in Malaysia probably because of the rapid increase in ICT investment, equipment, and infrastructure in recent decades. Malaysia should embrace the "green ICT" initiative which seeks to mitigate the unfavourable influence of ICT on environmental degradation. It underscores the need for effective and efficient ICT advancement that has negligible or no harmful environmental effect. ICT can abate environmental degradation if it creates environmental-friendly smarter cities, electrical grids, industrial and transportation systems. Finally, since Malaysia cannot afford to sacrifice industrialization, globalization, and ICT for environmental quality, it may be necessary to critically assess the environmental consequences of these activities. The stakeholders should be sensitized or educated on the need to adhere to environmental laws and regulations, and the government should strictly implement energy and environmental policies. The government may give incentives to firms that adopt energy-efficiency and clean production technologies (e.g., tax holiday) but penalize firms that pollute the environment (e.g., through imposition of carbon tax) to achieve environmental sustainability.

This study has analyzed the causal relationship between industrialization, globalization, ICT, and environmental degradation in Malaysia using two indicators of environmental degradation (i.e., CO2 emissions and ecological footprint). One of the limitations of this study is the inability to capture other aspects of environmental degradation (e.g., N_2O emissions, CH_4 emissions, and other greenhouse gases) due to unavailability of time series data in Malaysia. Moreover, the empirical strategies used in this study were unable to determine the impact of the interaction term between industrialization and globalization (or industrialization and ICT) on environmental degradation. Therefore, it is recommended for future research to investigate the impact of industrialization, globalization, and ICT on N_2O emissions, CH_4 emissions, and other greenhouse gases. Finally, it is recommended for future studies to explore the impact of the interaction term between industrialization and globalization (or industrialization and ICT) on environmental degradation for greater insights.

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Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Kizito Uyi Ehigiamusoe: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Hooi Hooi Lean:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Marina Mustapha:**

Investigation, Methodology, Validation, Visualization, Writing – review & editing. **Suresh Ramakrishnan:** Formal analysis, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Kizito Uyi Ehigiamusoe and Hooi Hooi Lean reports financial support was provided by Ministry of Higher Education of Malaysia.

Appendix 1. VECM Individual short-run causality

Dependent variables		Independent variables				
	$\Delta CO2$	ΔENC	ΔGDP	ΔIND	ΔGLO	ΔICT
$\Delta CO2$	–	8.168* (0.083)	7.621* (0.100)	14.915*** (0.004)	15.196*** (0.004)	7.101 (0.130)
ΔENC	3.003 (0.557)	–	5.632 (0.228)	3.476 (0.481)	12.006** (0.017)	5.167 (0.270)
ΔGDP	5.528 (0.237)	0.390 (0.983)	–	7.955* (0.093)	3.354 (0.500)	0.625 (0.960)
ΔIND	3.349 (0.501)	19.254*** (0.000)	12.653** (0.013)	–	19.075*** (0.000)	12.695** (0.012)
ΔGLO	2.962 (0.564)	3.374 (0.497)	6.071 (0.193)	2.480 (0.648)	–	3.908 (0.418)
ΔICT	10.482** (0.033)	4.032 (0.401)	16.072*** (0.003)	6.005 (0.198)	0.899 (924)	–

Notes: ***, ** and * indicate statistically significance at 1 %, 5 % and 10 % levels, respectively. *P*-values of F-statistics are reported in parenthesis.

Appendix 2. Robustness check of VECM Granger causality estimations controlling for trend

Causal Flow	Bound test	F-statistic	ECM statistic
$CO2 \leftarrow (ENC, GDP, IND, GLO, ICT)$	6.283***	48.507*** (0.000)	−0.062*** [−3.634]
$ENC \leftarrow (CO2, GDP, IND, GLO, ICT)$	9.868***	29.161* (0.085)	−0.017 [−1.243]
$GDP \leftarrow (CO2, ENC, IND, GLO, ICT)$	4.347**	22.602 (0.308)	−0.012 [−1.312]
$IND \leftarrow (CO2, ENC, GDP, GLO, ICT)$	6.519***	55.434*** (0.000)	−0.028*** [−4.698]
$GLO \leftarrow (CO2, ENC, GDP, IND, ICT)$	5.687***	27.937* (0.071)	−0.004 [−1.309]
$ICT \leftarrow (CO2, ENC, GDP, IND, GLO)$	4.413**	39.960** (0.011)	−0038** [−2.041]
$EFP \leftarrow (ENC, GDP, IND, GLO, ICT)$	4.589**	3.653 (1.000)	−0.185 [−0.977]
$ENC \leftarrow (EFP, GDP, IND, GLO, ICT)$	10.448***	51.174*** (0.000)	−0.175** [−2.089]
$GDP \leftarrow (EFP, ENC, IND, GLO, ICT)$	8.993***	10.227 (0.964)	−0.077 [−1.127]
$IND \leftarrow (EFP, ENC, GDP, GLO, ICT)$	7.843***	23.939 (0.245)	−0.071 [−1.318]
$GLO \leftarrow (EFP, ENC, GDP, IND, ICT)$	9.864***	16.151 (0.707)	0.172 [0.960]
$ICT \leftarrow (EFP, ENC, GDP, IND, GLO)$	3.835*	46.781*** (0.000)	0.426*** [3.870]

Notes: ***, ** and * indicate statistically significance at 1 %, 5 % and 10 % levels, respectively. The upper bound critical values of the bound test are 5.23, 4.25 and 3.79 at the 1 %, 5 % and 10 % respectively. *P*-values of F-statistics are reported in parenthesis, while the values in squared brackets are t-statistics of the coefficients of the ECT. In the VECM model with CO2 emissions, the coefficient (t-statistic) of the trend term is −0.277(−2.711) while the coefficient (t-statistic) of the trend term in the VECM model with CO2 ecological footprint is −0.022 (−1.569).

Appendix 3. Robustness check of VECM Granger causality estimations controlling for multicollinearity

Causal Flow	Bound test	F-statistic	ECM statistic
$CO2 \leftarrow (GDP, IND, GLO, ICT)$	5.183***	11.823** (0.018)	−0.156** [−1.995]
$GDP \leftarrow (CO2, IND, GLO, ICT)$	6.366***	9.445** (0.050)	−0.074** [−2.219]
$IND \leftarrow (CO2, GDP, GLO, ICT)$	6.457***	2.188 (0.701)	−0.034 [−0.815]
$GLO \leftarrow (CO2, GDP, IND, ICT)$	8.756***	4.467 (0.346)	0.039*** [3.972]
$ICT \leftarrow (CO2, GDP, IND, GLO)$	5.838***	2.273 (0.685)	0.088 [1.064]
$EFP \leftarrow (GDP, IND, GLO, ICT)$	6.195***	6.213 (0.623)	−0.102** [−1.963]
$GDP \leftarrow (EFP, IND, GLO, ICT)$	3.875***	10.292 (0.245)	−0.047** [−2.213]
$IND \leftarrow (EFP, GDP, GLO, ICT)$	4.102**	5.962 (0.651)	−0.025 [−0.978]
$GLO \leftarrow (EFP, GDP, IND, ICT)$	22.670***	7.233 (0.511)	0.016** [2.355]
$ICT \leftarrow (EFP, GDP, IND, GLO)$	4.635***	12.594 (0.126)	0.132*** [2.820]

Notes: ***, ** and * indicate statistically significance at 1 %, 5 % and 10 % levels, respectively. The upper bound critical values of the bound test are 4.37, 3.49 and 3.09 at the 1 %, 5 % and 10%levels, respectively. *P*-values of F-statistics are reported in parenthesis, while the values in squared brackets are t-statistics of the coefficients of the ECT.

Appendix 4. Robustness checks of causality tests at low and high frequencies using the de facto and the de jure indices of globalizationNotes: *, ** and * indicate statistically significance at 1 %, 5 % and 10 % levels respectively, and a rejection of null hypothesis (No Granger-causality). *P*-values are in parenthesis. GLOdj = dejure overall globalization index, GLOdf = defacto overall globalization index, EGLOdj = dejure economic globalization index, EGLOdf = defacto economic globalization index, SGLOdj = dejure social globalization index, SGLOdf = defacto social globalization index, PGLOdj = dejure political globalization index, PGLOdf = defacto political globalization index**

Causal flow	Permanent ($\omega = 0.5$)	Temporary ($\omega = 2.5$)
$GLOdf \nrightarrow CO2$	12.808**	2.243
	(0.001)	(0.325)
$CO2 \nrightarrow GLOdf$	1.453	3.194
	(0.483)	(0.202)
$GLOdj \nrightarrow CO2$	6.764**	1.397
	(0.034)	(0.497)
$CO2 \nrightarrow GLOdj$	7.049**	0.957
	(0.029)	(0.619)
$EGLOdf \nrightarrow CO2$	9.657***	0.474
	(0.008)	(0.788)
$CO2 \nrightarrow EGLOdf$	1.447	2.502
	(0.484)	(0.286)
$EGLOdj \nrightarrow CO2$	1.563	3.286
	(0.457)	(0.193)
$CO2 \nrightarrow EGLOdj$	8.436**	2.715
	(0.014)	(0.257)
$SGLOdf \nrightarrow CO2$	7.972**	0.344
	(0.018)	(0.842)
$CO2 \nrightarrow SGLOdf$	5.207*	7.237**
	(0.074)	(0.026)
$SGLOdj \nrightarrow CO2$	0.957	0.485
	(0.619)	(0.784)
$CO2 \nrightarrow SGLOdj$	23.326***	5.256*
	(0.000)	(0.070)
$PGLOdf \nrightarrow CO2$	33.054***	3.300
	(0.000)	(0.192)
$CO2 \nrightarrow PGLOdf$	0.165	2.593
	(0.920)	(0.273)
$PGLOdj \nrightarrow CO2$	4.733*	2.641
	(0.093)	(0.266)
$CO2 \nrightarrow PGLOdj$	12.523***	0.630
	(0.001)	(0.729)

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