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ORIGINAL ARTICLE

The Environmental Kuznets curve hypothesis for deforestation in Bangladesh: An ARDL analysis with multiple structural breaks

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Abstract This paper makes a novel attempt to test the validity of the environmental Kuznets curve hypothesis in the context of Bangladesh using deforestation propensities as indicators of environmental adversities and controlling for energy consumption, agricultural land coverage and population growth rate. Using annual frequency data from 1972 to 2018, the short- and long-run elasticity estimates from the autoregressive distributed lag-error correction modeling approach provide statistical support to the non-linear inverted-U-shaped association between economic growth and deforestation practices in Bangladesh. Thus, the results validate the deforestation-induced environmental Kuznets curve hypothesis in the context of Bangladesh. The elasticity estimates also reveal that energy consumption promotes deforestation activities in the long run but not in the short run. Besides, higher population growth rate and agricultural land expansion are found to account for greater deforestation propensities both in the short and long runs. Furthermore, the vector error correction model and the Hacker and Hatemi-J Granger causality exercises reveal the causal impacts of economic growth on deforestation propensities, both in the short and the long runs. Therefore, the overall results, in a nutshell, indicate a trade-off between economic and environmental welfares during the initial phases of economic growth in Bangladesh which can be anticipated to fade away in the long run. The overall results impose critically important policy implications regarding effective means to reduce deforestation practices in Bangladesh.

Keywords Deforestation · Environmental Kuznets curve · Economic growth · Energy consumption · Bangladesh

JEL Classification F64 · O13 · O44 · Q23 · Q43 · P28

1 Introduction

Global policies, over the past, were inherently biased toward the attainment of economic growth without imposing much emphasis on the associated environmental complexities. Consequently, this has resulted in unprecedented amounts of trade-off between economic and environmental welfares (Murshed and Dao 2020). Therefore, the global economies have gone on to thrive at the expense of the environmental hardships that accompanied the growth achievements (Adu and Denkyirah 2018). However, in the contemporary era, economic growth is often envisioned to simultaneously safeguard social and environmental well-being as well (Long and Ji 2019). In line with this notion, the United Nations' 2030 Sustainable Development Goals (SDG)[1] agenda predominantly builds upon the global commitment to sustain the rising trends in economic, social and environmental development (Nilsson et al. 2016). The SDG collectively aim at expediting socioeconomic development across the globe while simultaneously improving the quality of the global environment as well (Murshed and Mredula 2018). Hence, keeping the ultimate target of attaining the SDG into cognizance, it is pertinent to identify the factors that

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[1] For more information on the SDG see https://www.undp.org/content/undp/en/home/sustainable-development-goals.html.

account for environmental degradation along the economic growth stream.

The overarching linkage between economic growth and environmental quality is theoretically postulated in the environmental Kuznets curve (EKC) hypothesis which predicts an inverted-U-shaped association between these two key macroeconomic aggregates (Murshed et al. 2020a). This hypothesis advocates in favor of economic growth, in the primitive states, leading to environmental hazards. However, the impact can be expected to be reversed later on. Thus, the EKC hypothesis postulates economic growth to be both the short-run cause and the long-run solution to environmental sufferings. The conventional studies focusing on the empirical analysis of the EKC hypothesis have mostly considered emissions of carbon dioxide (CO_2) and other greenhouse gases as the central attributes of environmental dilapidation (Narayan and Narayan 2010; Wang, Han and Kubota 2016). However, the use of deforestation propensities within the economy as an indicator of environmental quality has received nominal attention in the relevant country-specific literature. Therefore, it is pertinent to extensively probe into the economic growth–environmental degradation nexus using deforestation propensities to quantify environmental quality (Van and Azomahou 2007).

Among the several diversified forms of environmental deterioration, tropical deforestation is asserted to be one of the major concerning issues which warrant to be critically addressed, particularly for ensuring the sustainability of the global ecosystem (Waluyo and Terawaki 2016; Murshed 2020a). Deforestation imposes chronic adversities on the ecology through instigating the climate change adversities (Lawrence and Vandecar 2015), thus attributing to desertification (Chakravarty et al. 2012), flooding (Tan-Soo et al. 2016), soil erosion (Anselmetti et al. 2007) and loss of natural habitats (Kushwaha and Hazarika 2004). As a consequence, ecological economists have often referred to deforestation as one of the core indicators of environmental quality whereby the dynamics linked to the global deforestation propensities along the growth cycle has become an interesting genre of research within the environmental economics narrative (Ehrhardt-Martinez et al. 2002). However, most environment-related studies have primarily examined the quality of the environment in terms of the greenhouse gases emitted into the atmosphere; thus, deforestation as a prime determinant of the environmental quality has largely been overlooked in the EKC narrative.

Against this milieu, this paper aims to examine the deforestation-induced EKC hypothesis in the context of Bangladesh, a South Asian economy that has encountered unprecedented incidences of deforestation over the past. Bangladesh is an appropriate country of choice courtesy the nation's historical susceptibility to climate change-induced environmental hazards (Pouliotte et al. 2009); and deforestation is referred to as one of the major attributes of such acute environmental hardships across Bangladesh (Iftekhar and Hoque 2005). Although a wide array of environmental indicators have been used to assess the environmental quality within Bangladesh, the use of deforestation to quantify the state of environmental welfare has largely remained ignored. Therefore, this paper contributes in multiple aspects. Firstly, to the best of knowledge, except for a paper by Miah et al. (2011) which provides a theoretical qualitative review of the EKC hypothesis for deforestation in the context of Bangladesh, there have not been many significant studies in this regard. Thus, this paper aims to bridge this gap in the literature. Secondly, this is only the second country-specific study that empirically analyzes the issue of deforestation within the EKC hypothesis framework for Bangladesh. Thirdly, the empirical analyses conducted in this paper account for the structural break issue that is yet to be extensively considered in the relevant literature that has addressed the deforestation-induced EKC hypothesis. Finally, this paper contributes to the EKC literature by using multiple indicators to demonstrate deforestation practices which add to the robustness of the statistical estimates. Most of the preceding studies have commonly used the deforestation rate as the solitary indicator of deforestation practices within the economy. In contrast, this paper considers three alternative measures of deforestation propensities in Bangladesh.

In line with the specific aims concerning this paper, the following questions are specifically addressed:

1. Does the growth of the Bangladesh economy trigger depletion of its natural forest reserves?
2. Is there an EKC for deforestation in the context of Bangladesh?
3. Does energy consumption affect the growth-deforestation nexus in Bangladesh?
4. Does economic growth have a causal impact on deforestation practices in Bangladesh?

The remainder of the paper is structured as follows. Section 2 provides an overview of environmental hardships and deforestation practices in Bangladesh. The literature review of the theoretical and empirical studies on the EKC hypothesis is presented in Sect. 3. The econometric models and the attributes of the dataset used are put forward in Sect. 4, while Sect. 5 explains the methodology of research. Section 6 reports and discusses the empirical findings from the econometric analyses. Finally, Sect. 7 provides concluding remarks and policy implications.

2 Some stylized facts on environmental issues and deforestation problems in Bangladesh

Natural calamities, stemming from the global warming-triggered climate change phenomena, have historically been more of an '*unwanted companion*' for the Bangladesh economy. The nation was ranked 7th among the most vulnerable global economies that are most likely to be experiencing the bitterness of adverse weather events in the near future (Eckstein et al. 2018). Moreover, due to a lion's share of the nation's economic activities being concentrated within the capital, Dhaka is said to be one of the top five global cities that are likely to succumb to the atrocities of climate change. Besides, the rising sea levels due to climate change have been estimated to claim the lives of as many as 27 million of the Bangladeshi citizens by the end of 2050 (UNDP 2019, February 22). Also, the sea level rises could account for 17% of total land areas of Bangladesh, thus miserably impacting the nation's cultivable lands to jeopardize the nation's overall food security (Mahmud 2017, February 26). Agricultural harvest in Bangladesh is conditional on extreme weather conditions whereby cyclones and flash floods have conventionally resulted in waste of seasonal agricultural produce to a large extent. Similarly, climate change is also anticipated to marginalize the prospects of attaining socioeconomic development within the rural communities of Bangladesh (Ericksen et al. 1993). Hence, curbing deforestation rates is thought of as a key reformative tool to mitigate environmental degradation in Bangladesh. Simultaneously, lower deforestation rates would also enhance the nation's overall resilience to the unforeseen climate change-induced carnages in the future.

On the other hand, the fact that Bangladesh is a tropical country with acute inequality in the living standards, across the urban and rural areas, makes it a frontier of deforestation. According to the World Bank, total forest areas in Bangladesh have shrunk by almost 700 square kilometers between 1990 and 2016, which has shrunk the nation's total forest area coverage by more than 4.5% (World Bank 2018). Although the recent incidents of deforestation in Bangladesh can largely be accredited to the razing of the forests in Cox's Bazar area for accommodating the latest influx of the Rohingya refugees (UNICEF 2018), deforestation practices in Bangladesh can primarily be attributed to the lack of availability of cultivable lands for agricultural activities, firewood supplies and industrial raw materials (Iftekhar and Hoque 2005). Consequently, these factors have persistently aggravated the deforestation woes of the nation, thereby worsening the quality of the local environment to a large extent (Islam and Sato 2012).

However, it is to be noted that Bangladesh in comparison to the leading global economies that are much more developed emits lower volumes of CO_2 per capita (Ahiduzzaman and Islam 2011). The per capita CO_2 emissions of Bangladesh are below that of the regional average across South Asia (World Bank 2018). According to the World Bank estimates, the nation's CO_2 emissions per capita in 2014 stood at 0.46 metric tonnes while the corresponding figures for India, Pakistan and Sri Lanka were around 1.73, 0.90 and 0.89 metric tonnes, respectively (World Bank 2018). On the other hand, despite accounting for low per capita CO_2 emissions, the nation's deforestation woes have simultaneously intensified over the years, therefore marginalizing the per capita forestlands as well (Iftekhar and Hoque 2005). Moreover, taking the rapid population growth rate in Bangladesh into consideration, it can be anticipated that the demand for the existing forestlands, especially for non-forest activities, is likely to surge in the future. This, in turn, could reverse the nation's low per capita CO_2 emission trends while triggering the deforestation propensities further. Therefore, deforestation can be referred to as a critically important issue for Bangladesh's ecological sustainability in the years to come.

Among the other fundamental causes of deforestation, energy consumption is believed to be the core contributor to the outrageously high deforestation rates in Bangladesh. Over the past, extraction of wood from the tropical forests to meet the rural energy demand, in particular, has resulted in unprecedented volumes of deforestation in Bangladesh (Akther et al. 2010). Firewood still accounts for a lion's share of the cooking fuels used within rural households across the nation (Tani and Rahman 2018). Approximately, 40% of the aggregate biomass fuel consumption figures in Bangladesh is sourced from wood extracted from the nation's homestead forests (Miah et al. 2009). Consequently, the search for fuelwood has triggered the incidences of forest encroachment in the country (Iftekhar and Hoque 2005). Apart from bridging the residential cooking fuel demands, wood is also a major means of energy for the brick-manufacturing industry in Bangladesh. In 2011, almost one-third of the total functional brick kilns in Bangladesh were reported to be fired by wood, which not only led to the loss of the forestlands but also attributed to environmental deterioration in terms of higher emissions of greenhouse gases (UNDP 2011, June 20).

3 Literature review

This particular section is divided into two subsections with the former discussing the theoretical framework adhering to the EKC hypothesis, while the latter focuses on the empirical findings documented in this regard.

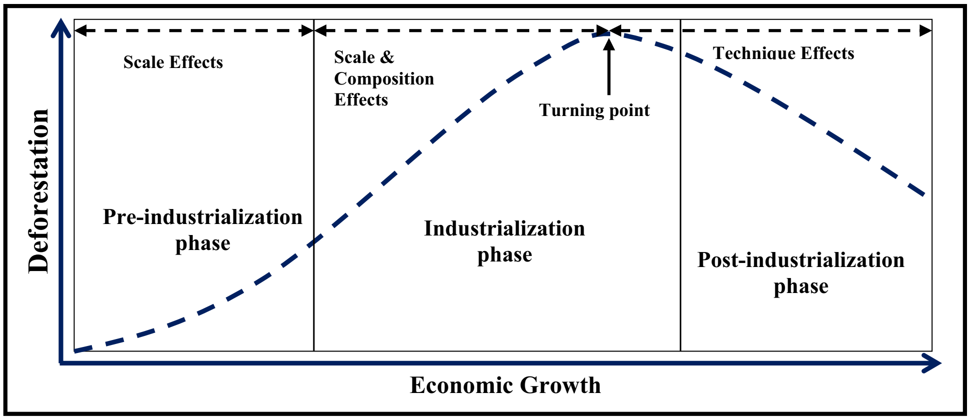

Fig. 1 The deforestation-induced environmental Kuznets curve

3.1 Theoretical framework

Emerging from the nonlinear nexus between economic growth and income inequality, as put forward by Simon Kuznets (Kuznets 1955), the EKC hypothesis has emerged to link the changes in the quality of the environment along the economic growth process (Saint Akadiri et al. 2019). The central idea of the EKC hypothesis asserts that as a nation undergoes structural transformations, involving industrialization of the traditional agrarian economy, it is likely to accept a trade-off between higher rates of economic growth and lower environmental quality (Pata and Aydin 2020; Leal and Marques 2020; Sarkodie and Ozturk 2020). Thus, during the premature stages of growth, the environmental miseries tend to be amplified whereby economic growth can be said to foster environmental deterioration. However, in the later phases, beyond a threshold level of national income, further growth of the economy can be anticipated to reduce the intensity of environmental degradation, thus gradually phasing out the initial trade-off between economic and environmental welfares (Acaravci and Ozturk 2010). Likewise, linking deforestation practices to changes in environmental quality, deforestation rates can be also expected to rise during the initial growth phases which, after a certain level, might decline to reinstate environmental well-being (Murshed 2020a).

The inverted-U shape of the deforestation-induced EKC, as illustrated in Fig. 1, can be described in terms of the scale, composition and technique effects that take place along the growth stream within an economy. In the early stages, which can be referred to as the pre-industrial phase, economic growth is likely to degrade the environment via catalyzing deforestation propensities. This can be initiated from the demand for clearing natural forests to source agricultural lands, housing areas and firewood supplies in particular. Then, as the economy makes a transition toward the industrialization phase, the scale effect can further stimulate the deforestation rates since forests are sources of key industrial inputs in the form of both timber and non-timber products. However, toward the end of the industrialization phase, and throughout the post-industrialization period, the need for restoring environmental balance is likely to induce afforestation and reforestation activities within the economy. Hence, the rate of deforestation is likely to go down. Moreover, technological advancement during this phase, in particular, could lead to changes in production processes whereby alternative inputs are likely to be used instead of conventional forest products. This phenomenon can be linked to the technique effect which results from technological advancement and goes on to improve the environment, particularly via facilitating the renewable energy transition within the economy.[2] Therefore, it can be said that the technique effect gradually eliminates the trade-off between economic and environmental welfares whereby deforestation rates are likely to decline in the future. The dynamics of deforestation along the growth process can also be explained in terms of the concept of '*forest transition.*'[3]

3.2 Empirical evidence

Empirical evidence certifying the correlation between economic growth and CO_2 emissions has been extensively documented in the literature (Murshed et al. 2020d). Among the relevant studies exploring the linear growth-CO_2 emission nexus, (Magazzino 2017 concluded in favor of a positive correlation between per capita real GDP and per capita CO_2 emissions in 19 Asia–Pacific Economic Cooperation (APEC) members. Similarly, Magazzino and Cerulli (2019) asserted per capita GDP to be a long-run determinant of higher levels of CO_2 emissions within the

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[2] For more information regarding renewable energy transition see Murshed and Tanha (2020), Murshed (2018; 2020b; 2020c) and Murshed et al. (2020c).

[3] For an in-depth understanding of the forest transition phenomenon see Singh et al. (2017).

Middle Eastern and North American economies. On the other hand, a plethora of studies have also attempted to empirically ascertain the nonlinear growth-CO_2 emission nexus under the EKC hypothesis framework (Murshed 2020d). However, most of these studies have popularly considered CO_2 emissions to proxy for environmental pollution, courtesy of the latency of the nature of the variables that precisely quantify environmental quality (Zhang et al. 2017). In a relevant study by Magazzino et al. (2020) on South Africa, the statistical estimates confirmed the long-run validity of the EKC hypothesis. Similarly, Alaali and Naser (2020) recently asserted that the EKC hypothesis held for both the short and the long runs in Bahrain. In contrast, Kunnas and Myllyntaus (2007) failed to statistically validate the EKC hypothesis in the context of Finland since higher national income levels were not found to be accompanied by lower CO_2 emissions in the long run. Similarly, Murshed (2020e) opined in favor of the EKC hypothesis being valid for the South Asian countries.

Besides CO_2 emissions, the EKC hypothesis has also been evaluated using other sources of air pollution including emissions of sulfur dioxide (Roca et al. 2001), methane (Miah et al. 2010), nitrous oxide (Sinha and Sengupta 2019), phosphorous (Paudel et al. 2005) and particulate matter (Miah et al. 2011). Besides, the EKC hypothesis for smog pollution was also tested by Xie et al.(2019). On the other hand, considering water pollution as another source of environmental deterioration, several studies have also checked for the robustness of the water pollution-induced EKC hypothesis. For instance, Orubu and Omotor (2011) found inadequate evidence regarding an inverted-U relationship between per capita income and organic water pollutants across Africa. In more recent studies, researchers have also considered the ecological footprints data to assess the authenticity of the EKC hypothesis (Ulucak and Bilgili 2018; Sharif et al. 2020).

However, in comparison to the aforementioned indicators of environmental pollution, the use of deforestation to quantify environmental quality has received minimal attention inside the EKC hypothesis narrative (Choumert et al. 2013). In a cross-country study on the deforestation impacts on the environment across the Latin American, African and Asian countries, Bhattarai and Hammig (2001) found strong statistical evidence regarding the validity of the deforestation-induced EKC hypothesis. Likewise, in the context of the underdeveloped world, Chiu (2012) explored the economic growth-deforestation nexus for a panel of 52 developing countries. The results from the econometric analysis validated the EKC hypothesis. In a similar study comprising of several Latin American, African and Asian nations, Culas (2007) opined that institutional factors play a major role in reducing deforestation practices which, in turn, exhibit key roles in affecting the turning points of the respective deforestation-induced EKCs. In contrast, Van and Azomahou (2007) did not find statistical evidence to conclude in favor of the authenticity of the EKC hypothesis for deforestation across 59 developing economies. Similarly, Jorgenson (2008) found economic growth to be statistically insignificant in explaining the changes in deforestation rates across 40 less-developed countries. Recently, Afawubo and Noglo (2019) found the deforestation-induced EKC hypothesis to be invalid in the context of 106 low and middle-income countries. Therefore, the findings from these aforementioned panel studies imply that the EKC for deforestation is not always guaranteed which justifies the need for probing into the country-specific analysis of the deforestation-induced EKC hypothesis.

Among the preceding country-specific studies, Naito and Traesupap (2014) found statistical validation of the EKC hypothesis for Thailand. The authors used provincial income data as a proxy for provincial growth rates and found that beyond a threshold level of income, further income growths result in lower deforestation rates across the Thai provinces. Similarly, Ahmed et al. (2015) concluded that economic growth in Pakistan causally influences the nation's deforestation propensities in the long run. Besides, the regression findings confirmed the validity of the EKC for deforestation as well. Identical findings were also put forward by Waluyo and Terawaki (2016) in the context of Indonesia. In a recent study by Gokmenoglu et al. (2019), the authors made a novel attempt to use deforestation as a factor attributing to environmental degradation. The results from the econometric analysis confirmed the validity of the deforestation-induced EKC hypothesis in the context of ten global economies that account for almost two-thirds of the global forest area coverage.

In contrast to the findings from these studies, Tsiantikoudis et al.(2019) opined that the growth-deforestation nexus in the context of Bulgaria rather depicts an N-shaped association which contradicts to the inverted-U-shaped relationship postulated under the principles of the EKC hypothesis. The author used the CO_2 emissions from deforestation to measure deforestation propensities and have concluded that although beyond a threshold national income level the deforestation-induced CO_2 emissions reduce in Bulgaria, this trend does not sustain. At the second threshold, the relationship once again reverses whereby further economic growth attributes to higher CO_2 emissions, thus debunking the notion of the EKC hypothesis. Hence, it is apparent that the country-specific empirical evidence documented in the literature also highlights the ambiguous nonlinearity between economic growth and deforestation rates. Therefore, from the point of view of evaluating the heterogeneity of the findings, considering the country-specific attributes, it is important to examine the deforestation-induced EKC hypothesis more extensively for unearthing comprehensive policy implications.

Apart from the national income levels, several studies have also identified various other macroeconomic factors that can influence the deforestation activities within an economy. For instance, Liu et al.(2008) concluded that rural energy consumption was responsible for the deforestation woes of Tibet. In another relevant study on Pakistan, Ahmed et al. (2015) found a positive correlation between energy consumption and deforestation rates in the short run only. Heltberg et al.(2000) alleged fuelwood consumption to catalyze the deterioration of forest reserves across the rural areas inside India. Conversely, Maji (2017) and Maji et al. (2017) could not establish any statistically significant impact of energy consumption on deforestation rates in Nigeria. On the other hand, the substitution between agricultural and forest lands was also highlighted in the literature. Barbier (2004) identified agricultural land expansion to be a major determinant of forest loss across tropical developing economies. Similarly, Jha and Bawa (2006) referred deforestation to be a mechanism to meet the basic human needs of the people within the developing economies from Asia, Africa and Latin America. Recently, in a study on Vietnam, Van Khuc et al. (2018) identified population growth, poverty and governance as the three important factors accountable for rising deforestation rates in Vietnam. In contrast, (Tritsch and Le Tourneau 2016) found a weak association between population density and deforestation rates in the Brazilian Amazon. Likewise, Galinato and Galinato (2016) alleged government spending for agricultural land expansion, in the short run, to be responsible for deforestation across economies which clear forestlands for sourcing agricultural lands. Similar conclusions were made by Kong et al. (2019) in the context of Cambodia. Cerri et al. (2018) recommended the intensification of agricultural activities in Brazil for minimizing Amazonian deforestation. Several other studies have also highlighted the adverse impacts of rising population size on deforestation rates. DeFries et al. (2010) found a positive correlation between urban population growth and deforestation rates, thus referring urbanization as a key driver of deforestation activities in the 21st century. Therefore, the inclusion of these critically important macroeconomic factors within the deforestation-induced EKC hypothesis analysis is pretty justified under the abovementioned theoretical underpinnings.

3.3 The literature on the EKC hypothesis in the context of Bangladesh

The existing studies focusing on the EKC hypothesis in the context of Bangladesh predominantly used CO_2 emissions to quantify environmental quality (Murshed and Dao 2020). For instance, Islam et al. (2013) explored the nonlinear association between economic growth and per capita CO_2 emissions in Bangladesh between 1971 and 2010. The results from the cointegration test revealed long-run associations between these variables. Moreover, the statistical estimates supported the EKC hypothesis for Bangladesh both in the short and the long runs. Besides, unidirectional causations were found to be running from trade openness and urbanization to per capita CO_2 emissions. In a similar study by Shahbaz et al. (2014), the authors modeled the nonlinear dynamics engulfing industrial value-added and CO_2 emissions in Bangladesh, controlling for electricity consumption, financial development and international trade flows. The results provided statistical validity to the EKC hypothesis for Bangladesh between 1975 and 2010. Besides, all three control variables were found to exert adverse impacts on the environment via attributing to higher CO_2 emissions. Likewise, Rabbi et al. (2015) found evidence of long-run associations between CO_2 emissions, national income, energy use and trade openness. Using annual data from 1971 to 2012, the results from the error correction model approach did not support the EKC hypothesis since the estimated coefficients revealed a U-shaped association between national income and CO_2 emissions. On the other hand, using deforestation as a measure of environmental quality, Miah et al. (2011) advocated in favor of the validity of the deforestation-induced EKC hypothesis in Bangladesh. This is the only existing study on Bangladesh that has attempted to provide a qualitative assessment of the deforestation-induced EKC hypothesis in the context of Bangladesh.

Among the other relevant studies that have probed into the macroeconomic factors responsible for stimulating CO_2 emissions in Bangladesh, Banerjee and Rahman (2012) opined that industrial output and population size stimulated CO_2 emissions in the country between 1972 and 2008. However, no statistical evidence regarding the impacts of foreign direct investment on CO_2 emissions could be ascertained. Kashem and Rahman (2019) probed into the causal dynamics between CO_2 emissions and its determinants in the context of Bangladesh over the 1972-2015 period. The results indicated that there are bidirectional causations between CO_2 emissions and urbanization and between CO_2 emissions and per capita growth in the national income while no causal association between population density and CO_2 emissions could be established. In another study by Rahman and Kashem (2017), the authors referred to industrial growth and consumption of energy resources to dampen environmental quality in Bangladesh. The study used annual data from 1972 to 2011 to perform the econometric analyses. Moreover, the results from the causality analysis revealed unidirectional causalities stemming from industrial growth and energy use to

CO_2 emissions. In a recent study by Ahmed et al. (2020), the authors considered the effects of democratic institutions and energy consumption on CO_2 emissions in Bangladesh. The results suggested that the quality of democratic institutions and CO_2 emissions are influenced by each other. Besides, better democratic institutions were also said to positively influence economic growth in Bangladesh.

Hence, it is evident from the aforementioned studies that the use of deforestation to quantify environmental quality within the EKC hypothesis analysis for Bangladesh is yet to be extensively documented in the literature. Thus, this paper particularly addresses this gap for unearthing critically important policy implications concerning the mitigation of the deforestation propensities for ensuring environmental sustainability in Bangladesh.

4 Empirical models and data

The impacts of economic growth on deforestation propensities in Bangladesh are assessed using quadratic models in which three different indicators of deforestation are expressed as separate functions of real national income levels and other key macroeconomic variables controlling the economic growth-deforestation nexus:

$$\begin{aligned}\ln farea_t &= \beta_0 + \beta_1 \ln GDP_t + \beta_2 \ln GDP_t^2 \\ &+ \beta_3 \ln ener_t + \beta_4 \ln agri_t + \beta_5 \ln popg_t + \varepsilon_t\end{aligned} \tag{1}$$

where the subscript t denotes the time period, β_1 is the intercept, β_i ($i = 1, \ldots, 5$) represent the elasticity parameters to be estimated, and ε is the random error term. The variable *farea* refers to the forest area coverage in Bangladesh, measured in terms of square kilometers. The coverage of forest lands is used as an indicator of deforestation in the sense that a decline in the total forest area in the country can be interpreted as a rise in the deforestation propensities and vice versa. Hence, it is to be noted that for this particular case, the corresponding EKC, if found to be statistically valid, is likely to depict a U-shaped association rather than the inverted-U-shaped relationship postulated in the deforestation-induced EKC hypothesis. The variable *GDP* and its squared term GDP^2, respectively, indicate the per capita real Gross Domestic Product of Bangladesh, measured in terms of constant 2010 US dollars. GDP per capita is used to assess the dynamic impacts of higher levels of national income on the nation's forest area coverage to comment on the validity of the EKC hypothesis. Among the other key explanatory variables of concern, the econometric model includes energy consumption in the econometric model. The variable *ener* denotes the per capita energy consumption levels, measured in terms kilograms of oil equivalent. It is pertinent to control for energy consumption since employment of energy resources attribute to economic growth (Ferdaus et al. 2020). Besides, energy consumption is acknowledged to be a critically important determinant of deforestation in Bangladesh (Hassan et al. 2013) which justifies its inclusion into the model.

Besides, the econometric model is also controlled for agricultural land coverage, as symbolized by *agri* and measured in terms of square kilometers. The inclusion of the agricultural land area into the model can be justified from the understanding that forest areas are often razed for agricultural purposes, especially across the rural regions (Etter et al. 2006). Thus, a substitution between forest and agricultural lands can be expected. Finally, population growth rate, denoted by *popg*, accounts for the size of the population within the EKC analysis which can be anticipated to reduce total forest areas across Bangladesh. The justification of controlling for the growth in population size can be explained in terms of the understanding that a rise in the population growth rate is likely to exert pressures to raze the forest lands for habitation purposes and firewood extraction in particular (DeFries et al. 2010). Following Murshed (2019), all the variables have been transformed into their natural logarithms for the ease of elasticity estimation. Moreover, log-transforming these variables reduce the possible sharpness of the time-series data, thus enhancing the consistency and reliability of the elasticity estimates. A similar approach was used in the study by Shahbaz and Rahman (2010).

For the robustness check of the growth-deforestation nexus, two alternate indicators of deforestation are augmented into the econometric analyses. This paper uses the deforestation and net forest depletion rates as alternatives to the forest area coverage variable shown in model (1). The modified econometric models can be specified as:

$$\begin{aligned}\ln deforest_t &= \beta_0 + \beta_1 \ln GDP_t + \beta_2 \ln GDP_t^2 \\ &+ \beta_3 \ln ener_t + \beta_4 \ln agri_t + \beta_5 \ln popg_t + \varepsilon_t\end{aligned} \tag{2}$$

$$\begin{aligned}\ln nfdep_t &= \beta_0 + \beta_1 \ln GDP_t + \beta_2 \ln GDP_t^2 \\ &+ \beta_3 \ln ener_t + \beta_4 \ln agri_t + \beta_5 \ln popg_t + \varepsilon_t\end{aligned} \tag{3}$$

where *deforest* and *nfdep* refer to the deforestation and net forest depletion rates, respectively. The deforestation rate is calculated from the current and previous years' forest area coverage figures for each year. The net forest depletion rate is estimated as the annual percentage change of net forest depletion figures in the current and the preceding years.

This paper pools annual time-series data in the context of all the aforementioned variables from 1972 to 2018. The data are sourced from the World Development Indicators database of the World Bank (2018). Table 6 in Appendix tabulates the descriptive statistics of the variables in their natural logarithmic forms.

5 Methodology

5.1 The unit root and cointegration analysis

Firstly, the data set is tested for the stationarity properties to determine the order of integration among the variables. Although many studies have used the conventional unit root testing methods, these techniques fail to account for the possible structural breaks issues in the data and generate biased estimates of the stationarity properties (Perron 1989). Thus, to resolve this limitation, this paper considers the Zivot–Andrews (ZA) and the Clemente–Montanes–Reyes (CMR) unit root tests proposed by Zivot and Andrews (2002) and Clemente et al. (1998), respectively. While the ZA method can account for one structural break in the data, the CMR technique can accommodate up to two structural breaks. For comparison purposes, the conventionally used unit root estimation techniques, namely the augmented Dickey–Fuller (ADF) test (Dickey and Fuller 1979), the Phillips–Perron (PP) test (Phillips and Perron 1988), the Dickey–Fuller generalized least squares (DF-GLS) test (Elliott et al. 1996), the Kapetanios and Shin unit root (KSUR) test (Kapetanios and Shin 2008), the Kapetanios–Shin–Snell unit root (KSSUR) test (Kapetanios et al. 2003) and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (Kwiatkowski et al. 1992), which do not take the structural break issues into account, are also performed.

The unit root tests are followed by the Gregory–Hansen (GH) cointegration analysis introduced by Gregory and Hansen (1996). This technique can also accommodate the possible structural breaks issues in the data that may be occurring particularly from the regime and trend shifts. Based on the identification of the break dates from both the unit root and cointegration exercises, the corresponding break date dummy variables are generated and augmented into the respective econometric models for performing the regression and causality analyses. Although the Bounds testing approach to cointegration is a preferred method for estimating the long run associations, it is not used due to its limitation in terms of not being able to account for the structural breaks in the data. The results are also checked using the conventionally used Johansen (1991) cointegration method which does not accommodate the structural breaks.

5.2 The autoregressive distributed lag-error correction model approach

The short and long-run elasticities are predicted using the autoregressive distributed lag (ARDL) technique developed by Pesaran et al. (2001). This methodology is believed to handle variables with mixed order of integration and generate unbiased results compared to the other estimation techniques that require a common order of integration among the variables. However, a limitation of this procedure is its inability to accommodate the structural breaks. This problem can be solved by incorporating the structural break year dummy variables into the econometric models. The ARDL approach is a two-step procedure in which the first step involves the estimation of an unrestricted error correction model (ECM). The ECM model in the context of model (1) can be specified as follows:

$$\begin{aligned}\Delta \ln farea_t = {} & \beta_0+\beta_1 \ln farea_{t-1}+\beta_2 \ln GDP_{t-1}+\beta_3 \ln GDP^2_{t-1} \\ & +\beta_4 \ln ener_{t-1}+\beta_5 \ln agri_{t-1}+\beta_6 \ln popg_{t-1} \\ & +\beta_7 D_{t-1}+\sum_{i=1}^{m}\alpha_{1i}\Delta \ln farea_{t-i} \\ & +\sum_{j=0}^{n}\alpha_{2j}\Delta \ln GDP_{t-j}+\sum_{k=0}^{o}\alpha_{3k}\Delta \ln GDP^2_{t-k} \\ & +\sum_{l=0}^{p}\alpha_{4l}\Delta \ln ener_{t-l} \\ & +\sum_{m=0}^{q}\alpha_{5m}\Delta \ln area_{t-m}+\sum_{w=0}^{r}\alpha_{6p}\Delta \ln popg_{t-w} \\ & +\sum_{v=0}^{s}\alpha_{7v}\Delta D_{t-v}+\theta_t\end{aligned} \tag{4}$$

where Δ denotes first difference form of the corresponding variables and D denotes the break year dummy variable. The short-run dynamics is observed from the model below:

$$\begin{aligned}\Delta \ln farea_t = {} & \delta_1+\sum_{i=1}^{m}\delta_{1i}\Delta \ln farea_{t-i} \\ & +\sum_{j=0}^{n}\delta_{2j}\Delta \ln GDP_{t-j}+\sum_{k=0}^{o}\delta_{3k}\Delta \ln GDP^2_{t-k} \\ & +\sum_{l=0}^{p}\alpha_{4l}\Delta \ln ener_{t-l}+\sum_{m=0}^{q}\alpha_{5m}\Delta \ln area_{t-m} \\ & +\sum_{w=0}^{r}\alpha_{6p}\Delta \ln popg_{t-w}+\sum_{v=0}^{s}\alpha_{7v}\Delta D_{t-v}+\tau_t\end{aligned} \tag{5}$$

where ECT_{t-1} represents the one-period-lagged ECT which is estimated from the residuals of the long-run equation shown in model (6). The ECT reflects the speed of adjustment of the variables in restoring long-run equilibrium following a deviation in the earlier period. The long-run elasticities are sourced from the model below:

$$\begin{aligned}\ln farea_t = \partial_0 + \partial_1 \ln farea_{t-1} \\ + \partial_2 \ln GDP_{t-1} + \partial_3 \ln GDP^2_{t-1} + \partial_4 \ln ener_{t-1} \\ + \partial_5 \ln agri_{t-1} + \partial_6 \ln popg_{t-1} + \partial_7 D_{t-1} + \vartheta_t\end{aligned} \tag{6}$$

The stability of the ARDL estimates are checked using the Breusch-Godfrey Lagrange multiplier test for autocorrelation (BGodfrey) proposed by Breusch and Godfrey (1981), the Engle's Lagrange multiplier test for the presence of autoregressive conditional heteroskedasticity (ARCH) proposed by Engle (1982), the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) analyses proposed by Chow (1960) and Brown, Durbin and Evans (1975), respectively. For the robustness check of the long-run elasticity findings, the regression analysis is repeated using the fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) regression techniques proposed by Phillips and Hansen (1990) and Stock and Watson (1993), respectively.

5.3 The vector error correction model approach to causality analysis

Following the inability of the ARDL technique to estimate the causal effects, the vector error correction model (VECM) approach, proposed by Engle and Granger (1987), is tapped to estimate the short and long-run causal associations between the variables. The VECM approach prerequisites the variables to have a common order of integration at their first differences and also requires the presence of cointegrating equations in the models. The model that estimates the short and long-run causalities, in the context of model (1), can be specified as:

$$\begin{bmatrix} \Delta \ln farea_t \\ \Delta \ln GDP_t \\ \Delta \ln GDP^2_t \\ \Delta \ln ener_t \\ \Delta \ln agri_t \\ \Delta inpopg_t \\ \Delta D_t \end{bmatrix} = \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \\ \varphi_7 \end{bmatrix} + \begin{bmatrix} \omega_{11,i} & \omega_{12,i} & \omega_{13,i} & \omega_{14,i} & \omega_{15,i} & \omega_{16,i} & \omega_{17,i} \\ \omega_{21,i} & \omega_{22,i} & \omega_{23,i} & \omega_{24,i} & \omega_{25,i} & \omega_{26,i} & \omega_{27,i} \\ \omega_{31,i} & \omega_{32,i} & \omega_{33,i} & \omega_{34,i} & \omega_{35,i} & \omega_{36,i} & \omega_{37,i} \\ \omega_{41,i} & \omega_{42,i} & \omega_{43,i} & \omega_{44,i} & \omega_{45,i} & \omega_{46,i} & \omega_{47,i} \\ \omega_{51,i} & \omega_{52,i} & \omega_{53,i} & \omega_{54,i} & \omega_{55,i} & \omega_{56,i} & \omega_{57,i} \\ \omega_{61,i} & \omega_{62,i} & \omega_{63,i} & \omega_{64,i} & \omega_{65,i} & \omega_{66,i} & \omega_{67,i} \\ \omega_{71,i} & \omega_{72,i} & \omega_{73,i} & \omega_{74,i} & \omega_{75,i} & \omega_{76,i} & \omega_{77,i} \end{bmatrix} \begin{bmatrix} \Delta \ln farea_{t-1} \\ \Delta \ln GDP_{t-1} \\ \Delta \ln GDP^2_{t-1} \\ \Delta \ln ener_{t-1} \\ \Delta \ln agri_{t-1} \\ \Delta \ln popg_{t-1} \\ \Delta D_{t-1} \end{bmatrix} + \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \mu_5 \\ \mu_6 \\ \mu_7 \end{bmatrix} ECT_{t-1} + \begin{bmatrix} \emptyset_{1t} \\ \emptyset_{2t} \\ \emptyset_{3t} \\ \emptyset_{4t} \\ \emptyset_{5t} \\ \emptyset_{6t} \\ \emptyset_{7t} \end{bmatrix} \tag{7}$$

where the statistical significances of the elasticity parameters attached to the ECT ($\mu_1, \ldots \mu_7$) provide the long-run causal associations while the joint statistical significances of the elasticity parameters attached to the lagged terms of the variables in their first differences (ω_{11}, i,… $\omega_{77,\ i}$), estimated by the Wald test of joint significance, provide the short-run causal associations. The long-run causal associations are also checked using the leveraged bootstrapped causality estimation technique proposed by Hacker and Hatem-J (2012).

6 Results and discussions

6.1 Results from the unit root analysis

The estimates from both the ZA and CMR unit root testing methods are reported in Table 1 and Table 2, respectively. The results denote that all the variables are non-stationary at their respective level forms. However, they do become stationary at their respective first differences. Hence, a common order of integration, at their first differences, among the variables is ascertained. The statistically significant estimated t-statistics in both of the tests affirm these claims. Moreover, the relevant break dates are also reported. Table 7 in Appendix reports the results from the conventional ADF, PP, DF-GLS, KSUR, KSSUR and KPSS unit root tests that do not appropriately accommodate the structural break issues. The corresponding results,

Table 1 The Zivot–Andrews structural break unit root test results

Variable	Level, I (0)		1st Difference, I (1)		Decision on stationarity
	t-statistic	Break year	t-statistic	Break year	
lnfarea_t	− 2.557 (1)	1997	− 7.796* (1)	1997	I (1)
lndeforest_t	− 1.650 (2)	1990	− 7.616* (2)	1990	I (1)
lnnfdep_t	− 1.311 (1)	1978	− 7.156* (2)	1978	I (1)
lnGDP_t	− 2.407 (1)	2007	− 4.610*** (1)	2007	I (1)
lnGDP_t^2	− 2.234 (2)	2011	− 5.135** (1)	2011	I (1)
lnener_t	− 2.718 (2)	2010	− 6.002* (2)	2010	I(1)
lnpopg_t	− 2.745 (2)	2011	− 6.341* (2)	2011	I (1)
lnagri_t	− 1.903 (2)	1990	− 6.421* (2)	1990	I (1)

Notes The optimal lags, based on Akaike Information Criterion (AIC), are provided within the parentheses; *, ** and *** denote statistical significance at 1%, 5% and 10% significance levels.

Table 2 The Clemente–Montanes–Reyes structural breaks unit root test results

Variable	Level, I (0)			1^{st} Difference, I (1)			Decision on Stationarity
	t-statistic	Break year 1	Break year 2	t-statistic	Break year 1	Break year 2	
lnfarea_t	− 3.711 (1)	1997	2008	6.117** (2)	1987	1990	I (1)
lndeforest_t	− 3.585 (1)	1990	2015	− 9.606** (3)	1990	2013	I (1)
nfdep_t	− 3.775 (4)	1978	2005	− 6.112** (4)	1978	1979	I (1)
lnGDP_t	− 3.313 (1)	1994	2009	− 5.553** (4)	2001	2012	I (1)
lnGDP_t^2	− 4.021 (4)	2002	2012	− 6.893** (4)	2002	2012	I (1)
lnener_t	− 2.212 (2)	2005	2010	− 6.999** (3)	2006	2010	I(1)
lnpopg_t	− 2.017 (0)	1992	2004	− 5.668** (2)	1981	1987	I (1)
lnagri_t	− 2.187 (4)	1986	1993	− 7.114** (3)	1986	1990	I (1)

Notes The optimal lags, based on AIC, are provided within the parentheses; ** denotes statistical significance at 5% significance level.

Table 3 Gregory-Hansen Cointegration test results

Model	Break (constant)						Break (constant and trend)						Coint.
	ADF	BY	Zt	BY	Za	BY	ADF	BY	Zt	BY	Za	BY	
1	− 9.71*	1997	− 11.75*	1999	− 22.21	1999	− 9.00*	1997	− 9.05*	1997	− 28.51	1997	Yes
2	− 9.52*	1978	− 10.22*	1990	− 66.29**	1990	− 9.50*	1991	− 10.41*	1990	− 66.87**	1990	Yes
3	− 9.49*	1981	− 10.77*	1978	− 68.33**	1978	− 11.29*	1981	− 11.41*	1978	− 71.47**	1978	Yes

Notes The optimal lags are based on AIC; ADF denotes augmented Dickey–Fuller test statistic and Zt & Za are the two z-statistics; BY denotes predicted break year; * and ** denote statistical significance at 1% and 5% significance levels.

in contrast to the estimates provided in Tables 1 and 2, suggest a mixed order of integration among the variables. Hence, these dissimilar unit root results justify the importance of accounting for the structural break issues when testing for unit roots involving long time-series.

6.2 Results from the cointegration analysis

The GH cointegration test results are tabulated in Table 3. The overall findings from these tests reveal the presence of cointegrating equations in all the three models considered in this paper. Hence, these collectively imply that economic growth, deforestation practices, population growth and agricultural land shares have long-run associations between them. Similarly, the results from the Johansen

Table 4 ARDL-ECM regression results

Model	(1)	(1)	(2)	(2)	(3)	(3)
Lag structure	(2,2,2,2,2,2)	(2,2,2,2,2,2,1)	(2,2,2,2,2,2)	(2,2,2,2,2,2,1)	(2,2,2,2,2,2)	(2,2,2,2,2,2,1)
Breaks	No	Yes	No	Yes	No	Yes
Short run coefficients						
$\Delta \mathrm{lnfarea}_t$	− 0.361	− 0.271	–	–	–	–
	(0.306)	(0.213)				
$\Delta \mathrm{lndeforest}_t$	–	–	0.724*	0.727*	–	–
			(0.219)	(0.225)		
$\Delta \mathrm{lnnfdep}_t$	–	–	–	–	0.091	0.344*
					(0.188)	(0.098)
$\Delta \mathrm{lnGDP}_t$	− 1.161	− 1.254*	0.008	0.003*	0.021	2.159
	(3.301)	(0.283)	(0.022)	(0.000)	(0.091)	(3.116)
$\Delta \mathrm{lnGDP}_{t-1}$	− 4.361	− 4.275**	0.002	0.006	0.097	3.291
	(3.339)	(2.136)	(0.029)	(0.004)	(0.115)	(3.681)
$\Delta \mathrm{lnGDP}_t^2$	0.004	0.004*	− 0.000	− 0.001**	− 0.000	− 0.007
	(0.013)	(0.002)	(0.001)	(0.000)	(0.000)	(0.057)
$\Delta \mathrm{lnGDP}_{t-1}^2$	0.062***	0.060***	− 0.000	− 0.000	− 0.000	− 0.047
	(0.021)	(0.030)	(0.000)	(0.000)	(0.001)	(0.167)
$\Delta \mathrm{lnener}_t$	− 2.012	− 2.122	3.210	3.402	2.512	2.932
	(1.611)	(1.700)	(2.541)	(3.232)	(1.699)	(2.350)
$\Delta \mathrm{lnener}_{t-1}$	− 2.019	− 2.230	3.412	3.430	2.829	3.030
	(1.621)	(1.823)	(2.771)	(3.010)	(1.792)	(2.023)
$\Delta \mathrm{lnpopg}_t$	− 18.955*	− 20.691*	3.599	3514*	47.192**	15.761*
	(6.119)	(9.113)	(5.435)	(0.173)	(23.137)	(6.114)
$\Delta \mathrm{lnpopg}_{t-1}$	− 57.124*	− 55.391*	5.789	0.156*	17.209***	22.441*
	(19.992)	(21.227)	(4.440)	(0.008)	(8.991)	(8.191)
$\Delta \mathrm{lnagri}_t$	− 0.002	− 0.003***	0.000	0.000*	0.000	0.002
	(0.002)	(0.002)	(0.081)	(0.000)	(0.146)	(0.006)
$\Delta \mathrm{lnagri}_{t-1}$	− 0.002	− 0.004***	0.00***	0.001*	0.000	0.003
	(0.002)	(0.002)	(0.000)	(0.000)	(0.000)	(0.007)
$\Delta D(1997)_t$	–	14.322*	–	–	–	–
		(4.982)				
$\Delta D(1991)_t$	–	–	–	− 0.008*	–	–
				(0.003)		
$\Delta D(1981)_t$	–	–	–		–	2.665*
						(1.117)
Constant	1531.13***	2716.855**	1.121	0.972	33.436	− 42.051
	(858.11)	(1227.04)	(2.158)	(0.881)	(28.371)	(32.181)
ECT_{t-1}	− 0.256*	− 0.429*	− 0.359*	− 0.436*	− 0.744*	− 0.798*
	(0.101)	(0.148)	(0.098)	(0.133)	(0.235)	(0.334)
Long run coefficients						
lnGDP_t	− 13.976*	− 12.719*	0.003	0.002*	0.512*	0.689*
	(4.716)	(2.291)	(0.003)	(0.001)	(0.048)	(0.098)
lnGDP_t^2	0.020*	0.022*	− 0.000	− 0.001*	− 0.001	− 0.004 **
	(0.001)	(0.000)	(0.000)	(0.000)	(0.003)	(0.002)
lnener_t	− 2.992**	− 3.010**	4.114*	4.200*	3.229*	3.500*
	(1.500)	(1.491)	(1.001)	(1.211)	(1.021)	(1.599)
lnpopg_t	− 45.047*	− 41.131*	0.107	0.101*	1.898	2.582*
	(17.147)	(15.667)	(0.125)	(0.049)	(1.703)	(0.182)

Table 4 continued

Model Lag structure Breaks	(1) (2,2,2,2,2,2) No	(1) (2,2,2,2,2,2,1) Yes	(2) (2,2,2,2,2,2) No	(2) (2,2,2,2,2,2,1) Yes	(3) (2,2,2,2,2,2) No	(3) (2,2,2,2,2,2,1) Yes
lnagri_t	− 0.019**	− 0.012**	0.000*	0.000*	0.001	0.003**
	(0.008)	(0.005)	(0.000)	(0.000)	(0.003)	(0.002)
$\mathrm{D(1997)}_t$	–	− 46.414**	–	–	–	–
		(22.045)				
$\mathrm{D(1991)}_t$	–	–	–	0.205*	–	–
				(0.054)		
$\mathrm{D(1981)}_t$	–	–	–	–	–	− 21.731*
						(8.117)
Adj. R2	0.625	0.628	0.691	0.672	0.509	0.635
Diagnostics tests						
BGodfrey	2.575	2.173	2.271	2.155	1.295	2.228
ARCH	3.231	2.053	2.608	1.161	4.558	3.994

Note The standard errors are reported within the parentheses; optimal lag selection is based on the AIC. The BGodfrey test is performed under the null hypothesis of no autocorrelation against the alternative hypothesis of otherwise; The ARCH test is performed under the null hypothesis of homoscedastic variance against the alternative hypothesis of otherwise; * and ** denote statistical significance at 1% and 5% significance levels

(1991) cointegration analysis, as reported in Table 8 in Appendix, also confirm the presence of cointegrating equations in all the three models. Thus, the robustness to the overall findings of the long-run associations between the variables of concern is affirmed. The identification of the order of integration from the unit root analyses and the cointegrating associations from the cointegration analyses permit us to proceed to ARDL-ECM regression and the causality exercises.

6.3 Results from the regression analysis

The results from the ARDL-ECM analysis are reported in Table 4. The findings, in general, depict that upon controlling for the structural breaks within the data there are notable improvements in the statistical significances of the estimated short and long-run elasticities. Moreover, the magnitude of the R-squared values has also improved, implicating higher explanatory powers of the regressors in explaining the variations in the dependent variables. Furthermore, upon controlling for the structural breaks in the data, the magnitudes of the one-period-lagged ECTs have also gone up which indicates that any deviation from the long-run equilibrium is adjusted at a relatively faster rate due to augmenting the break year dummies into the empirical models. These findings certify the pertinence of accounting for structural break issues within the econometric analysis. Hence, only the results from the regression analysis that controlled for the structural break issues are discussed.

In the context of model (1), it can be observed that economic growth initially attributes to the razing down of forests in Bangladesh whereby the total forest area coverage seems to shrink. The statistically significant and negative estimates of the elasticity parameters attached to $\Delta lnGDP_t$ and $\Delta lnGDP_{t-1}$ provide statistical support in this conjecture. The corresponding elasticity estimates reveal that one standard deviation shocks to per capita real GDP in its current and one-period-lagged forms lead to 1.25% and 4.28% reductions in the total forest areas, respectively, on average, *ceteris paribus.* However, with the attainment of higher growth in the national income levels, the impact is found to be reciprocated which is evident from the statistically significant and positive signs of predicted elasticity parameters attached to $\Delta lnGDP_t^2$ and $\Delta lnGDP_{t-1}^2$. These estimates imply that one standard deviation shocks to the squared term of per capita real GDP, both in its current and lagged levels, stimulate increments in the forest areas on average by 0.10% and 0.06%, respectively, *ceteris paribus*. Thus, the results collectively confirm the existence of the deforestation-induced EKC hypothesis for Bangladesh. Besides, the predicted ECT is found to be negative and statistically significant at 1% level. The ECT value of -0.429 indicates that any deviation from the long-run equilibrium is corrected at a rate of almost 43% in the next period.

As far as the long-run regression analysis is concerned, similar results are found which can be perceived from the similar signs and statistical significance of the corresponding short and long-run elasticity estimates. A 1%

increase in the real GDP per capita of Bangladesh is found to reduce the local forest areas by almost 13% in the long run, while, after attaining a threshold national income level, the marginal impact of income growth is found to enhance forest coverage by 0.02%, on average, *ceteris paribus.* Hence, it can be inferred that both the short- and long-run results validate the deforestation-induced EKC hypothesis in the context of Bangladesh, using the forest area coverage as an indicator of deforestation practices in the county. The findings possibly indicate that following the attainment of a significant amount of economic growth, social awareness regarding the climate change adversities linked to loss of forest areas, in particular, is likely to trigger afforestation and reforestation initiatives within Bangladesh. Such measures can be termed as reformative policies that are taken to counter the environmental disharmony caused by rapid deforestation during the initial phases of growth.

Similarly, in the context of model (2), economic growth in the initial phases is found to amplify deforestation rates in the short run. However, beyond a threshold growth level, the relationship is reciprocated as the deforestation rates seem to decline. The corresponding short-run elasticity results express that one standard deviation shocks to real GDP per capita at its current level increases deforestation rates by 0.003% on average, *ceteris paribus*. Later on, upon achievement of a certain level of economic growth, a one standard deviation shock to the current level of the squared term of real GDP per capita is seen to curb deforestation rates by 0.001% on average, *ceteris paribus.* Notably, no lagged effects of economic growth on the deforestation rates could be found which is perceived from the statistical insignificance of the corresponding elasticity estimates. The statistically significant and negative estimate of the ECT, in the context of model (2), implicates that any long run disequilibrium in the current period is restored at a rate of 43.6% in the next period. On the other hand, the long-run elasticity estimates in this regard also confirm the nonlinearity of the economic growth-deforestation rate nexus in the context of Bangladesh. Based on the estimates, it can be said that the marginal impacts of economic growth on the deforestation rates, during the initial phases, accounts for a rise in the deforestation rates by 0.002%, on average, *ceteris paribus,* while reducing it by 0.001%, on average, *ceteris paribus*, in the later phases. The statistical significances, at 1% level, of the long-run predicted elasticity parameters attached to $lnGDP_t$ and $lnGDP_t^2$ affirm these assertions. Hence, both the short- and long-run estimates once again corroborate to the deforestation-induced EKC hypothesis for Bangladesh implying an inverted-U association between the macroeconomic aggregates.

Finally, the robustness of the findings is further established from the validity of the deforestation-induced EKC hypothesis using the net forest depletion rate to quantify deforestation propensities in Bangladesh. The ARDL-ECM results in the context of model (3) reveal that only in the long run there is statistical significance to the deforestation-induced-EKC hypothesis. The corresponding long-run elasticity estimates, accounting for the structural breaks in the data, quantify that an initial increase in the per capita real GDP level by 1% stimulates the net forest depletion rates by almost 0.70%, on average, *ceteris paribus.* However, beyond a threshold per capita real GDP level, the marginal impact of income growth is found to reduce the net forest depletion rates by 0.004% on average, *ceteris paribus.* Hence, these results also support the inverted-U-shaped association between economic growth and deforestation activities in Bangladesh which coincide with the theoretical underpinnings postulated by the deforestation-induced EKC hypothesis.

The overall results from all the three models implicate that the deforestation-induced EKC hypothesis holds in the context of Bangladesh. These findings corroborate the conclusions put forward by Miah et al. (2011) and Murshed (2020a) as all these three studies have opined in favor of the economic growth initially promoting deforestation in Bangladesh while reducing it eventually. Besides, these findings are also parallel to the results reported by Naito and Traesupap (2014), Ahmed et al. (2015) and Waluyo and Terawaki (2016) for Thailand, Pakistan and Indonesia, respectively. A plausible explanation behind these findings in the context of Bangladesh could possibly be reasoned by the *scale* and *composition effects* of economic growth, resulting in environmental degradation via triggering deforestation practices during the initial phases of growth, while the *technique effect* reversing it in the later stages. Hence, it can be said that Bangladesh can pursue growth strategies without being fearful of the deforestation woes at present since the results suggest that further growth of the Bangladeshi economy would eventually ensure lower deforestation propensities, possibly through instigating afforestation and reforestation activities within the economy.

Among the other key findings, energy consumption is found to adversely impact the long-run deforestation propensities in Bangladesh. The corresponding elasticity estimates reveal that a 1% rise in the energy consumption level reduces aggregate forest area coverage by around 3%, increases deforestation rates by 4.11–4.20% and elevates the net forest depletion rates by 3.23–3.50%, on average, *ceteris paribus.* The results corroborate the conclusions put forward by Heltberg et al. (2000) for India. Such similar findings could be because Bangladesh and India match each other with respect to a wide range of economic, democratic, political and cultural norms. In contrast, the findings refute the conclusions asserted by Ahmed et al. (2015) for Pakistan. Besides, the elasticity estimates also denote the negative impacts of population growth on Bangladesh's deforestation problems both in the short and long runs. These imply that deforestation practices are often triggered by the demand for forest resources which attributes to higher propensities of deforestation across the country. These findings echo with those put forward by Van Khuc et al. (2018) in the context of Vietnam. On the other hand, agricultural land shares in the total land area of Bangladesh is also found to impose adverse impacts on all three indicators of deforestation, both in the short and the long runs. Thus, these findings, to an extent, advocate in favor of agricultural expansion being responsible for the loss of natural forestlands in Bangladesh. Hence, it is ideal for the government to invest in research and development for enhancing the yield rates of the existing agricultural lands. Enhancing the yield rates could be efficient in reducing the need for converting forests into agricultural lands. These findings support the views put forward Iftekhar and Hoque (2005) in which the authors recommended similar agricultural policy reforms to counter deforestation activities in Bangladesh. Similarly, Kong et al. (2019) also found evidence of agricultural and forest lands being substituted for one another in Cambodia.

Table 4 reports the results from the diagnostic tests performed to evaluate the stability and efficiency of the elasticity estimates. The results collectively imply that the models considered in this paper do not suffer from autocorrelation and heteroskedasticity problems, as perceived from the statistical insignificance of the corresponding test statistics. Moreover, the stability of the elasticity estimates from the ARDL models is confirmed by the CUSUM and CUSUMSQ plots illustrated in Fig. 2. The fitted values of the CUSUM and the CUSUMSQ plots are largely within the upper and lower critical boundaries at 5% significance levels (within the 95% confidence interval). Thus, the ARDL-ECM elasticity estimates can be referred to be stable across the period of study.

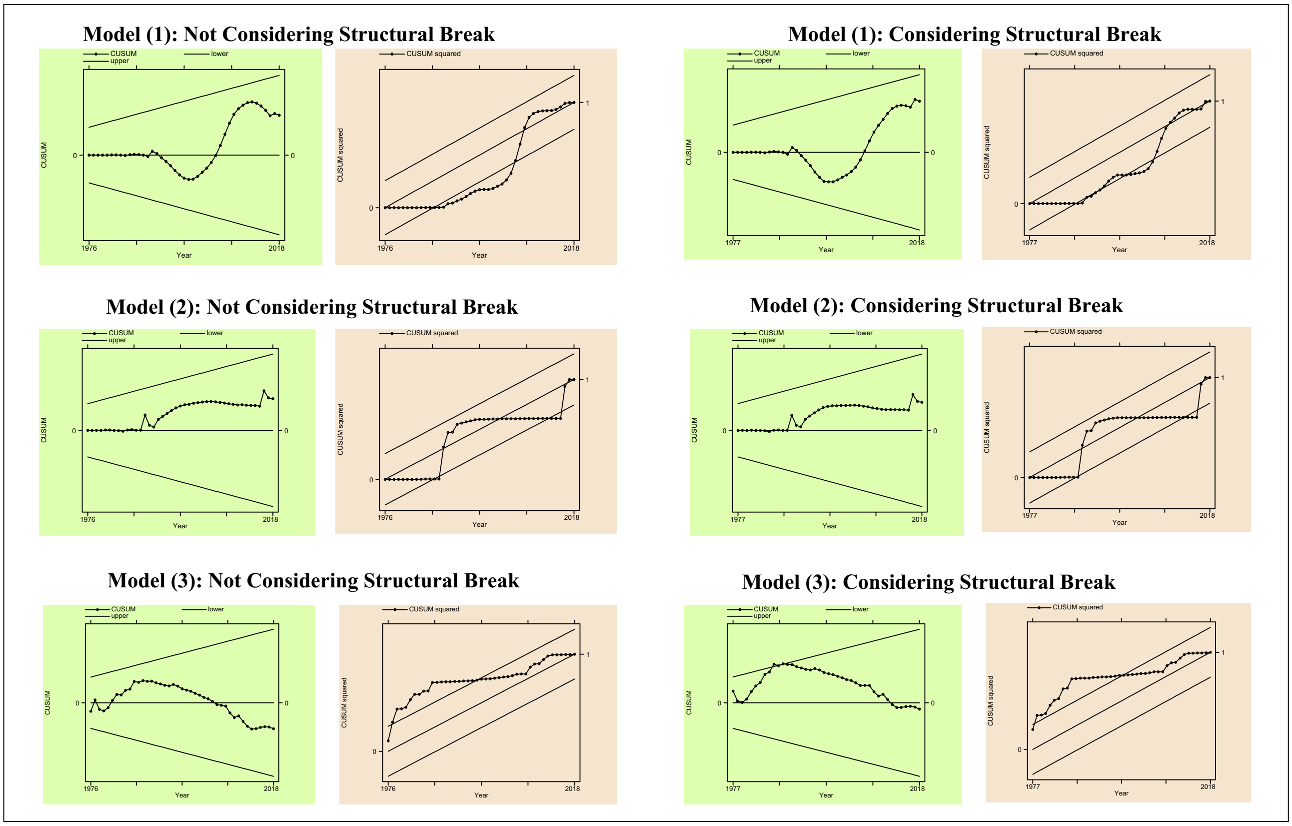
The robustness of the long-run elasticity estimates is checked using the FMOLS and DOLS estimators. The corresponding results, as reported in Table 9 in Appendix, conform to the long-run findings from the ARDL-ECM analysis in terms of the predicted signs and, more or less, to the statistical significance of the predicted elasticity parameters. Hence, it can be asserted that the overall findings are largely homogeneous across different regression techniques whereby the robustness of the elasticity estimates can be affirmed.

6.4 The results from the causality analysis

Although the signs of the elasticity estimates validate the existence of the deforestation-induced EKC hypothesis in Bangladesh, it is imperative to investigate the causal linkages as well. Thus, the causality analysis is performed using the VECM causality estimation technique. The corresponding short and long-run causality estimates from the VECM analysis are reported in Table 5. As per the estimates, bidirectional short-run causality between economic growth in the initial phases and coverage of forest lands is found while unidirectional causation is evidenced to stem from economic growth in later phases to total forest area coverage. These imply that during the initial stages of growth, there is pressure to raze down forests particularly to expedite the industrialization process. However, at the same time, loss of forest areas can also be viewed in terms of forests acting as possible sources of industrial inputs. Thus, the feedback causality between economic growth and forest area coverage can be justified in this manner. On the other hand, after the attainment of a certain level of national income, the awareness to undertake afforestation and reforestation activities could well be linked to the unidirectional causal association mentioned above. As far as the long-run causality is concerned, the estimates indicate toward economic growth, both in the initial and later phases, influencing changes in forest area coverage without the feedback causation. These, in contrast to the bidirectional short-run causal relationships, imply that in the long run, it is rather the growth of the economy that is responsible for the changes in the total forest areas in Bangladesh, thus depicting symptoms of the *technique effect* coming into action.

Similarly, in the context of model (2), the results provide statistical evidence regarding unidirectional causalities running from economic growth to deforestation rates, both in the short and long runs. Thus, it is evident from these findings that deforestation decisions are largely dependent on the stage of economic growth in Bangladesh. Finally, the causal estimates concerning model (3) also reveal bidirectional short-run causal linkage between economic growth and net forest depletion rates, while in the long run a unidirectional causality is found to be running from economic growth to net forest depletion rates in Bangladesh. Therefore, keeping the corresponding elasticity estimates form the ARDL-ECM analysis into consideration, the causality results also denote that economic growth is both the cause and future solution to the deforestation woes of Bangladesh.

The long-run causality findings from the Hacker and Hatemi-J causality analysis, as reported in Table 10 in Appendix, reveal that economic growth influences deforestation activities in Bangladesh. This is evident from the



Model (1): Not Considering Structural Break

Model (1): Considering Structural Break

Model (2): Not Considering Structural Break

Model (2): Considering Structural Break

Model (3): Not Considering Structural Break

Model (3): Considering Structural Break

Note: The model specifications are said to be stable if the CUSUM and the CUSUMSQ plots are largely within the upper and lower critical boundaries denoted by the straight lines at 5% significance levels (within the 95% confidence interval).

Fig. 2 The CUSUM and CUSUMSQ Plots

statistical validation of unidirectional causalities stemming from economic growth to all the three indicators of deforestation in the context of Bangladesh. Hence, in line with the findings from these long-run elasticity estimates, it can be asserted that the growth of the Bangladesh economy, in the long run, can be expected to mitigate the deforestation propensities to account for the environmental distress emerging from the initial stages of growth. Moreover, the long-run causal estimates from the Hacker and Hatemi-J analysis also reveal that energy consumption influences all the three indicators of deforestation used in this paper, without the feedback. Therefore, in line with the corresponding elasticity estimates reported earlier, consumption of energy can be claimed to be a key determinant of tropical deforestation in Bangladesh. Besides, the growth of the population size is also found to cause changes in the deforestation propensities, as evidenced by the unidirectional causalities stemming from population growth rate to all three indicators of deforestation. Hence, controlling the population growth rate is key to keeping the human demand for forest resources within manageable ranges whereby the rise in the deforestation propensities can be effectively contained. Finally, statistical evidence regarding bidirectional causation between agricultural lands and forest land coverage in Bangladesh is found which further advocates in favor of classifying these land types as substitutes of one another in the long run.

7 Conclusion

The trade-off between economic and environmental welfare has been a much-debated topic of research which is often tested in light of the EKC hypothesis. Although a plethora of studies in the existing literature has explored this nexus via quantifying environmental degradation in terms of CO_2 emissions, the use of deforestation propensities to indicate environmental quality has largely been ignored in the EKC narrative. Thus, this paper attempted to bridge this gap in the literature by empirically investigating the authenticity of the deforestation-induced EKC hypothesis in the context of Bangladesh. The empirical analysis accommodated annual frequency data from 1972 to 2018. The corresponding findings from the econometric analyses indicated that deforestation propensities, both in the short and long runs, are affected by the nation's per capita national income levels. The elasticity estimates, overall, validated the EKC hypothesis for deforestation in

Table 5 The VECM causality results

Dependent variable	Short run (F-Stat.)						Long run (t-stat.)
	lnfarea$_t$	lnGDP$_t$	lnGDP$_t^2$	lnener$_t$	lnagri$_t$	lnpopg$_t$	ECT$_{t-1}$
Model (1)							
lnfarea$_t$	–	11.796*	15.486*	1.711	8.093*	1.608	− 0.429*
lngdp$_t$	5.652**	–	1.708	9.309*	4.062**	0.006	− 0.389
lngdp$_t^2$	0.572	3.1193	–	7.999*	2.017	2.771***	− 0.515
lnener$_t$	1.333	1.459	2.222	–	1.923	1.988	− 0.490
lnagri$_t$	0.928	2.761***	2.902***	1.200	–	0.295	− 0.141
lnpopg$_t$	1.568	26.366*	29.552*	8.398*	0.569	–	− 0.029
Model (2)							
lndeforest$_t$	–	3.048**	5.067*	2.068	0.398	0.173	− 0.436*
lnGDP$_t$	0.072	–	7.794*	12.989*	1.357	3.954**	− 0.407
lnGDP$_t^2$	0.043	11.331*	–	13.998*	1.106	8.647*	− 0.089
lnener$_t$	0.111	2.170	9.879*	–	9.300*	2.090	− 1.991
lnagri$_t$	0.504	2.039	1.999	2.090	–	0.108	− 0.071
popg$_t$	0.306	7.447*	8.229*	1.983	0.507	–	− 0.206*
Model (3)							
lnnfdep$_t$	–	6.171*	3.348**	1.129	2.965***	6.229*	− 0.738*
lnGDP$_t$	5.412**	–	10.725*	8.112*	0.949	7.420*	− 0.169
lnGDP$_t^2$	6.237*	12.723*	–	12.129*	0.887	11.613*	− 0.229
lnener$_t$	1.911	8.291*	9.229*	–	2.001	9.212*	− 0.129
lnagri$_t$	0.127	1.815	1.783	1.289	–	0.629	− 0.115
lnpopg$_t$	6.599*	6.718*	8.818*	1.992	1.129	–	− 0.108*

Note Optimal lag selection is based on the AIC. * and ** denote statistical significance at 1% and 5% significance levels.

the context of Bangladesh. Furthermore, the results from the causality analysis provided evidence of economic growth influencing deforestation propensities both in the short and long runs. Thus, these results, in a nutshell, point out a trade-off between economic and environmental welfares during the initial phases of economic growth which seem to be diminished beyond a certain threshold level of per capita real income of the county. Thus, economic growth in Bangladesh can be claimed to be both the short-run cause and the long-run solution to the nation's deforestation issues. Besides, energy consumption, population growth and agricultural land expansion were also identified as factors that adversely impact deforestation propensities across Bangladesh.

The findings, overall, impose critically important policy implications keeping the sustainability of Bangladesh's forest reserves and, more importantly, the nation's overall environmental well-being into cognizance. In line with the results, the following recommendations can be put forward. Firstly, the government needs to incentivize reforestation drives at both public and private levels. Such measures to re-expand the lost forest reserves could be ideal in countering the environmental hardships that have emerged from the persistently rising deforestation propensities in Bangladesh. Consequently, the environmental well-being of Bangladesh can be sustained over time. Secondly, reforms in the national energy policies need to be addressed. More importantly, the government has to think of introducing alternative cooking fuels, particularly across the rural households that have historically been dependent on firewood supplies for cooking purposes. In this regard, subsiding price of liquefied petroleum gases could reduce the firewood demand to a large extent. Similarly, switching from wood to eco-friendly alternatives to fuel the brick kilns in Bangladesh can also safeguard the nation's forest reserves while curbing environmental pollution in tandem. Thirdly, investments in research and development for enhancing yields of agricultural lands and amplification of cropping intensities can be effective in reducing the need for conversion of tropical forests into agricultural spaces. Moreover, making use of technology to promote agro-forestry across the country could also be useful in reducing deforestation in Bangladesh. Fourthly, the overall production processes in Bangladesh should look to adopt green technologies in combating the loss of tropical forests that are sources of timber and non-timber industrial inputs. Thus, technological innovation is essential in tackling deforestation which, in turn, is likely to ensure environmental sustainability in Bangladesh. Thus, in this regard, the government should also incentivize investments in research and development, from both public and private sectors, for stimulating technological advancement within the country. Finally, the government needs to improve the quality of the associated public institutions that are authorized to safeguard the forest reserves of Bangladesh. In this regard, controlling corruption within the forest ministry could be an ideal policy reform that would slash down illegal forest encroachments and therefore reduce the deforestation rates to a large extent. Besides, making use of technologies like Global Positioning System (GPS) mapping and satellite imaging to provide near real-time monitoring of forest reserves could further prevent unlawful deforestation activities in Bangladesh.

As part of the future scope of research, this paper can be extended to evaluate the deforestation-induced EKC hypothesis in the context of Bangladesh using the nation's sectoral growth figures. Disaggregation of the economic growth figures could be effective in evaluating the impacts of structural transformation, within the Bangladesh economy, on the overall nexus between economic growth and tropical deforestation. Besides, the deforestation-induced EKC hypothesis can also be re-investigated controlling for the quality of the institutions in Bangladesh which could ideally assist the policymakers in formulating appropriate strategies to conserve the national forest reserves. Furthermore, natural experimental studies can be undertaken to assess whether the adoption of green technologies can be effective in combating deforestation in Bangladesh since technological advancement is often envisioned to complement strategies aimed at reducing deforestation propensities along the economic growth stream.

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Compliance with ethical standards

Conflicts of interest The authors report no conflict of interest.

Appendix

See Tables 6, 7, 8, 9 and 10 in the appendix.

Table 6 Descriptive statistics of the variables in their natural logarithms

Variable	Description	Maximum	Minimum	Mean	Std. Dev.	Skewness	Kurtosis	Obvs.
lnfarea	Forest area coverage	9.61	9.57	9.596	0.016	− 0.772	1.982	47
lndeforest	Deforestation rate	− 1.05	− 7.39	− 3.349	1.355	− 0.185	2.611	46
lnnfdep	Net forest depletion rate	19.94	16.78	− 2.646	0.745	− 0.332	1.326	46
lnGDP	Real gross domestic product	5.19	3.07	4.001	0.641	0.295	1.853	47
lnener	Energy consumption per capita	4.78	2.41	4.917	0.270	0.449	1.935	47
lnpopg	Population growth rate	18.90	17.98	18.149	0.294	0.302	1.732	47
lnagri	Agricultural land area	11.56	11.42	11.472	0.428	0.322	1.704	47

Source Author's own calculation

Table 7 The results from the unit root tests without structural breaks

Test	ADF		PP		DF-GLS	
Variable	Level	Δ	Level	Δ	Level	Δ
lnfarea$_t$	− 1.789	− 5.187*	− 1.879	− 5.187*	− 1.428	− 5.272*
lndeforest$_t$	− 3.500***	− 7.761*	− 5.562*	− 11.913*	− 2.066	− 4.795*
lnnfdep$_t$	− 2.664	− 5.480*	− 2.778	− 8.642*	− 2.634	− 8.534*
lnGDP$_t$	− 4.320*	− 7.052*	− 4.986*	− 4.736*	− 1.624	− 4.133*
lnGDP$_t^2$	− 2.914	− 5.241*	− 3.390**	− 3.952**	− 1.802	− 4.314*
lnener$_t$	− 2.112	− 6.128*	− 2.998	− 4.878*	− 2.039	− 3.812*
lnpopg$_t$	− 2.345	− 10.148*	− 2.459	− 4.773*	− 5.892*	− 6.025*
lnagri$_t$	− 3.071	− 4.034**	− 2.631	− 5.559*	− 2.228	− 3.995*

Test	KSUR		KSSUR		KPSS	
Variable	Level	Δ	Level	Δ	Level	Δ
lnfarea$_t$	− 3.132***	− 5.963**	− 3.364**	− 5.789*	0.420*	0.178**
lndeforest$_t$	− 4.088*	− 3.215***	− 4.027*	− 3.279***	0.161**	0.051
lnnfdep$_t$	− 1.762	− 4.907*	− 2.651	− 5.134*	0.148**	0.079
lnGDP$_t$	− 2.549	− 3.296**	− 0.414	− 3.106***	0.377*	0.141***
lnGDP$_t^2$	− 2.643	− 2.894***	− 3.426**	− 3.659**	0.308*	0.140***
lnener$_t$	− 1.447	− 2.958***	− 2.201	− 5.242*	0.135***	0.118
lnpopg$_t$	− 3.138**	− 4.851*	− 2.093	− 6.554*	0.412*	0.293*
lnagri$_t$	− 2.980***	− 3.317**	− 3.121***	− 3.315**	0.163**	0.074

Note ADF, PP, DF-GLS, KSUR, KSSUR and KPSS stand for the augmented Dickey–Fuller, Phillips–Perron, Dickey–Fuller generalized least squares, Kapetanios and Shin, Kapetanios, Shin and Snell and Kwiatkowski–Phillips–Schmidt–Shin unit root tests; Δ denotes first difference; the optimal lag selection is based on the AIC; the test statistics are reported and estimated using considering both trends and intercept under the null hypothesis of non-stationarity against the alternate hypothesis of stationarity; *, ** and *** denote statistical significance at 1%, 5% and 10% levels, respectively.

Table 8 The Johansen cointegration test results

Model	Null hyp.	Alternat. hyp.	Trace test			Max. Eigenvalue test		
			Test statistic	95% Critical value	No. of Cointegrating equations	Test statistic	95% Critical value	No. of Cointegrating equations
(1)	r = 0	r = 1	755.50**	59.46	3	565.22**	30.04	3
	r <=1	r = 2	190.29**	39.89		164.32**	23.80	
	r <=2	r = 3	25.98**	24.31		25.61**	17.89	
	r <=3	r = 4	0.36	12.53		0.36	11.44	
(2)	r = 0	r = 1	466.60**	59.46	3	357.49**	30.04	3
	r <=1	r = 2	108.81**	39.89		83.06**	23.80	
	r <=2	r = 3	25.74**	24.31		25.09**	17.89	
	r <=3	r = 4	0.64	12.53		0.58	11.44	
(3)	r = 0	r = 1	486.41**	59.46	4	361.68**	30.04	4
	r <=1	r = 2	124.73**	39.89		96.90**	23.80	
	r <=2	r = 3	27.83**	24.31		27.35**	17.89	
	r <=3	r = 4	14.49**	12.53		13.42**	11.44	
	r <=4	r = 5	0.05	3.84		0.06	3.84	

Note r refers to the number of cointegrating equations; the optimal lag selection is based on the AIC; ** denotes statistical significance at 5% level.

Table 9 The results from the FMOLS and DOLS regression analyses

Model Estimator	(1) FMOLS	(1) DOLS	(2) FMOLS	(2) DOLS	(3) FMOLS	(3) DOLS
lnGDP_t	− 12.399*	− 12.854*	0.002**	0.003**	0.701*	0.759*
	(2.118)	(2.506)	(0.001)	(0.001)	(0.091)	(0.112)
lnGDP_t^2	0.027*	0.028*	− 0.000*	− 0.000*	− 0.005**	− 0.006**
	(0.008)	(0.010)	(0.000)	(0.000)	(0.003)	(0.003)
lnener_t	− 3.212*	− 3.220*	4.112**	4.312**	3.229*	3.500*
	(1.001)	(1.210)	(2.051)	(2.150)	(1.220)	(1.291)
lnpopg_t	− 44.621*	− 44.923*	0.118*	0.121**	3.101*	3.217*
	(12.421)	(12.989)	(0.039)	(0.059)	(1.010)	(1.110)
lnagri_t	− 0.017*	− 0.019**	0.102**	0.113**	0.004**	0.003**
	(0.003)	(0.094)	(0.050)	(0.058)	(0.002)	(0.002)
$\Delta D(1997)_t$	− 45.542*	− 42.62*				
	(16.295)	(16.389)				
$\Delta D(1991)_t$			0.212**	0.233**		
			(0.105)	(0.110)		
$\Delta D(1981)_t$					− 21.924*	− 22.219*
					(7.104)	(7.084)
Adj. R2	0.857	0.849	0.801	0.812	0.828	0.839

Notes The robust standard errors are reported within the parentheses; * and ** denote statistical significance at 1% and 5% levels, respectively.

Table 10 The Hacker and Hatemi-J Granger causality results

Model (1)			Model (2)			Model (3)		
Dependent variable	Independent variable	Modified Wald test statistic	Dependent variable	Independent variable	Modified Wald test statistic	Dependent variable	Independent variable	Modified Wald test statistic
$\mathrm{lnfarea}_t$	lngdp_t	6.820**	$\mathrm{lndeforest}_t$	lngdp_t	5.137**	$\mathrm{lnnfdep}_t$	lngdp_t	9.156*
lngdp_t	$\mathrm{lnfarea}_t$	1.989	lngdp_t	$\mathrm{lndeforest}_t$	1.605	lngdp_t	$\mathrm{lnnfdep}_t$	1.933
$\mathrm{lnfarea}_t$	lnener_t	10.229*	$\mathrm{lndeforest}_t$	lnener_t	12.229*	$\mathrm{lnnfdep}_t$	lnener_t	10.191*
lnener_t	$\mathrm{lnfarea}_t$	1.791	lnener_t	$\mathrm{lndeforest}_t$	1.920	lnener_t	$\mathrm{lnnfdep}_t$	1.310
$\mathrm{lnfarea}_t$	lnpopg_t	8.757*	$\mathrm{lndeforest}_t$	lnpopg_t	7.002*	$\mathrm{lnnfdep}_t$	lnpopg_t	10.243*
lnpopg_t	$\mathrm{lnfarea}_t$	1.691	lnpopg_t	$\mathrm{lndeforest}_t$	2.112	lnpopg_t	$\mathrm{lnnfdep}_t$	2.001
$\mathrm{lnfarea}_t$	lnagri_t	8.128*	$\mathrm{lndeforest}_t$	lnagri_t	1.109	$\mathrm{lnnfdep}_t$	lnagri_t	1.290
lnagri_t	$\mathrm{lnfarea}_t$	8.217*	lnagri_t	$\mathrm{lndeforest}_t$	1.269	lnagri_t	$\mathrm{lnnfdep}_t$	1.993

Notes The null hypothesis of the independent variable not Granger causing the dependent variable is tested under the alternate hypothesis of otherwise; the modified Wald statistics are estimated using bootstrapped approach; *, ** and *** denote statistical significance at 1%, 5% and 10% significance levels, respectively.

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