Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jes

JES JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

Decomposition and decoupling analysis of carbon dioxide emissions in African countries during 1984–2014

Claudien Habimana Simbi [1,2], *Jianyi Lin* [1,*], *Dewei Yang* [3,*], *Jean Claude Ndayishimiye* [1,2], *Yang Liu* [1,2], *Huimei Li* [1], *Lingxing Xu* [1], *Weijing Ma* [4]

[1] *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China*

[2] *University of Chinese Academy of Sciences, Beijing 100049, China*

[3] *School of Geographical Sciences, Southwest University, Chongqing 400715, China*

[4] *Faculty of Geography, University of Marburg, Marburg 35032, Germany*

A R T I C L E   I N F O

Article history:
Received 14 May 2020
Revised 15 September 2020
Accepted 16 September 2020

Keywords:
CO_2 emissions
Decoupling
Driving forces
Logarithmic mean divisia index method
Patterns
Africa

A B S T R A C T

The potential for mitigating climate change is growing worldwide, with an increasing emphasis on reducing CO_2 emissions and minimising the impact on the environment. African continent is faced with the unique challenge of climate change whilst coping with extreme poverty, explosive population growth and economic difficulties. CO_2 emission patterns in Africa are analysed in this study to understand primary CO_2 sources and underlying driving forces further. Data are examined using gravity model, logarithmic mean divisia index and Tapio's decoupling indicator of CO_2 emissions from economic development in 20 selected African countries during 1984−2014. Results reveal that CO_2 emissions increased by 2.11% (453.73 million ton) over the research period. Gravity centre for African CO_2 emissions had shifted towards the northeast direction. Population and economic growth were primary driving forces of CO_2 emissions. Industrial structure and emission efficiency effects partially offset the growth of CO_2 emissions. The economic growth effect was an offset factor in central African countries and Zimbabwe due to political instability and economic mismanagement. Industrial structure and emission efficiency were insufficient to decouple economic development from CO_2 emissions and relieve the pressure of population explosion on CO_2 emissions in Africa. Thus, future efforts in reducing CO_2 emissions should focus on scale-up energy-efficient technologies, renewable energy update, emission pricing and long-term green development towards sustainable development goals by 2030.

* Corresponding authors.
E-mails: jylin@iue.ac.cn (J. Lin), younglansing@gmail.com (D. Yang).

https://doi.org/10.1016/j.jes.2020.09.006
1001-0742/

Introduction

Global climate change has attracted considerable attention from scientists, policymakers and citizens in recent decades (Dessler and Parson, 2019; Shi et al., 2019; Solaymani, 2019). Numerous global conferences have been held to discuss feasible responses to greenhouse gas (GHG) effects (Dong et al., 2020; IPCC, 2018; Tian et al., 2014). Mitigating global warming requires knowledge about primary sources of GHGs and underlying driving forces (Gruca–Rokosz et al., 2017; Shi et al., 2019). CO_2 emissions accounting for more than 80% of the total GHG emissions (Foster and Bedrosyan, 2014) and their associated environmental burdens have caused global concerns (Dong et al., 2019; Tu and Li, 2017).

The African continent is vulnerable to the impact of global climate change (IPCC, 2018; Sakiru, 2014) because of its geographic location (Busby, 2012) and lack of provision to satisfy basic human needs (Russo et al., 2016). Moreover, Africa is characterised by demographic explosion and rapid economic development in a few nations, such as South Africa, Egypt, Nigeria, Ethiopia and Kenya (Coulibaly, 2020; Weforum, 2019), whereas other African countries experience continuous growth of urban dwellers, serious poverty and rapid industrialisation. Hence, the role of Africa in global climate change during extreme socioeconomic changes has attracted considerable attention from researchers (Weforum, 2019). For example, 79 African cities (48% of African gross domestic production) are amongst the world's top 100 fastest-growing cities but "extremely" threatened by climate change and natural disasters (Cameron, 2019; Coulibaly, 2020; Weforum, 2019). African governments must reduce energy consumption whilst maintaining economic growth. Furthermore, accelerating access and use of energy sources for businesses and governments to support economic growth without increasing CO_2 emissions and climate risks is challenging (EIA, 2018; Maji et al., 2019; Ssali et al., 2019). Therefore, understanding characteristics of CO_2 emission patterns and their influencing factors during socioeconomic transformation in Africa is crucial for adequately mitigating the effects of global climate change and achieving sustainable development goals (Dong et al., 2019; Peters et al., 2014).

Recent studies have examined driving forces of CO_2 emissions using different methods, such as Kaya equation and its modified STIRPAT (stochastic impacts by regression on population, affluence and technology) model (Yeh and Liao, 2017), statistical analysis (Yang et al., 2017b), system dynamics (Liu et al., 2017) and planning system of long-range energy alternatives (Yang et al., 2017a) and logarithmic mean divisia index (LMDI) (Ang, 2004, 2005). Amongst these methods, LMDI is commonly used because of its consistency in aggregation and path independence, high decomposition accuracy, ability to treat zero-value and residue-free cases and wide adaptability and accessibility (Ang, 2004, 2005, 2015; Ang and Liu, 2001; Ang et al., 2003; Kang et al., 2017). LMDI has been intensively applied to decompose carbon emissions and resulting environmental, economic and climate impacts virtually at global, national and regional scales. For instance, LMDI is commonly used to investigate CO_2 emission decomposition (Lin et al., 2015; Ma and Cai, 2018), driving forces of CO_2 emissions (Dong et al., 2019; Luo et al., 2016; Mousavi et al., 2017), CO_2 emission patterns (Solaymani, 2019), determinants of energy-related CO_2 emissions (Gao et al., 2019; Lin and Ouyang, 2014; Wang et al., 2019) and energy consumption factors (Zhang et al., 2015a, 2015b; Wang et al., 2014).

Decomposition analysis is typically combined with a decoupling model to investigate the relationship of driving forces (Song and Zhang, 2019; Zhang et al., 2020) and separate economic development from CO_2 emissions for sustainable development goals (OECD, 2002; Tapio, 2005). The decoupling concept was initially presented by Zhang (2000) to describe the separation of CO_2 emission from China's economic development (Song et al., 2020). The extent of decoupling is measured by indicators based on the elasticity concept developed by the Organisation for Economic Cooperation and Development (OECD, 2002). An earlier decoupling concept framework developed by Tapio (2005) has been extensively used by many researchers (Shuai et al., 2019; Song and Zhang, 2017). The decoupling indicator presents eight possible decoupling states (strong, weak, recessive, strong negative, weak negative and expansive negative decoupling as well as expansive and recessive coupling) (Tapio, 2005), which have been used in various contexts at different levels, including global (Chen et al., 2018a; Shuai et al., 2019; Song et al., 2019), national (Wang et al., 2017a; Zhang et al., 2020, 2015b), provincial and city scales (Dong et al., 2016; Song et al., 2020; Wang et al., 2017b).

The shift in the gravity centre of CO_2 emissions can show the space transfer trajectory of CO_2 emissions (Song and Zhang, 2019). "Centre of gravity", a physics concept, refers to a single point where the weighted relative position of dispersed mass is equal to zero (Chen et al., 2018b). In the social economy, centre of gravity refers to the key point at which economic power can maintain full balance. Hilgard (1872) adopted gravitation theory to investigate distributions of the American population. Gravitation theory has been used to investigate geographical distributions in many fields, such as population distribution (Zhang et al., 2018), economic growth (Fu et al., 2011), ecosystem services (He et al., 2011), air pollution (Li et al., 2017), CO_2 emissions (Song and Zhang, 2019; Zhang et al., 2015a) and CO_2 emission per capita footprint (Li et al., 2019).

Investigations on driving forces of CO_2 emissions and their characteristics in Africa are limited (Beidari et al., 2017). A few reports with limited information on carbon-associated issues in Africa have been typically conducted in South Africa in the context of socioeconomic status. For example, CO_2 emissions from coal-sourced electricity production in South Africa (Zhang et al., 2015a), driving forces of CO_2 emissions in South Africa as a member of G20 countries (Yao et al., 2015) and emerging BRICS (Brazil, Russia, India, China and South Africa) economies (Inglesi–Lotz, 2018). Researchers have rarely focused on multiple African countries and the comparison of driving forces at different time scales or sub regional levels.

On the basis of the abovementioned analysis, the gravity theory model and contribution decomposition method were used in investigating the gravity shift of African CO_2 emissions and its leading driving forces. LMDI was then employed to identify driving forces behind changes in CO_2 emission pat-

Table 1 – Description of the 20 selected countries in African sub-regions.

African sub-region	Area (million km^2)	Population (million)	Population growth rate (%)	Urbanization rate (%)	Selected countries
North	7.77	245.00	3.16	52.4	Morocco, Egypt, Sudan, and Tunisia
East	6.67	442.18	5.71	29.8	Ethiopia, Kenya, Mozambique, Mauritius, Zambia, and Zimbabwe
Central	6.50	178.10	2.3	50.5	Cameroon, Congo Rep., Congo Dem. and Gabon
West	6.06	398.94	5.16	47.7	Benin, Nigeria, Senegal, and Togo
South	2.65	67.26	0.87	64.7	South Africa and Botswana

Source: Worldometer March 2020 (www.Worldometers.info).

terns in the 20 selected African countries. A decoupling indicator was also established to describe the dependence of economic development on CO_2 emissions in the 20 selected African countries from 1984 to 2014. This study attempts to narrow the research gap in climate strategy mitigation and adaptation, and help decision-makers control CO_2 emissions and quantify changes in CO_2 emissions and associated driving forces in 20 African countries from 1984 to 2014. This study aims to (1) identify potential driving forces behind CO_2 emission patterns for over 30 years, (2) relate CO_2 emissions to driving forces in different African sub-regions, (3) decouple the economic development from CO_2 emissions to understand influencing factors of CO_2 emission patterns further, and (4) provide suggestions for CO_2 emission reduction in Africa.

1. Methods

1.1. Study area

Twenty countries from five African sub-regions, that is, northern (number (n) = 4), eastern (n = 6), central (n = 4), western (n = 4) and southern (n = 2) Africa, were selected in the case study because of their data availability (Table 1 and Appendix A Table S1), economic importance or CO_2 emission contribution. Northern Africa is an economically prosperous region that covers one-third of the total African gross domestic product. Eastern Africa comprises the majority of poverty-stricken countries of the world, is located in the horn of Africa, and has various agricultural outputs. The central African region is covered with the second-largest rainforest in the world with oil as its leading export. Western Africa is made up of large low-lying planes with an altitude of less than 300 m above sea level, with agriculture as the fundamental driver of the economy. This region has been revived in recent years but faced economic recession due to long postcolonial civil wars. Southern Africa, the most productive for its precious mineral deposits (e.g. gold and diamonds), is a manufacturing hub and fosters the most industrialised and diversified economy amongst the sub-regions (Pitt, 2020).

1.2. Data sources

Primary sources of GHGs should be identified initially to mitigate climate change (Dong et al., 2020; Gruca–Rokosz et al., 2017; Shi et al., 2019). CO_2 is a potent anthropogenic GHGs (Letcher, 2020). A balanced panel dataset is used in the 20 selected African countries to investigate driving forces behind CO_2 emissions in Africa from 1984 to 2014. The investigation was divided into the following periods at five-year intervals: 1984–1989, 1989–1994, 1994–1999, 1999–2004, 2004–2009 and 2009–2014. CO_2 emissions were calculated from five sectors (transport, manufacturing and construction, electricity and heat production, residential buildings, commercial and public services and other sectors) and gross domestic product share in three economic sectors (agriculture, industry and services) (Fig. 1).

Sectoral data of CO_2 emissions were obtained from the International Energy Agency (IEA, 2014), whilst socioeconomic data, such as gross domestic product per sector, total gross domestic product and population, were collected from the World Bank database (World Bank, 2019). Gross domestic product data were adjusted at the constant price in 2010. The zero value in the dataset was examined using the method in Ang et al. (1998). Longitudes and latitudes of capital cities of 20 selected countries were sampled using Google Earth and Quantum Geographic Information System (QGIS) version 3.10.0 (QGIS Development Team, 2019) for depicting the shift trajectory of CO_2 emissions (Chen et al., 2018b; Song and Zhang, 2019).

1.3. Gravity theory model

The shift trajectory of CO_2 emissions was described according to the gravity theory model (Song and Zhang, 2019). The gravity centre for attribute value (M) in year t can be expressed as follows:

$$X^t = \frac{\sum_{i=1}^{n} M_i^t \times x_i}{\sum_{i=1}^{n} M_i^t} \quad (1)$$

$$Y^t = \frac{\sum_{i=1}^{n} M_i^t \times y_i}{\sum_{i=1}^{n} M_i^t} \quad (2)$$

where (x_i, y_i) represents the longitude and the latitude of the capital of the ith country; M_i^t represents the attribute value of the ith country in year t and X^t and Y^t denote the longitude and latitude of gravity centre of the attribute value, respectively.

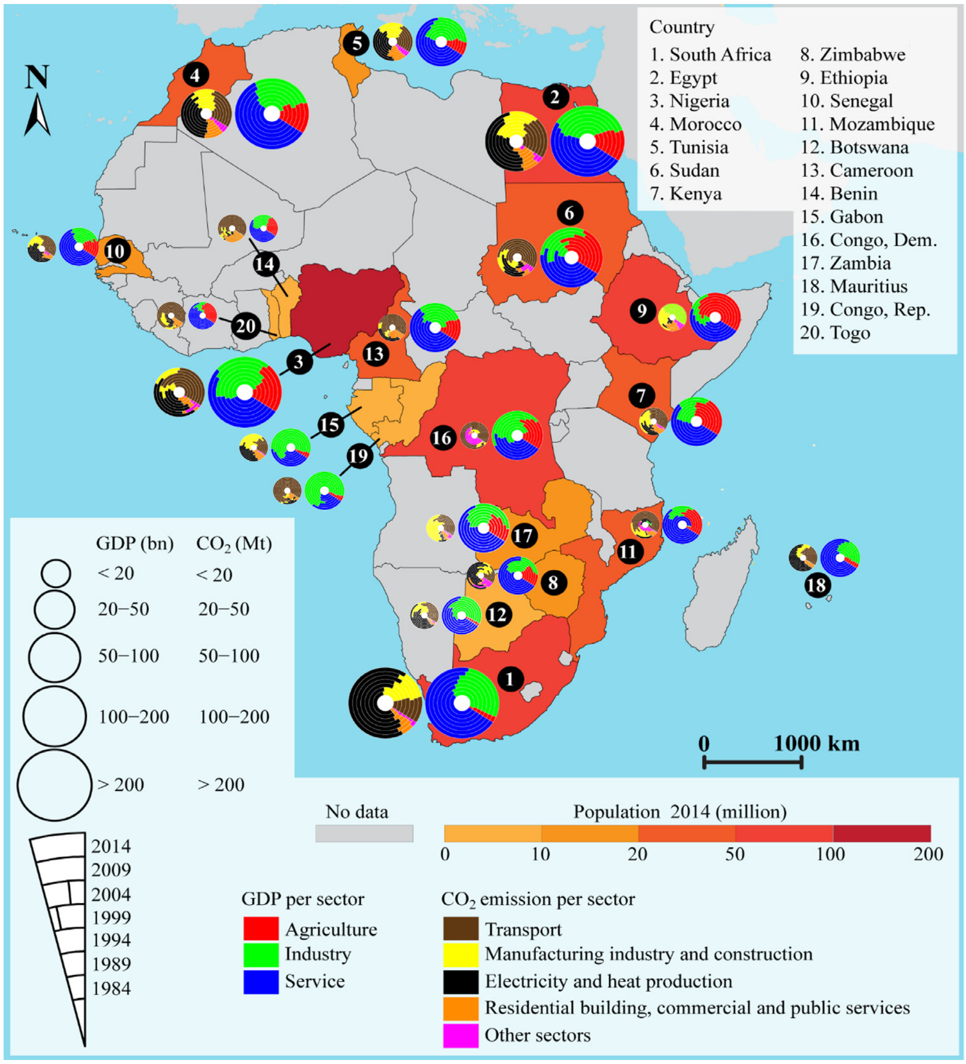

Fig. 1 – Location and information map of the 20 selected African countries between 1984 and 2014. The rank of CO_2 emissions of each country in 2014 is shown by white numbers in black circular symbols. GDP: gross domestic product; CO_2: carbon dioxide. The map was created by Quantum Geographic Information System (QGIS) version 3.10.0 (QGIS development team, 2019). Mt: million ton.

1.4. *Decomposition methods*

Decomposition methods were used to decompose CO_2 emission changes and determine factors that influence CO_2 emissions (Ang and Zhang, 2000; Dong et al., 2019). The following extended conventional Kaya identity method is preferred in the analysis of CO_2 emission decomposition at national and regional levels (Cloud, 2019; IEA, 2019):

$$C = \sum_{i}^{n} \left(\frac{C_i}{GDP_i} \times \frac{GDP_i}{GDP} \times \frac{GDP}{P} \times P \right) = \sum_{i}^{n} (CE \times IS \times EG \times P) \quad (5)$$

where C denotes the total CO_2 emissions, measured in million ton (Mt); C_i represents the amount of CO_2 emissions in sector i; GDP_i denotes the gross domestic product in sector i; GDP denotes the total gross domestic product; P refers to the total population (measured in millions); CE indicates the emission efficiency of sector *i* (measured in tonnes/2010 USD); IS represents the industrial structure of sector *i* (measured in 2010 USD) and EG denotes the economic growth (measured in 2010 USD).

LMDI is used to investigate driving forces of CO_2 emissions determined by the Kaya identity method (Ma and Cai, 2018; Shen et al., 2018; Shi et al., 2019). On the basis of Eq. (1) and LMDI, factors influencing CO_2 emission changes can be expressed as follows:

$$\Delta C = C^t - C^0 = \Delta C_{CE} + \Delta C_{IS} + \Delta C_{EG} + \Delta C_P \quad (6)$$

where *t* denotes the final year; 0 represents the benchmark year; and ΔC_{CE}, ΔC_{IS}, ΔC_{EG} and ΔC_P refer to the emission efficiency, industrial structure, economic growth and population effects, respectively.

These four effects can be expressed as follows:

$$\Delta C_{CE} = \frac{C_i^t - C_i^o}{\ln\left(C_i^t\right) - \ln\left(C_i^o\right)} \times \ln\left(\frac{EC^t}{EC^0}\right) \quad (7)$$

$$\Delta C_{IS} = \frac{C_i^t - C_i^o}{\ln\left(C_i^t\right) - \ln\left(C_i^o\right)} \times \ln\left(\frac{IS^t}{IS^0}\right) \quad (8)$$

$$\Delta C_{EG} = \frac{C_i^t - C_i^o}{\ln\left(C_i^t\right) - \ln\left(C_i^o\right)} \times \ln\left(\frac{EG^t}{EG^0}\right) \quad (9)$$

$$\Delta C_{P} = \frac{C_i^t - C_i^o}{\ln\left(C_i^t\right) - \ln\left(C_i^o\right)} \times \ln\left(\frac{P^t}{P^0}\right) \quad (10)$$

1.5. *Decoupling indicator*

The decoupling analysis was used to identify the linkage of economic development and CO_2 emissions (OECD, 2002; Tapio, 2005). The decoupling indicator (D^t) of CO_2 emissions (C) from the gross domestic product (G) in a certain period can be expressed as follows:

$$D^t = \frac{\Delta C^t / C^0}{\Delta G^t / G^0} \quad (11)$$

where the superscript 0 indicates the initial year, ΔC^t refers to the change in CO_2 emissions and ΔG^t refers to the change in gross domestic product. These values are calculated from the initial year 0 to the final year *t*. The variables $\Delta C^t/C^0$ and $\Delta G^t/G^0$ refer to the growth rates of CO_2 emissions and gross domestic product, respectively.

Tapio (2005) defined the decoupling indicator in eight decoupling states (Appendix A Table S2). Hence, Eq. (11) can be expressed as follows:

$$\begin{aligned} D^t &= \frac{G^0}{C^0 \times \left(G^t - G^0\right)} \times \left(C^t - C^0\right) \\ &= \frac{G^0}{C^0} \times \frac{\Delta C_{CE}^t + \Delta C_{IS}^t + \Delta C_{EG}^t + \Delta C_P^t}{\Delta G^t} \\ &= D_{CE}^t + D_{IS}^t + D_{EG}^t + D_P^t \end{aligned} \quad (12)$$

where $\Delta G^t = G^t - G^0$. According to Eq. (12), the decoupling indicator of CO_2 emissions from the gross domestic product can be decomposed into four decoupling indicator effects, namely, emission efficiency (D_{CE}^t), industrial structure (D_{IS}^t), economic growth (D_{EG}^t) and population (D_P^t) decoupling effects.

2. Results

2.1. *Gravity shift of CO_2 emissions*

The gravity shift of CO_2 emissions in 20 African countries between 1984 and 2014 is illustrated in Appendix A Fig. S1. The gravity centre for CO_2 emissions was located in the areas between 23.52E and 24.97E as well as −9.50N and −3.06N, with an overall shift towards the northeast direction. The shift was divided into the following periods: 1984–1989, 1989–1994, 1994–1999, 1999–2004, 2004–2009 and 2009–2014. The long shift of gravity centre of CO_2 emissions that occurred during 1999–2004 was driven by South Africa towards the east direction and then overturned primarily to the west direction by Nigeria. The long shift of gravity centre of CO_2 emissions that occurred during 1994–1999 was driven by Egypt and South Africa towards the north direction. Appendix A Table S3 shows the top four engine and inverse engine countries that largely contribute to the shift of the gravity centre of CO_2 emissions in each period.

Table 2 – Decomposition of CO_2 emissions in the 20 selected African countries between 1984 and 2014.

Period	CO_2 emissions (million ton)				
	ΔC	ΔC_{CE}	ΔC_{IS}	ΔC_{EG}	ΔC_P
1984−1989	24.57	-8.36	-31.65	-2.32	66.90
1989−1994	11.43	-18.66	-2.28	-33.71	66.08
1994−1999	87.86	20.83	-27.44	38.39	56.08
1999−2004	177.52	49.41	-14.97	86.54	56.54
2004−2009	104.36	-48.20	-39.65	122.70	69.52
2009−2014	47.80	-87.75	-19.42	67.61	87.36

ΔC: total emissions changes; ΔC_{CE}: emission efficiency; ΔC_{IS}: industrial structure; ΔC_{EG}: economic growth; ΔC_P: population.

2.2. *Performance of four driving forces of CO_2 emissions*

The aggregate decomposition results are listed in Table 2 and depicted in Appendix A Fig. S2. Population and economic growth showed positive effects that led to a significant increase in the overall CO_2 emission pattern between 1984 and 2014. Industrial structure and emission efficiency demonstrated negative influences on the increase in CO_2 emissions. Amongst the driving forces, population was the most critical contributor to the increase in CO_2 emissions and remained positive in all the selected countries during 1984–2014. Economic growth showed a negative role in the increase in CO_2 emissions during the first two periods (1984–1994) and a positive contribution in the last three periods (1994–2014). The industrial structure was the most balancing factor that led to the reduction in the overall CO_2 emissions from 1984 to 2014.

The contribution percentage of the four driving forces to CO_2 emission changes are illustrated in Fig. 2. CO_2 emissions were high (4.96%) during 1999–2004 but low (0.41%) in 1989−1994. Population revealed a cumulative positive contribution (> 1.5%) in 1984–2014, whilst industrial structure reduced CO_2 emissions at each period, with the largest (1.18%) and smallest (0.08%) contributions occurring during 1984−1989 and 1989−1994, respectively. The contribution of economic growth changed gradually from negative to positive, whilst the emission efficiency remained unstable. The results of the decomposition of changes in CO_2 emissions of each country are listed in Appendix A Table S4.

2.3. *Changes in CO_2 emission patterns*

Twenty selected countries demonstrated various trajectories that shaped African CO_2 emission patterns over the past 30 years (Appendix A Fig. S3). South Africa was the largest CO_2 emitter, followed by Egypt, Morocco and Nigeria. Intensive industrial development and fuel oil consumption were the ma-

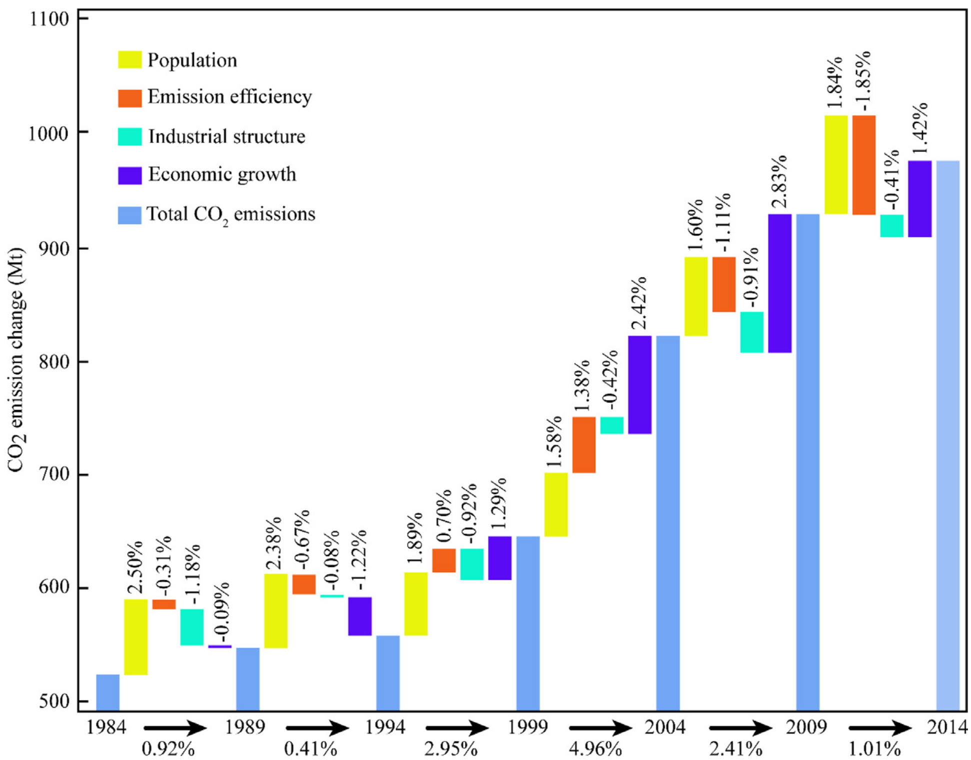

Fig. 2 – Contributions of the driving forces to CO_2 emissions in the 20 selected African countries during six periods.

jor causes of emissions. Population growth was the dominant driver in half of the selected countries, namely, Sudan, Kenya, Zambia, Zimbabwe, Cameroon, Republic of the Congo, Democratic Republic of the Congo, Gabon, Senegal and South Africa (Fig. 3). Economic growth was the primary driving force for Morocco, Egypt, Tunisia, Ethiopia, Nigeria, Botswana, Mauritius and Togo. CO_2 emissions from Mozambique and Benin were dominantly driven by emission efficiency. These drivers that increase CO_2 emissions were slightly offset by industrial structure change in many countries (e.g. Morocco, Tunisia, Kenya, Mozambique, Mauritius, Zimbabwe, South Africa and Botswana). Emission efficiency was the principal downward-driving factor in Egypt, Ethiopia, Zambia and Togo. CO_2 emissions in central African subregion countries were primarily driven by population growth and balanced by economic growth. The economic growth contributed negatively to Zimbabwe during 1994–1999. The examined factors contributed positively to the increase in CO_2 emissions in Sudan, Benin and Senegal.

2.4. *Impact of four driving forces on CO_2 emission patterns*

The emission efficiency led to the reduction of CO_2 emissions of approximately 92.74 Mt, which accounts for 10.19% of the total emitted CO_2, from 1984 to 2014 (Fig. 4 and Appendix A Fig. S4). Nigeria and Egypt were the highest contributors to the overall reduction of CO_2 emissions at 66.76 and 33.93 Mt, respectively, which account for 46.83% of the total emission efficiency contribution. A slight reduction of CO_2 emissions (9.58 Mt or 6.85%) was observed in Tunisia, Ethiopia, Kenya, Zambia, Cameroon, Democratic Republic of the Congo, Gabon, Togo and South Africa. The emission efficiency displayed a fluctuating effect in many countries with some exceptions to Zimbabwe between 1984 and 1989, Gabon and Democratic Republic of the Congo between 1989 and 1994, Mauritius between 1994 and 1999, Kenya between 1999 and 2004, Benin between 2004 and 2009 and Mozambique, South Africa and Togo between 2009 and 2014 (Fig. 4).

The industrial structure reduced CO_2 emissions of approximately 135.41 Mt, which accounts for 14.88% of the total emitted CO_2, during 1984–2014 (Fig. 5). At the national level, South Africa was the most critical contributor to the overall reduction of CO_2 emissions, with a cumulative contribution of approximately 116.69 Mt, which accounts for 86.2% of the total industrial structure contribution. The industrial structure showed a negative impact on CO_2 emissions in 12 countries, with particular attention to South Africa, Nigeria and Morocco. The industrial structure exerted a weak positive contribution in eight countries, particularly in Egypt, Ethiopia and Sudan. At the temporal scale, Zimbabwe's emissions decreased by 8.8 Mt, which accounts for 80% of total CO_2 emission reduction, during 1984–1989 with the assistance of the industrial structure in Zimbabwe in 1984–2014.

Economic growth led to the continuous growth of CO_2 emissions in 1984–2014 (Fig. 6) at approximately 279.22 Mt, which accounts for 30.69% of the total emitted CO_2. At the national level, the economic growth stimulated CO_2 emission changes, especially in the last two periods. The cumulative economic growth effect in Egypt was the most substantial contributor to the total changes in the emitted CO_2. South Africa, Nigeria and Morocco demonstrated cumulative

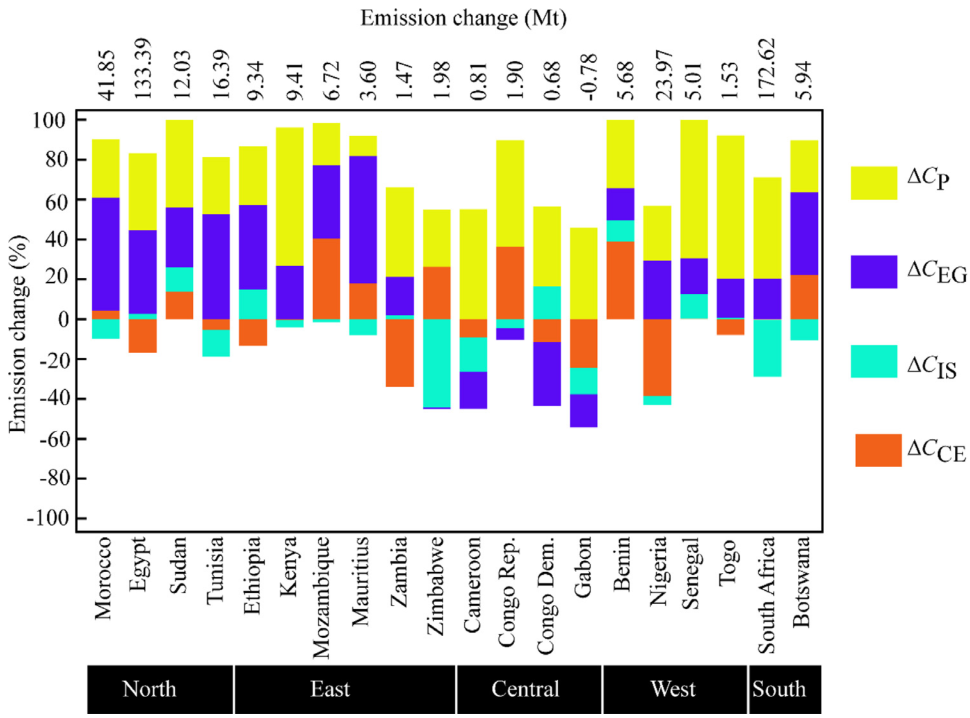

Fig. 3 – Changes in CO_2 emissions in the 20 selected African countries between 1984 and 2014. $\triangle C_{CE}$: emissions efficiency; $\triangle C_{IS}$: industrial structure; $\triangle C_{EG}$: economic growth; $\triangle C_P$: population.

increases of 84.14, 82.42, 51.06 and 29.53 Mt, respectively. Economic growth showed a considerable effect on countries with high industrial activities or massive CO_2 emissions. By contrast, a negative effect was detected in countries of the central African subregion.

The population increased the CO_2 emissions of approximately 402.49 Mt (44.24%) during 1984–2014 (Fig. 7). The increase in CO_2 emissions was evident at the national level (e.g. a positive effect was observed in all the countries).

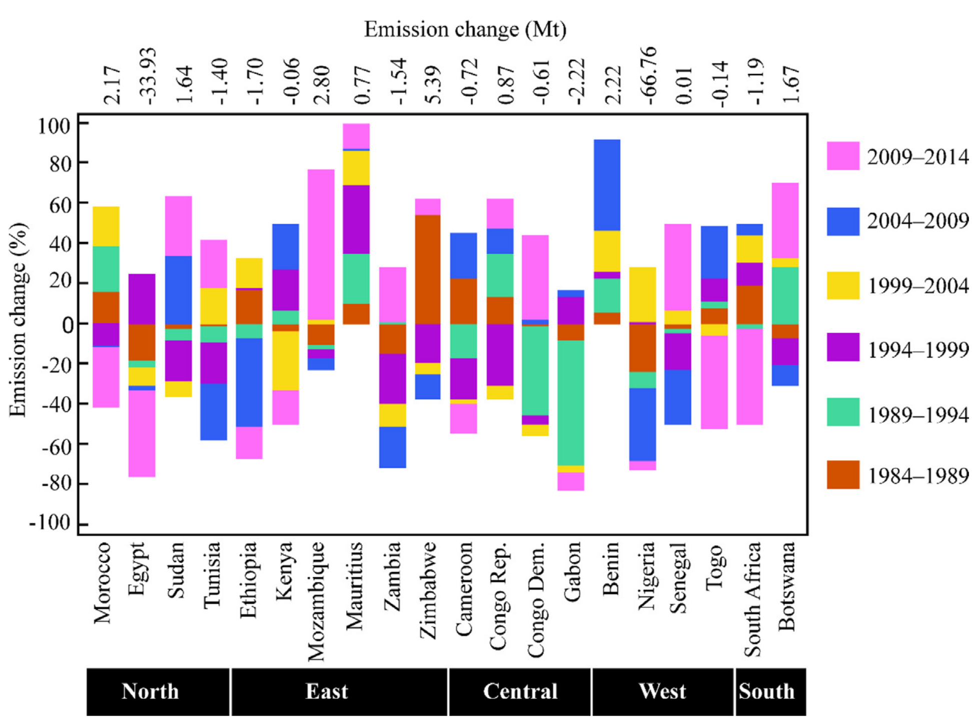

Fig. 4 – Changes in CO_2 emissions resulting from the emission efficiency in the 20 selected African countries between 1984 and 2014.

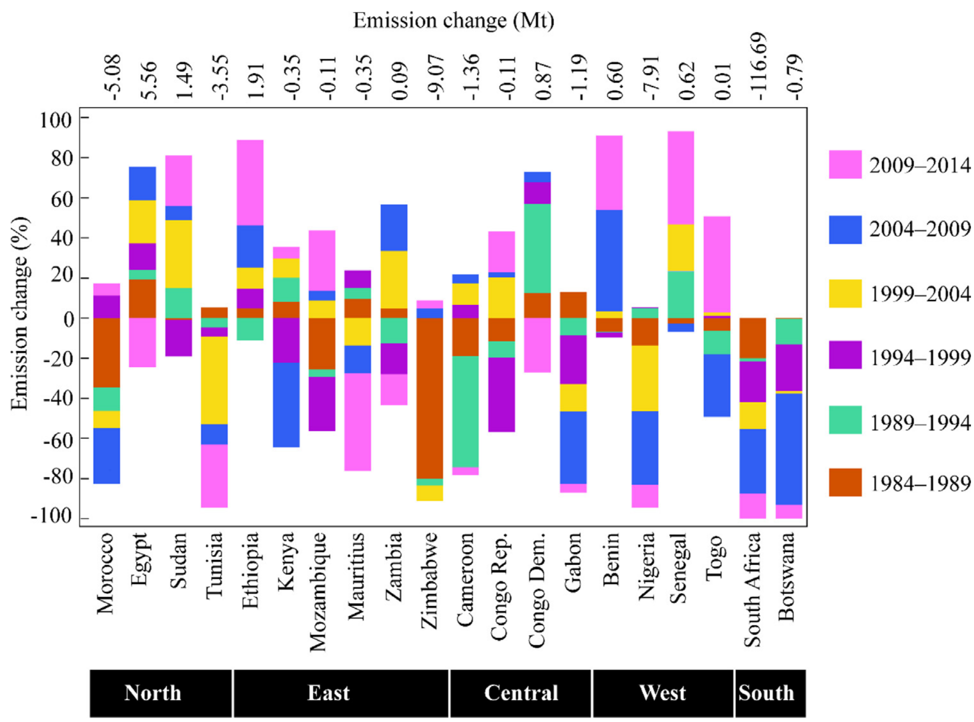

Fig. 5 – Changes in CO_2 emissions resulting from the industrial structure in the 20 selected African countries between 1984 and 2014.

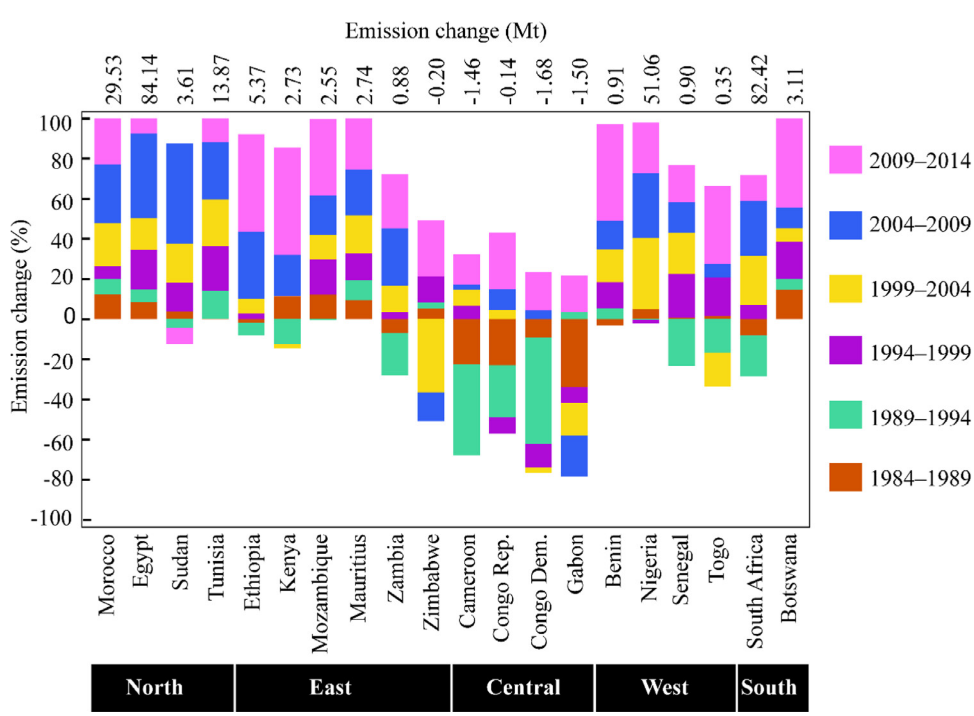

Fig. 6 – Changes in CO_2 emissions resulting from the economic growth in the 20 selected African countries between 1984 and 2014.

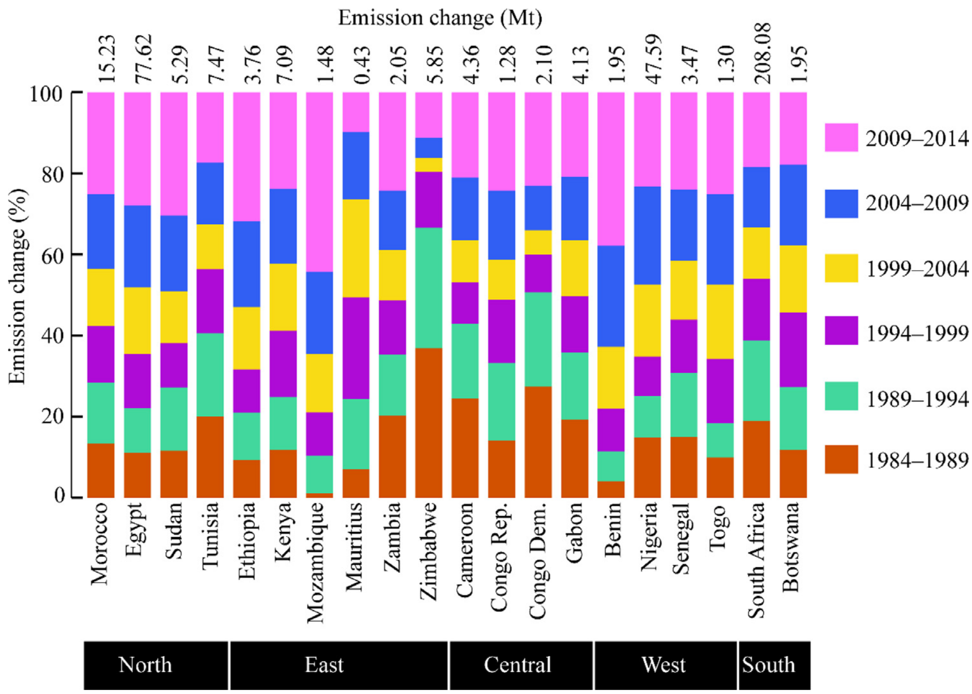

Fig. 7 – Changes in CO_2 emissions resulting from the population in the 20 selected African countries between 1984 and 2014.

2.5. *Decoupling analysis*

The decoupling states of CO_2 emissions based on the gross domestic product during 1984–2014 are presented in Table 3. Strong decoupling, weak decoupling and expansive coupling occurred in different countries within different periods. Expansive negative decoupling was evident in the examined countries, except Gabon and South Africa, at different periods. Strong negative decoupling only occurred in the Republic of the Congo in 1984–1994. Weak negative decoupling was observed in Togo during 1989–1994. Recessive decoupling occurred in Gabon, Zambia, Democratic Republic of the Congo and Zimbabwe during 1984–1989, 1989–1994, 1989–1999 and 1999–2009, respectively. Population and economic growth decoupling effects indicated the strong role in the development of decoupling of the selected countries in 1984–2014 (Appendix A Fig. S5). Emission efficiency decoupling exhibited a substantial adverse effect during 1989–2004, particularly in the Republic of the Congo and Ethiopia. Emission efficiency and industrial structure decoupling effects indicated the negative role in the collective development of decoupling in 20 countries.

3. Discussion

3.1. *Driving forces of CO_2 emissions*

The industrial structure has a positively important effect on CO_2 emissions either by the change in industrial structure from agriculture, mining and light industries to heavy carbon-based industries or the adjustment in the production structure, particularly in construction and service sectors (Tian et al., 2014). Similarly, the decomposition results demonstrated that the industrial structure is the inhibitory effect that compensated for the increase in CO_2 emissions in the selected 20 African countries, followed by emission efficiency between 1984 and 2014 (Fig. 3 and Appendix A Fig. S2). This finding showed the lacking industrial structure change and regression in manufacturing in a few of the selected African countries (e.g. South Africa) that continued to be biased towards mineral and resource-based sectors (Bell et al., 2018). By comparison, some of the country's development was dependent on aid, which may have increased regional CO_2 emissions through international trade by importing low-carbon products whilst exporting carbon-rich products (Tian et al., 2014).

Population growth and GHGs are closely linked. Given that Africa is the fastest-growing region in the world, climate change caused by its rapid population growth must be considered (O'Neill et al., 2012; Shi, 2003; Tenaw, 2020). Despite the global and African implementation of population control policies from 2015, the total African population is projected to increase by 42% in 2030 (UN, 2015). This prediction indicates that the population explosion will directly result in the increasing demand for high-carbon fossil fuels, such as fuel oil for transport systems, gas for daily life and coal for industrial development, in the future.

Economic growth exerts a negative effect on CO_2 emissions of countries with slow economic growth but a positive effect on countries with rapid economic growth (Aye et al., 2017). Similarly, economic growth is an essential driving force that influences the overall CO_2 increase in the African countries under this study in 1984–2014, especially in countries with intensive industrial activities that consume large fuel oil. For ex-

Table 3 – Decoupling states for the 20 selected African countries between 1984 and 2014.

	1984–1989		1989–1994		1994–1999		1999–2004		2004–2009		2009–2014	
Morocco	0.88	EC	1.53	END	0.83	EC	1.27	END	0.79	WD	0.64	WD
Egypt	0.47	WD	0.93	EC	1.57	END	0.94	EC	1.05	EC	-0.18	SD
Sudan	0.76	WD	1.07	EC	-0.29	SD	1.25	END	1.89	END	3.27	END
Tunisia	1.09	EC	0.72	WD	0.52	WD	0.93	EC	0.44	WD	1.24	END
Ethiopia	6.24	END	-12.24	SD	1.61	END	2.25	END	0.37	WD	1.08	EC
Kenya	0.63	WD	3.31	END	3.60	END	-1.90	SD	2.45	END	0.42	WD
Mozambique	-1.04	SD	0.20	WD	0.11	WD	1.42	END	0.67	WD	5.79	END
Mauritius	1.59	END	1.82	END	1.82	END	1.07	EC	0.88	EC	0.68	WD
Zambia	-0.76	SD	1.60	RD	-1.39	SD	0.59	WD	0.30	WD	2.05	END
Zimbabwe	2.53	END	0.72	WD	-0.70	SD	1.33	RD	2.17	RD	1.73	END
Cameroon	11.57	END	2.84	RD	-0.86	SD	1.12	EC	4.13	END	0.16	WD
Congo Rep.	-7.86	SND	-65.43	SND	-6.92	SD	0.72	WD	3.01	END	2.57	END
Congo Dem.	1.45	END	1.73	RD	1.38	RD	-2.67	SD	1.59	END	3.75	END
Gabon	1.71	RD	-1.49	SD	1.12	EC	-1.40	SD	-3.17	SD	0.69	WD
Benin	2.42	END	3.75	END	1.18	EC	2.32	END	3.99	END	1.44	END
Nigeria	-2.00	SD	-1.32	SD	1.38	END	3.17	END	-0.71	SD	0.69	WD
Senegal	0.69	WD	0.97	EC	-0.24	SD	1.72	END	-0.77	SD	4.61	END
Togo	2.56	END	0.49	WND	2.44	END	-1.83	SD	3.21	END	-0.54	SD
South Africa	1.04	EC	-0.67	SD	0.78	WD	1.02	EC	0.62	WD	-0.20	SD
Botswana	0.49	WD	4.51	END	0.14	WD	1.37	END	-0.16	SD	2.18	END

SD: strong decoupling; WD: weak decoupling; EC: expansive coupling; END: expansive negative decoupling; SND: strong negative decoupling; WND: weak negative decoupling; RD: recessive decoupling.

ample, Egypt, South Africa, Nigeria, Morocco and Tunisia consumed 797,000, 663,000, 296,000 and 89,000 bbl/day, respectively, in 2014.

The present study showed that CO_2 emissions in Africa are primarily caused by a few countries, including South Africa, which contribute to approximately a quarter of the total CO_2 emissions (EIA, 2014). Countries with high CO_2 emissions ($\geq$ 10 Mt/year) in this study include South Africa, Egypt, Morocco and Nigeria, but other countries, such as Algeria and Libya, were also highlighted in Boden et al. (2017). However, economic growth was the dominant mitigating factor of CO_2 emissions in central African countries (e.g. Cameroon, Republic of the Congo, Democratic Republic of the Congo, and Gabon) and Zimbabwe possibly due to the low-level economic diversification, infrastructure deficits and political instability (ADB, 2019; Kanyenze et al., 2017; Munangagwa, 2009; Tyson, 2017).

3.2. *Decoupling of CO_2 emissions from economic development*

The decoupling of CO_2 emissions from economic development is crucial for countries that aim to mitigate climate change and CO_2 emissions (Mikayilov et al., 2018). Hence, seven out of eight decoupling states, as defined in Tapio (2005), occurred in the 20 selected African countries between 1984 and 2014 (Table 3). However, expansive negative decoupling states observed in many selected countries in 1984–2014 suggested that the increase in growth rate of CO_2 emissions was faster than the gross domestic product (OECD, 2002; Tapio, 2005). Consistent with the work conducted by Grand (2017) in 22 sub-Saharan African countries, the results of this study imply that rapid economic growth can lead to fast growth rate of CO_2 emissions and environmental degradation in many African countries.

Population and economic growth effects are the primary driving forces for the growth of CO_2 emissions based on LMDI (Dong et al., 2018, 2019; Tenaw, 2020). Similarly, decoupling indicators of population and economic growth effects were positive contributions with 37.63% and 24.61%, respectively (Appendix A Fig. S5). This finding may indicate that the growth rate of CO_2 emissions increased primarily due to the effects of population and economic growth. The gross domestic product showed a strong negative decoupling relationship with CO_2 emissions in the Republic of the Congo between 1984 and 1994 likely due to the declining economic development caused by political instability and civil wars in the past two decades (ADB, 2019).

3.3. *Comparison of driving forces with global industrial countries*

Africa is a lower source of global CO_2 emissions compared with Asia, America and Europe and even countries, such as

China, the United States of America and India (Rithie, 2019). However, the African continent is highly vulnerable to the impact of global climate change (Field, 2014; IPCC, 2018; Sakiru Adebola, 2014). At the global scale, our results showed that driving forces of CO_2 in the 20 selected African countries were consistent with the findings of Dong et al. (2018, 2019), which considered different income levels in more than 100 countries. Such findings were also compared with those found in the top 20 developed countries (Yao et al., 2015) and 27 European Union members (Fernández González et al., 2014a, 2014b). The results showed that similar to Brazil, Mexico, Argentina, Turkey, Germany and France, the population growth in the selected countries in this study was a major driving force influencing the increase in CO_2 emissions (Fernández González et al., 2014a; Yao et al., 2015). Our results in economic growth were similar to the findings of highly industrialised and advanced economies (e.g. China, India, Australia, South Korea, Italy and Spain) (Fernández González et al., 2014a). As the foremost downward-driving factor of CO_2 emissions, industrial structure has been highlighted in findings related to the United Kingdom, USA, the Russian Federation, Canada, Brazil, Germany, Australia, Italy, Argentina and Saudi Arabia (Fernández González et al., 2014b; Yao et al., 2015).

The negative contribution of economic growth from CO_2 emissions in the majority of least developed countries (e.g. selected countries in the central African sub-region) and the positive contribution of economic growth from CO_2 emissions from countries with a relatively growing economy (e.g. South Africa, Egypt, Morocco, Nigeria and Tunisia) (Fig. 6) confirmed that economic growth is a driving force of CO_2 emissions globally but may depend on national economic and population growth rates (Aye et al., 2017).

3.4. *Policy implications*

The following are suggested policy implications based on our findings. Weak evidence of emission efficiency and industrial structure effects found in many countries indicated that climate policy measures in Africa are insufficient in mitigating CO_2 emission growth. Specific and active policy interventions should be implemented to improve people's livelihoods and resilience to climate change. African countries can reflect the diversity of climate risks (e.g. heat stress, flood and drought), vulnerabilities and ecosystems (forests, watersheds and drylands). Nature continues to change due to unsustainable consumption. African countries should raise awareness regarding the role of nature-based solutions that can support climate resilience and adaptation by prioritising large-scale and coordinated approaches at the landscape or seascape level and maximising various local benefits that contribute to international commitments (e.g. Sustainable Development Goals, Paris and Aichi) (Ouedraogo, 2019).

The following suggestions are presented on the basis of the results of our study. (1) Improved carbon sequestration and decreased GHG emissions must be achieved to enhance the conservation and restoration of ecosystems and mitigate climate change in African countries. The Paris Agreement emphasises this critical role and encourages countries to conserve and enhance sinks and reservoirs of GHGs when necessary (Seddon et al., 2019). Ecosystems play a crucial role in the global carbon cycle and adapting to climate change (Kalantari et al., 2018) whilst offering a wide range of ecosystem services, which are essential to human well-being and achieving sustainable development goals in 2030. (2) Locally upgrading industrial structure, promoting emission efficiency technologies, shifting from fossil fuels to environmentally friendly energy sources and carbon pricing must be emphasised. (3) The global community must focus on consumption-based carbon emissions in international climate negotiations and target setting discussions because territorial emissions only vaguely indicate the total amount of emissions related to international trade (Tenaw, 2020).

4. Conclusions

The African continent is seriously affected by global climate change due to the continuous growth of urban dwellers, substantial proportion of poverty, high dependence on ecosystem goods and rapid development of industrialisation. CO_2 emission patterns in 20 African countries were investigated to understand CO_2 emission characteristics and their influencing factors further. In this study, the shift trajectory of the gravity centre of CO_2 emissions is depicted and driving forces that influence CO_2 emissions are identified using LMDI and decoupling methods during 1984–2014.

The primary findings of this study are presented as follows: (1) CO_2 emissions increased by 2.11% (453.73 Mt) in the selected 20 African countries, and the largest CO_2 emitters include South Africa, Egypt, Morocco and Nigeria. (2) The gravity centre for African CO_2 emissions was an overall shift towards the northeast direction. The gravity centre towards the east direction was primarily pushed by Nigeria, Egypt, Zimbabwe and Senegal. The shift of gravity centre, towards the north direction was driven by Egypt, South Africa, Nigeria and Tunisia. (3) The population effect, followed by the economic growth effect with a cumulative contribution rate of approximately 30.69%, was the main driving force of CO_2 emissions with a cumulative contribution rate of around 44.24%. At the national scale, the population growth displayed a positive effect on CO_2 emissions whilst the economic growth effect demonstrated a balanced factor in central African countries and Zimbabwe. The industrial structure and emission efficiency effects were offset factors with cumulative contribution rates of approximately 14.88% and 10.19%, respectively. (4) CO_2 emissions were considered a consequence of economic development in many countries that presented expansively negative decoupling and weak decoupling with economic development. (5) The industrial structure and emission efficiency contributed to the reduction of CO_2 emissions but were inadequate to offset the positive contribution of population and economic growth. Thus, future efforts to mitigate CO_2 emissions should combine energy-related measures with economic benefits, such as energy-efficient technologies, renewable energy and carbon market. African countries are advised to increase awareness on the role of nature-based solutions in addressing climate change adaptation and resilience. The global community should also pay additional attention to consumption-based carbon emissions in international climate negotiations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the National Water Pollution Control and Treatment Science and Technology Major Project (No. 2017ZX07101001), the National Natural Science Foundation of China (Nos. 41690142 and 41371535), and the Fundamental Research Funds for the Central Universities (No. SWU019047).

Appendix A. Supplementary data

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jes.2020.09.006.

REFERENCES

ADB (African Development Bank Group), 2019. Central Africa Economic Outlook 2019. Available: https://www.afdb.org/en/countries/central-africa/central-african-republic/central-african-republic-economic-outlook. Accessed March 17, 2020.

Ang, B.W., 2004. Decomposition analysis for policymaking in energy. Energy Policy 32, 1131–1139.

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33, 867–871.

Ang, B.W., 2015. LMDI decomposition approach: a guide for implementation. Energy Policy 86, 233–238.

Ang, B.W., Liu, F.L., 2001. A new energy decomposition method: perfect in decomposition and consistent in aggregation. Energy 26, 537–548.

Ang, B.W., Liu, F.L., Chew, E.P., 2003. Perfect decomposition techniques in energy and environmental analysis. Energy Policy 31, 1561–1566.

Ang, B.W., Zhang, F.Q., 2000. A survey of index decomposition analysis in energy and environmental studies. Energy 25, 1149–1176.

Ang, B., Zhang, F., Choi, K., 1998. Factorizing changes in energy and environmental indicators through decomposition. Energy 23, 489–495.

Aye, G.C., Edoja, P.E., Charfeddine, L., 2017. Effect of economic growth on CO_2 emission in developing countries: evidence from a dynamic panel threshold model. Cogent Econ. Financ. 5 (1), 1379239.

Beidari, M., Lin, S.-J., Lewis, C., 2017. Decomposition analysis of CO_2 emissions from coal - sourced electricity production in South Africa. Aerosol Air Qual. Res. 17, 1043–1051.

Bell, J., Goga, S., Mondliwa, P., Roberts, S., 2018. Structural Transformation in South Africa: Moving Towards a Smart, Open Economy For All. Available: https://www.competition.org.za/structural-transformation-in-south-africa-moving-towards-a-smart-open-economy-for-all. Accessed: February 19, 2020.

Boden, T.A., Marland, G., Andres, R.J., 2017. Global, Regional, and National Fossil-fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. US Department of Energy, Oak Ridge, Tenn. USA 2009.

Busby, J.W., Smith, T.G., White, K.L., Strange, S.M., 2012. In: Locating Climate Insecurity: Where are the Most Vulnerable Places in Africa? Climate Change, Human Security and Violent Conflict, 8. Springer, Berlin, Heidelberg, pp. 463–511.

Cameron, E., 2019. Business Adaptation to Climate Change and Global Supply Chains. Manchester, VT. Licensed under Creative Commons Attribution-Noncommercial 4.0 International license. Available: https://creativecommons.org/licenses/by-nc/4.0/. Accessed: March 15, 2020.

Chen, J., Wang, P., Cui, L., Huang, S., Song, M., 2018a. Decomposition and decoupling analysis of CO_2 emissions in OECD. Appl. Energy 231, 937–950.

Chen, J., Xu, C., Li, K., Song, M., 2018b. A gravity model and exploratory spatial data analysis of prefecture-scale pollutant and CO_2 emissions in China. Ecol. Indic. 90, 554–563.

Cloud, J., 2019. The Kaya Identity. A Tool Which We as Actuaries Can Use to Understand and Measure How CO_2 Emissions and Their Underlying Drivers Change. Springer, Cham Available: https://www.actuaries.org.uk/system/files/field/document/Kaya%20identity_JC%20Final%20050219.pdf .

Coulibaly, B.S., 2020. Foresight Africa: Top Priorities for the Continent 2020 to 2030. Brookings Available https://www.brookings.edu/multi-chapter-report/foresight-africa-top-priorities-for-the-continent-in-2020/ .

Dessler, A.E., Parson, E.A., 2019. The Science and Politics of Global Climate Change: A Guide to the Debate. Cambridge University Press Available: www.cambridge.org/desslerparson3 .

Dong, B., Zhang, M., Mu, H., Su, X., 2016. Study on decoupling analysis between energy consumption and economic growth in Liaoning Province. Energy Policy 97, 414–420.

Dong, K., Hochman, G., Timilsina, G.R., 2018. Are Driving Forces of CO_2 Emissions Different across Countries? Insights From Identity and Econometric Analyses. The World Bank WPS8477.

Dong, K., Hochman, G., Timilsina, G.R., 2020. Do drivers of CO_2 emission growth alter overtime and by the stage of economic development? Energy Policy 140, 111420.

Dong, K., Jiang, H., Sun, R., Dong, X., 2019. Driving forces and mitigation potential of global CO_2 emissions from 1980 through 2030: evidence from countries with different income levels. Sci. Total Environ. 649, 335–343.

EIA (U.S. Energy Information Administration), 2014. Oil Consumption Data. Available: https://www.eia.gov/international/analysis/country. Accessed June 22, 2020.

EIA (U.S. Energy Information Administration), 2018. Energy Implications of Higher Economic in Africa. Available: https://www.eia.gov/outlooks/ieo/africa/pdf/africa_detailed.pdf . Accessed April 2, 2020.

Fernández González, P., Landajo, M., Presno, M.J., 2014a. The driving forces behind changes in CO_2 emission levels in EU-27. Differences between member states. Environ. Sci. Policy 38, 11–16.

Fernández González, P., Landajo, M., Presno, M.J., 2014b. Tracking European Union CO_2 emissions through LMDI decomposition. The activity revaluation approach. Energy 73, 741–750.

Field, C.B., 2014. Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Foster, V., Bedrosyan, D., 2014. Understanding CO_2 Emissions From the Global Energy Sector. The World Bank Available:

https://openknowledge.worldbank.org/bitstream/handle/10986/17143/851260BRI0Live00Box382147B00PUBLIC0.pdf .
Fu, J., Gao, Z., Huang, L., Zhang, L., 2011. The shift route of consumption gravity center of Xinjiang from 1965 to 2009 based on GIS. Procedia Earth Planet. Sci. 2, 321–326.
Gao, Z., Geng, Y., Wu, R., Chen, W., Wu, F., Tian, X., 2019. Analysis of energy-related CO_2 emissions in China's pharmaceutical industry and its driving forces. J. Clean. Prod. 223, 94–108.
Grand, M.C., 2017. Beyond the Question 'Is There Decoupling?': A Decoupling Ranking Serie Documentos de Trabajo No. 622. Universidad del Centro de Estudios Macroeconómicos de Argentina (UCEMA), Buenos Aires.
Gruca-Rokosz, R., Bartoszek, L., Koszelnik, P., 2017. The influence of environmental factors on the carbon dioxide flux across the water-air interface of reservoirs in south-eastern Poland. J. Environ. Sci. 56, 290–299.
He, Y., Chen, Y., Tang, H., Yao, Y., Yang, P., Chen, Z., 2011. Exploring spatial change and gravity center shift for ecosystem services value using a spatially explicit ecosystem services value index and gravity model. Environ. Monit. Assess. 175, 563–571.
Hilgard, J.E., 1872. The advance of population in the United States. Scribner's Mon. 4, 214–218.
IEA (International Energy Agency), 2019. CO_2 Emissions From Fuel Combustion 2019 Edition. World CO_2 Documentation. Available: http://wds.iea.org/wds/pdf/WorldCo2_Documentation.pdf. Accessed November 1, 2019.
IEA, 2014. CO_2 Emissions per sector data. IEA Statistics OECD/IEA 2014. http://www.iea.org/stats/index.asp. Accessed October 10, 2019.
Inglesi-Lotz, R., 2018. Decomposing the South African CO_2 emissions within a BRICS countries context: signaling potential energy rebound effects. Energy 147, 648–654.
IPCC (Intergovernmental Panel on Climate Change), 2018. Global Warming of 1.5°C. ISBN 978-92-9169-151-7. Available: www.ipcc.ch .
Kalantari, Z., Ferreira, C.S.S., Keesstra, S., Destouni, G., 2018. Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa. Curr. Opin. Environ. Sci. Health 5, 73–78.
Kang, J., Lin, J., Zhao, X., Zhao, S., Kou, L., 2017. Decomposition of the urban water footprint of food consumption: a case study of Xiamen City. Sustainability 9 (1), 135.
Kanyenze, G., Chitambara, P., Tyson, J., 2017. The Outlook for the Zimbabwean Economy. SET, UKAID, September. Available: https://set.odi.org/wp-content/uploads/2017/08/SET-Outlook-for-Zimbabwe. Accessed April 5, 2020.
Letcher, T.M., 2020. Introduction with a focus on atmospheric carbon dioxide and climate change. Future Energy 3–17.
Li, H., Song, Y., Zhang, M., 2017. Study on the gravity center evolution of air pollution in Yangtze River Delta of China. Nat. Hazards 90, 1447–1459.
Li, X., Xiong, S., Li, Z., Zhou, M., Li, H., 2019. Variation of global fossil-energy carbon footprints based on regional net primary productivity and the gravity model. J. Clean. Prod. 213, 225–241.
Lin, B., Ouyang, X., 2014. Analysis of energy-related CO_2 emissions and reduction potential in the Chinese non-metallic mineral products industry. Energy 68, 688–697.
Lin, J., Liu, Y., Hu, Y., Cui, S., Zhao, S., 2015. Factor decomposition of Chinese GHG emission intensity based on the logarithmic mean divisia index method. Carbon Manag. 5, 579–586.
Liu, Y., Yang, D., Xu, H., 2017. Factors influencing consumer willingness to pay for low-carbon products: a simulation study in China. Bus. Strateg. Environ. 26, 972–984.
Luo, X., Dong, L., Dou, Y., Liang, H., Ren, J., Fang, K., 2016. Regional disparity analysis of Chinese freight transport CO_2 emissions from 1990 to 2007: driving forces and policy challenges. J. Transp. Geogr. 56, 1–14.
Ma, M., Cai, W., 2018. What drives the carbon mitigation in Chinese commercial building sector? Evidence from decomposing an extended Kaya identity. Sci. Total Environ. 634, 884–899.
Maji, I.K., Sulaiman, C., Abdul-Rahim, A.S., 2019. Renewable energy consumption and economic growth nexus: a fresh evidence from West Africa. Energy Rep. 5, 384–392.
Mikayilov, J.I., Hasanov, F.J., Galeotti, M., 2018. Decoupling of CO_2 emissions and GDP: a time-varying cointegration approach. Ecol. Indic. 95, 615–628.
Mousavi, B., Lopez, N.S.A., Biona, J.B.M., Chiu, A.S.F., Blesl, M., 2017. Driving forces of Iran's CO_2 emissions from energy consumption: an LMDI decomposition approach. Appl. Energy 206, 804–814.
Munangagwa, C.L., 2009. The economic decline of Zimbabwe. Gettysbg. Econ. Rev.. Available: https://cupola.gettysburg.edu/ger/vol3/iss1/9 . Accessed April 5, 2020.
OECD, 2002. Indicators to Measure Decoupling of Environmental Pressure From Economic Growth. Sustain. Dev. SG/SD 20.
O'Neill, B.C., Liddle, B., Jiang, L., Smith, K.R., Pachauri, S., Dalton, M., et al., 2012. Demographic change and carbon dioxide emissions. Lancet 380, 157–164.
Ouedraogo, N.S., 2019. Transition pathways for North Africa to meet its (intended) nationally determined contributions ((I)NDCs) under the Paris agreement: a model-based assessment. Clim. Policy 20, 71–94.
Peters, G.P., Andrew, R.M., Canadell, J.G., Fuss, S., Jackson, R.B., Korsbakken, J.I., et al., 2014. Key indicators to track current progress and future ambition of the Paris Agreement. Budget Comment. 2016_20161210.
Pitt, 2020. African Studies and African Country Resources. University of Pittsburgh Available: https://pitt.libguides.com/c.php?g=12378&=65815 .
QGIS Development Team, 2019. QGIS Geographic Information System. Open Source Geospatial Foundation, Gossau, Switzerland.
Rithie, H., 2019. Who Emits the Most CO2 Today? Our World in Data. Available: https://ourworldindata.org/annual-co2-emissions. Accessed June 20, 2020.
Russo, S., Marchese, A.F., Sillmann, J., Immé, G., 2016. When will unusual heat waves become normal in a warming Africa? Environ. Res. Lett. 11 (5), 054016.
Sakiru Adebola, S., 2014. Convergence of CO_2 emission levels: evidence from African countries. J. Econ. Res. 19, 65–92.
Seddon, N., Turner, B., Berry, P., Chausson, A., Girardin, C.A., 2019. Grounding nature-based climate solutions in sound biodiversity science. Nat. Clim. Change 9 (2), 84–87.
Shen, L., Wu, Y., Lou, Y., Zeng, D., Shuai, C., Song, X., 2018. What drives the carbon emission in the Chinese cities? A case of pilot low carbon city of Beijing. J. Clean. Prod. 174, 343–354.
Shi, A., 2003. The impact of population pressure on global carbon dioxide emissions, 1975–1996: evidence from pooled cross-country data. Ecol. Econ. 44, 29–42.
Shi, L., Sun, J., Lin, J., Zhao, Y., 2019. Factor decomposition of carbon emissions in Chinese megacities. J. Environ. Sci. 75, 209–215.
Shuai, C., Chen, X., Wu, Y., Zhang, Y., Tan, Y., 2019. A three-step strategy for decoupling economic growth from carbon emission: empirical evidences from 133 countries. Sci. Total Environ. 646, 524–543.
Solaymani, S., 2019. CO_2 emissions patterns in 7 top carbon emitter economies: the case of transport sector. Energy 168, 989–1001.
Song, Y., Sun, J., Zhang, M., Su, B., 2020. Using the Tapio-Z decoupling model to evaluate the decoupling status of China's CO_2 emissions at provincial level and its dynamic trend. Struct. Change Econ. D 52, 120–129.

Song, Y., Zhang, M., 2017. Using a new decoupling indicator (ZM decoupling indicator) to study the relationship between the economic growth and energy consumption in China. Nat. Hazards 88, 1013–1022.
Song, Y., Zhang, M., 2019. Research on the gravity shift and mitigation potential of Asia's carbon dioxide emissions. Energy 170, 31–39.
Song, Y., Zhang, M., Zhou, M., 2019. Study on the decoupling relationship between CO_2 emissions and economic development based on two-dimensional decoupling theory: a case between China and the United States. Ecol. Indic. 102, 230–236.
Ssali, M.W., Du, J., Mensah, I.A., Hongo, D.O., 2019. Investigating the nexus among environmental pollution, economic growth, energy use, and foreign direct investment in 6 selected sub-Saharan African countries. Environ. Sci. Pollut. Res. Int. 26, 11245–11260.
Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transp. Policy 12, 137–151.
Tenaw, D, 2020. Is Carbon Decoupling Likely to Happen in Africa: Evidence From Production and Consumption-based Carbon Emissions. Available: https://assets.researchsquare.com/files/rs-37926/v1_stamped.pdf. Accessed June 30, 2020.
Tian, X., Chang, M., Shi, F., Tanikawa, H., 2014. How does industrial structure change impact carbon dioxide emissions? A comparative analysis focusing on nine provincial regions in China. Environ. Sci. Policy 37, 243–254.
Tu, C., Li, F., 2017. Responses of greenhouse gas fluxes to experimental warming in wheat season under conventional tillage and no-tillage fields. J. Environ. Sci. 54, 314–327.
Tyson, J.E., 2017. Zimbabwe: a roadmap for economic transformation. Support. Econ. Transform.. Available: https://set.odi.org/zimbabwe-roadmap-economic-transformation . Accessed April 5, 2020.
UN (United Nations), 2015. Population 2030. Demographic Challenges and Opportunities for Sustainable Development Planning (ST/ESA/SER.A/389). Available: https://www.un.org/en/development/desa/population/publications/pdf/trends/Population2030.pdf. Accessed March 26, 2020.
Wang, F., Wang, C., Chen, J., Li, Z., Li, L., 2019. Examining the determinants of energy-related carbon emissions in Central Asia: country-level LMDI and EKC analysis during different phases. Environ. Dev. Sustain. 019-00545-8.
Wang, W., Li, M., Zhang, M., 2017a. Study on the changes of the decoupling indicator between energy-related CO_2 emission and GDP in China. Energy 128, 11–18.
Wang, W., Liu, X., Zhang, M., Song, X., 2014. Using a new generalized LMDI method to analyze China's energy consumption. Energy 67, 617–622.
Wang, Y., Xie, T., Yang, S., 2017b. Carbon emission and its decoupling research of transportation in Jiangsu Province. J. Clean. Prod. 142, 907–914.
Weforum, 2019. The Global Risks Report 2019 14th Edition. African Fastest-growing Cities are the Most Vulnerable to Climate Change Globally. The World Economic Forum Available: https://www.weforum.org/agenda/2018/12/africa-s-fastest-growing-cities-are-the-most-vulnerable-to-climate-change-globally .
World Bank, 2019. World Bank National Accounts Data, and OECD National Accounts Data Files. The World Bank Data. Accessed April 27, 2020.
Yang, D., Liu, B., Ma, W., Guo, Q, Li, F., Yang, D., 2017a. Sectoral energy-carbon nexus and low-carbon policy alternatives: a case study of Ningbo. China. J. Clean. Prod. 156, 480–490.
Yang, Y., Liu, J., Zhang, Y., 2017b. An analysis of the implications of China's urbanization policy for economic growth and energy consumption. J. Clean. Prod. 161, 1251–1262.
Yao, C., Feng, K., Hubacek, K., 2015. Driving forces of CO_2 emissions in the G20 countries: an index decomposition analysis from 1971 to 2010. Ecol. Inform. 26, 93–100.
Yeh, J.-C., Liao, C.-H., 2017. Impact of population and economic growth on carbon emissions in Taiwan using an analytic tool STIRPAT. Sustain. Environ. Res. 27, 41–48.
Zhang, G., Zhang, N., Liao, W., 2018. How do population and land urbanization affect CO_2 emissions under gravity center change? A spatial econometric analysis. J. Clean. Prod. 202, 510–523.
Zhang, J., Fan, Z., Chen, Y., Gao, J., Liu, W., 2020. Decomposition and decoupling analysis of carbon dioxide emissions from economic growth in the context of China and the ASEAN countries. Sci. Total Environ. 714, 136649.
Zhang, M., Dai, S., Song, Y., 2015a. Decomposition analysis of energy-related CO_2 emissions in South Africa. J. Energy South Afr. 26 (1), 67–73.
Zhang, M., Song, Y., Su, B., Sun, X., 2015b. Decomposing the decoupling indicator between the economic growth and energy consumption in China. Energ. Effic. 8, 1231–1239.
Zhang, Z., 2000. Decoupling China's carbon emissions increase from economic growth: an economic analysis and policy implications. World Dev. 28, 739–752.