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Drivers of the water–energy–food nexus in Cameroon and implications for sustainable development

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Abstract
Concerted efforts towards integrating water, energy, food, and ecosystem services remain critical for managing natural resources and building resilience in developing economies. This study examines the interdependent relationships between the water–energy–food (WEF) nexus, focusing on factors that interplay to drive resource security and sustainability in Cameroon. Using national-level data from 2000 to 2021, we employ the simultaneous equation model (SEM) with structural equations and use the 2SLS estimator with instrument variables (IV) to evaluate the level of interaction between the nexus components. The results indicate that urban population growth significantly increases water consumption by 13.17%. Industrial and economic growth increase energy consumption by 0.39%, while an increase in energy supply per capita raises food production by 2.81%. System analysis indicates that population growth has a holistic impact on all subsystems, with significant negative effects on the water subsystem. Policy and Institutions for sustainable development and Cultivated Area, also generated holistic effects with positive impacts on the food subsystem. Water-use efficiency also forms a key nexus point, positively increasing food production and reducing water consumption. A major feedback loop occurs where an increase in food production leads to a decrease in water resources (−0.82%), resulting in a reduction in energy production (−0.51%) and a potential decline in food production (−4.51%). This study enhances nexus modeling in developing economies, allowing for resource optimization through effective cultivated area management, water-use efficiency, and institutional advancement. A paradigm change towards effective WEF nexus integration is essential for maintaining resource security and high-level human development with minimal environmental impact in developing countries.

Keywords Holistic impact, Paradigm shift, Resource security, Structural equation modeling, Water–energy–food nexus

1 Introduction

Water, energy, and food systems are intricately connected and interlinked with the ecological environment in complex ways. Throughout history, the intricate interplay between these core components has been pivotal in shaping the rise and fall of world civilizations [43]. Economic growth and development of nations across the globe largely depend on the availability and accessibility of water, energy, and food resources, along with healthy ecosystems that underpin their functioning. While projections indicate that world water, energy, and food demands will effectively double by 2050 [4, 74], the supply side faces challenges of rapid population growth, a rising middle-income class that follows Bennett's law,[1] unsustainable urbanization, climate change, and resource scarcity [10, 26, 38].

Developing economies are expanding rapidly, and human activities are imposing growing pressures on ecological systems. When the human economy develops to a certain extent, the relationship between water, energy, food, and their interaction with the ecosystem grows stronger [78]. Drivers may intensify existing linkages and produce unintended consequences [4], thus creating a complex water–energy–food–ecosystem (WEFE) nexus with externalities and feedback loops that require careful understanding. Addressing the challenges presented by these interconnections, particularly ensuring sustainable resource use, tackling trade-offs between competing demands, and mitigating negative externalities within the nexus system, is unprecedented and particularly urgent for developing nations like Cameroon.

Cameroon is remarkably blessed with abundant WEFE-related natural resources, making it one of the most resource-endowed regions in Sub-Saharan Africa. located on the Gulf of Guinea along the west coast of Central Africa, Cameroon is renowned for its rich ecological diversity [14, 17], often referred to as Africa in Miniature.[2] Cameroon boasts significant water resources in both surface and groundwater reservoirs and experiences substantial annual rainfall, particularly in the southern regions [16, 58]. Huge potential exists for renewable energy supplies (hydro, biomass, solar, and wind), particularly in the Northern and Eastern regions [44, 59]. Hydropower potentials are mostly harnessed for electricity in the country. Agriculture forms the backbone of the economy, employing over 70% of the workforce and contributing about 44% to gross domestic product [63]. Cash crops, including cotton, cocoa, coffee, banana, rubber, and palm oil, contribute over 30% of export revenue, while plantains, cassava, corn, sorghum, rice, etc. are mostly produced for domestic consumption [5]. Food production varies by agroecological zones,[3] with animal husbandry practiced throughout the country, particularly in the northern region [57].

Despite Cameroon's endowment of WEFE resources and abundance, the country continues to face significant challenges in achieving sustainable development. There are persistent gaps between resource availability and accessibility, leading to widespread water scarcity, energy poverty, and food insecurity. This paradox highlights systemic inefficiencies in resource management, which are exacerbated by sectoral silos,[4] weak policy integration, and a lack of coordinated governance within the WEFE nexus. This fragmented approach often results in suboptimal resource allocation, environmental degradation,

[1] "Bennett's law"—As income rises, the per capita consumption of starchy food staples falls.

[2] "Africa in Miniature"- the nickname for Cameroon derived from the fact that Cameroon embodies various aspects of African culture, geography, and biodiversity within its borders, representing a miniature version of the entire African continent. This includes different ethnic groups, languages, landscapes, and wildlife.

[3] Cameroon can be divided into five major agroecological zones (Bimodal Humid Forest, Mono-modal Humid, Western Highlands, High Guinea Savanna, and Sudano-Sahelian) distinguishable by dominant physical, climatic, and vegetative features.

[4] Resources are managed independently due to sectorial interests enforced by various ministries liable for sustainability.

and missed opportunities for synergies that could enhance sustainability. While the WEFE nexus framework has gained global recognition as a holistic approach to sustainable resource management, few studies have empirically examined its complex feedback loops and trade-offs in developing economies. To the best of our knowledge, no such research has been undertaken in the context of Cameroon.

This study provides the first empirical assessment exploring how the water, energy, and food systems interact, creating complex feedback loops and trade-offs within the WEFE nexus of Cameroon. This is particularly aimed at identifying critical factors that interplay to drive resource security and sustainable development in Cameroon. Specifically, the study integrates socio-economic and ecological theories to examine the internal mechanisms that drive the nexus performance and analyze the extent to which the interconnections and interactions between the water, energy, and food systems contribute to WEFE resource security. We then examine the elasticities between the nexus components to determine key areas where interventions and improvements are most needed. This is aimed at deriving actionable strategies and policy recommendations that will enhance the performance of the WEFE nexus toward achieving resource security and sustainable growth in Cameroon, while contributing to meet Cameroon's Agenda 2035 for emergence and Africa Agenda 2063 for internal growth and sustainable development in Africa [8, 15]. The rest of the paper discusses the WEFE nexus concept with an empirical review of the literature (Sect. 2), specifies the data, and introduces the structural equation model used in the study in Sect. 3. Section 4 presents and discusses the empirical results, considering both linear and systems perspectives. Conclusions and recommendations follow in Sect. 5.

2 The concept of water–energy–food–ecosystem (WEFE) nexus

The WEFE nexus is a holistic framework that stems from the understanding that water, energy, food, and the environment are intricately interconnected [27, 32, 48]. It is a multifaceted concept, illuminated from various levels and perspectives. At the national level, the WEFE nexus addresses the complex relationships between water resources, energy production, food security, and environmental sustainability, guiding policy formulation and resource management strategies. This intricate interconnectedness recognizes that elements of the WEFE nexus largely depend on each other such that, 'water' is critical for food production and energy generation; 'energy' is crucial for extraction, treatment, and distribution of water and food production; 'food' is vital for anaerobic digestion and bioenergy production (Fig. 1). Actions, changes, or disruptions in one sector can create ripple effects throughout the system thus, affecting the availability, accessibility, and affordability of resources. The effectiveness of each process hinges on the health and resilience of the underlying ecosystem (Fig. 1).

The water–energy–food (WEF) nexus emerged at the 2011 Bonn conference as a conceptual framework for sustainable development and has grown to encompass external factors such as climate [65], land [9], economy [81], and the environment. Research in WEF nexus studies has advanced with increasing interest in ecosystem connections and has become particularly salient in the context of global sustainable development and poverty alleviation in vulnerable communities [1, 47, 73]. Sustainable development is often seen as the practice that meets the needs of the present population without compromising the ability of future generations to meet their own needs [55, 73]. This

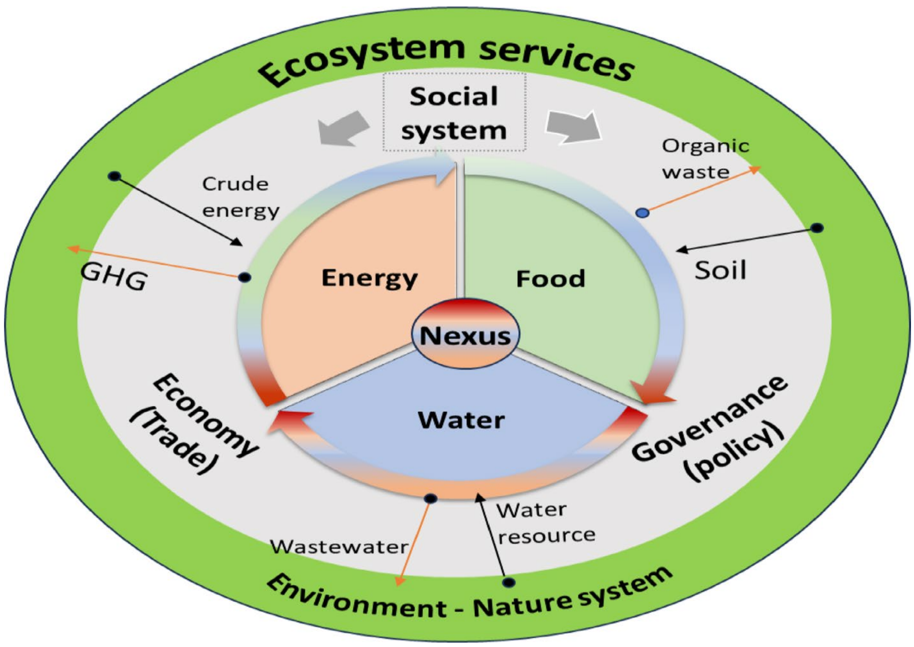

Fig. 1 Conceptual framework of water–energy–food–ecosystem nexus—Nature/Social base interaction

concept gained global attention in the 1970s when nations began recognizing the urgent need to align economic growth with environmental protection and social equity [54]. Concerns regarding global environmental change and sustainable development became pressing, necessitating improved modeling techniques for nature-society dynamics.

Cities and communities around the globe are not only 'resource islands', but concentrated areas of production, consumption, and waste disposal [65]. The scale of operations intensifies or reduces the impact on natural resources in the nation, making sustainable strategic management crucial for environmental protection, economic development, and social well-being. Garcia and You [24] argue that system engineering and resource management should focus on supply, consumption, and waste disposal processes. These processes have so far followed linear programming, resulting in unsustainable use of resources. According to Hysa et al. [37], the circular economy approach can enhance resource management, closing resource loops, reducing waste generation, and promoting resource reuse and recycling (Fig. 2).

The WEFE nexus approach emphasizes the need for integrated solutions to sustainable management and efficient use of WEFE resources, identifying, evaluating, and implementing synergies, trade-offs, and benefits [61, 68]. Many researchers agree that development agendas in places around the world are most likely to fail unless the complexities of the interlinkages between water, energy, food, and ecosystems are addressed [11, 23]. The challenges observed in implementing the Integrated Natural Resources Management (INRM) and the Integrated Water Resources Management (IWRM) programs to meet the Millennium Development Goals (MDGs) have induced different studies to argue that, another call for "integration" is questionable [68, 76]. Nevertheless, the Nexus framework has gained popularity in policy and development circles worldwide [64, 68]. Many of these studies widely establish that countries in Sub-Saharan Africa can largely benefit from adopting the nexus approach [10, 39, 69]. Improving resource use

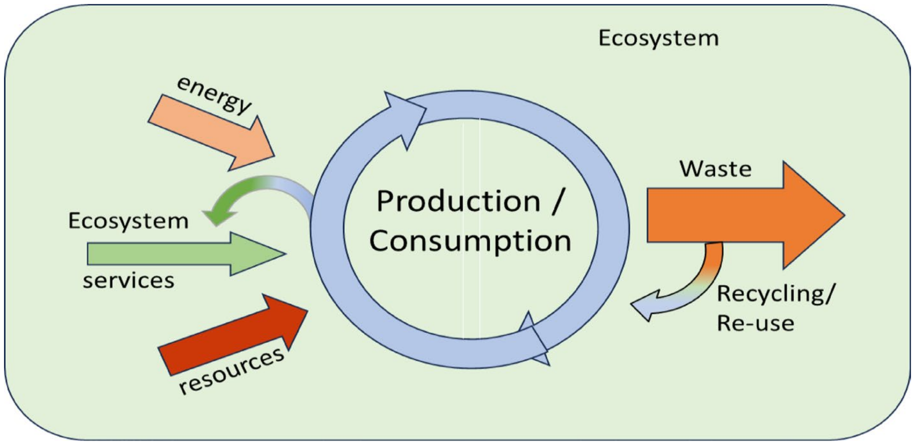

Fig. 2 Sustainable resource consumption in a circular economy

efficiency, climate adaptation, and building resilience in subsystems is crucial to improving livelihoods [6, 49].

The importance of exploring interactions and quantifying relationships in the WEFE nexus is widely acknowledged in nexus studies [22, 71]. Current studies in the WEFE nexus primarily focus on supply aspects, aiming to optimize local production systems and integrate available renewable resources [13, 79]. Others examine demand-side dynamics, investigating how consumption patterns influence resource use in the WEFE nexus. Hao et al. [30] analyze consumption based on material flow input–output processes, proposing a generic integrated intensity index for the WEF material nexus. Other studies assess human behaviors that could alter WEFE consumption patterns with a rebound effect [3]. However, calculations of supply–demand interaction and causal impacts are still lacking, especially regarding the interactions between water consumption, energy consumption, and food production. Integrated WEFE governance, characterized by sectoral silos and weak policy coherence, hinders sustainable resource management. This study builds on these findings by analyzing the dynamic interactions, feedback loops, and elasticities within Cameroon's WEFE nexus to inform actionable policy interventions.

3 Data and method

3.1 Data collection

Considering the dynamic nature of resources within the WEFE nexus framework, it is crucial to explore all available data sources for reliable information on the WEFE nexus in Cameroon. Using country reports and data aggregated in open data sources (World Bank Report, FAO-AQUASTAT, and IEA) and an up-to-date literature review of issues surrounding the WEFE in Cameroon, we considered annual data from 2000 to 2021, collecting relevant information on land use and water resources, electricity access and consumption, economic well-being, and the environmental statutory scrawniness to build up the panel data for this study. The period under review is considered rational given that the last two decades mark significant phases in Cameroon's economic growth. After the Structural Adjustment Program (SAP)[5] ended in Cameroon in 1999, the country

[5] SAP—Structural Adjustment Program in Cameroon was introduced in 1989 and ended in 2000. This program was typically designed by the International Monetary Fund (IMF) and the World Bank to address economic challenges such as high levels of debt, inflation, and fiscal imbalances. The program included key reforms such as; (i) restructur-

witnessed a steady increase in economic growth driven by developments in the oil and gas, agriculture, and service industries. Sustainable resource management became a critical concern during this time, and the government adopted “Cameroon Vision 2035,” aimed at balancing economic exploitation with environmental conservation and social responsibility to achieve “Emergence” by 2035. The period under review covers the first phase of Vision 2035 (i.e., 2010–2019), which includes developing the vision, setting priorities, engaging stakeholders, and policy reforms. Variable selection was based on their direct link to drivers of resource security—Availability, Accessibility, Self-sufficiency, and Productivity—as well as key aspects of sustainability, including increasing resource efficiency, accelerating access for all, and investment in ecological conservation. The variables are specified in Table 1.

3.2 The multi-equation modeling technique

The empirical model developed in this study is based on the general specification of a production function. Following the Environmental Kuznets Curve (EKC) hypothesis of Grossman and Krueger [29], it can be hypothesized that environmental resource security and sustainable development in Cameroon are directly related to the complex integration of the WEFE nexus components and the optimal combination of factors driving its performance. Generally, the WEFE nexus performance model for sustainability can be specified as follows.

$$\mathrm{Y_t} = \mathrm{f}\left(\mathrm{W_t},\ \mathrm{E_t},\ \mathrm{F_t},\ \mathrm{E_t}\right). \tag{1}$$

where: $\mathrm{Y_t}$ is the output (nexus performance) and $\mathrm{W_t}$, $\mathrm{E_t}$, $\mathrm{F_t}$, and $\mathrm{E_t}$ represent the independent variables for water availability, energy efficiency and productivity, food production and self-sufficiency, and ecosystem service at time t.

The linear relationship forms a system of equations, representing the system’s structure and behavior in time and space. When one or two “explanatory” variables in the equation set are jointly determined with the “dependent” variable, typically through an equilibrium mechanism, simultaneity occurs, to form the simultaneous equations model (SEM) [77]. The SEM simultaneously evaluates the system of equations to determine the values of the endogenous variables. It is commonly used in different dimensions of economic studies, describing interactions and identifying potential synergistic effects amongst agents [18, 33]. The SEM is not only valuable for exploring synergies between WEFE components and their driving factors, but far more useful in differentiating direct effects from factor variations and indirect (induced) effects arising from system feedback loops [35].

To analyze synergies and trade-offs in this study, we focus on linear models in SEM [28, 82], which can be expressed analytically as follows;

$$\mathrm{Y_t}\Gamma + \beta \mathrm{X_t} + \mu_t = 0;\ t = 1, 2, \ldots, \mathrm{T}. \tag{2}$$

where: Y and X are vectors of the dependent and independent variables (Table 1) in time t, respectively. Γ is a matrix of interrelated effects amongst dependent variables (the

ing of public finances over the medium term; (ii) restructuring and rehabilitation of the public enterprise and banking sectors; (iii) in agriculture, financial stabilization of the marketing structures for the principal export crop; (iv) deregulation of internal commerce to lower the domestic cost structure; (v) improvement of incentives for petroleum exploration and promotion; (vi) reorientation of the policies in the forestry, health, and education sectors; and (vii) establishment of specific action programs to reduce the social cost of adjustment.

Table 1 Variable measurements and specifications

Variables	Specifications	Driving factors	Data source
TRWRc	Total renewable water resource/capita (m3/inhab/capita)	Water security and availability	FAO-AQUA-STAT
W_C	Total water withdrawal/capita agriculture, industrial, and domestic consumption (m3/inhab/year)	Water demand and management processes	FAO-AQUA-STAT
F_P	Food production index (2014–2016 = 100); food crops produced	Food processes and management	World Bank
GDP	Gross domestic product/capita (current US$)	Economic development and growth	World Bank Report
Edu	Education: Adult literacy rate (% of people ages 15 and above)	Enhance knowledge and awareness of environmental issues,	World Bank
CY	Cereal Crop yield (kilograms/hectare of harvested land)	Food security and efficiency	World Bank report
WUE	Water use efficiency: grain produced/unit of water used (US$/m3)	Resource conservation	AQUASTAT
DC	Dam capacity: water stored in dams (m3/inhab/capita)	water storage and water management	AQUASTAT
TP	Total population	Resource use and waste production	World Bank
TPASDW	Total population with access to safe drinking water	Environmental sustainability, ensuring water quality and availability	FAO-AQUA-STAT
UP	Urban population (000 inhabitants)	Urbanization, driving resource demand and availability	AQUASTAT
RP	Rural population (000 inhabitants)	Food production and agriculture	FAO-AQUA-STAT
TES	Total energy supply—fossil fuels and renewables produced (TJ)	Industrial growth and environmental degradation	IEA
TESc	Total energy supply/capita	Energy access and equity	IEA
E_C	Total energy final consumption (TJ)	Energy use and management	IEA
REC	Renewable Energy consumption; Share in final energy consumption (%)	Energy diversification and sustainability	IEA
B&W	Biofuels and waste produced (TJ)	Energy production and diversification	IEA
GHG	Greenhouse gas emission from fuel combustion (T)	environmental degradation	IEA
ACE	Access to electricity; population with access to an electricity supply	Energy Access and Social Equity	World Bank
CA	Cultivated area; Arable land + permanent crops (000/ha)	Food production and food security	FAO-AQUA-STAT
Fetz	Fertilizer consumption (kilograms/hectare of arable land)	Environmental degradation and land use	World Bank
CPIA	Policy and institutions for environmental sustainability rating (1 = low to 6 = high)	Promote sustainability in resource use	World Bank

covariate matrix for natural and social subsystems that interact to drive system performance). β represents the coefficient of interaction, while μ is the vector of error terms.

Since ecosystems underpin the functioning of the water, energy, and food subsystems, providing ecosystem services that regulate and support the system structure, three behavioral equations can be formulated for water, energy, and food production to model the WEFE nexus structure [25].

$$\begin{cases} W_t = f1\left(E_t, F_t, X_{wt}\right) & (3a) \\ E_t = f2\left(W_t, F_t, X_{Et}\right) & (3b) \\ F_t = f3\left(E_t, W_t, X_{Ft}\right) & (3c) \end{cases} \quad (3)$$

where: W_t, E_t, and F_t represent the water, energy, and food subsystem equations, respectively, and X_{Wt}, X_{Et}, and X_{Ft} represent the driving factors (exogenous variables) for water, energy, and food production, respectively, at time t.

Considering that water withdrawal for domestic, agricultural, and industrial use always equals water demand, Total freshwater withdrawal in Cameroon was therefore selected as the Y-variable for water consumption (W_C) in the Eq. (3a). Total Energy Final Consumption represents the country's total energy consumption (E_C) and is considered the Y-variable for the energy Eq. (3b). The Food Production index, which measures the aggregate agricultural output of the country (F_P), is considered the Y-variable for the food Eq. (3c). Based on the above explanation, the vector-Y can be defined by (W_C, E_C, F_P) such that: -

$$\begin{cases} \ln(W\_C) = \alpha_0 + \alpha_1 \ln(F\_P) + \alpha_2 \ln(E\_C) + \alpha \ln X_w + \mu_w \\ \ln(E\_C) = \beta_0 + \beta_1 \ln(W\_C) + \beta_2 \ln(F\_P) + \beta \ln X_E + \mu_E \\ \ln(F\_P) = \gamma_0 + \gamma_1 \ln(E\_C) + \gamma_2 \ln(W\_C) + \gamma \ln X_F + \mu_F \end{cases} \tag{4}$$

where: X_w, X_E, X_F are vectors of exogenous variables for each subsystem. i.e.

$$Xw = TP + CPIA + TPASDW + WUE + DC + CA + UP + REC + RP + GDP + Edu + ACE + CY.$$

$$X_E = TP + CPIA + TPASDW + WUE + CA + UP + REC + TES + BW + Edu + DC + TGHG + CY.$$

$$X_F = TP + CPIA + WUE + DC + CA + BW + REC + TESc + Fetz + CY + TRWR + GDP + Edu + ACE + TGHG)$$

The Generalized Moments Method (GMM) and Two Stage Least Squares (2SLS) or Three Stage Least Squares (3SLS) methods with instrumental variables (IV) are commonly used to estimate systems of equations. Given that the 2SLS estimation method is simple and widely used in system modeling, this paper employs the 2SLS estimation technique and the IV approach (equation-by-equation technique) suggested by Khatib [41] to measure the magnitude of interaction and performance of the system. The explanatory variables defined in (X_W, X_E, X_F) are instruments for themselves selected to meet equation requirements, such as multicollinearity. Effective instrumental variables are formed with a vector of predetermined variables, and the ordinary least squares (OLS) is employed to estimate the IV as an estimator of the endogenous variables. The estimated endogenous variables (uncorrelated to the error terms) are then substituted for the endogenous variables, and the OLS is conducted again to obtain the coefficients and interrelated effects [46]. Estimation was performed in STATA using robust standard errors to control for heteroscedasticity.

4 Results and discussion

Data for individual variables was compiled with a log transformation to normalize the variables. The Jarque–Bera test for normality was conducted, and the results indicate that the data set is normally distributed. Summary statistics and distribution are presented in Table 2. The first-stage least squares estimation results are presented in Appendix Table 4. The F-statistic is statistically significant ($p = 0.000$), indicating model fitness and a collective significance of the explanatory variable in explaining variation in the model. W_C, E_C, and F_P in Eq. (4) are selected as endogenous variables. GDP, education, access to electricity, and crop yield are specified as predetermined variables in the water equation. Education, dam capacity, greenhouse gas emissions, and crop yield are

Table 2 Summary and descriptive statistics of variables

Variables	Mean	Std. dev	Min	Max
year	2010.5	6.494	2000	2021
ln(TRWR)	9.529	0.175	9.251	9.812
ln(W_C)	3.953	0.152	3.714	4.132
ln(F_P)	4.326	0.311	3.819	4.677
ln(GDP)	7.153	0.265	6.551	7.411
ln(Edu)	4.265	0.046	4.22	4.357
ln(CY)	7.457	0.159	7.354	8.152
ln(WUE)	2.916	0.241	2.564	3.295
ln(DC)	6.631	0.175	6.353	6.914
ln(TP)	16.822	0.184	16.53	17.119
ln(TPASDW)	16.478	0.252	16.047	16.839
ln(UP)	16.162	0.261	15.753	16.574
ln(RP)	16.089	0.102	15.913	16.251
ln(TES)	12.698	0.171	12.491	12.98
ln(TESc)	8.521	0.109	8.407	8.718
ln(E_C)	12.54	0.129	12.319	12.774
ln(REC)	10.61	0.36	10.073	11.11
ln(BW)	12.364	0.169	12.079	12.64
ln(GHG)	2.278	0.174	2.001	2.549
ln(ACE)	16.19	0.319	15.638	16.694
ln(CA)	15.83	0.037	15.784	15.863
ln(Fetz)	2.306	0.224	1.881	2.609
ln(CPIA)	1.124	0.106	1	1.386
Obs (N)	22			
Jarque–Bera test		0.334	Chi (2).8463	

also selected for the energy equation, while GDP, education, access to electricity, and greenhouse gas emissions are specified for the food equation. Each equation takes only two endogenous variables and has more than 3 different predetermined variables, which may be considered over-identified according to the order and rank conditions. We therefore employ the Sargan test to check the overidentifying restrictions and validity of the instrument variables. The results show that p-values for all 3 equations are statistically insignificant ($p > 0.1$), indicating that all IVs are uncorrelated with the error term and therefore valid instruments. Wu-Hausman test for endogeneity also reveals insignificant p-values, indicating that the model is endogenous and consistent with reliable estimators (Table 3).

4.1 Empirical results

The empirical estimation and results of factors driving the WEF nexus performance in Cameroon are presented in Table 3. The coefficients obtained indicate that a 1% increase or decrease in the explanatory variable in one equation will invariably lead to an α% rise or decrease in the endogenous variable, assuming all other factors remain constant. Based on changes in the explanatory variable, a positive coefficient indicates a percentage increase in the endogenous variable, while a negative coefficients indicate a percentage decrease. A linear and systems approach is employed to interpret the results and effectively underscore their relevance.

Table 3 Estimated drivers of the water–energy–food nexus (2SLS estimation)

Explanatory	Endogenous		
	Water subsystem ln(W_C)	**Energy subsystem ln(E_C)**	**Food subsystem ln(F_P)**
_constant	14.83**	7.599	68.19*
	(− 2.04)	(− 0.78)	(− 1.74)
ln(F_P)	− 0.825***	− 0.435***	
	(− 3.57)	(− 2.87)	
ln(E_C)	− 0.098		− 4.561***
	(− 1.33)		(− 8.23)
ln(W_C)		− 0.512*	1.143**
		(− 1.86)	(− 2.42)
ln(TP)	− 24.90***	− 1.705**	− 3.195**
	(− 3.71)	(− 2.12)	(− 2.31)
ln(CPIA)	0.124**	0.160***	0.356***
	(− 2.57)	(− 6.52)	(− 6.68)
ln(TPASDW)	0.858*	1.069**	
	(− 1.96)	(− 2.08)	
ln(WUE)	− 1.002***	0.0835	2.271***
	(− 4.93)	(− 0.33)	(− 4.67)
ln(DC)	− 0.0674		− 2.390***
	(− 0.58)		(− 4.93)
ln(CA)	− 0.565**	0.422*	2.508***
	(− 2.22)	(− 1.76)	(− 6.03)
ln(UP)	13.17***	0.216	
	(− 3.42)	(− 0.56)	
ln(REC)	0.158***	− 0.0293	− 0.206***
	(− 3.03)	(− 0.81)	(− 3.44)
ln(RP)	12.20***		
	(− 3.51)		
ln(B&W)		0.371***	1.626***
		(− 4.85)	(− 5.6)
ln(TES)		0.397***	
		(− 4.12)	
ln(TESc)			2.813***
			(− 5.74)
ln(Fetz)			− 0.0958**
			(− 2.19)
ln(CY)			0.165***
			(− 3.44)
ln(TRWR)			− 3.274**
			(− 2.16)
N	22	22	22
adj. R-sq	0.993	0.992	0.991
Sargan test	1.90233	2.78271	3.65141
	(p = 0.3863)	(p = 0.2487)	(p = 0.1611)
Wu-Hausman	2.96441	1.05156	2.98708
	(p = 0.1088)	(p = 0.3931)	(p = 0.1258)

t-statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ (significant at 10%, 5% & 1%)

4.1.1 Linear perspective

The linear approach focuses on individual equations, identifying key drivers and elucidating mechanisms for interaction—the ecological footprint of various factors in each subsystem.

4.1.1.1 Linear interactions in the water subsystem In the "water subsystem," the results indicate that a 1% increase in urban population (UP) leads to a significant 13.17% increase in water consumption. This result highlights the challenges posed by rapid urbanization in Cameroon, which is exacerbated by the socio-political crisis in the Northern, Northwest, and Southwestern regions of the country. Kookana et al. [45] argue that 60 to 90% of the urban population in emerging economies relies on septic tanks, which are more water-demanding. A unit increase in the rural population (RP) also results in a significant increase in water consumption by 12.2%. Given that rural communities in Cameroon are typically agrarian, this result underlines their impact on water withdrawal for irrigation, livestock, and crop cultivation as the population increases, which aligns with the findings of Huang et al. [36]. However, contrary to expectations, the results indicate that an increase in total population (TP) significantly decreases water consumption by 24.90%. The negative effect is attributed to Cameroon's declining per capita water consumption, resulting from scarcity and limited water supply infrastructure in many areas [56, 75]. Water-use efficiency (WUE) is also significantly negative in the water subsystem, such that a percentage increase in WUE leads to a 1.002% significant decrease in water consumption. Tagny et al. [72] highlighted that water use efficiency through soil mulching reduced soil water evaporation, promoting water saving by 402.3 mm in West Cameroon. Food production (F_P) is also negative and significantly decreases water consumption by 0.82%. In practice, agriculture in Cameroon is primarily rain-fed, with rainfall lasting 7 to 8 months every year. Local farmers have developed techniques for rainwater harvesting, including rooftop collection for drinking, cooking, and cleaning, as well as roadside runoff collection for irrigation [53]. Many farmers have adopted drought-resistant crops such as the 'New Rice for Africa' for cultivation [80]. These techniques significantly reduce dependence on water resources [62]. Renewable energy consumption (REC) is positive in the water subsystem, indicating that a unit increase in REC leads to a 0.15% increase in water consumption. Given that hydropower is the primary source of electricity in Cameroon [7], a rising energy consumption leads to an increase in water demand for power generation. Al-Mulali et al. [2] also argue that renewable energy consumption increases water and land use inefficiency. Increasing renewable energy consumption therefore increases water abstraction and waste production, with increasing effects on the ecological footprint.

4.1.1.2 Linear interactions in the energy subsystem The findings in the energy subsystem indicate that a percentage increase in the total population with access to drinking water leads to a significant increase in energy consumption (1.06%). This significant impact stems from the growing water demand involving energy-intensive processes for extraction and distribution. As a proxy for industrial growth and economic activities, total energy supply also indicated that a unit increase in industrial growth leads to a significant 0.39% increase in energy consumption. This positive relationship underscores the growing demand for energy as the economy expands. Similarly, a percentage increase in biofuels and waste production leads to a significant 0.37% increase in energy consumption. This significant impact underscores the importance of biofuels and waste in Cameroon's energy mix, serving as the largest energy source, especially in rural areas where access to conventional energy is limited [52, 60]. A percentage increase in cultivated area leads to a 0.42% increase in energy consumption. Food production increment in Cameroon is usually achieved through agricultural extensification, often leading to deforestation. This process results in greater land degradation and biodiversity loss [21]. To maintain crop yield, large amounts of synthetic chemical fertilizers and pesticides are applied, thus increasing energy consumption.

Total population and food production have negative effects on energy consumption. A percentage increase in TP significantly decreases energy consumption by 1.7%. A growing population generally increases energy demand [42]. However, the negative relationship in this study is attributed to the declining per capita energy consumption in Cameroon, which suggests that as the population grows, the average energy available for consumption per person decreases. This trend is due to limited energy supply, economic constraints, and energy access challenges. An increase in food production also significantly reduces energy available for consumption by 0.43%. Food production requires substantial energy inputs for various planting, harvesting, storing, and transportation processes. However, agriculture in Cameroon is more rudimentary, rainfed, and labor-intensive, with limited infrastructure and lacking modern techniques for farming [12, 19].

4.1.1.3 Linear interactions in the food subsystem In the food subsystem, a unit increase in water consumption significantly leads to a 1.1% increase in food production. Water use efficiency also increases food production by 2.27%. Cameroon also faces significant challenges related to water scarcity, particularly in the northern Sahel region during the dry season. Increasing adaptation through crop selection, rotational farming techniques, and rainwater harvesting can ensure an adequate water supply and efficiency in crop growth. This is consistent with the findings of Hatfield and Dold [31]. A unit increase in policy and institutions for sustainability rating (CPIA) also significantly increases food production by 0.35%, underscoring the critical importance of strong policy and institutional frameworks in promoting sustainable food production in Cameroon.

The results also present that a percentage increase in energy consumption (E_C) leads to a significant 4.56% decrease in food production. This result may be counterfactual, but practically, Cameroon relies heavily on hydropower and biomass for its energy supply. Increasing energy consumption will require expanding hydropower infrastructure and fuelwood production. These activities often compete with agricultural land use, reducing available land for food production [50].

Total population growth also significantly reduces food production by 3.19%. This follows that population growth exerts significant pressure on agricultural land and existing infrastructures, which increases land degradation and reduces crop yields [51]. Total renewable water resources per capita also show significant negative impacts on food production (3.27%). This counterfactual result may reflect the combined effects of population-driven water scarcity and inefficiencies in water distribution that exist in Cameroon. Dam capacity also significantly decreases food production by 2.39%. Over 70% of the electricity consumed in Cameroon is generated from hydropower [7]. Increasing the capacity of dams for hydropower affects water flow qualities and quantities, reducing biodiversity and disrupting essential ecosystem functioning, which adversely affects crop yield [2, 66].

4.1.2 System perspective

The system perspective helps identify nexus points (leverage points for intervention), feedback loops, and a balanced state within the system. Total population, Cultivated Area, and Policy and Institutions for Environmental Sustainability are three entry points with significant effects on all subsystems. Population growth exerts a holistic impact with negative effects on Water consumption (− 24.95%), Energy Consumption (− 1.705%), and Food production (− 3.19%). This implies that processes in water supply to meet demand dominate the WEF nexus and require careful management for sustainability, supported by Huang et al. [35]. The Cultivated Area also exerts holistic impacts with a negative effect on Water consumption (− 0.56%) and a positive effect on Energy (0.42%) and Food production (2.51%). This reveals that interactions at this entry point are primarily driven by production processes within the food subsystem. Increasing cultivated area thus increases food security, but raises energy consumption and decreases water resources, as supported by Smolenaars et al. [70]. Policy and institutions for environmental sustainability (CPIA) also have a holistic impact on the WEF nexus, positively affecting the W_C (0.12%), E_C (0.17%), and F_P (0.3%) subsystems. The CPIA forms a critical entry point, with the food subsystem dominating the network. Effective policies can facilitate the collaboration of stakeholders, ensuring that the interdependencies between resources are recognized and addressed. Institutions are necessary for enforcing regulations, guiding investments, fostering innovation, balancing competing demands, and optimizing resource use.

In the Water–Energy (WE) nexus, the total population with access to safe drinking water (TPASDW) exhibits the only nexus entry point connecting the water and energy subsystems. TPASDW presents a positive elasticity of 0.85% on water consumption and a 1.06% elasticity on energy consumption. The energy subsystem, therefore, dominates interactions within the nexus. An increasing number of people with access to safe drinking water would require substantial energy to extract, treat, and distribute water to meet the growing demand [75]. Enhancing nexus management by improving access to drinking water can lead to water and energy savings through a centralized water supply system. However, increasing water access also increases wastewater production and energy consumption for waste management, as untreated wastewater damages the ecological environment [34].

In the Water–Food (WF) nexus, water use efficiency (WUE) and renewable energy consumption (REC) represent two key entry points that influence interactions within the WF nexus. Water use efficiency has a positive impact on food production (2.27%) while negatively impacting water consumption (− 1.002%). Thus, improving water use efficiency in food production processes enhances food production while decreasing water consumption, as supported by Et-taibi et al. [20]. Renewable energy consumption has a weaker impact on the WF nexus, positively affecting water consumption (0.15%) and negatively influencing food production (− 0.206%).

In the Energy-Food (EF) nexus, Biofuels and waste (B&W) form the only nexus entry point with a positive effect on Energy use (0.37) and Food production (1.62). As a form of renewable energy in Cameroon, biofuels reduce total dependency on fossil fuels, enhancing energy supply and the ecological environment for crop growth and food production. However, biofuel production and conversion processes often increase primary energy consumption.

The interrelations and interactions between the WEF subsystems are interconnected in various ways, generating causal relationships and feedback loops, as illustrated in Fig. 3. The positive and negative forces represent different behaviors in the various subsystems, interacting to create a new balance within the system. A significant negative feedback loop exists at the point where an increase in water consumption leads to a decrease in energy consumption (0.51%), energy consumption reduces food production (– 4.56%), and food production decreases water consumption (0.82%), bringing the system to a new balance. This process may continue until there is a long-run ecological overshoot[6] and ultimate collapse of the system, as illuminated by the "limits to growth theory" [54]. Other major feedback loops occur where W_C positively influences F_P and F_P negatively impacts W_C. Another also occurs where F_P negatively affects E_C while E_C negatively affects F_P. Therefore, any factor(s) affecting W_C, E_C, or F_P can initiate movement in the loop, influencing all sub-systems and creating a new balance within the nexus core. As suggested by Meadows et al. [54], the present growth trends in the world's population, industrialization, pollution, food production, and resource depletion on a finite planet will require a paradigm shift from resource depletion to resource conservation.

In SEM, every behavior corresponds to a specific government sector. The different sectors govern processes in the subsystem. Sectors with higher coefficient values can be identified as the core to achieving effective nexus governance. As such, the sectors corresponding to urban population and urban planning, total population with access to safe drinking water (TPASDW), total renewable water resource (TRWRc) management, total energy supply (TES), water use efficiency (WUE), and dam capacity (DC) form core sectors for WEFE nexus governance in Cameroon. Capacity building of dams has been a

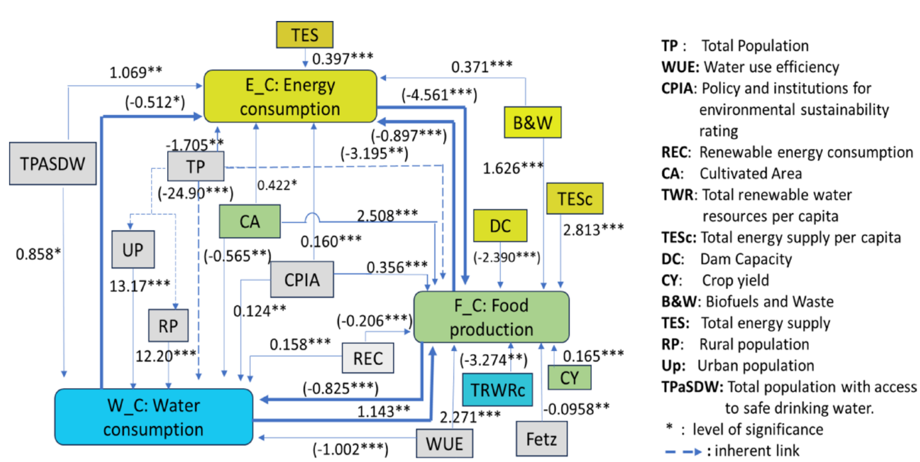

Fig. 3 Casual effect and feedback loops in the WEF nexus

[6] The extent to which consumption-based CO2 emissions and material footprint exceed fair shares of planetary boundaries.

crucial factor for energy supply in Cameroon. Large-scale hydropower exploitation in Cameroon began as early as 1951 with the Edéa run-of-the-river power plant generating more than 15 MW [40]. Several dams have been developed to boost Cameroon's energy supply. The Nachtigal Dam project is the most recent and is expected to produce about 420 MW after commissioning. Land use changes from such activities create imbalances in the WEFE nexus, requiring integrated management approaches.

Integrating the nexus approach into Cameroon's policy framework remains challenging. Policies related to water, energy, food, and the ecological environment do not effectively account for the interlinkages existing between these resources. The focus on sectoral isolation and the existence of multiple stakeholders, each facing competing national development interests, limits the vision of policymakers to adopt a nexus approach. While opportunities exist for the nexus approach to be realized through the integrated management of projects in Cameroon, clear policy directions and guidelines for project management, including dam construction, energy supply, and water use, must be explicitly incorporated into the national agendas to maximize benefits across various resources. A paradigm shift in resource management is necessary to drive sustainable growth and development in the country.

5 Conclusion and recommendation

The 'silo' approach to resource management in Cameroon has proven unsustainable, often leading to inefficiencies, resource wastage, and environmental degradation. Recognizing that development must take place within planetary boundaries, a paradigm shift in resource management is crucial for the sustainable growth and development of Cameroon. Although intensity and footprints are commonly used to quantify and explain complex interconnections in current nexus studies, elasticity measures are weakly explored. This study compiles national-level statistics from a cross-section of socioeconomic and environmental indicators, employs the simultaneous equation model (SEM) with structural equations to connect systems in the WEF nexus, and applies 'nexus thinking' to provide integrated management solutions to the water, energy, and food crisis in Cameroon. The study thus demonstrates critical interactions amongst water, energy, and food subsystems, establishing elasticities and revealing the underlying synergies and feedback loops within Cameroon's WEF nexus.

The linear analysis reveals that in the water subsystem, urban population growth significantly increases water consumption by 13.17%, underscoring the critical need for managing urban population growth to ensure water security in the country. In the energy subsystem, a percentage rise in the total population with access to safe drinking water leads to a significant increase in energy consumption by 1.01%, reflecting the energy intensity of expanded water services and requiring integrated infrastructural planning that promotes low energy use in water supply. In the food subsystem, a percentage increase in total energy supply per capita results in a 2.8% increase in food production, highlighting agriculture's dependence on reliable energy. These factors significantly impact sustainability in Cameroon, creating challenges and influencing opportunities in synergies and trade-offs. System analysis determines that population growth (TP) exerts holistic impacts within the WEF nexus, negatively affecting the water, energy, and food subsystems. Processes in the water subsystem dominate the nexus at this entry point. The cultivated area (CA) also creates a holistic influence across the system, dominated by processes in food production. Policy and institutions for environmental sustainability (CPIA) also exert holistic impacts across the system. This implies interventions through population growth management, cultivated area management and optimization, and policies and institutions for environmental sustainability send direct signals through all subsystems, requiring nexus thinking to optimize resource use efficiency. Water consumption, energy consumption, and food production form a major negative feedback loop dominated by changes in food production (−4.56%). Actions or interventions in any subsystem interact to bring the system into a new balanced state.

The interdependencies and interactions between Cameroon's WEF systems highlight the need for integrated policy interventions that prioritize system thinking and nexus-based strategies. Strengthening policies and institutions that facilitate cross-sectoral planning and adopt metrics designed to capture nexus synergies is essential for advancing environmental sustainability and fostering sustainable development without worsening sectoral imbalances. Cultivated area management and water use efficiency can enhance food production and water consumption, aligning with Cameroon Vision 2035 and Africa's Agenda 2063 for sustainable growth. This study is limited in data availability for ecosystem services (valuation of ecosystem services), which could be integrated to capture the full effects of the ecosystem services in nexus interactions. Future endeavors are encouraged to bridge the gap by valuing ecosystem services and providing a deeper understanding of interactions between the water, energy, food, and ecosystems (WEFE) Nexus in Cameroon. Tools like system entropy and game theory could help measure how well these systems work together, while Structural Equation Modeling (SEM) can show how human behavior affects the nexus. Using these methods together would give a clearer picture for better decision-making.

Appendix
See Tables 4 and 5.

Table 4 First stage least squares estimation for endogenous variables (OLS estimation)

Explanatory	Endogenous		
	Water subsystem ln(W–C)	**Energy subsystem ln(E_C)**	**Food subsystem ln(F_P)**
_cons	− 3.916	− 10.99	253.5
	(− 0.25)	(− 0.57)	(− 1.31)
lnF_P	− 0.0376	− 0.226	
	(− 0.18)	(− 1.04)	
lnE_C	0.0506		− 1.972
	(− 0.71)		(− 2.02)
lnW_C		0.261	2.926*
		(− 0.68)	(− 2.47)
lnTP	− 6.936	− 0.373	− 8.438
	(− 0.96)	(− 0.23)	(− 1.24)
lnCPIA	0.0299	0.077	0.099
	(− 0.61)	(− 1.33)	(− 0.87)
lnTPASDW	− 0.545	0.224	
	(− 0.92)	(− 0.31)	
lnWUE	− 0.47	0.0701	1.476
	(− 1.58)	(− 0.19)	(− 1.14)
lnDC	0.768	0.201	− 3.972**
	(− 1.18)	(− 0.24)	(− 3.09)
lnCA	− 0.21	0.678*	1.379
	(− 0.88)	(− 2.32)	(− 1.61)
lnUP	3.9	0.274	
	(− 0.95)	(− 0.51)	
lnREC	0.013	0.0152	0.0405
	(− 0.27)	(− 0.24)	(− 0.33)
lnRP	4.079		
	(− 1.07)		
lnGDP	0.098		− 0.369
	(− 1.66)		(− 1.48)
lnEdu	− 0.0219	0.23	− 0.899
	(− 0.08)	(− 0.65)	(− 1.61)
lnACE	0.216		− 0.69
	(− 1.67)		(− 1.65)
lnCY	− 0.0389	− 0.0142	0.229**
	(− 1.05)	(− 0.30)	(− 3.06)
lnTES		0.154	
		(− 0.48)	
lnB&W		0.458**	0.294
		(− 3.26)	(− 0.58)
lnTGHG		0.28	0.408
		(− 0.99)	(− 1.03)
lnTESc			1.384
			(− 1.73)
lnFetz			− 0.106
			(− 1.84)
lnTRWR			− 9.928
			(− 1.40)
N	22	22	22
adj. R-sq	0.997	0.993	0.996

t-statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$(significant at 10%, 5% & 1%)

Table 5 The Levin-Lin-Chu (LLC) test values for variables including trends

Variable	Adjusted t values	Variable	Adjusted t values	Variable	Adjusted t values
lnGDP	− 2.0131*	lnDC	− 5.3086***	lnTESc	− 1.012
lnEdu	0.7188	lnTP	1.5899	lnE_C	1.0709
lnTRWR	− 3.3204 ***	lnTPASDW	− 8.6284***	lnREC	0.805
lnW_C	− 2.2759*	lnUP	0.1078	lnB&W	0.9892
lnCY	− 3.0689**	lnRP	− 2.6912**	TGHG	− 0.2416
lnWUE	− 1.3742*	lnTES	0.8692	lnACE	− 7.0486***
lnF_P	− 1.7683*	lnFetz	− 1.8271*		
lnCA	− 0.3001	lnCPIA	− 2.0284*		

The number of lags chosen is based on the Akaike information criterion (AIC). The AIC suggests a common lag of 0 for this study; level of significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$

Author contributions
Nde I. Zama, Fang Lan, and Eric F. Zama contributed to the conceptualization, methodology and writing of the original draft. Yaofeng Yang assisted in the methodology and interpretation of the results, while Yvette Baninla and Agnes Millimouno contributed to the review and visualization of the findings. All authors approved the submitted version of the manuscript.

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Data availability
Data is provided within the manuscript.

Declarations

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