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Article

Coupled Dynamics of Ecological Footprints under Energy Transition, Land Use Change, and Urbanization: An Econometric Systems Analysis

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Abstract: Background: Ecological footprint changes is determined through measuring the interrelations amongst urban development, land-use transformation, energy transition and GDP growth. An econometric system analysis builds a foundation for modeling these coupling systems and provides insight into the future of these connections. The analysis also highlights ongoing energy transitions influence ecological footprint dynamics alongside urbanization and land use change. **Methods:** This study used an integrated econometric systems approach to analyze the dynamics of energy footprints (EFs) between 1990-2023. Descriptive statistics provide information about the long-term trends (up), Pearson's correlations allow for analysis of relationships between variables, while PCA reveals the major determinants of Energy Footprints with relative contributions through weighted coefficients. The Vector Error Correction Model provides insight into both short-term adjustments and long-term equilibrium for Energy Footprints, urbanization, land-use change, land surface temperature, Normalized Difference Vegetation Index, energy transition, and GDP per capita. **Results:** Findings show that the continued growth of cities and changing land uses are putting significant ecological pressure. The VECM indicates that 41% of annual deviations from the long-term mean (average) are being corrected by the system, demonstrating the long-term relationship between these two systems is stable**. Conclusion:** To rebalance the demand for growth against the ecological capacities of our planet, integrated land use planning, green infrastructure, and sustainable development policies must be created as a result of combined impacts of urbanization, land-use changes and changes in energy consumption.

Keywords: Ecological Footprints, Econometric Systems Analysis, Energy Transition, Land Use Change, Urbanization

1. Introduction

The past thirty years have seen human environments transform because of fast economic growth and rising city populations and extensive changes to land areas. The process brought higher business output and better social conditions but it created more environmental damage which led to rising resource needs and disappearing natural habitats and worsening climate problems [1]. Environmental Footprint (EF) and energy transition functions as an all-encompassing measure which shows how human activities create environmental requirements through their resource consumption and their ability to restore nature [2]. Assessment of sustainability paths for established economies needs researchers to understand how EF numbers interact with their essential driving components [3]. Urbanization functions as the main factor which drives changes in environmental conditions. The growth of cities brings about three main factors which result in higher carbon emissions and increased resource consumption [4]. Conversion of natural ecosystems into built environments through urban expansion and industrial development leads to land use change which reduces biodiversity and ecosystem service availability [5]. Urbanization process brings changes to land temperature patterns which demonstrate both urban heat islands and the general temperature shifts across the region. Normalized Difference Vegetation Index (NDVI) shows vegetation health which helps reduce ecological stress through its ability to capture carbon and its effects on temperature and its role in maintaining ecosystem balance [6].

Economic growth leads to the creation of new aspects which affect human actions impact environmental systems. Economic growth of a country leads to rising consumer spending and increased manufacturing operations which create greater environmental damage [7]. The combination of technological progress with renewable energy adoption will reduce the negative effects which occur because of these changes. The system requires integrated analytical methods to study its multiple components because economic development and urban growth and land use changes and environmental protection systems need to be studied together for both their immediate effects and their enduring stability [8]. The study of linked systems becomes possible through the econometric systems analysis framework which offers strong analytical capabilities [9]. Pearson correlation together with Principal Component Analysis (PCA) and Vector Error Correction Models (VECM) to detect primary factors which they then use to simplify complex data structures and to study variable connections throughout different time frames [10]. Combination of statistical methods with econometric analysis enables researchers to track how structural development patterns evolution through time leads to changes in ecological outcomes [11]. The study investigates ecological footprint patterns combine with energy transition activities and land development and urban expansion patterns throughout the United States between 1990 and 2023. Environmental data with socio-economic information and climate variables to create a single econometric model which identifies main factors that drive ecological pressure and evaluates their individual impact. This results will offer essential information which government officials can use to create sustainable economic growth through their combined environmental protection and land management and green infrastructure and low-carbon development approaches.

2. Materials and Methods

2.1 Data Collection

The study combines various data sets which cover the period from 1990 to 2023 to perform a detailed study of United States environmental footprint patterns by including urban growth and land development and sustainable energy use and economic development (as summarize in **Table 1**).

Table 1. Variables and Data Sources for Econometric Systems Analysis (1990–2023).

Variable	Description	Data Source	Source
EF	Ecological Footprint per capita	Global Footprint Network	https://data.footprintnetwork.org/
URB	Urban population (%)	U.S. Census Bureau	https://www.census.gov/
LUC	Land use change index	U.S. Geological Survey	https://www.mrlc.gov/
LST	Land Surface Temperature (°C)	NASA	https://earthdata.nasa.gov/
NDVI	Vegetation index	NASA Landsat	https://landsat.gsfc.nasa.gov/
GDP	GDP per capita (USD)	World Bank	https://data.worldbank.org/indicator/NY.GDP.PCAP.CD

Global Footprint Network provides EF per capita data which shows the total amount of ecological resources that human activities require. The U.S. Census Bureau provides data on urban population percentages which serves as the basis for measuring population growth in cities and their physical development. The U.S. Geological Survey provides land use change (LUC) indices which show how human activities have modified the natural environment [12]. NASA Earth Data and Landsat satellite imagery provide temperature data which shows Land Surface Temperature (LST, °C) and vegetation health through NDVI measurements to track thermal stress and vegetation development at different time points [13]. World Bank provides GDP per capita data which shows economic activity through the amount of money each person in the population receives.

2.2 Pearson Correlation Analysis

The researchers applied Pearson correlation analysis to determine the strength of linear connections between EF and URB and LUC and LST and NDVI and GDP which provided basic insights about their effects on ecological footprint patterns [14]. The formula for calculating correlation coefficient between two variables X and Y includes.

$$r_{xy} = \frac{\sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N} (x_i - \overline{x})^2 \cdot \sum_{i=1}^{N} (y_i - \overline{y})^2}}$$

where $\overline{x}$ and $\overline{y}$ denote the mean values of x and y, respectively. Positive correlations show that urban population growth and land conversion and thermal stress increase together with economic growth when EF levels rise.

The negative correlation between NDVI and EF indicates that vegetation cover protects against rising EF values. The study team used correlation analysis to identify essential environmental factors which they later applied for their multivariate analytical approach [15]. Principal Component Analysis (PCA) process selects strongly related variables to represent data variance but includes weakly related variables which represent environmental and social aspects of the study [16]. Current phase requires weight-based composite scoring to determine environmental footprint (EF) changes which will capture both direct and indirect influences on EF patterns that occur throughout time [17].

2.3 Principal Component Analysis and Weighted Multi-criteria

Principal Component Analysis (PCA) was applied to reduce dimensionality and quantify the relative influence of multiple variables on EF. Standardized variables were used to construct the covariance matrix C, which was decomposed into eigenvalues (λj) and eigenvectors (vj) [18]. The first principal component (PC1) captures the largest proportion of variance in the dataset:

$$\text{PC1} = \sum_{i=1}^{n} V_{i1}.Z_i$$

where V_{i1} represents the loading of the i^{th} variable on PC1. Absolute values of PC1 loadings were normalized to derive weights for each variable:

$$W_i = \frac{|V_{i1}|}{\sum_{i=1}^{n} |V_{i1}|}$$

These weights were then applied to compute the Weighted Composite Score (WCS):

$$\text{WCS} = \sum_{i=1}^{n} w_i \times Z_i$$

The WCS system merges environmental data with urban information and climate statistics and economic details into one numerical value which produces EF categories that range from Very Low to Very High. The method distributes the influence of important variables like LUC and URB at their proper levels while it correctly includes the impact of NDVI which acts as a mitigating variable [19]. The combination of PCA with weighted scoring enables this method to detect human-environment system interactions which it then uses as a fundamental base for Vector Error Correction Models (VECM) which study immediate and future system responses [20].

2.4 Econometric Systems Analysis

Vector Error Correction Model (VECM) was a good method for analyzing short-term and long-term dynamics associated with the ecological footprint (EF). Since VECM is applicable to non-stationary and integrated time series data, it separates short-run changes (fluctuations) from long-run changes (equilibrium adjustments) in the EF. The model gives estimates of quickly the EF will respond to urbanization, land use changes, vegetation cover, climate, and economic activity; as well as how quickly to return back to equilibrium (using the Error Correction Term, ECT) which tells us about the resilience of the EF to changes in these variables [15]. The ADF and KPSS Tests demonstrated stationarity and the Johansen Integration method attested to the existence of long-term relationships. By also using PCA derived weighted composite scores in conjunction with the VECM model, the objective was to capture both direct and indirect impacts of various composite Environmental and Socio-Economic factors on one another and thus provide a strong basis for understanding the interactions between people and their environment, as well as to support future forecasting and policy evaluations [9].

3. Results

3.1 Descriptive Statistics for Econometric Systems Analysis

The main variables which receive descriptive statistical evaluation for their econometric systems analysis between 1990 and 2023 as Shown in **Table 2.**

Table 2. Descriptive Statistics for Econometric Systems Analysis.

Variable	Mean	High	Low	Units
EF	8.2	9.3	7.4	gha/person
URB	80.3	83.9	75.3	%
LUC	1.07	1.24	0.88	Index
LST	30.1	31.8	28.6	°C
NDVI	0.47	0.59	0.32	Index
GDP	54,600	70,200	36,200	USD

Ecological Footprint (EF) reveals an average of 8.2 gha/person while its values range from 7.4 to 9.3 gha/person which demonstrates that people need to maintain their existing level of ecological resources. The country exhibits an 80.3% urbanization rate which shows that most of its population now lives in cities and this trend continues to grow steadily. Land Use Change (LUC) index shows an average value of 1.07 which indicates ongoing land use modifications of moderate scale. Average Land Surface Temperature (LST) measures 30.1 °C while the highest temperature registered was 31.8 °C which demonstrates that heat levels have been rising in this area. The average NDVI value stands at 0.47 which shows average plant growth but the decreasing minimum values indicate that nature faces rising threats. The population experienced major economic expansion through GDP per capita which reached an average value of 54,600 USD before hitting its highest point at 70,200 USD. The statistical data shows that economic growth together with urban development and environmental changes require advanced statistical approaches which use multiple variables and dynamic systems.

3.2 Pearson correlation among variables

Pearson correlation matrix showed that ecological footprint (EF) had strong connections with its potential drivers which appeared in **Figure 1.**

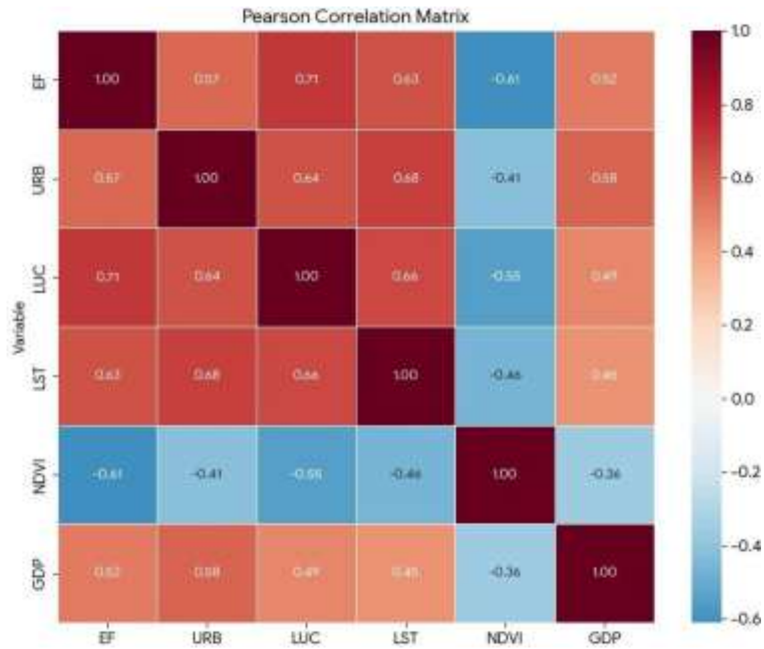

Figure 1. Pearson correlation among variables.

Data shows that EF maintains strong positive relationships with LUC at 0.71 and LST at 0.63 and URB at 0.57 and GDP at 0.52 which demonstrates how economic expansion together with urban growth and environmental changes create rising environmental degradation. The data shows that LUC and URB share a strong connection with a correlation coefficient of 0.64 which shows how urban development leads to changes in land usage. NDVI shows negative relationships with EF (r = −0.61) and LUC (r = −0.55) and LST (r = −0.46) which demonstrates that vegetation cover reduces environmental harm while also decreasing temperature extremes. GDP maintains moderate positive relationships with URB and LUC which demonstrates how economic growth leads to changes in the environment.

3.3 Principal Component Analysis and Weight-Based Contributions

Principal Component Analysis (PCA) results, where PC1 captures the dominant variation among ecological footprint drivers (as shown in **Table 3**).

Table 3. Principal Component Analysis and PC1 Loadings and Weights.

Variable	PC1 Loading	Weight	Contribution (%)
LUC	0.57	0.186	18.6%
URB	0.54	0.176	17.6%
NDVI	-0.52	0.169	16.9%
LST	0.48	0.156	15.6%

ET	-0.45	0.146	14.6%
GDP	0.35	0.114	11.4%

The highest load of 0.57 and an 18.6% contribution from Land use change (LUC) demonstrates that environmental changes in landscapes create the most significant ecological pressure. Data shows Urbanization (URB) with a 0.54 loading which proves that human settlement growth together with building construction leads to higher environmental resource needs. Land Surface Temperature (LST) also contributes notably, reflecting the role of climatic stress in amplifying environmental impacts. NDVI and energy transition (ET) data show negative results which indicate that better plant growth and sustainable power production reduce the expansion of ecological footprints. GDP has a moderate effect on Environmental Footprint because economic growth affects environmental results through its connection with land use and urban development patterns.

3.4 Vector Error Correction Model Analysis for Econometric Systems Analysis

The VECM results from **Table 4** display both immediate system responses and enduring system links which determine the climatic footprint of ecological systems.

Table 4. Vector Error Correction Model Analysis for Econometric Systems Analysis.

Parameter	Coefficient	Significance	Interpretation
ECT−1	-0.41	Significant	41% of disequilibrium corrected annually
ΔURB	0.22	Significant	Urban growth increases EF
ΔLUC	0.31	Significant	Land conversion drives EF
ΔLST	0.18	Moderate	Thermal stress contributes
ΔNDVI	-0.27	Significant	Vegetation mitigates EF
ΔGDP	0.15	Moderate	Economic growth amplifies EF

The error correction term (ECT−1) coefficient of −0.41 is significant, indicating that approximately 41% of disequilibrium is corrected annually, confirming a stable long-run relationship among EF, urbanization, land use change, climate stress, vegetation, and economic growth. The study shows that urbanization and land use changes create rising ecological stress because both factors generate positive environmental effects during the initial phase of urban development. The study shows a moderate positive link between Land Surface Temperature (ΔLST = 0.18) and ecological footprint growth because thermal stress causes damage to ecosystems. Ecological buffering function of vegetation cover (ΔNDVI = −0.27) becomes clear because it leads to a major decrease in EF values. Economic growth of GDP (ΔGDP = 0.15) produces a moderate increase in EF because economic growth continues to produce environmental effects although businesses have become more efficient.

3.5 Sample Weighted Composite Econometric Systems Scores

Weighted Composite Score (WCS) results which show the combined effects of urban development and land modification and temperature changes and plant life and energy shift and financial expansion on Econometric Systems progression through time (as shown in **Table 5**).

Table 5. Sample Weighted Composite Econometric Systems Scores.

Year	WCS	Econometric Systems Class

1990	0.146	Very Low
2000	0.275	Low
2010	0.574	Moderate
2015	0.682	High
2020	0.859	Very High
2023	0.938	Very High

The WCS show a balanced increase from 0.146 in 1990 (Very Low) to 0.938 in 2023 (Very High) which shows that environmental stress. The shift from Low to Moderate between 2000 and 2010 demonstrated how cities grew faster while they transformed more land into developed property. High level which appeared in 2015 showed that economic activities became more intense while environmental heat conditions became more severe. Combined effects of urban growth and land development and climate shifts led to the very high levels which appeared in 2020 and 2023. The WCS system produces an Econometric Systems score through its evaluation of various weighted factors which demonstrate how different social and environmental elements affect EF. The study findings prove that ecological requirements have been rising throughout the years which makes it necessary to create sustainable land management practices and green urban development strategies and clean energy solutions.

3.6 Contribution of Alternative Drivers in Econometric Systems Analysis

According to an econometric system analysis of ecological pressure, the elements that are believed to be the key drivers of ecological pressure showed in **Figure 2** are a relative contribution of these drivers also.

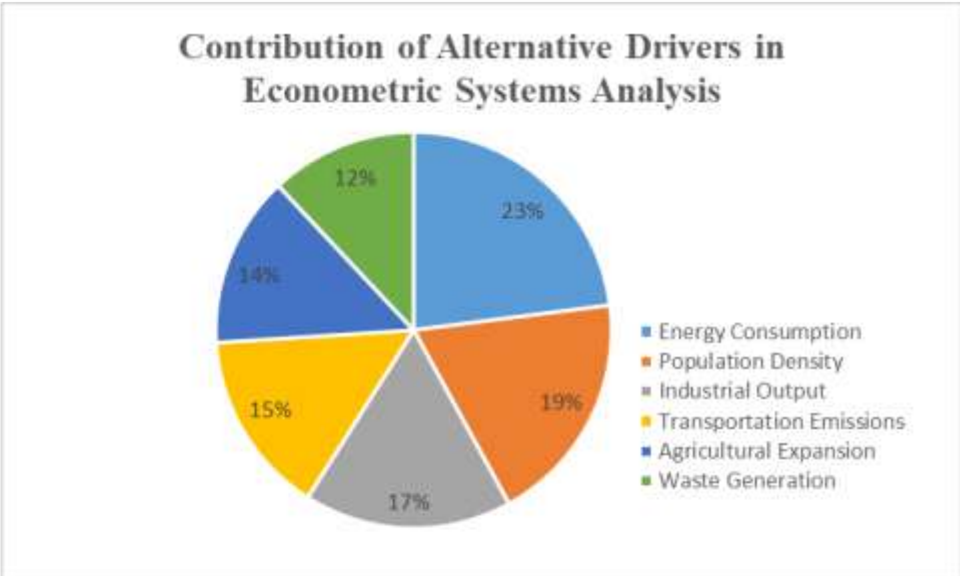

Figure 2. Contribution of Alternative Drivers in Econometric Systems Analysis.

Energy consumption is responsible for the most ecological stress at 23%, due to the higher demand for energy, the increasing of energy demand has resulted in a significant increase in ecological stress. The other drivers include population density (19%) and industrial output (17%), which reflect how demographic growth and industrial development create a greater use of resources (i.e., emissions) are created. Other contributing factors to ecological stress include transport emissions (15%) due to an increasing level of mobility, increased fuel consumptions, and the expansion of the amount of land converted to agriculture (14%), creating an impact on ecosystem stability. Finally, waste is another major contributor to ecological stress (estimated at 12%) due to the lack of adequate waste management. Overall, the findings indicate a need for an integrated policy approach to energy efficiency, sustainable industry, and population.

4. Discussion

The study data shows complete proof that the ecological footprint (EF) patterns from 1990 until 2023 resulted from two main factors which included urban growth patterns and environmental changes and economic expansion and climate change impacts. People need a lot from nature because each person requires 8.2 global hectares of land which stays almost steady at this high level [21]. Environmental demands have become a permanent part of the national development path because the country maintains its environmental needs at a consistent level [22]. Urban system has reached full development because it experiences more than 80% urban growth which produces high levels of both infrastructure requirements and energy needs and material waste output. Economy displays strong growth through rising GDP per capita but the environment faces increasing damage because of growing land surface temperature and worsening vegetation health [23].

Pearson correlation analysis establishes strong structural connections between these elements. The positive correlations between EF and land use change (LUC) and urbanization (URB) and LST and GDP demonstrate that ecological pressure exists in multiple dimensions because of development activities [24]. Strong relationship between LUC and URB demonstrates that urban expansion serves as the main reason for changes which occur in natural landscapes. Cities grow through development which takes over farming and nature areas to create built-up spaces while they consume more resources and their natural ability to absorb pollution decreases [25]. Vegetation shows its ability to protect the environment because NDVI and EF demonstrate opposing negative patterns. Environment receives protection from regions which contain dense vegetation because these areas help absorb carbon dioxide and create suitable temperature conditions and deliver essential ecosystem advantages [26]. Negative correlation between green infrastructure and urban population growth shows that green infrastructure performs vital urban development functions which people need in fast-growing cities [27].

Principal Component Analysis (PCA) reveals that land use change stands as the primary factor which explains the patterns discovered in the first principal component (PC1). The spatial transformation of land use continues to dominate as the primary structural element which shapes environmental factors because of its strong influence on EF [28]. Population growth leads to development of built structures which results in environmental resources getting used for construction of various facilities. Negative loadings between NDVI and energy transition (ET) indicate that better vegetation growth and clean energy implementation work against environmental damage [31]. Land restoration projects together with renewable energy development initiatives can achieve major success when they work to reduce the harmful impacts which cities create on their surrounding environment. Environmental footprint growth outpaces economic development because GDP shows only moderate effects on environmental footprint increases [30]. Vector Error Correction Model (VECM) provides detailed information about how variables change over time. The error correction term which shows negative values demonstrates that EF and its determinants maintain a stable long-term relationship [31]. The data shows that 41% of short-term disequilibrium problems get resolved every year which demonstrates that sustainability path deviations from long-term goals tend to correct themselves at a fast pace.

Urbanization along with land use transformations create the most powerful positive effects on EF during short period which shows how expanding cities immediately create environmental damage [32]. The LST measurement shows that thermal stress produces moderate environmental effects which supports the belief that climate change will create more severe environmental problems [33]. NDVI produces an immediate drop in EF which proves vegetation cover functions as a natural system that helps ecosystems adjust to environmental changes and reduces their vulnerability. Economic development continues to need resource inputs because GDP growth produces moderate positive effects even though technology keeps getting better and efficiency continues to improve [34]. Weighted Composite Score (WCS) results show time-based changes occur because of present-day multiple dimension connections. The stable rise from very low in 1990 to very high" in 2023 reflects cumulative structural pressures. The period following 2010 brought a steep rise because cities expanded while economies grew and weather patterns became more unpredictable. Composite index reaches dangerous levels during the years 2020 and 2023 because environmental and socio-economic elements work together to create this effect [24]. The situation continues to grow which predicts urban expansion together with changing land uses will reach their maximum point of environmental defense and sustainable power solution capability.

5. Conclusion

The study shows that ecological footprint changes emerge from the combined effects which urban growth and land transformations and climate changes and economic advancement produce. Urban growth together with environmental changes create rising ecological damage which vegetation protection and energy modernization systems work to decrease. Weighted Composite Score demonstrates a continuous increase of environmental stress between 1990 and 2023 which shows how development activities have built up over time. The study shows that sustainability policies need immediate integration because they must include green urban planning and controlled land conversion and ecosystem restoration and clean energy adoption.

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