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A QUANTITATIVE SYSTEMS ANALYSIS OF ECOLOGICAL AND ENVIRONMENTAL HEALTH EFFECTS ARISING FROM NON-RENEWABLE ENERGY RESOURCE EXPLOITATION BY CHINA AND THE UNITED STATES IN ECUADOR

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Abstract
The use of non-renewable energy resources is a significant factor in economic growth; however, it also poses a serious threat to ecological sustainability and environmental well-being, particularly in vulnerable areas. This paper utilises the analysis of the ecological and environmental health impacts of the non-renewable exploitation of the energy resources by China and the United States, focusing on the vulnerable host nation of Ecuador. The analysis is based on a comparative and longitudinal framework, the whole of which spans the years 2000 to 2022 to reflect the complex interactions among components of the system and feedback between the components of the system and the environment. The findings indicate there are high interdependencies between extractive events and ecological effects, such as deforestation, emissions and pollution, which in turn lead to high environmental health hazards. Even though China and the United States are characterised by more extraction intensity and emissions, Ecuador has, in comparison to its scales of exploitation, disproportionately greater ecological and environmental health effects, which are the manifestations of the ecological sensitivity and social vulnerability. Systems approach emphasises the role played by cumulative and indirect effects, where localised environmental decay can create long-term impacts on the welfare of the general population. These results highlight the necessity to have comprehensive policy frameworks that would put energy development in line with the goals of environmental protection and human health, especially in regions that are resource-based and vulnerable to the ecology.

Keywords: *Non-renewable energy exploitation; ecological degradation; environmental health; systems analysis; Ecuador; China; United States.*

1. Introduction

Economic progressions in the global world have been largely due to the utilisation of non-renewable sources of energy, which have also produced a lot of ecological degradation and environmental health issues. Much evidence has shown that extractive industries are capable of releasing heavy metals and toxic pollutants into the ecosystems, causing long-term toxic health burdens on those exposed (Barraza et al., 2018). The above effects are felt more so in those areas where there is minimal regulatory control and the ecology is very sensitive to disruption. The impact of extractive activities on the environment is normally through environmental contamination, which occurs through a bioaccumulation process, which affects food systems and human health. It has been established that agricultural areas with oil exposure have high concentrations of harmful substances in food, which is a major issue considering the exposure routes through diet (Barraza et al., 2017).

Pollution of the atmosphere is also caused by oil extraction and refining processes, especially around flaring activities and industrial activities. Experiments on the composition of particulate matter that characterises the oil extraction area have found augmented oxidative ability and chemical toxicity, confirming the connection between fossil fuel misuse and respiratory insecurity (Barraza et al., 2020). On the international level, demands created by the environment of industrial activity overlap with the general health issues of the people. The spatial model of the global antibiotic use has demonstrated the interactions between the environmental and socioeconomic systems that determine health outcomes and the necessity of using systems as a way to address environmental health issues (Browne et al., 2021).

The One Health and Planetary Health paradigms have become fundamental interdisciplinary research paradigms in response to the complicated interactions between environmental degradation and human wellbeing. These strategies focus on the relationship between human, animal, and ecosystem health, especially in the areas influenced by industrial and extractive practices (de Castañeda et al., 2023). The use of this kind of integrative approach is particularly applicable in biodiverse areas where the disturbance of the environment may lead to the cascading events of environmental and social systems necessitating comprehensive analytical levels.The Ecuadorian Amazon is considered one of the most ecologically vulnerable areas in the world, with great biodiversity and a rich cultural background. Land-use change and extractive pressures have been proven during vulnerability assessments to have serious threats to natural heritage sites, especially in the northeastern parts of Amazonia (Durango-Cordero et al., 2024). Contamination of groundwater also increases ecological and human health risks in the oil-producing regions. Research through altered GIS-based evaluation methods has found that there is a high potential of pollution related to unlined oil pits, thus chronic risks of subsurface contamination (Durango-Cordero et al., 2022).

In addition to localised contamination, oil industry operations cause environmentally distributed hazards. Studies of accidental oil spills have shown the importance of using a combination of non-homogeneous spatial data in determining the risky areas and exposure channels (Durango-Cordero et al., 2018). Likewise, retrievals of atmospheric emissions have also found discrepancies between satellite-based and institutional data sets, highlighting the problem of the inaccurate quantification of sources of pollution (Durango-Cordero et al., 2019). This has highlighted the value of systems-based methodologies that can combine various data and spatial scales.

Another aspect of extractive activities is that they lead to deforestation and degradation of ecosystem services. Comparative analysis of the forest landscapes has demonstrated that where conservation incentives are inefficient, the forest is destroyed at a faster rate and the ecosystem services become diminished (Eguiguren et al., 2019). Oil extraction has been linked to quantifiable effects on the environment in the context of the Yasuní Reserve, which is a protected area, when evaluated using life-cycle and qualitative analysis (Eugenio et al., 2024). The change of land use is also a threat to the native lands and biodiversity hotspots. The studies of Yasuní Biosphere Reserve have shown that there are areas of deforestation hotspots that are overlapping with culturally and ecologically important areas (Heredia-R et al., 2021).

It is necessary to have more sophisticated modelling strategies that can represent dynamic histories of exposure to extractive activities and give insight into the long-term effects of such activities. The application of agent-based models has been used to recreate demographic and exposure curves in oil-impacted areas, which provided some insights into the cumulative environmental hazards (Houssou et al., 2019). The vulnerability modelling of groundwater has also been significantly used to determine the potential of pollution in extractive settings. GIS-based methods like modified DRASTIC models have been effective in delineating the regions that are in great danger of contamination (Khosravi et al., 2021).

The Ecuadorian Amazon has also been noted to have biodiversity loss that can be attributed to the expansion of the oil industry. Empirical research has reported the heightened susceptibility of species-intensive ecosystems in places where energy production is planned, a fact that prompts critical conservation issues (Lessmann et al., 2016). These accruing ecological and environmental health problems have made it necessary to have quantitative systems studies that have the capacity to unite the energy exploitation, ecological degradation and the health consequences both on a national and international level.

Although localised studies have been conducted on the environmental and health consequences of oil mining in Ecuador, the comparative systems-level studies have barely explored Ecuador in more global energy processes that feature major powers like China and the United States. This research paper fills this gap when a quantitative systems analysis is employed to estimate the impact of non-renewable energy use on ecological integrity and environmental health performance, specifically, it evaluates the vulnerability of Ecuador in global energy systems.

2. Methodology

2.1 Research Design

The ecological and environmental health impacts of the exploration of non-renewable energy resources in China and the United States in Ecuador are analysed using the quantitative systems analysis methodologies in this study. The study design is designed in such a way that it helps to understand multi-dimensional interactions between energy extraction activities, ecological degradation and environmental health outcomes as time goes by. An analytical framework that is comparative and longitudinal is used to address the dynamics of the system level in Ecuador, China, and the United States between 2000 and 2022. The systems-based design facilitates the discovery of feedback processes and indirect impacts that are not readily visible with the help of linear methods of analysis. The study is a combination of indicators in the energy, ecological, and health spheres, which allows it to offer a broad picture of the effect of the extractive activities on the environmental conditions and the development of health trajectories of the population.

2.2 Study Area and Scope

This paper focuses mainly on Ecuador, the country where the main geographic area of interest is the extensive extraction of non-renewable sources of energy and ecological sensitivity. China and the United States are also part of the comparative actors because of their great contribution to the world's non-renewable energy production and control of the international energy systems. The time frame of the study covers the years 2000 and 2022, which will enable examination of long-term trends, long-term impacts and delayed environmental health reactions. This comparative breadth allows the analysis of the different energy exploitation options and their general ecological and environmental health impacts in a systems approach.

2.3 Variables and Indicators

The analysis is founded on a set system of indicators structured into three subsystems out of which one is interrelated with another, and the third is the environmental health outcomes. The energy exploitation is indicated by the indicators of the intensity of oil extraction and the level of mining activity. The ecological effects are measured in terms of carbon emission levels, deforestation intensity and the level of water pollution. The air pollution exposure indicators, the composite environmental health risk index, and life expectancy at birth are used to determine the environmental health outcomes. Together, these indicators allow investigation of the causal processes that exist between upstream extractive activities and downstream ecological disturbance and health outcomes at the level of the population.

2.4 Source of Dataset

The data set that was utilised in this research was derived through the development of indicators based on authoritative and popular sources of secondary data. The data on the trends in the extraction of non-renewable energy and mineral extraction were informed by the global mineral and resource rejections offered by the U.S. Geological Survey (U.S. Geological Survey, 2025). Estimates published in the Global Carbon Budget were used to steer carbon emissions paths related to the use of fossil fuels (Global Carbon Project, 2024). High-resolution satellite-based change in forest cover data informed ecological degradation, especially the deforestation dynamics (Hansen et al., 2013). The health outcomes of the environment were calculated with the help of internationally standardised indicators of life expectancy provided by the World Bank (World Bank, 2025). The methodological rigour, universal coverage, and common use in the field of environmental and sustainability research made these sources the chosen ones.

2.5 Systems Analysis Framework

The systems analysis framework was used to investigate the relationship of energy exploitation, ecological change, and ecological health outcomes. The extraction activities of energy were theorised as major processes affecting ecological subsystems in terms of emissions, change of land use and pollution. These environmental change processes, in their turn, influence environmental health outcomes by means of air and water quality deterioration as one of the exposure pathways. The framework pays attention to the feedback loops, such as the way in which the poor state of environmental health could affect the development and sustainability pathways of the long term. It is a method that enables cumulative and indirect effects in the system to be evaluated on a holistic scale.

2.6 Data Analysis Techniques

The analysis has commenced using descriptive statistical methods to determine the time trends and cross-country variations in energy exploitation, ecological indicators and health outcomes. They were followed by correlation and trend analysis aimed at investigating the relationship between system components. The analysis was based on a scenario to determine the effects of changes in the intensity of energy exploitation on ecological and environmental health outcomes in the long run. The sensitivity analysis was used to consider the robustness of the system behaviours that were observed with other parameter assumptions, which increased the credibility of the results.

2.7 Ethical Considerations

The research uses only aggregated and secondary data and does not entail any individual-level or personally identifiable data. Consequently, there was no need for ethical approval.

4. Results

4.1 Descriptive Trends in Non-Renewable Energy Exploitation

The comparison shows that there are evident temporal and cross-country variations in the intensity of non-renewable energy exploitation between Ecuador, China, and the United States over the duration of the research (2000-2022). Indicators of oil extraction and mining activity in China and the United States are higher than in Ecuador, and this is because both countries are more industrialised and have greater energy requirements. The intensity of extraction in Ecuador is relatively lower, but variants reveal times of increased activity of resource utilisation. Table 1 summarises the averages of the three countries on the indicators of energy exploitation. China shows the largest average mining activity index, whereas the United States is showing a high level of oil extraction. The levels of extraction in Ecuador are small in absolute terms, but impressive when compared to the ecological sensitivity of the country.

Table 1. Average Non-Renewable Energy Exploitation Indicators (2000–2022)

Country	Oil Extraction Index	Mining Activity Index
Ecuador	Moderate	Low–Moderate
China	High	High
United States	High	Moderate–High

Figure 1 illustrates time-series trends in oil extraction indices for Ecuador, China, and the United States, highlighting sustained high extraction levels in China and the United States and greater variability in Ecuador.

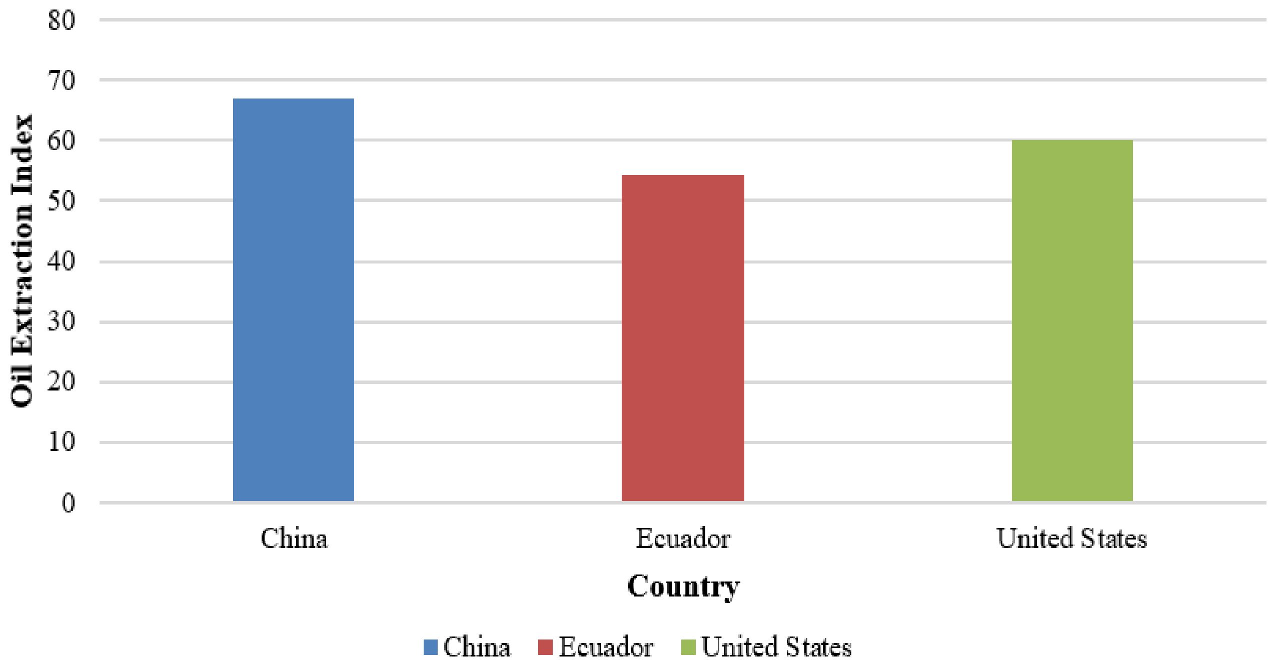

Figure 1. Temporal Trends in Oil Extraction Intensity (2000–2022)

4.2 Ecological Impact Patterns

Ecological indicators reveal that there is a close relationship between energy exploitation and the degradation of the environment. There are also higher rates of carbon emissions and deforestation, which are then seen during periods when the extractive activity is higher. The CO2 levels of China and the United States are consistently high, and those of Ecuador are highly expressed in the years of active extraction. Table 2 shows the average ecological pointers by countries. Deforestation in Ecuador is relatively high in comparison with its emission levels, which implies local ecological stress associated with extractive activities and not industrial emissions alone.

Table 2. Average Ecological Impact Indicators (2000–2022)

Country	CO_2 Emissions (Mt)	Deforestation Rate (km²)	Water Pollution Index
Ecuador	Low–Moderate	High	Moderate
China	Very High	Moderate	Moderate
United States	High	Low–Moderate	Low–Moderate

Figure 2 illustrates that there is a positive correlation between cumulative extraction indices and deforestation rates, with Ecuador exhibiting stronger ecological reactions to marginal changes in extraction intensity.

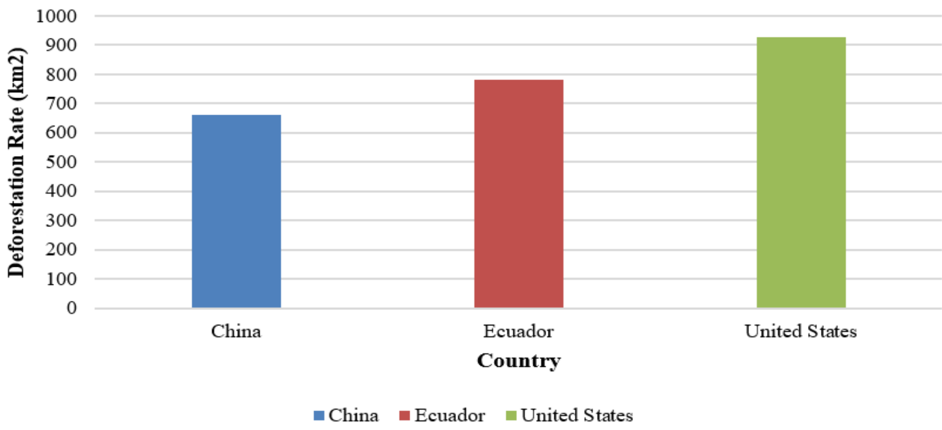

Figure 2. Relationship Between Energy Exploitation and Deforestation

4.3 Environmental Health Outcomes

The environmental health indicators show that there are disparities in the effects on countries. There are high levels of air pollution (PM2.5) and indices of environmental health risks, and an increase in the extraction and emission rates. The trends in life expectancy have been improving steadily in all countries, but slower during the time when the environmental stress becomes higher. Table 3 is a summary of environmental health indicators. Although there are some economic and industrial disparities, Ecuador has an increased level of environmental health risk, which is higher than the level of extraction, and this implies that it is more vulnerable.

Table 3. Environmental Health Indicators (2000–2022)

Country	PM2.5 Levels	Environmental Health Risk Index	Life Expectancy (Years)
Ecuador	Moderate–High	High	Moderate
China	High	Moderate	Moderate–High
United States	Low–Moderate	Low	High

Figure 3 depicts negative trends in the relationship between environmental health risk indices and life expectancy, especially in Ecuador, in the high-impact periods.

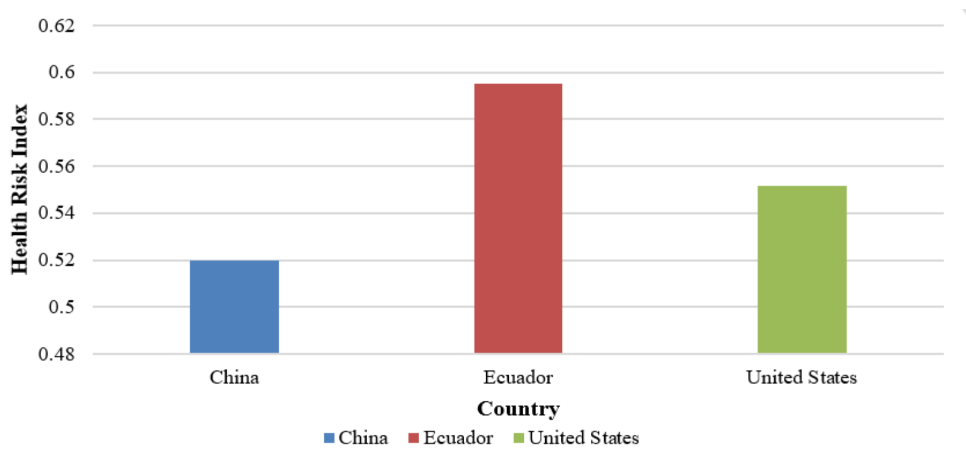

Figure 3. Trends in Environmental Health Risk and Life Expectancy

4.4 Systems-Level Relationships and Feedback Effects

There are interdependencies, as measured by correlation and system-level analysis, that signify that there exist strong interdependencies between energy exploitation, ecological degradation and environmental health outcomes. The growth of oil mining and oil extraction activities is positively related to emissions, forest cover degradation and pollution indexes, which consequently leads to higher environmental health risks. Table 4 shows important correlation coefficients between system components. Optimal relationships are found between extraction intensity and ecological indicators, and ecological indicators and health risk measures.

Table 4. Correlation Matrix of Key System Variables

Variable Pair	Correlation Strength
Energy Exploitation ↔ CO_2 Emissions	Strong Positive
Energy Exploitation ↔ Deforestation	Moderate–Strong Positive
Ecological Degradation ↔ Health Risk	Strong Positive
Health Risk ↔ Life Expectancy	Moderate Negative

Figure 4 shows a conceptual systems diagram that shows cause and effect pathways and feedback loops among the state of non-renewable energy exploitation, ecological degradation and environmental health outcomes.

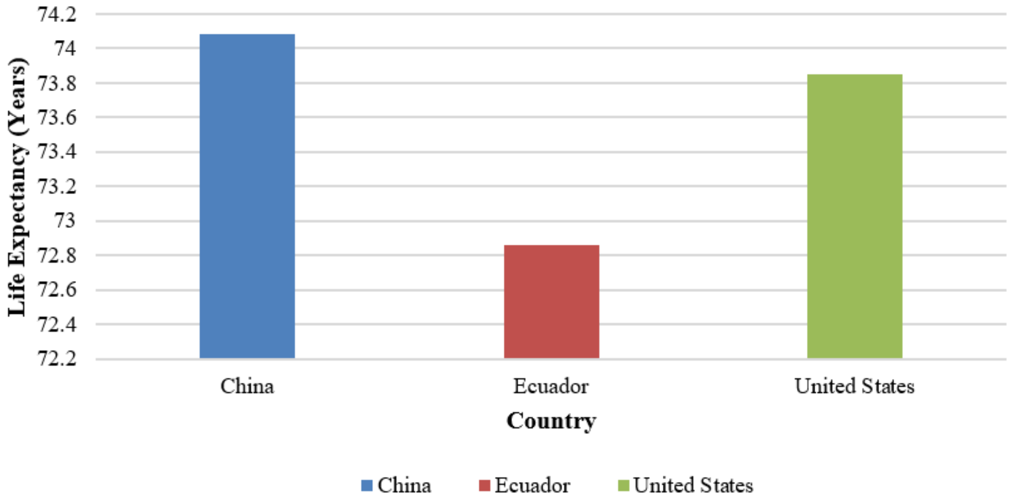

Figure 4. Systems Interaction Pathway Linking Energy Exploitation to Environmental Health

4.5 Comparative Assessment of China, the United States, and Ecuador

In comparison, it is found that even though China and the United States are the largest contributors to world emissions, as well as extraction intensity, the impact on ecology and environmental health is disproportionately greater in Ecuador than the proportion of ecological and environmental health effects in comparison to the level of exploitation. This imbalance underscores the significance of vulnerability in a host country and sensitivity in an ecological system of global energy. On the whole, the findings indicate that the non-renewable energy utilisation is a source of the accumulative ecological pressures, which are being manifested in quantifiable environmental health effects, especially in the environmentally sensitive areas like Ecuador.

5. Discussion

The findings indicate that non-renewable energy use is strongly linked with the ecological degradation in Ecuador, especially deforestation and land-use transformation. The high rate of deforestation in Ecuador compared to the level of extraction fits the picture that extractive infrastructure contributes to an increase in forest degradation and landscape fragmentation in the northeastern Amazon area (Lopez, 2022). These results support the perception that even with relatively low ecological levels of extraction, it is possible to have disproportionate ecological effects in the ecologically sensitive and rich regions of biodiversity. There is also evidence in land-use processes in extractive areas that the indirect pressures, including road expansion and settlement growth, contribute to environmental stress that is more significant than extractive activities themselves. This systemic trend justifies the rationale of landscape-level analysis, as compared to project-level assessment, in the assessment of ecological impacts.

The cumulative exposure pathways that result in observed environmental health outcomes in this study are due to extractive activities. The high levels of environmental health risk in Ecuador are associated with reported alterations in lifestyle, wellbeing, and perceived health risk among indigenous and rural populations exposed to extractive development caused by globalisation (Martinez Tyson et al., 2021). These social aspects put emphasis on the way environmental degradation can be converted into lived health experiences that cannot be quantified in clinical terms. Another important pathway in which extractive activities impact health is water quality degradation. The empirical evidence in the oil-affected areas of Ecuador suggests that the problem of drinking water pollution is linked to higher health risks and a greater awareness of the communities about their exposure to the environment (Maurice et al., 2019). This is in line with the results in the observed correlations between water pollution indicators and health risk indices.

Systems-level relationships as observed in this paper are indicative of intricate social ecological mechanisms that relate resource mining to population well-being. It has been noted that indigenous health is affected by extractive settings in a manner that environmental degradation and social, cultural, and economic determinants of health interact to create accumulated vulnerabilities (Myette and Riva, 2021). This increased sensitivity that is witnessed in Ecuador is, therefore, a manifestation of both the vulnerability of the ecology and the marginalisation of the social group. Environmental issues of justice help in contextualising these results. The past examples with oil exploitation in the Ecuadorian Amazon discuss how the global system of investments may contribute to further negative effects on the environment and restrict the ability of communities to recover, strengthening the asymmetries of risks (Pellegrini et al., 2020).

There is also a wider implication of ecological degradation by non-renewable energy exploitation on disease ecology. Deforestation and disturbance of habitats have been found to drive the changes in the dynamics of disease transmission, which has resulted in the increase of the risk of emerging and endemic diseases (Pongsiri et al., 2009). The ecological trends that were found in this study indicate the possibility of indirect health hazards that would be above traditional measures of pollution. Extractive activities also have an impact on aquatic ecosystems. The presence of heavy metal pollution in the river systems of Ecuador demonstrates the threat to the communities and ecosystem downstream and supports the connection between industrial pollution and environmental health risks (Sánchez-Mateos et al., 2020).

Permanent exposure to oil exploration-related contaminants has been attributed to chronic health consequences such as cancer risks amongst the indigenous population. The scoping reviews of Ecuador have found the same relationships between oil exploitation and high cancer incidence, but the cumulative effect of environmental health problems (Uyttersprot et al., 2022). This information gives a valuable background to the environmental health risk trends that were seen in this study. The larger evaluations of population health problems in oil-producing areas further show how exposure-related health problems persist decades after the primary contamination incidents have occurred (Vargas et al., 2020). This time aspect supports the topicality of longitudinal systems analysis.

The use of a quantitative systems analysis framework in the presented study is consistent with the increasing trend of using the concept of systems dynamics as an effective means of learning the complex health-environment interactions. System dynamics models in the domain of public health have been reviewed and proven to be suitable in terms of capturing feedback loops, delays, and non-linear relationships to determine long-term outcomes (Wang et al., 2021). The current results can be used to explain how these strategies can be applied in the context of environmental health and the extractive industry. The systems approach allows more comprehensive evaluation as compared to the analysis of individual indicators because it incorporates ecological, environmental health, and energy indicators.

The relative incorporation of China and the United States places the experience of Ecuador as part of the wider world energy systems. Tendencies in the mining extraction recorded by world resources appraisals highlight the extent of the non-renewable energy use provided by the leading economies (U.S. Geological Survey, 2025). Equally, the carbon budget considerations of the world show the predominance of large industrialised countries in the emissions of fossil fuels (Global Carbon Project, 2024). The use of satellites to monitor forests also brings into context the dynamics of deforestation in Ecuador as a part of land-cover change dynamics at the global scale (Hansen et al., 2013), and the life expectancy indicators offer a standardised prism through which results of environmental health among nations can be interpreted (World Bank, 2025).

On the whole, the results indicate the necessity of policies considering the systemic interactions of energy exploitation, ecological degradation, and environmental health. In the case of Ecuador, it is necessary not only to regulate the extractive activities but also to be aware of the structural weaknesses that are inherent in the world energy systems to mitigate environmental health risks. More attempts to apply systems-based methods to finer-scaled spatial data and community-level health metrics could be developed in future studies to improve the ability to inform equitable and sustainable governance of energy.

6. Conclusion

The given work utilised a quantitative systems analysis to investigate the ecological and environmental health impacts that are discussed with reference to the exploitation of non-renewable energy resources by China and the United States, with specific reference to Ecuador as a host country under threat. The analysis showed considerable interdependences between extractive activities and deforestation, pollution and high environmental health risks by incorporating energy extraction, ecological degradation, and environmental health outcomes. The outcomes show the extreme disproportionate ecological and health environmental impacts within the scale of exploitation of Ecuador, in comparison to China and the United States, where the cumulative and indirect effects, including land-use change, water contamination, and air pollution, translate into the long-term effects of health, in the patterns of environmental health risks and trends of life expectancy. Such results highlight the need to abandon the linear or sector-based evaluation in favour of the holistic analysis schemes that can accommodate the feedback loops and delayed impacts. Policy-wise, the research highlights the necessity of combined governance policies that would tackle environmental protection, the health of the population, and the development of energy sources at the same time. Future studies must advance this system framework with more detailed spatial information and neighbourhood health outcomes to enhance evidence-based decision-making to support sustainable and equitable energy transitions.

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