CO_2 Emission Intensity, GHG Dynamics by Economic Sectors and the Impact of Natural Disasters on Population Health in Romania

Carmelia Mariana Bălănică Dragomir[1*)], Cecilia Șerban[2)], Mirela Crețu[3)], Marian Tiberiu Coadă[4)], Geanina Marcela Podaru[5)], Iulia Graur[6)], Ciprian Cuzmin[7)], Maricica Stoica[8)]

[1*)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: carmelia.dragomir@ugal.ro; https://orcid.org/0000-0001-7743-928X
[2)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: cecilia.serban@ugal.ro; https://orcid.org/0000-0002-6754-7954
[3)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: mirela.cretu@ugal.ro; https://orcid.org/0000-0003-1269-4647
[4)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: Marian.Coada@ugal.ro; https://orcid.org/0000-0002-3107-1595
[5)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: geanina.podaru@ugal.ro; https://orcid.org/0009-0000-5698-350X
[6)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: iulia.graur@ugal.ro; https://orcid.org/0000-0003-1740-4338
[7)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: ciprian.cuzmin@ugal.ro; https://orcid.org/0000-0002-2830-6728
[8)] "Dunărea de Jos" University of Galați, Domnească Street, no. 47, Galați, 800008, Romania; email: Maricica.Stoica@ugal.ro; https://orcid.org/0000-0001-7315-1860

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Abstract

Climate change and the risks associated with natural disasters exert simultaneous pressures on the economy and public health. This study leverages the statistical series of the National Institute of Statistics for Romania, analyzing three dimensions: (i) CO_2 emission intensity relative to value added, (ii) greenhouse gases (GHG) emissions by economic sectors, and (iii) public health outcomes expressed as the number of deaths and injuries attributed to natural disasters. Overall, the intensity of CO_2 emissions decreased from 0.12 thousand tons CO_2 equivalent / million lei in 2008 to 0.06 in 2023 (a halving of the intensity) — suggesting efficiency gains and/or structural changes in the economy. In parallel, total GHG emissions decreased from 136,004.23 thousand tons CO_2 equivalent (2008) to 82,745.26 thousand tons CO_2 equivalent (2023), which corresponds to a reduction of ~39%. In 2023, the largest sectoral contributions came from Agriculture, forestry and fishing (20,003.03), Manufacturing (18,465.06) and Production and supply of electricity, heat, gas, hot water and air conditioning (16,395.37 thousand tons CO_2 equivalent); Cumulatively, these three sectors accounted for approximately 66% of total emissions in the economy. In terms of health impact, the indicator of deaths and injuries attributed to natural disasters per 100,000 inhabitants remained at very low levels, with higher point values in 2012 (0.08) and 2018 (0.067), respectively 0.052 in 2024; these values indicate a relatively low but persistent burden, potentially influenced by the frequency and severity of natural phenomena and the institutional response capacity. Methodologically, the study combines trend analysis (2008–2024), assessment of sectoral contributions and descriptive correlation between performance in reducing the intensity/volume of emissions and the consequences on public health. The results motivate the strengthening of sector-targeted decarbonization policies, together with investments in adaptation and disaster risk management, to mitigate human and economic losses in a changing climate context.

Keywords: *greenhouse gases; disaster risk management; economy and public health; decarbonization policies*

1. Introduction

Assessing the dynamics of greenhouse gas (GHG) emissions is an essential element in monitoring Romania's status in managing this challenge, but specially to observe the impact that climate change has on the health or even the lives of the population due to the risk of natural disasters, more specifically floods. The period 2008–2024 covers both stages of economic growth and episodes of structural contraction, providing a valuable framework for analysing sectoral changes. The data used in this paper comes from National Institute of Statistics from Romania and include: greenhouse gas emissions by economic activities from the top 6 activities of the national economy plus other activities with lower impact (Agriculture, forestry and fishing; Extractive industry; Manufacturing industry; Production and supply of electricity, heat, gas, hot water and air conditioning; Water distribution; sanitation, waste management, decontamination activities; Construction) with values expressed in thousands of tonnes of CO_2 equivalent. In addition to these data, in this article we also used: Affected persons (deaths + injuries); CO_2 intensity (thousand t CO_2e / million RON); Anti-hail area (ha); Intervention's count (Number of IGSU - Inspectorate for Emergency Situations) interventions to dangerous weather phenomena); Flood impact (affected localities, affected counties, human casualties).

According to IPCC (Intergovernmental Panel on Climate Change. Climate Change) confirms that anthropogenic intervention since the Industrial Revolution has led to a major alteration of biogeochemical cycles. Emissions resulting from human activities have led to a significant increase in greenhouse gas concentrations in the atmosphere: carbon dioxide (CO_2) has increased by

approximately 50% and methane (CH_4) by over 150% compared to pre-industrial levels [1]. These values far exceed natural fluctuations over the last hundreds of thousands of years, constituting the scientific basis for anthropogenic global warming.

The significant increase in economic activity, the upward dynamics of the population, the expansion of infrastructure and the accelerated process of urbanization have generated considerable pressures on mobility systems. Added to these are the increase in disposable income, the diversification of social and recreational activities, as well as the rapid proliferation of the private car. At the same time, the unequal distribution of material and energy resources accentuates the existing imbalances. The convergence of these factors has led to a substantial increase in the demand for transport [2].

The risks associated with extreme weather and climate phenomena result from the interaction between the nature of the physical hazard (such as wind intensity or precipitation amount), the level of exposure of the population and infrastructure, the vulnerability of individuals and communities, and the institutional and social capacity to prepare for, respond to, and recover from extreme events. Severe impacts on a community or region do not always require the occurrence of an extreme weather event; even a moderate-intensity weather event can have disproportionately severe consequences when it occurs in a context characterized by high vulnerability of the population, infrastructure or support systems [3]. Similarly, the reverse is also true: an extreme weather event can have limited effects when communities have adequate levels of preparedness, response capacity and effective adaptation mechanisms. Thus, the severity of impacts is not determined solely by the magnitude of the hazard, but by the interaction between hazard, exposure, vulnerability and the adaptive capacity of socio-ecological structures [4].

Extreme weather events and natural disasters have an impact that goes beyond infrastructure damage; they can have profound effects on the health and well-being of individuals and have catastrophic consequences for communities and health systems. Exposure to such events can lead to a range of physical effects, such as heat exhaustion, trauma from severe storms, or respiratory illnesses associated with mould growth following flooding. In addition to these immediate consequences, there can also be long-term mental health effects, including post-traumatic stress, anxiety, or depression, which increase the vulnerability of affected populations. [5].

Rising carbon dioxide (CO_2) concentrations are the main driver of extreme weather events on a global scale. Recent climate reports show that greenhouse gas levels have continued to rise, contributing to the highest global average temperature ever recorded in 2024, a trend closely linked to the increase in extreme events such as storms, heat waves and heavy rainfall. These atmospheric conditions created by excess CO_2 lead to an atmosphere with a greater capacity to retain water vapor, thus favouring the formation of much more violent rainfall and severe flooding episodes. [6]

A series of recent analyses highlight that floods are increasing in both frequency and severity. In 2025, a single flash flood event caused 135 deaths, making it the deadliest such event in the United States in the last five decades. The economic impact of floods is growing, with recent estimates indicating annual costs ranging from $179.8 billion to $496 billion, when infrastructure damage, ecosystem losses, and health impacts are included. Vulnerable populations—including low-income communities, minority groups, and underprepared regions—are disproportionately affected, confirming the link between hazard, exposure, and social vulnerability. [7]

At the same time, data from the World Meteorological Organization indicates that the number of people affected by climate-related disasters continues to grow rapidly. In 2024, more than 150 major climate-related disasters were reported, many of which displaced more than 800,000 people, a record for the past two decades. This trend demonstrates that extreme events, amplified by climate change, are having increasingly severe consequences on people's health, well-being, and economic security. [8]

To limit the effects of such phenomena, countries such as Romania have actively developed and expanded hail suppression systems as climate adaptation measures. Hail suppression systems rely on advanced meteorological monitoring and cloud seeding interventions with silver iodide, designed to reduce the size and kinetic energy of hail. Radar studies of 51 seeded storms between 2017 and 2022 show a 10–15% decrease in hail parameters after the intervention, as well as a reduction in areas with dangerous kinetic energy (>300 J/m²) within protected areas. The expansion of this system is also supported by new public policies, with Romania adopting a national strategy in 2024 that includes active atmospheric interventions as an official part of climate change adaptation measures. [9]

The purpose of this article is to examine, in an integrated and multidimensional manner, the connections between greenhouse gas emissions generated by economic activities and a series of indicators that reflect the socio-economic impact of extreme weather events. The analysis aims to explore the relationships between the number of people affected (including deaths and injuries), the intensity of CO_2 emissions reported to the economic value (thousand t CO_2e per million RON), the area protected by anti-hail systems (ha) and the number of interventions carried out by General Inspectorate for Emergency Situations (IGSU) in response to dangerous weather events. The study also investigates how floods, through variables such as affected localities and counties or human losses, correlate with climate pressures and structural vulnerabilities. Through this complex approach, the article aims to highlight the critical interdependencies between anthropogenic climate pressure, territorial exposure and institutional response capacity, thus contributing to the substantiation of evidence-based climate risk adaptation and reduction strategies.

2. Materials and Methods

The analysis presented in this study is based entirely on official data provided by the National Institute of Statistics (INS), through the TEMPO-Online database, which is the main national statistical reporting system. TEMPO provides harmonized time series, methodologically coherent and subject to a rigorous verification process, which ensures the robustness and comparability of the datasets used. For the period 2008–2024, exclusively data from thematic matrices related to the following areas were extracted and processed: greenhouse gas emissions, CO_2 emission intensity, flood impact, people affected by natural disasters, interventions by IGSU and areas protected by anti-hail systems. The indicators on greenhouse gas emissions by economic activities and CO_2 emission intensity were taken from the INS matrices dedicated to accounting for air emissions, in accordance with European standards on GHG reporting. These indicators provide information on both the absolute level of emissions and the efficiency of emissions relative to economic performance, allowing an integrated assessment of the climate pressure exerted by economic activities.

Data on the number of people affected by natural disasters (deaths and injuries) and the number of IGSU interventions caused by dangerous meteorological phenomena were extracted from the INS matrices that aggregate the institutional reports of the operational structures. They represent essential indicators for quantifying the human impact and the pressure on institutional response capacities.

To assess the hydrological impact, data on annual damage caused by floods were used, including variables such as the number of localities and counties affected, the length of damaged infrastructure and the number of human victims. This information allows for a detailed characterization of the territorial exposure and severity of hydrometeorological events.

Regarding the areas protected by hail protection systems, the analysis was based on dedicated indicators from TEMPO, which quantify the annual evolution of the atmospheric intervention infrastructure. These indicators reflect institutional investments in the capacity to adapt

to severe weather phenomena.

Methodologically, the study used descriptive and inferential statistical techniques to analyse the relationships between climatic, economic and operational indicators. Data processing involved normalization, multi-indicator integration and temporal comparison, in order to identify trends, correlations and systemic dynamics. All processing stages respected good practices regarding the reproducibility of results and analytical transparency, using exclusively data officially validated by the INS [10-15]. For an easier understanding of the dataset used, we have organized the information in Table 1.

Tab. 1. TEMPO Matrices Table

Indicator	TEMPO Matrix	Code	Source
Greenhouse gas emissions by economic activities	GHG Emissions by NACE Rev.2	ZAB1311	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table
Affected persons (deaths + injuries)	People affected by disasters	TOM1314	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table
CO_2 intensity	CO2 Emissions Intensity	TPC1342	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table
Anti-hail area (ha)	Anti-hail protected area	TOR1321	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table
IGSU interventions (weather events)	IGSU interventions for hazardous phenomena	TOS1322	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table
Flood impact	Annual flood damage	TON1315	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table
Greenhouse gas emissions by economic activities	GHG Emissions by NACE Rev.2	ZAB1311	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table

[a] If you need, notes are referenced using alpha superscripts

The statistical analysis carried out in this study followed an integrated approach, aimed at capturing both the individual behaviour of each indicator and the structural relationships between the variables. In a first step, a comprehensive set of descriptive statistics was applied to all time series, which included the determination of the number of observations, the mean and median, the standard deviation (estimated with ddof = 1), as well as the extremes (minimum and maximum values) and the Q25 and Q75 quartiles. In addition, the coefficient of variation was calculated, used to assess the relative dispersion of each indicator and to allow comparisons between variables with different measurement scales. These statistics provided a detailed understanding of the internal structure of the series and formed the basis for subsequent interpretation.

In order to examine the temporal evolution of the indicators in the analysed interval, a trend analysis was performed by estimating OLS linear regression models, in which the annual value of each variable was expressed as a function of year. This procedure allowed the identification of the direction and magnitude of long-term changes, with the estimated annual slope (slope/year) representing an approximation of the average rate of change. In parallel, the Pearson coefficient (r) and the Spearman coefficient (ρ) were calculated for each regression, along with their statistical significance values. Pearson provided information on the intensity of the linear relationship between time and indicator, while Spearman allowed the capture of monotonic relationships, even in the absence of strict linearity. The conventional significance threshold of $p < 0.05$ was used in the interpretation of the results, which ensures a rigorous level of confidence in the identification of statistical trends associated with each indicator. To assess the interdependencies between variables, the study included an in-depth analysis of bivariate correlations, using both the Pearson coefficient and the Spearman coefficient. The resulting correlation matrices allowed for the simultaneous observation of the intensity and direction of the relationships, from both a linear and non-normalized perspective, thus providing a complete picture of how various climatic, economic or operational indicators influence each other. To facilitate visual interpretation, the Pearson results were also represented in the form of a heatmap, quickly highlighting pairs of variables that exhibit strong associations.

To complete the analyses, for indicators with structural relevance, the compound annual growth rate (CAGR) was calculated, which captures the average rate of evolution over the entire period 2008–2024. This method is particularly useful for variables with progressive evolutions or long-term trends, providing a synthetic and comparable measure of growth or decrease over time. The calculation was performed according to the standard formula:

$$\boldsymbol{CAGR} = \left(\frac{\boldsymbol{Value_{2024}}}{\boldsymbol{Value_{2008}}}\right)^{\frac{1}{2024-2008}} - \mathbf{1} \quad (1)$$

which allows the transformation of irregular annual variations into a single value representative of the entire interval.

By combining these methods – from descriptive statistics to linear regressions, bivariate correlations and composite indicators – the analysis managed to provide a clear and robust picture of the dynamics of the studied phenomena, as well as of the links between climatic, economic and operational variables. The methodological texture thus constructed ensures both analytical rigor and interpretative relevance for the integrated assessment of risks and trends associated with the analysed data.

3. Results and Discussions

The evolution of greenhouse gas emissions in Romania between 2008 and 2024 highlights a broad and constant process of reducing emissions intensity across the economy, a process confirmed by all sectoral series reported in the national database. In 2008, total emissions were approximately 136,004 thousand tonnes of CO_2 equivalent, while in 2024 they reach only 82,743 thousand tonnes of CO_2 equivalent, which represents a decrease of almost 40% from the initial level. This reduction is significant, both in comparative terms and in relation to the economic structure of the country, and is systematically documented in the sectoral data and in the summary of annual totals calculated for this period.

The annual analysis highlights two moments of strong inflection. The first is the year 2009, when total emissions drop sharply by over 22,000 thousand tons of CO_2e compared to the previous year, a decline that reflects the impact of the economic contraction that set in after the global financial crisis. The second moment is observed in 2011, when the total temporarily increases by about 7,123 thousand tons of CO_2e, an increase influenced by the return of industrial activity. The subsequent series shows, however, that the dominant trend is a downward one, with local minima in 2020 and a continuation of the decrease until 2024.

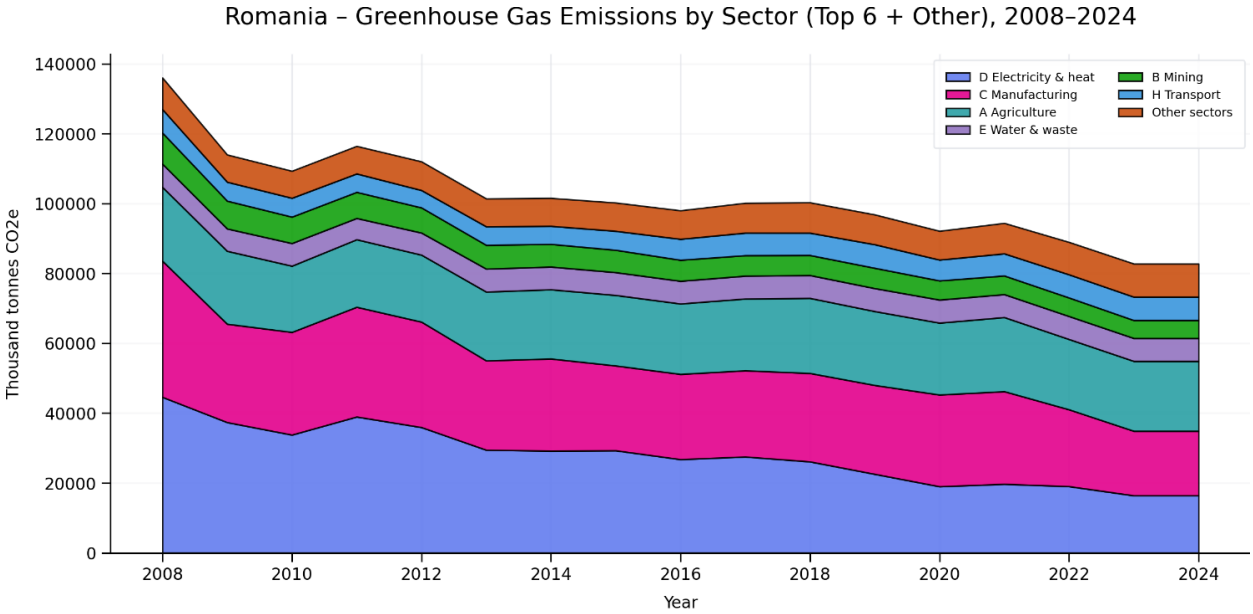

Fig. 1. The GHGs emissions by economic sectors in Romania, 2008-2024

The most significant contribution to the total reduction comes from the energy sector, defined in the national statistical nomenclature as "Production and supply of electricity and heat, gas, hot water and air conditioning". This sector records a decrease of over 28,000 thousand tons of CO_2e between 2008 and 2024, being by far the main generator of the total decrease. At the same time, the industrial sector, including the manufacturing industry, adds an additional reduction of over 20,000 thousand tons of CO_2e, which indicates a profound structural transformation in both energy consumption and the productive technologies used in the economy. These trends are clearly visible in the sectoral series in the file provided. On the other hand, certain sectors change their relative share in total emissions, even if the absolute reduction is not spectacular. Agriculture, for example, increases its share from approximately 15.5% of total emissions in 2008 to over 24% in 2024, thus becoming the sector with the largest relative contribution to the structure of national emissions. This evolution does not necessarily imply an absolute increase in agricultural emissions, but mainly reflects the steep and constant decrease in emissions from energy and industry. Other sectors such as transport, waste management, professional services or trade also change their share, some showing slight absolute increases, but generally remaining at much lower values compared to the large industrial sectors.

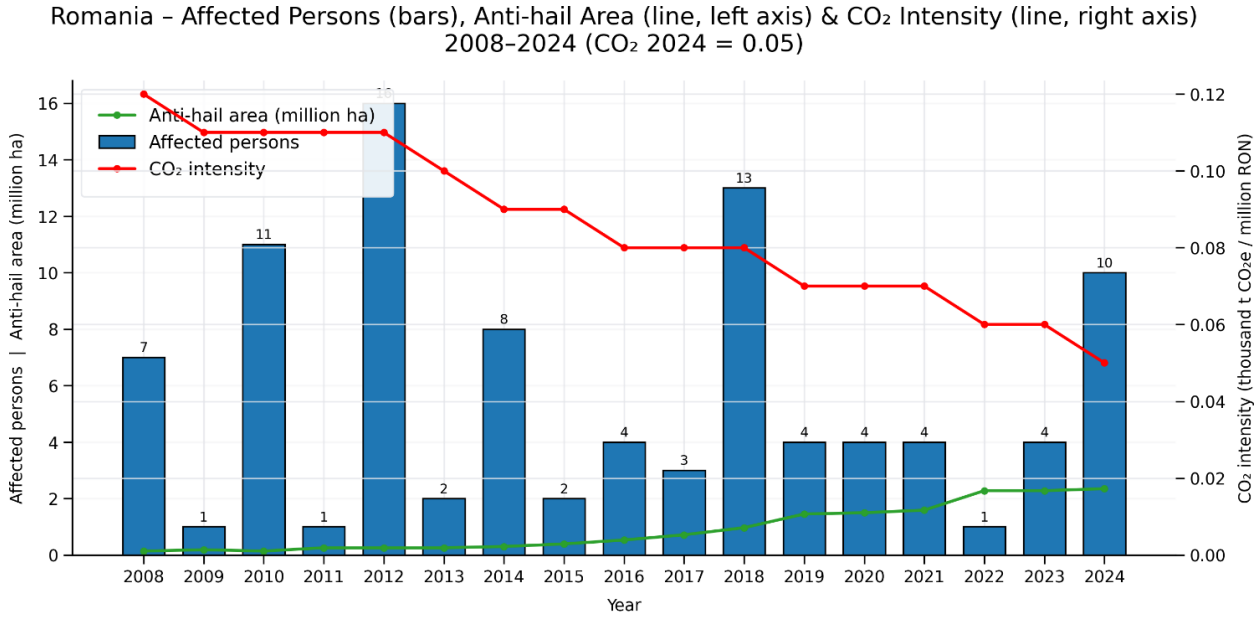

Fig. 2. The interdependence between Affected persons – bars; Anti-hail area – line on the left axis; CO_2 intensity – line on the right axis), in Romania for 2008–2024

Taken as a whole, the period 2008–2024 describes a coherent trajectory of structural decarbonization of the Romanian economy. The reduction in emissions from the energy sector suggests both the effects of infrastructure modernization and changes in the energy mix, as well as increased efficiency in energy production and distribution. At the same time, the manufacturing industry has undergone a process of efficiency improvement and restructuring, contributing substantially to the reduction of the national total. In contrast, the increase in the share of agriculture and transport indicates that, as large and intensively polluting sectors reduce their footprint, the responsibility for future reductions will inevitably shift to non-industrialized sectors, with diffuse emissions and much more dependent on locally applied behaviours, practices and policies.

The longitudinal analysis highlights three distinct trajectories. First, the annual number of people affected (deaths + injuries) remains at extremely low levels throughout the interval, with a cumulative total of 95 people in 17 years, corresponding to an average of ~5.6 people/year and a median of 4 people/year; extreme values occur in 2012 (16 people) and 2024 (10 people), and minima (of 1 person) are recorded in 2009, 2011 and 2022. This discrete and weak amplitude distribution confirms the episodic nature of human-impacted events, without a robust directional trend over the period (figure 2).

Second, the area protected by hail protection systems is experiencing a massive and almost monotonous expansion, from ~138,000 ha in 2008 to ~2,346,000 ha in 2024 (+2,208,000 ha), which is equivalent to an increase of ~17× compared to the initial level (≈ +1,600%, CAGR ≈ 19%/year over the 16 years). This dynamic signals an accelerated adaptation program in agriculture, coherent with the intensification of convective risks and with sustained public investments in protection infrastructure.

Thirdly, the intensity of CO_2 emissions at the economy level is reduced substantially, from ~0.12 thousand t CO_2e/million lei in 2008 to ~0.05–0.06 in 2023–2024, which represents a decline of ~58% over the entire interval (Compound Annual Growth Rate CAGR ≈ −5%/year). This sustained decrease indicates a structural decarbonization, through improvements in energy efficiency, industrial technological modernization and changes in the sectoral composition of the economy, in line with the directions of climate policy at the European level.

Viewed in an integrated manner, the results show a clear divergence between the three dimensions: while Anti-hail area increases rapidly (~138,000 → ~2,346,000 ha), and CO_2 intensity decreases strongly (~0.12 → ~0.05–0.06 thousand t CO_2e/million lei), Affected persons remains low and irregular (median 4; maximum 16 in 2012; minimum 1 in 2009/2011/2022), without a visible co-evolution with the other series. In substantial terms, anti-hail mainly mitigates agricultural economic risk, and the reduction of CO_2 intensity reflects macroeconomic efficiency; however, the annual human impact of hazards remains dependent on local events and year-specific hydro-meteorological conditions, not on structural trends at the economy or infrastructure scale.

Consequently, the results support the idea that Romania has made significant progress both in mitigation (decreasing CO_2 intensity) and adaptation (expanding anti-hail surfaces), while the direct risk to the population has remained very low numerically and inconsistent, reflecting isolated hazards rather than slow and systemic processes. This configuration suggests that interventions aimed at reducing human vulnerability should continue to target local measures (early warning, surface water management, small infrastructure works), complementary to sectoral investments and structural transformations of the economy.

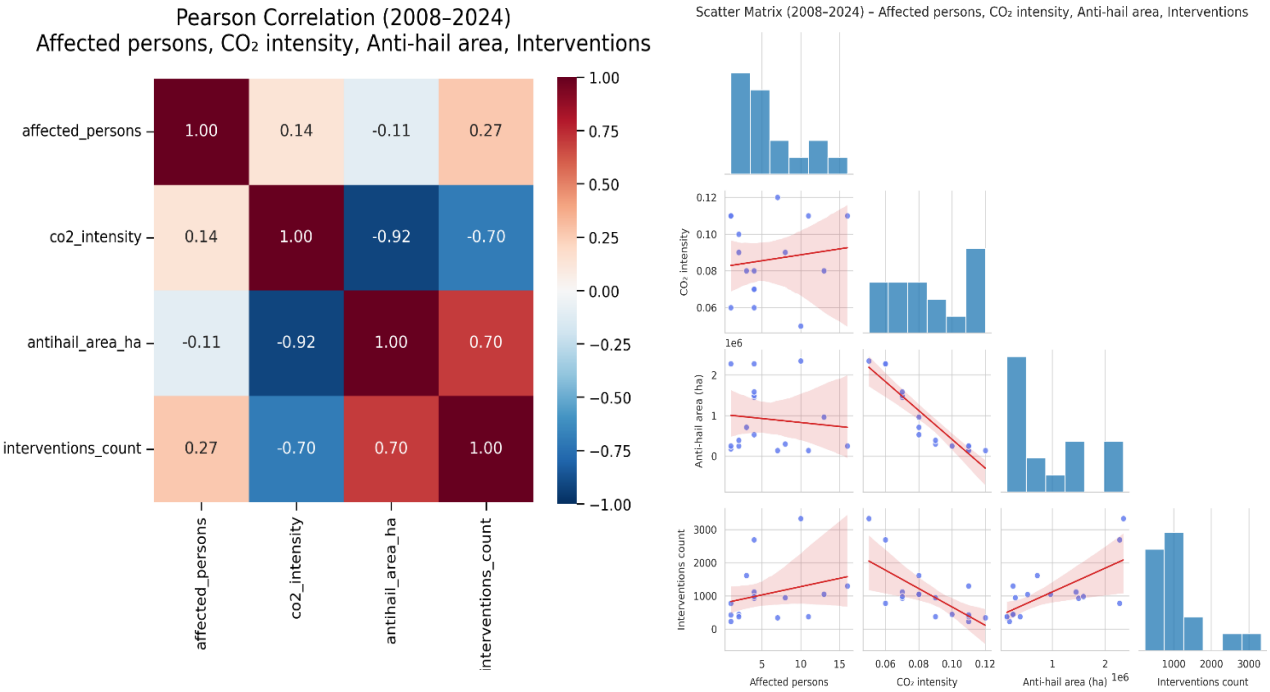

Fig. 3. Pearson correlation and scatter matrix for four parameters: Affected persons (deaths + injuries); CO_2 intensity (thousand t CO_2e / million RON); Anti-hail area (ha); Intervention's count (Number of IGSU interventions to dangerous weather phenomena) in Romania for 2008–2024

The integrated statistical analysis for the period 2008–2024 highlights distinct dynamics of the four indicators studied – Affected persons, CO_2 intensity, Anti-hail area and Intervention's count – as well as significant structural relationships between them. Descriptive data indicate that the human impact of hazardous weather phenomena remains very low, with annual values ranging from 1 to 16 people and a median of 4 people/year, confirming the discrete and episodic nature of this series. In contrast, the other variables show pronounced dynamics: anti-hail area increases rapidly throughout the period, reaching over 2.3 million ha in 2024, and CO_2 intensity registers a constant decline to 0.05 in the same year.

The relationships between the variables are clearly reflected in the correlation matrix. CO_2 intensity and anti-hail area show a very strong negative correlation (Pearson $r = -0.920$, $p < 0.001$; Spearman $\rho = -0.982$), indicating opposite temporal developments: the reduction of emission intensity is associated with the expansion of anti-hail protection infrastructure. This robust relationship, confirmed by both parametric and non-parametric correlation, suggests converging structural processes in the direction of adaptation and decarbonization. Also, a strong positive association is observed between anti-hail area and interventions count (Pearson $r = 0.699$, $p \approx 0.0018$; Spearman $\rho \approx 0.673$), while the relationship between CO_2 intensity and interventions count is negative and significant (Pearson $r = -0.702$, $p \approx 0.0017$; Spearman $\rho \approx -0.654$). These correlations suggest that in years characterized by low emission intensity and expansion of anti-hail systems, episodes with a high number of IGSU interventions also occurred, although the causal interpretation requires caution.

In contrast, the Affected persons variable does not show any significant correlation with the other three series (all $p > 0.05$), a fact

confirmed by both the Pearson and Spearman coefficients. This lack of association, accompanied by the discrete distribution visible in the scatter matrix, indicates that the number of people affected is mainly determined by isolated atmospheric events, not by structural trends in the economy, infrastructure or hazardous weather phenomena as a whole.

Visually, these relationships are supported by the correlation heatmap (which highlights the strong block CO_2–Anti-hail–Interventions) and by the scatter matrix that clearly shows negative slopes between CO_2 intensity and Anti-hail area, and positive slopes between Interventions and Anti-hail area. In contrast, the point clouds in the panels associated with Affected persons remain dispersed, without a linear shape, confirming the statistical independence of this series. Overall, the results highlight a double structural transformation – the reduction of CO_2 intensity and the accelerated growth of anti-hail protected areas – concomitant with an increase in IGSU operational activity (interventions), but without an increase in the direct impact on the population. This statistical divergence suggests that, although hazardous meteorological phenomena may become more frequent or more intense (reflected by interventions), the effects on the population remain limited, probably due to protection, warning and response mechanisms. The structural indicators (Anti-hail and CO_2) thus seem to reflect strategic processes of adaptation and climate transition, while the impact on the population continues to depend predominantly on the local and stochastic nature of the hazards.

Overall, the results indicate a relative stability of the impact on the population (small numbers, no trend), concomitant with major progress in agricultural adaptation (expansion of hail-protected areas) and climate mitigation (decrease in CO_2 intensity). This configuration suggests that reducing human vulnerability still requires local hazard-specific measures (early warning, drainage works, water management), in parallel with sectoral investments and structural transformations of the economy.

The figure 4 integrates the relative evolutions of the four analysed indicators – CO_2 intensity and three measures of flood impact (affected localities, affected counties, human casualties) – by indexing all series to 2008=100, for comparability on a single axis.

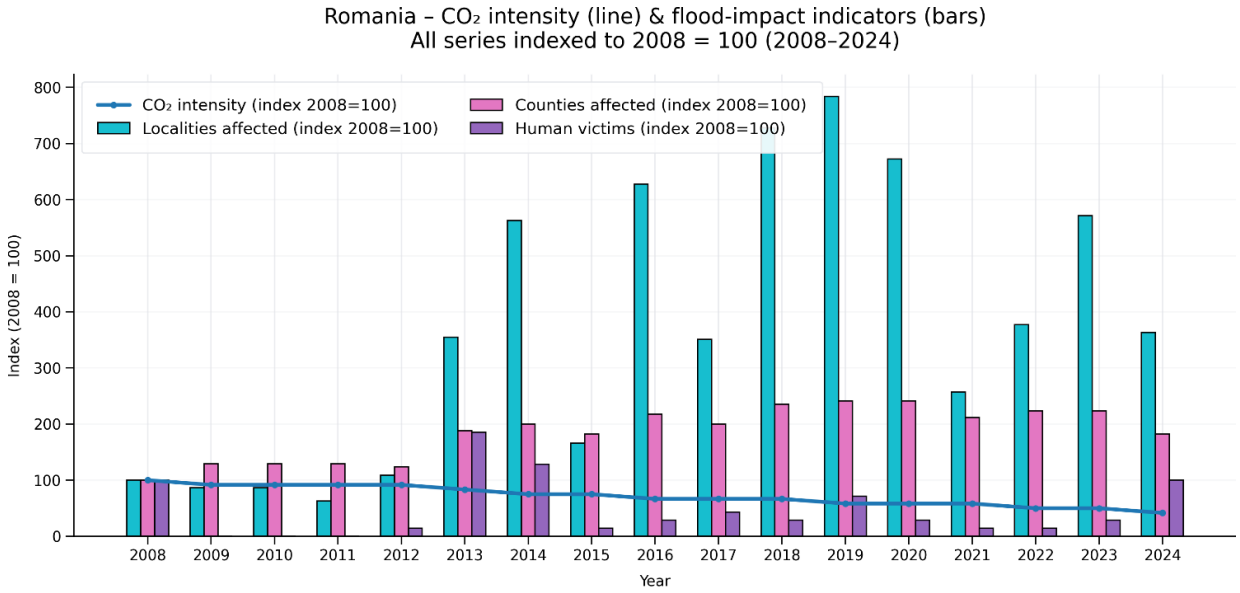

Fig. 4. The evolution of CO_2 intensity and three measures of flood impact (affected localities, affected counties, human casualties), in Romania for 2008–2024

The graphic representation in the figure clearly shows that, over the period 2008–2024, the intensity of CO_2 emissions follows a robust downward trajectory, falling from the benchmark of 100 (2008) to ≈41.7 in 2024 (~58–60% reduction), with intermediate benchmarks of ≈75.0 in 2014, ≈66.7 in 2016, ≈58.3 in 2019 and ≈50.0 in 2023 (period average ≈71.6, median ≈66.7). This almost monotonic decrease, captured by the blue line, is compatible with a structural decarbonization process – a cumulative effect of energy efficiency, technological changes and sectoral adjustments –, without persistent reversals of the long-term trend.

In contrast, the flood impact indicators represented by bars have an episodic profile marked by large oscillations. The affected localities increase in certain years to substantial multiples of the benchmark: ≈562.8 in 2014, ≈627.8 in 2016, ≈784.1 (maximum) in 2019 and ≈571.5 in 2023, followed by rapid adjustments (for example, ≈363.5 in 2024; the minimum of the period occurs in 2011, ≈62.6). The mean and median located at ≈368.1 and ≈354.6, respectively, indicate a pronouncedly asymmetric distribution, "pulled" upwards by years with very high impact. The affected counties have more moderate but persistent variations above the benchmark: between ≈200–240 in the 2017–2021 period (maximum in 2019, ≈241.2), with a level of ≈182.4 in 2024 (mean ≈185.8, median 200.0), suggesting recurrent regional expansions of the events, although less volatile than the number of localities involved. Finally, human casualties remain at very low levels (mean ≈47.1, median 28.6), with zero minimums (e.g. 2009) and punctual peaks (maximum in 2013, ≈185.7; 2014 ≈128.6; 2024 ≈100.0), which suggests that although the phenomena can severely affect infrastructure or territory in a given year, the direct impact on the population is mitigated by warning and intervention capacities.

Taken together, these developments highlight a decoupling between the structural downward trend of CO_2 intensity (slow signal, multiannual) and the annual oscillations of flood impacts (fast signals, event-driven). While decarbonisation progresses gradually, the peaks of impact remain conditioned by hydro-meteorological variability and local hazard characteristics. From an applied perspective, the figure supports a dual strategy: continuing and accelerating mitigation (to maintain the downward slope of emissions intensity) and, simultaneously, strengthening local adaptation (hydrotechnical infrastructure, water management, operational plans and civil protection) capable of cushioning high-impact episodes when they occur.

To assess the relationship between CO_2 intensity and flood impact indicators – affected localities, affected counties and human casualties – we applied both bivariate correlations (Pearson and Spearman) and partial correlations, controlling for the effect of the variable “year”, so that we can distinguish between associations generated by the temporal trend and real underlying relationships. The full results are summarized in the statistical table obtained by analysing the data for the period 2008–2024, figure 5.

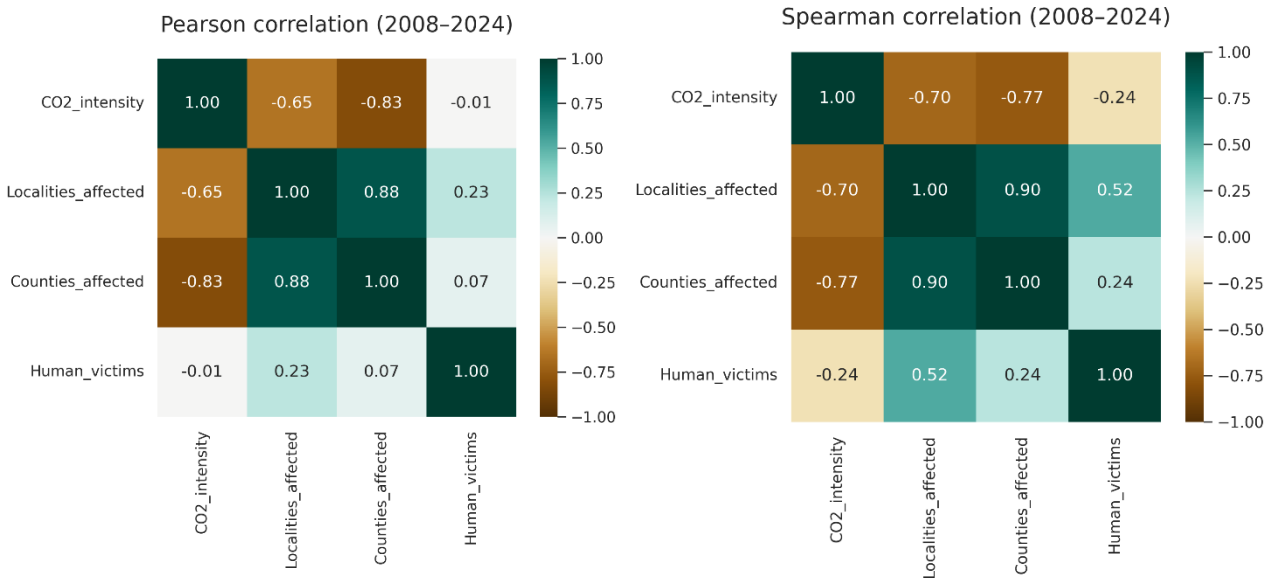

Fig. 5. Pearson and Spearman correlation between CO_2 intensity and three measures of flood impact (affected localities, affected counties, human casualties), in Romania for 2008–2024

The statistical analysis indicates statistically significant negative associations between CO_2 intensity and flood-affected localities (Pearson $r = -0.653$, $p = 0.0044$; Spearman $\rho = -0.704$, $p = 0.0016$), as well as between CO_2 intensity and affected counties (Pearson $r = -0.826$, $p < 0.001$; Spearman $\rho = -0.766$, $p < 0.001$). In simple terms, in years with lower emission intensity, the number of affected localities and counties tends to be higher. At a descriptive level, this relationship visually overlaps with the dynamics of the two types of variables: CO_2 intensity decreases steadily between 2008 and 2024, while impact indicators show recurring peaks in 2014, 2016, 2019 and 2023 – years in which many of the indexed values for affected localities exceed the 2008 benchmark by five to almost eight times. However, this relationship cannot be interpreted as a direct one. The crude correlations largely reflect the effect of time, given that CO_2 intensity has an almost linear downward trend, while impact indicators show extreme episodes in recent periods. Once the "year" effect is controlled, the partial correlations lose their statistical significance: for localities, $r = -0.374$ ($p = 0.139$), and for counties $r = -0.324$ ($p = 0.205$). This result shows that the association between the decrease in emissions and the increase in flood impact does not reflect a causal link, but rather the superposition of a downward structural trend (CO_2 intensity) on an event-driven phenomenon, with determining variations in years with accentuated hydro-meteorological hazards.

In contrast, for human victims, no type of significant correlation is observed, neither in the raw data (Pearson $r = -0.008$, $p = 0.977$), nor after controlling for the temporal effect ($r = -0.179$, $p = 0.492$). This reflects both the low number of victims in most years and the discrete, discontinuous nature of this series, which does not align with any observable long-term pattern in emissions dynamics.

Overall, the results indicate that there is no structural correlation between CO_2 emission intensity and annual flood impact, once the common effect of time is removed. Crude correlations may suggest an inverse relationship, but this relationship disappears completely in the partial analysis, confirming that the two categories of variables are driven by fundamentally different processes:

CO_2 intensity reflects slow, cumulative economic and technological transformations, while the impact of floods is determined by interannual climate variability, extreme hazards and local hydrological conditions that are difficult to predict. Therefore, the correct interpretation is that emission reductions and fluctuations in flood impact are not linked by direct mechanisms, and robust statistical analysis shows that the relationship between them is only an appearance generated by the superposition of distinct temporal developments.

4. Conclusion

The integrated analysis of data for the period 2008–2024 highlights the existence of important structural transformations in terms of both the institutional response to hazardous weather phenomena and the evolution of climate indicators and protection infrastructure. The results show a systematic divergence between the evolution of structural factors and the direct impact on the population. Thus, while the area protected by anti-hail systems has registered a substantial and continuous increase, and the intensity of CO_2 emissions has followed a consistent downward trajectory, the number of people affected has remained at an extremely low level, with minimal annual variations and without a predictable pattern. The correlations identified between the structural variables suggest strong and coherent relationships: the decrease in CO_2 intensity is significantly associated with the expansion of anti-hail systems, indicating a simultaneous evolution of climate mitigation and adaptation measures. Also, the number of IGSU interventions shows significant associations with both structural indicators, potentially reflecting an increase in the frequency or complexity of hazardous weather phenomena. However, the impact on the population remains uncorrelated with these determinants, confirming that local factors, event specificity and the efficiency of warning and intervention systems are critical determinants for the protection of life.

From the perspective of the structure of emissions by sector, the cumulative representation over the entire interval shows that a small number of sectors concentrate the major share of emissions. Specifically, the energy and industrial sectors (such as Electricity & heat supply, Manufacturing) are among the dominant contributors to the cumulative emissions 2008–2024, while other sectors (e.g. Transport, Agriculture) contribute substantially, but with different orders of magnitude, according to the "Top 8 + Other sectors" in the pie chart and the related dataset. This concentration of emissions in a few branches remains relevant for targeting public policy interventions.

Regarding the dynamics 2008 vs 2024 by sector, the graphical comparisons highlight a pronounced reduction in emissions in the energy sectors and in certain industrial branches, in line with the decarbonization trend of economic intensity observed at the aggregate level; At the same time, relative repositioning of sectors such as Transport or Agriculture is observed, with specific variations in their technological profile

and final demand. These changes suggest technological and efficiency advances in heavy sectors, but also persistent pressures from activities with increasing mobility/final energy demand, which requires targeted policies on each value chain.

The analysis for the period 2008–2024 shows that there is no structural correlation between the intensity of CO_2 emissions and annual flood impact indicators; the negative links in the raw series (e.g.: CO_2 vs affected localities: $r=-0.653$, $p=0.004$; CO_2 vs affected counties: $r=-0.826$, $p<0.001$) dissipate when we control for the effect of time (partial correlations on residuals: $r=-0.374$, $p=0.140$, respectively $r=-0.324$, $p=0.205$), and for victims no association is found (Pearson $r=-0.008$, $p=0.977$); Therefore, decarbonization (slow, multi-annual signal) and flood impact (episodic, event-driven signal) evolve on distinct time horizons, which requires a dual strategy: continuing mitigation (reducing emissions intensity) and, simultaneously, strengthening local adaptation (infrastructure and operational response) to cushion impact peaks when they occur.

Generally, the results suggest that Romania is in a clear process of strengthening climate adaptation infrastructure and reducing emissions intensity, without these processes being accompanied by an increase in population vulnerability. This dissociation between exposure and direct impact indicates both the effectiveness of institutional measures and the need for future climate risk management strategies to continue to combine structural investments with prevention, education, monitoring and rapid intervention programs. Strengthening these directions can support the maintenance of a low level of impact on the population, in the context in which the variability and intensity of extreme phenomena are likely to increase in the coming decades.

Broadly speaking, the link between CO_2 intensity, increased flooding, the use of weather modification technologies, and the increase in the number of people affected by disasters highlights the complexity of the interaction between climate processes, social vulnerability, and adaptation measures. Against the backdrop of accelerating climate change, the development of integrated strategies — from reducing emissions to strengthening protective infrastructure — becomes essential to protect populations exposed to the increasingly severe risks of extreme phenomena.

Policy implications. Given both the structure (concentration of emissions in a few key sectors) and the dynamics (strong declines in energy and industry, relative repositioning in transport and agriculture), priorities should combine: (i) accelerating the decarbonisation of electricity and heat production (clean electrification, flexibility, storage), (ii) efficiency and alternative substances/fuels in manufacturing, (iii) electromobility and demand management in transport, (iv) GHG-smart measures in agriculture (nutrient management, climate-smart practices). These need to be complemented by adaptive programmes (e.g. hail protection, blue-green infrastructure, urban/rural drainage) and strengthened warning and intervention systems — directions that can keep the impact on the population low even in the face of increasing weather hazards.

Overall, Romania is simultaneously advancing on mitigation and adaptation: emissions in heavy sectors are compressed (in line with the decrease in CO_2 intensity), and the protection infrastructure is expanded, without an increase in population victimization. The window of opportunity consists in accelerating investments in high-weight sectors and calibrating interventions on specific chains (transport, agriculture), so as to maintain the pace of reductions and maximize resilience at local and national levels.

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