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Simulation of Rainfall Erosivity Dynamics in Romania under Climate Change Scenarios

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Abstract: Soil erosion is triggered by rainfall through the detachment of soil particles and their transport downslope, playing a key role in soil erosion models. Together with the vegetation cover, rainfall is a temporal dynamic factor, inducing corresponding time variations of erosion rates. Under current climate change, rainfall is also changing its characteristics and our study aimed to reveal whether these changes will significantly affect rainfall erosivity in Romania, and implicitly the soil erosion. To achieve this purpose, we developed a statistical non-parametric model for predicting rainfall erosivity on the basis on the modified Fournier index and applied it to future precipitation evolution scenarios. The precipitation data were extracted from the CHESLA database for the Romanian territory for two climate change contrasting scenarios (RCP 4.5 and 8.5). Average predictions from five selected climate models were used in order to minimize prediction uncertainty. The results show that rainfall erosivity is likely to increase, at least during the 2041–2060 period, especially in the south-western, western and eastern part of the country, which may cause a corresponding increase in soil erosion rates, with an average of 1–2 t ha^{-1} yr^{-1}. During the 2061–2080 period, rainfall erosivity is likely to decrease in central and eastern Romania.

Keywords: rainfall erosivity; soil erosion; climate change; Romania

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Citation: Patriche, C.V.; Roșca, B.; Pîrnău, R.G.; Vasiliniuc, I.; Irimia, L.M. Simulation of Rainfall Erosivity Dynamics in Romania under Climate Change Scenarios. *Sustainability* **2023**, *15*, 1469. https://doi.org/10.3390/su15021469

Academic Editor: Antonio Miguel Martínez-Graña

Received: 29 November 2022
Revised: 26 December 2022
Accepted: 10 January 2023
Published: 12 January 2023

1. Introduction

Climate change has an impact on all climate variables, including precipitations. Unlike temperature, the evolution trends of precipitations are not as clear. In some regions, they tend to grow, while in others they tend to decrease. However, there seems to be a common pattern in rainfall evolution under climate change, that of concentrating and becoming more aggressive, which will theoretically lead to increased soil erosion. Consequently, our study investigated the possible evolution of the rainfall erosivity factor, as defined in RUSLE model [1], within the territory of Romania, under different climate change scenarios.

Rainfall erosivity has been mapped in the European Union at annual [2] and monthly [3] time scales. Ref. [4] reconstructed past rainfall erosivity across Europe and found an increase in R factor for 15% of the stations for the 1961–2018 period. Predictions of the future possible evolution of this parameter have been approached by [5], based on the Rainfall Erosivity Database at European Scale (REDES) and WorldClim datasets [6], for the 2041–2060 period, showing that an overall relative increase of 18%, compared to the year 2010, is expected in Europe. A very close percentage (18.5%) was computed for the Romanian territory, the mean R factor values increasing from 785 to 930.2 MJ mm ha^{-1} h^{-1} yr^{-1} from 2010 to 2050. Based on this projection of rainfall erosivity evolution, as well as the simulated evolution of land use, ref. [7] estimated the future soil erosion rates across EU under different RCP scenarios. The study indicates that the average erosion rates are expected to grow from 3.07 t/ha^{-1} yr^{-1} in 2016 to 3.46, under RCP 2.6, and 3.76, RCP 8.5 scenarios, in 2050.

At a country scale, several recent studies focused on the computation of the rainfall erosivity using high temporal resolution precipitation data: ref. [8] for Switzerland, ref. [9] for the Czech Republic, ref. [10] for Greece, ref. [11] for Italy. Also, there are several regional studies regarding the evolution of rainfall erosivity under climate change scenarios. Ref. [12] showed that, for the Mediterranean island of Crete, predictions differ according to climate change scenarios, with the RCP 2.6 indicating an increase in rainfall erosivity, while the RCP 8.5 projected a decrease. For Saxony (Germany), ref. [13] found that the total number of erosive rainstorms is likely to decrease, while their intensity is likely to increase, therefore leading to increased rainfall erosivity. Ref. [14] investigated how model conceptualization may affect soil loss projections under climate change. The authors compared the outputs of three erosion models (RUSLE, MUSLE and MMF) and found that RUSLE projects a decrease in soil erosion, MUSLE projects an increase, while MMF stands in the middle with a projected moderate increase of soil erosion. Such studies bring to the forefront the uncertainty issue related to soil erosion modeling, especially when future projections are considered.

Referring strictly to Romania, up to present there are no studies regarding the computation of rainfall erosivity factor, as defined by RUSLE methodology, at either a country or regional scale. An USLE-inspired model was elaborated in the 1970s by [15,16], which still constitutes the standard methodology for soil erosion risk evaluation [17]. Within this methodology, a rainfall erosivity factor is defined and mapped for the Romanian territory, which is quite different from the one defined in USLE/RUSLE methodology. It is based on an index called rainfall aggressiveness, which is the product between rainfall quantity and its peak 15 min intensity [18]. The Romanian model was applied country-wide for the first time in the GIS environment by [19] with good results. However, this model is very difficult to extrapolate for the future, mainly because the data needed for rainfall erosivity factor computation are not readily available [19]. For this main reason, in our present study, we chose to apply the RUSLE model, which can be projected into the future, provided future estimates of precipitation are available [20]. This is the first time a study regarding the simulation of rainfall erosivity evolution under climate change scenarios was carried out in Romania.

2. Materials and Methods

2.1. Study Region

Our study focuses on the entire Romanian territory, a middle-size country (237,500 km^2) situated in central-eastern Europe. The relief comprises all landforms, from the Carpathian Mountains ring enclosing the Transylvanian Depression, to the outer plateau, hilly and plain areas. The surface lithology is quite varied, including hard metamorphic, igneous and sedimentary rocks in the mountain area, and loose gravel, sand and silt (loess) formations in the plateau and plain areas. The Subcarpathians, the plateau and hilly areas of Romania are especially prone to erosion processes, being made up of loose sandstone, marl and clay formations. The climate is temperate continental, with rainfall ranging from 350 to 1400 mm yr^{-1}, unevenly distributed along the year, the wettest months being June and May and the driest October and March. The climate continentality increases towards East which causes a corresponding enhancement of rainfall erosivity, the critical erosion season being from March to July [21]. The vegetation cover is made up of coniferous, mixed and deciduous forests especially in the mountain area, while the lower, hilly and plain zones are dominated by agricultural land. Annual crops, including maize, winter wheat, and sunflower, cover large areas and frequently occupy low- and medium-gradient slopes, which favor soil erosion. The soil cover is also varied, represented by acid soils in the mountain area (especially Cambisols and Spodosols), forest soils (Luvisols) in the plateau and hilly areas and steppe and forest steppe soils (especially Chernozems) in the plain regions.

According to a rill and interrill soil erosion assessment [19], based on the Romanian standard methodology [15–17], the average soil erosion rate in Romania is 2.98 t ha^{-1} yr^{-1}, the highest erosion rates being specific to the Transylvanian Plateau, in the central part of the country (6.36 t ha^{-1} yr^{-1}), and to the Subcarpathians (5.93 t ha^{-1} yr^{-1}) (Figure 1). The high and very-high erosion risk classes (>16 t ha^{-1} yr^{-1}) represent 7.0% of the agricultural land, while medium erosion risk (8–16 t ha^{-1} yr^{-1}) characterizes 12% of the agricultural area.

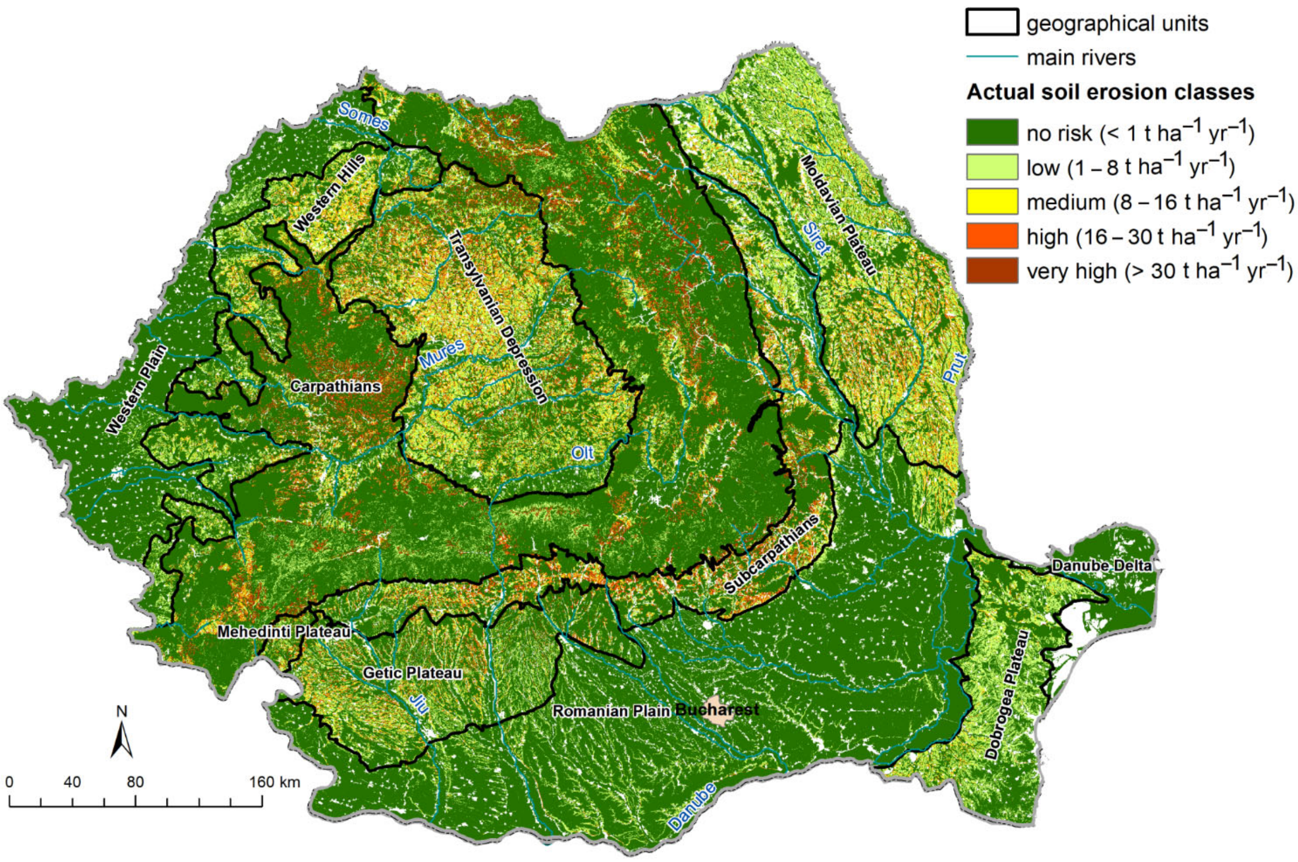

Figure 1. Actual rill and interrill soil erosion map of Romania (Reprinted with permission from [19]. 2019, Soil Use and Management Journal).

2.2. Input Data

Our study is based on CHELSA version 1.2 precipitation data and the European RUSLE 2015 rainfall erosivity factor [2,22]. CHELSA (https://chelsa-climate.org/ (accessed on 11 January 2023) is a global raster database at ~1 km resolution including temperature and precipitation monthly data for current, future and past climates [23]. In our study, we used the precipitation data for 5 climate models and 2 representative concentration pathways (RCP) of extreme scenarios (4.5, the milder scenario and 8.5, the more extreme scenario) and 2 time periods (2041–2060 and 2061–2080). The selection of the 5 climate models (CESM1-BGC, CESM1-CAM5, CMCC-CM, MIROC5, MPI-ESM-MR) was based on the lowest amount of models' interdependence as specified by [24]. The average predictions of these models were further used to estimate future rainfall erosivity.

The current rainfall erosivity was computed and mapped at the level of the European Union by [2] at 500 m resolution, starting from a large database of erosive rainfalls recorded at meteorological stations throughout Europe (Rainfall Erosivity Database at European Scale—REDES) and the Rainfall Intensity Summarization Tool (RIST) software [25]. This factor was extracted for the Romanian territory and used further to estimate current and future R factors, based on statistical relationships with the modified Fournier index.

2.3. Methods

Rainfall erosivity (R factor) is the capacity of rainfall to produce erosion and it was defined by [26] in the Universal Soil Loss Equation (USLE) methodology, revised later on by [27]. It depends on rainfall intensity and duration [28]:

$$e = 0.29\ [1 - 0.72\ e^{(-0.05i)}]$$

- e—unit rainfall energy (MJ ha^{-1} mm^{-1});
- i—rain intensity (mm h^{-1}).

$$R = \sum EI_{30}$$

- R—annual rainfall erosivity (MJ mm ha^{-1} h^{-1} yr^{-1});
- Erainfall energy (MJ ha^{-1});
- I_{30}—maximum rainfall intensity during a 30 min period (mm h^{-1}).

The rainfall erosivity factor, together with crop and crop management factor, is a temporally dynamic factor, subject to changes according to climate evolution. It determines soil erosion rates, which may also have further impacts on landslide mobility [29]. Because rainfall duration and intensity has not yet been estimated for future climate change scenarios, the future R factor cannot be directly computed and therefore, it has to be estimated from climate parameters, which are available for these scenarios. Such climate parameters and the monthly precipitation data are available in the CHELSA database. To link future precipitation data to R factors, we first computed the modified Fournier index (MFI), which was proposed by [30]:

$$MFI = \frac{\sum_{i=1}^{12} p_i^2}{P}$$

where:

- p_i—mean monthly precipitations (mm);
- P—mean annual precipitation (mm).

In the initial Fournier index formula (p^2/P), p^2 is the average rainfall of the month with the highest rainfall, but the index did not correlate very well with the R factor values. Consequently, the author modified the index as in the above formula and achieved much higher correlations [30]. Other studies have also demonstrated the usefulness of the modified Fournier index for the estimation of rainfall erosivity because it generally correlates very well with this parameter [31].

Several statistical regression equations were proposed by [1] for the continental United States for the estimation of R factor based on F index. Their application to the Romanian territory led however to values larger than expected, probably because the continental climate of eastern US is more excessive than the one of Romania. Therefore, these relationships could not be applied to the Romania territory. Consequently, our solution was to adopt the spatial model computed by [2] and to link it statistically to the modified Fournier index in order to estimate the R factor for future climate scenarios. To compute this link, we tested both linear regression and non-parametric regression models, using, as predictor variables, the MFI, the natural logarithm of MFI, and X and Y coordinates. We generated 5×5 km grid points over the Romanian territory and extracted the current rainfall erosivity, F index and X, Y coordinates values and exported them to Excel/XLSTAT software [32] for statistical analysis. Unlike linear regression, the non-parametric regression can be applied even when the assumptions on linearity cannot be verified. The non-parametric regression is a locally weighted type of regression [33] and it is oriented mainly towards model prediction rather than revealing its structure.

3. Results

The continuous spatial distribution of rainfall erosivity in Romania is characterized by values ranging from 462 to 1150 MJ mm ha^{-1} h^{-1} yr^{-1}, with an average of 785 and a standard deviation of 95.4. According to the classification proposed by [34], these values belong to the low erosivity class. The classified rainfall erosivity map (Figure 2a) is characterized by a balanced distribution of the relative frequency of classes, most of the percentages ranging from 14% to 19%. The values between 800 and 900 MJ mm ha^{-1} h^{-1} yr^{-1} are the dominant ones, cumulating a relative frequency of 35%. The values > 900 MJ mm ha^{-1} h^{-1} yr^{-1} have still an important share (about 12% of the country). These areas with higher rainfall erosivity values (>800 MJ mm ha^{-1} h^{-1} yr^{-1}) are found mainly in the Carpathians, the Subcarpathians, the eastern Romania (Moldavian Plateau) and parts of the Getic Plateau, making these areas prone to erosion processes.

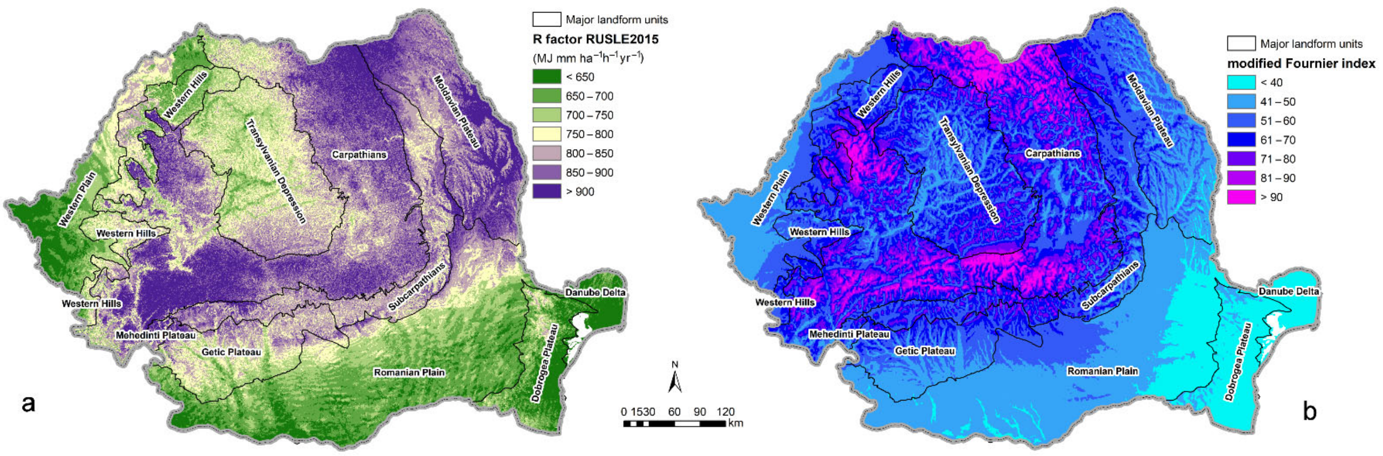

Figure 2. RUSLE 2015 R factor (**a**) and the modified Fournier index (**b**) for the current climate.

The modified Fournier index computed for the current climate (Figure 2b), based on the CHELSA database, is characterized by an average value of 56.49, a standard deviation of 14.13 and a value range from 23 to 131. These values place most of the Romanian territory into the low erosivity class [35]. Only the values over 90, which are present in the high mountain area, are classified as intermediate.

Obviously, there is a good correlation between the spatial distributions of rainfall erosivity (Figure 2a) and MFI (Figure 2b). Table 1 shows the characteristics of the statistical models that were tested for R factor prediction. We notice that linear models have a lower explanation degree, compared to the non-linear ones, while the use of the natural logarithm of MFI improves the prediction. The best model to predict rainfall erosivity was selected based on the coefficient of determination (R^2) and root mean square error (RMSE) values (Table 1). We can see that the non-parametric model (R^2 = 0.714, RMSE = 50.9), using the natural logarithm of F index, X and Y coordinates as predictors, performs better than the other models (Figure 3).

Table 1. Characteristics of the tested statistical models for R factor prediction.

Statistical Model	Predictors	R^2	RMSE
Linear regression	- MFI - X coordinates - Y coordinates	0.477	68.880
Linear regression	- LN(MFI) - X coordinates - Y coordinates	0.522	65.872

Table 1. *Cont.*

Statistical Model	Predictors	R^2	RMSE
Non-parametric regression	- MFI - X coordinates - Y coordinates	0.705	51.694
Non-parametric regression	- LN(MFI) - X coordinates - Y coordinates	0.714	50.965

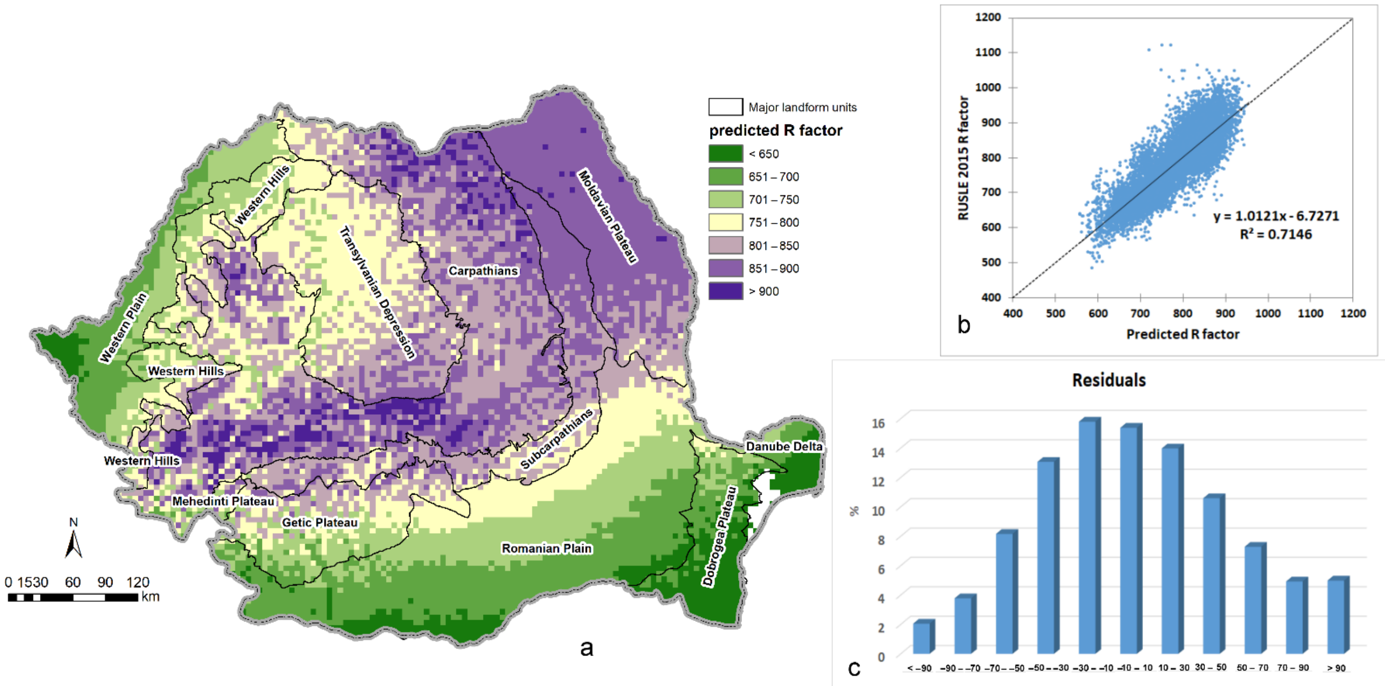

Figure 3. Estimated current R factor at 5 × 5 km resolution based on the non-parametric regression model using LN (MFI), X and Y coordinates as predictor variables: (**a**) spatial distribution; (**b**) predicted vs. actual R factor values; (**c**) distribution of regression residuals.

To analyze the future possible evolution of rainfall erosivity, we compared the predicted future R factor values (Figure 4) with the predicted current R factor values (Figure 3a). Though they may look quite similar, the statistical indices computed for the entire Romanian territory (Table 2) show that there is an overall increase in rainfall erosivity average, minimum and maximum values from the present to the 2041–2060 period, while for 2061–2080 there is a decline of these values compared to the previous period, but they still continue to be higher than the current ones.

Table 2. Statistics of predicted current and future R factor for Romania (MJ mm ha^{-1} h^{-1} yr^{-1}).

Statistics	Current	2041–2060		2061–2080	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Average	782.8	801.4	803.0	790	785.2
Minimum	558	580	587	566	573
Maximum	955	974	976	960	950
Standard deviation	79.6	74.3	73.9	75.2	74.4

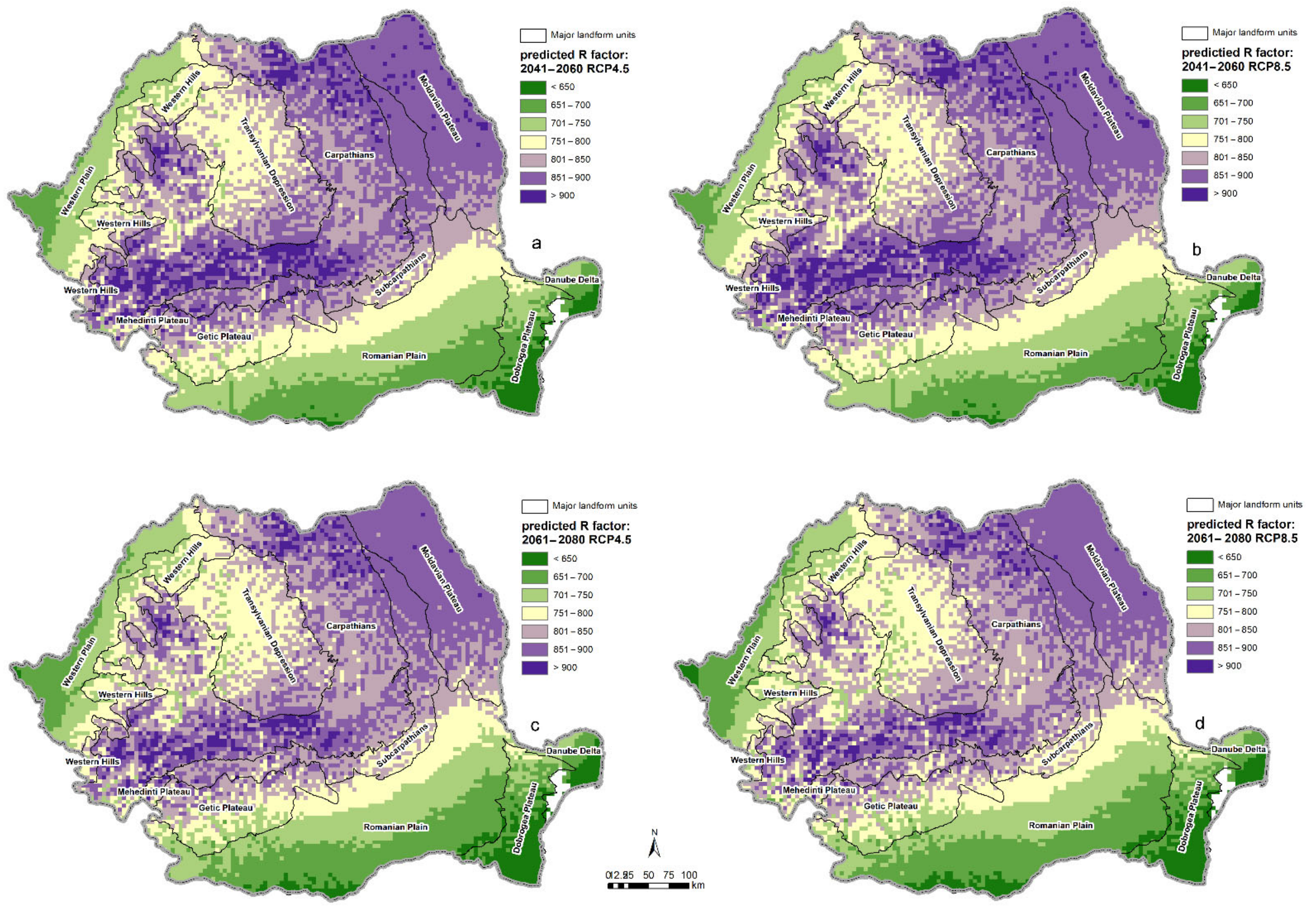

Figure 4. Predicted future rainfall erosivity: (**a**) 2041–2060 period and RCP 4.5 scenario; (**b**) 2041–2060 period and RCP 8.5 scenario; (**c**) 2061–2080 period and RCP 4.5 scenario; (**d**) 2061–2080 period and RCP 8.5 scenario.

The averages computed for the major landform units of Romania (Table 3) show that the overall increasing trend is also present within the major landform units. The highest increase of R factor values from present to the next period of time (2041–2060) is likely to occur in the Mehedinți and Getic Plateaus (SW of Romania), where averages will increase with 52.5 and 40.5 MJ mm ha^{-1} h^{-1} yr^{-1} respectively, under the RCP 4.5, and to 56.7 and 41.1 MJ mm ha^{-1} h^{-1} yr^{-1} respectively, under the RCP 8.5 scenario. In the third place is Danube Delta (E of Romania), where an average increase of 33.2 and 36.2 MJ mm ha^{-1} h^{-1} yr^{-1}, respectively, is expected under the two climate change scenarios. The lowest increase of rainfall erosivity was found for the Moldavian Plateau, situated in the eastern part of the country.

For the 2061–2080 time period, there is a general decrease of rainfall erosivity, compared to the 2041–2060 period, but the average values remain higher than at present, excepting the Moldavian Plateau, under RCP 4.5 scenario, and the Carpathians, Subcarpathians, Transylvanian Depression and Moldavian Plateau, under the RCP 8.5 scenario.

Mapping the differences between the predicted future and current R factor values (Figure 5) shows the same spatial trend of rainfall erosivity increasing during the 2041–2060 time period and then decreasing during the 2061–2080 period. The areas most affected by an increase in rainfall erosivity (>40 MJ mm ha^{-1} h^{-1} yr^{-1}) are in the South West (Western Getic Plateau, Mehedinți Plateau), as we already pointed out. Also, such areas are found in the West (parts of the Western Hills and Plain, parts of the Western Carpathians) and East (Danube Delta) of Romania. These areas cumulate 6.9% (about 16,500 km^2) of the country in the RCP 4.5 scenario and 9.8% (about 23,000 km^2) in the RCP

8.5 scenario (Table 4). An increase with >40 MJ mm ha^{-1} h^{-1} yr^{-1} of rainfall erosivity will induce a corresponding increase in soil erosion rate of >1–2 t ha^{-1} yr^{-1}. Locally, the soil erosion rates may grow as much as 10–20 t ha^{-1} yr^{-1}.

Table 3. Average values of predicted current and future R factor for the major landform unis of Romania (MJ mm-ha^{-1} h^{-1} yr^{-1}).

Landform Unit	Current	2041–2060		2061–2080	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Carpathians	842.8	858.9	860.7	847.9	841.3
Subcarpathians	834.5	848.0	847.9	837.0	831.4
Transylvanian Depression	799.1	810.4	812.2	800.5	795.9
Western Hills	765.3	787.7	793.1	778.6	771.7
Mehedinti Plateau	806.1	858.6	862.8	844.8	840.6
Getic Plateau	770.3	810.9	811.4	792.3	784.6
Moldavian Plateau	866.7	873.0	873.3	865.2	864.2
Western Plain	698.4	723.8	730.1	715.2	707.7
Romanian Plain	708.0	729.6	729.4	716.4	712.6
Dobrogea Plateau	649.5	671.7	673.8	658.6	660.8
Danube Delta	643.5	676.7	679.7	660.5	665.2

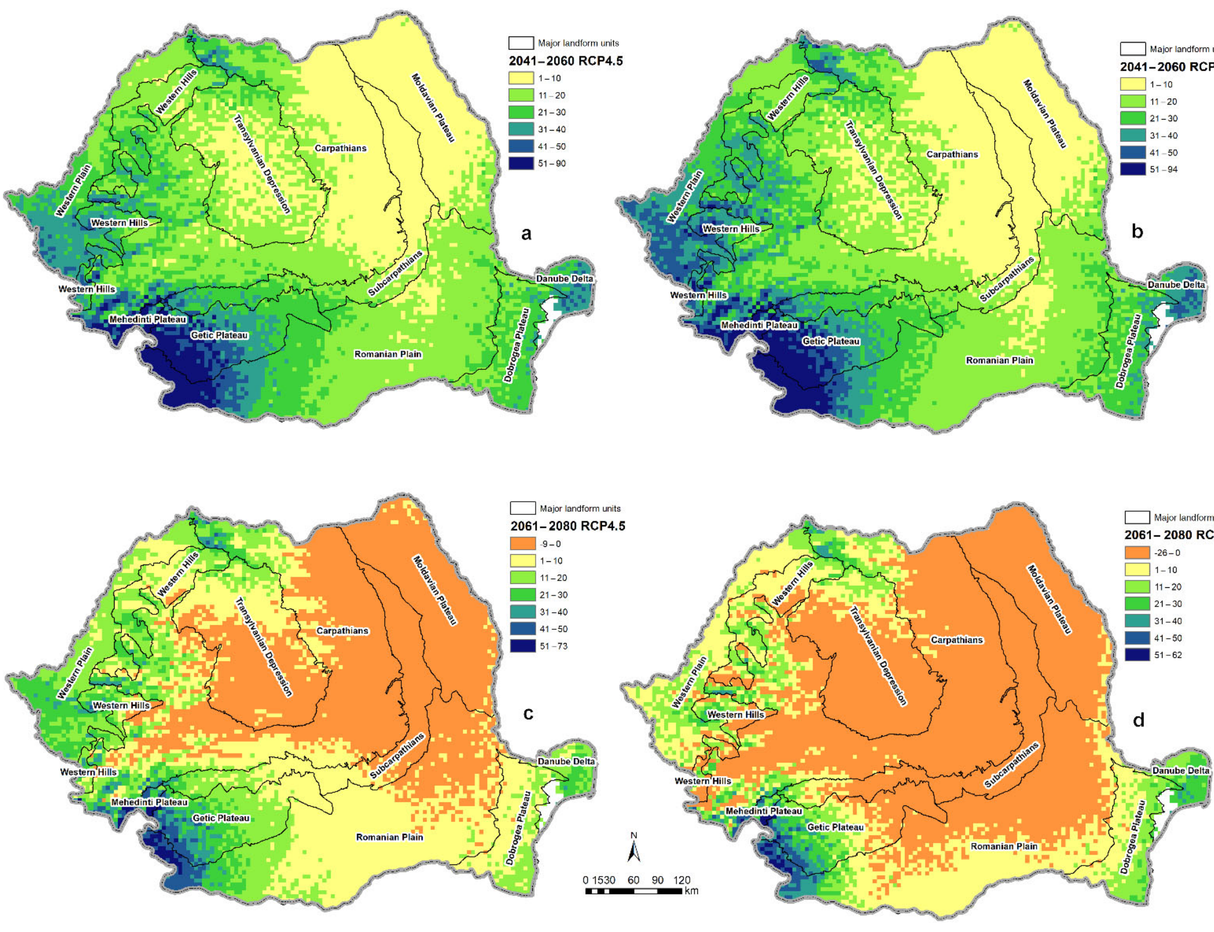

Figure 5. Differences between future and current rainfall erosivity: (**a**) 2041–2060 period and RCP 4.5 scenario; (**b**) 2041–2060 period and RCP 8.5 scenario; (**c**) 2061–2080 period and RCP 4.5 scenario; (**d**) 2061–2080 period and RCP 8.5 scenario.

Table 4. Percentages of classes showing the differences between future and current R factor values.

Differences (MJ mm ha^{-1} h^{-1} yr^{-1})	2041–2060		2061–2080	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
<0	0.0	0.0	39.4	58.5
0–10	27.8	26.3	30.6	23.6
11–20	37.0	34.2	18.0	10.7
21–30	19.4	19.1	7.6	4.0
31–40	8.8	10.7	2.2	1.8
41–50	3.2	5.4	1.7	1.0
>50	3.7	4.4	0.6	0.3

During the 2061–2080 period, the differences mapped in Figure 5 show that the rainfall erosivity is expected to decrease, probably because of the precipitation decline as a consequence of global warming. Most of the country (39.4% under RCP 4.5 scenario and 58.5% under RCP 8.5 scenario—Table 4) is likely to have R factor values slightly lower than at present (Figure 5c,d). However, the regions previously mentioned from south-western, western and eastern Romania, which are likely to have increased rainfall erosivity during the 2041–2060 period, will continue to have R factor values higher than present.

The same patterns of R factor increase in the W, NW and E parts of Romania were found by [4] in a study which attempted to reconstruct the rainfall erosivity in Europe for the 1961–2018 period. This enhances our finding that there is a significant increasing trend in these parts of the country.

For the European Union, ref. [5] found a similar positive trend of rainfall erosivity for most of the continent based on the HadGEM2 climate model. However, the differences between 2050 and current R factor values estimated for Romania under the RCP 4.5 scenario are much higher than the values estimated in our study. An average of 930.2 MJ mm ha^{-1} h^{-1} yr^{-1} is estimated for the Romanian territory, compared to the average of values of 801.4 MJ mm ha^{-1} h^{-1} yr^{-1} which resulted from our study. On the other hand, a more recent study [7] on future possible changes of soil erosion rates under different climate change scenarios (RCP 2.6, 4.5 and 8.5) on agricultural land in Europe and using average predictions of 19 climate models, shows similar estimates on erosion rate growth of 0–2.5 t ha^{-1} yr^{-1} for most of the agricultural land of Romania.

Predicting the impacts of climate change on the environmental components is a process subject to a certain degree of uncertainty. There are several sources of possible errors, including the uncertainty of climate models' predictions, which can be minimized by considering an average prediction of multiple models, as we did in our study. Additionally, our predictions are based on the modified Fournier index–rainfall erosivity statistical relationship and therefore the predicted R factor values are in a narrower range compared to the current R factor values. Nevertheless, though the computed changes in R factor values and the estimated soil erosion rates may be subject to uncertainty, the real values being more or less different from the estimated ones, we believe that the growing rainfall erosivity trend we identified for the next time period (2041–2060) and that the spatial patterns showing higher R factor values in the south-western, western and eastern part of the country are real characteristics of the temporal and spatial dynamics of rainfall erosivity in Romania.

4. Conclusions

The present study attempted to predict rainfall erosivity factor for the entire Romanian territory for the next few decades. To fulfill this purpose, we used a non-parametric statistical model relating this factor to the modified Fournier index, the latter being computed based on average monthly precipitations. The model was then applied using as input data the future estimated MFI. The results we achieved clearly show an increasing trend of rainfall erosivity for the 2041–2060 period, especially in the south-western, western and eastern parts of the country. According to our estimations, this increase is likely to induce a corresponding enhancement in soil erosion rates, with an average of 1–2 t ha^{-1} yr^{-1}. After this period of rainfall erosivity and soil erosion increase, our study shows that it is likely for the rainfall erosivity values to decrease, especially in the central and eastern parts of the country, due to precipitation decreases during 2061–2080 period as a consequence of climate warming. However, the south-western, western and eastern areas, previously identified as being more affected by increased rainfall erosivity, will continue to have R factor values higher those at present.

Author Contributions: Conceptualization, C.V.P.; Methodology, C.V.P.; Software, C.V.P. and B.R.; Validation, C.V.P.; Data curation, B.R., R.G.P. and I.V.; Writing—original draft, C.V.P.; Writing—review & editing, R.G.P. and L.M.I.; Visualization, I.V.; Funding acquisition, C.V.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS—UEFISCDI, project number PN-III-P4-PCE-2021-1350, within PNCDI III.

Data Availability Statement: The data presented in this paper are available on request.

Conflicts of Interest: The authors declare no conflict of interest.

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