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Effect of erosive efficient rains specification on rainfall erosivity factor

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Abstract: The water erosion represents one of the most dangerous degradation processes on agricultural land. Its estimation is thus necessary for setting rules and defining appropriate strategies for soil protection. An estimation of a long-term average annual soil loss by water erosion is frequently based on the Universal Soil Loss Equation (USLE) defined as a product of six factors, where rainfall erosivity factor (R factor) is a leading one. R factor is a multi-annual average index that measures rainfall kinetic energy and intensity describing the effect of erosive efficient rains (EER) on sheet and rill erosion. EER were defined by total higher than 12.7 mm and intensity higher than 6.4 mm in 15 minutes. As those ERR criteria are being used differently by various studies, we decided to compare R factor derived by two variants of ERR criteria: i) EER must fulfil both minimal total and minimal intensity (VAR_AND); ERR must fulfil either minimal total or minimal intensity (VAR_OR). Based on 1-minute precipitation totals database of Czech hydrometeorological institute for 111 stations for 1991–2021 we conclude that mean of Ra VAR_AND across altitude is about 30% lower than Ra VAR_OR while there is high statistical significant correlation between those two variants. In addition, annual values of R factor derived by both variants show a statistically significant increase in a long run which calls for updating the R-factor values to reflect increasing climate change impacts.

Key words: storms, kinetic energy, climate change, water erosion

1. Introduction

Water erosion is gradually becoming one of the most dangerous degradation processes, threatening agricultural land and ecosystems globally. Having

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said that due to natural characteristics (such as wind prone climate and sites, low landscape roughness, specific physical soil characteristics, low soil surface coverage etc.) wind soil erosion can be even more problematic in some regions (*Scheper et al., 2021; Středová et al., 2021*). Prediction of average annual soil loss produced by sheer and rill erosion at different spatial scales and for different areas of the world (*Alewell et al., 2019, Kumar et al., 2022*) is frequently based on the empirically based Universal Soil Loss Equation (USLE) (*Wischmeier and Smith, 1965; Wischmeier and Smith, 1978*) or USLE family models. USLE and the Revisited Universal Soil Loss Equation RUSLE (*Renard et al., 1997*) is defined as a product of 6 factors: R is the climatic factor often referred to as the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope gradient factor, C is the crop and crop management factor, and P is the soil conservation practice factor. Basically, rains trigger erosion, while soil has certain ability to resist it. R-factor is a multi-annual average index that measures rainfall kinetic energy and intensity describing the effect of rainfall on sheet and rill erosion. R factor formula has developed over time. *Wischmeier (1959)* defined a "Rainfall Erosion Index" as a product of the total kinetic energy of the storm and its maximum 30-min intensity (EI) of storms > 0.5 inch (12.7 mm) which explained as high as 94% of the yearly deviation in total soil loss. Consequently, the so called iso-erodent maps (*Wischmeier and Smith, 1965*) were produced from rainfall data of about 2000 locations evenly distributed over US using 22-yr station rainfall records. The R-factor was included as one of the inputs in the USLE model (*Wischmeier and Smith, 1978*). Erosive efficient rains (EER) were defined as "Rain showers of less than one half inch separated from other rains period by more than 6 hours were omitted from the erosion index computations, unless as much as 0.25 inch of rain fell in 15 minutes" (*Wischmeier and Smith, 1978,; Renard et al., 1997*). Converted into SI, rainfall events of less than 12.7 mm were omitted from the erosivity computations, unless at least 6.4 mm of rain fell in 15 min. Furthermore, a storm period with less than 1.3 mm over 6 h was used to divide a longer storm period into two storms. As the definition is a bit tricky, especially for non-native speakers, the studies dealing with R factor apply basically two EER criteria: i) EER must fulfil both minimal total and minimal intensity (VAR_AND); ii) ERR must fulfil either minimal total or minimal intensity (VAR_OR).

VAR_OR was used by *Di Lena et al. (2021)*, *Hanel et al. (2016)* who considered as erosive only storms with a total rainfall amount ≥ 12.7 mm or with at least 6.35 mm in 15 min. An individual rainfall was defined as a rain-period separated from other rains by more than 6 hours with less than 1.3 mm. This approach was used also by *Kinnell (2023)*, *Bonila and Vidal (2011)* and *Sholagberu et al. (2016)*. *Ávila and Ávila (2015)* and *Krása et al. (2014)* estimated R factor based on the sum of the erosivity index of individual storms greater than 12.5 mm or storms greater than 6 mm and longer than 15 min. *Guesri et al. (2020)* claimed the following criteria proposed by *Wischmeier and Smith (1978)* and generally described the selection of EER as the cumulative rainfall during a rainfall event that must be greater than the seasonal threshold ($T_{\text{autumn}} = 3$ mm, $T_{\text{winter}} = 6$ mm, $T_{\text{spring}} = 2.5$ mm and $T_{\text{summer}} = 2$ mm) or, if the cumulative rainfall during a 15-min rainfall period is taken into account, than a rainfall event has to be greater than T/2. Cumulative rainfall of less than T/10 over a period of 6 h separates the event into two rainfall events.

Some studies respecting VAR_OR employs certain modification of the threshold. *Delgado et al. (2022)* discretized rainfall events from continuous records using standardized criteria identifying 2 possible events: 1) when the accumulated precipitation of an event is greater than 12.7 mm; 2) when the event accumulates a peak greater than 6.35 mm in less than 30 min. However, *Wischmeier and Smith (1978)* suggested 15-min intensity threshold. It is not considered an event when the rainfall accumulation is less than 1.27 mm (0.5 inch) during a period of 6 h, dividing a long storm period into two storms. They also concluded that these criteria have been widely applied in many investigations worldwide (*Panagos et al., 2015; Kim et al., 2020; Matthews et al., 2022*). *Fischer et al. (2016)* employed an attitude of *Rogler and Schwertmann (1981)* and defined EER as rains that deliver more than 10 mm of rain or have a $\text{Imax}_{30} \geq 10\ \text{mm h}^{-1}$. *Kreklow et al. (2020)* respected DIN 19708 (*Deutsches Institut für Normung, 2017*), which is based on the results of *Schwertmann et al. (1990)* where EER have a precipitation sum of at least 10 mm or a precipitation intensity exceeding $10\ \text{mm h}^{-1}$ within a time window of 30 min (i.e., an actual precipitation quantity of 5 mm in 30 min). *Back et al. (2017)* followed *Cabeda (1976)* using EER as pluviometric precipitation of 10 mm or more, or rain precipitation of 6 mm or greater over a maximum interval of 15 min. *Rutebuka et* *al. (2020)* followed *Stocking and Elwell (1973)* suggested that rainfall events that accumulated at least 12.5 mm or had an intensity exceeding 24 $\text{mm}\,\text{h}^{-1}$, should be considered as erosive ones.

Among surveys employing VAR_AND either directly or with some threshold modifications is *Talchabhadel et al. (2020)* whose criteria for an EER were as follows: (i) total rainfall of an event is greater than 12.7 mm, (ii) there should be at least one peak which is greater than 6.35 mm in 15 min, (iii) a rainfall less than 1.27 mm in 6 h is considered to divide a longer rainfall period into two storm events. *Martins et al. (2010)* calculated the rainfall erosivity parameter only for rainfall events $>$ 10 mm, with maximum intensity $>$ 24 $\text{mm}\,\text{h}^{-1}$ within 15 min, or kinetic energy $>$ 3.6 MJ. Long rainfall events were distinguished from one to another if there was a 6 h period between them with $<$1 mm of precipitation. *Wu et al. (2014)* followed *Wischmeier and Smith (1978)*, however EER was defined as rainfall events $\geq$ 12.7 mm and with 30-min intensity $\geq$ 6.4 $\text{mm}\,\text{h}^{-1}$. Also *Janeček et al. (2006)* referred to original methodology of *Wischmeier and Smith (1978)*, however, provided R factor results also for ERR meeting VAR_AND criteria.

Onderka and Pecho (2019) described selection of EER unclearly as rain following criteria: 12.5 mm threshold of total rainfall depth and/or 6.25 mm as maximum 15-min intensity. *Středová et al. (2014)* used criteria of EER as rains with precipitation total exceeding 12.5 mm; maximum intensity exceeding 24 $\text{mm}\,\text{h}^{-1}$. They noted that the criterion of EER intensity defined by *Wischmeier and Smith (1978)* as 6 mm in 15 minutes was modified to 24 $\text{mm}\,\text{h}^{-1}$ by them, while by *Hudson (1971)* as 0.4 $\text{mm}\,\text{min}^{-1}$. Another, more lenient definition of EER was applied by *Zhu et al. (2019)* who recommended including all storm events in the R factor calculation. Even though they admitted that most literature has defined EER as cumulative rainfall events greater than 12.7 mm, together with *Yu (1999)* they argue that the discrepancy in the calculated R factor due to different rainfall thresholds increases as the mean annual rainfall decreases because the relative contribution of small storm events to the R factor increases in dry areas. Hence, the threshold was set as 5 $\text{mm}\,\text{d}^{-1}$ instead of 12.7 mm to ensure that small events that did not produce runoff were not included in the determination of daily erosivity. Exact estimation of climate/site specific EER criteria is extremely important for setting methodological procedures for rainfall simulation experiments using rainfall simulators (*Stašek et al., 2023*). Only clearly defined conditions within these simulations allow comparison with natural rains.

The main objective of this paper was the use of long-term, high-resolution data that was subjected to sophisticated quality control to calculate the R-factor. A side effect of this goal was a fully automated calculation procedure using minute data as input providing all sub-results of the R factor described in the methodology section. Such automation combined with a suitable data source enables the specification of the EER variant and thus the comparison of its two frequently used variants (VAR_AND and VAR_OR). In addition, we examined the long-term course of the R-factor results regardless of the ERR variant applied to see if this is a statistical trend. The revealed increasing/decreasing tendency can then help adjust various anti-erosion tools and measures.

2. Materials and methods

2.1. Rainfall erosivity factor (R) calculation and employed equations

1) Specification of erosive efficient rains (EER):

   EER were considered as rains exceeding certain threshold of precipitation total and 15-minute intensity, while one rainfall episode was defined as a rain separated from other rains by a break of 6 or more hours (if the break between rains was less than 6 hours, then these rains formed a single rainfall episode).

   Tested variants of EER specification were applied as follows:

   VAR_OR: $\mathrm{ER_t} > 12.5$ mm OR $\mathrm{I_{ER\_15}} \geq 6$ mm
   VAR_AND: $\mathrm{ER_t} > 12.5$ mm AND $\mathrm{I_{ER\_15}} \geq 6$ mm

   where $\mathrm{ER_t}$ is precipitation total of EER,
   $\mathrm{I_{ER\_15}}$ is maximal 15-minute intensity of EER;

2) $\mathrm{E_{kin\_m}}$ calculation for a minute interval of EER (*Brown and Foster, 1987* in *Renard et al., 1997*):

$$\mathrm{E_{kin\_m}} = 0.29\,(1 - 0.72\,\mathrm{e}^{-0.05\,\mathrm{IEER\_m}})\,.\,\mathrm{Hs}\,, \tag{1}$$

where E_{kin_m} is kinetic energy *for a minute interval* (MJ ha^{-1}),
I_{EER_m} is EER intensity (mm h^{-1}),
EER_t is EER total (mm);

3) <u>E_{kin} calculation for a whole EER:</u>

$$E_{kin} = \sum E_{kin\_m-1} \text{ to } E_{kin\_m-n} , \tag{2}$$

where n is a number of minutes in particular ERR;

4) <u>R factor calculation for individual EER:</u>

$$E_{EER} = E_{kin} \,.\, I_{30} , \tag{3}$$

where E_{kin} – total kinetic energy of EER (MJ ha^{-1}),
I_{30} – maximal 30-min intensity of EER (cm h^{-1});

5) <u>Annual R factor calculation:</u>

$$Ra = \sum R_{EER-1} \text{ to } R_{EER-y} , \tag{4}$$

where y is number of EER in particular year;

6) <u>Long-term average R factor calculation:</u>

$$Ra_{avg} = \sum Ra/Na , \tag{5}$$

where Na – number of years.

2.2. Employed data

Data source: Database management system CLIDATA of Czech hydrometeorological institute (CHMI) with a selection of 111 meteorological stations across altitude ranges from 170 to 1350 m a.s.l. (further details are given in the next section).

Data specification: precipitation totals in 1 minute step were used as an input for E_{kin} and R_{EER} factor calculation. For a purpose of data quality control, precipitation totals in daily step that underwent data quality check (in database management system CLIDATA), were used as well.

Evaluated period: 1991–2021 which included both automated stations and measurements by ombrographs.

2.3. Data quality control

As the CHMI does not revise precipitation totals in minute steps based on standard manner, the calculation of the R factor was preceded by a special quality control. Data were compared with daily precipitation totals, which are being revised systematically by various sophisticated control equations including spatial evaluation by means of GIS (*Lipina et al., 2016*). The control was based mainly on the comparison between these two data sets using their differences and ratios, possibly in interaction with other meteorological phenomena and elements. Days with zero daily precipitation in both series were not subjected to any control; on the other hand, the presence of zero in only one of the two series was further investigated. For non-zero values, one of the main rules applied was that a ratio between daily sums of official daily precipitation totals and daily sums obtained from 1 minute records were not allowed to exceed 25% (values with ratios beyond 75–125% were removed from further processing). Further, time evolution of every significant rainfall event (defined by the above mentioned limits) was inspected in a form of plots and, based on expertise, curious occasions were excluded from further processing. In case of removing any data from 1 minute database, the whole year was excluded from further processing, to unsure that values of Ra are guaranteed.

The final dataset consisted of a combination of measurements from automated stations (from the roughly beginning of the millennium) and measurements by ombrographs used before the automation, which was carried out continuously in the area of the Czech Republic, not at the same moment). The basis for the calculation of R factor were 111 stations that were selected out of 356 station (coming from both ombrographs and automated stations, half by half), where the selection was based on a length of series (at least 5 years without any interruption); in case of longer series, gaps in measurements were considered as well, and the selection reflected also outputs of data quality control (stations with more problems were discarded from further data processing). Further rules for station removal were based at the same time on detailed metadata information and knowledge of station measurements conditions, i.e. combination of both objective and subjective criteria were applied based on expert knowledge.

In the next step, R_{EER} according to Eqs. (1)–(3) were calculated for all ERR. If the analysed ERR was evaluated as relevant for the calculation, the corresponding values of R_{ERR} were summed into Ra. Values of Ra based on stations that were not excluded from calculation within a particular year, were then interpolated for the area of the whole Czech Republic by a method of regression kriging applying geographical coordinates, elevation and other terrain characteristics as predictors into a gridded data set with spatial resolution of 500 m. To ensure that the maps preserve measured values at the station locations, another layer with interpolated residuals (at station locations) was added to the interpolation model. Relationship between predictors and a predictand was estimated for each meteorological variable and each year individually, and only predictors that were significant for the regression were used for the final estimates. For each of the cases, the best type of semi-variogram was assessed.

Having maps of Ra values for each year, a final table with values for all those 111 selected stations was gained in the way, that values in stations positions were read from the annual maps of Ra values. In case a read value was based on station measurements, thanks to the residuals added to regression estimates, the exact (station) values were gained. In case of missing data for a given year (missing measurement, failed quality control, etc.), interpolated value was read. Thus the final table consists of complete time series and statistics over several years are fully comparable.

3. Results and discussions

The results comprise a set of annual rainfall erosivity factor (Ra) values from 1991 to 2021 for 111 stations, it means 3330 Ra values.

As stations cover all altitude ranges of the Czech Republic with majority in altitude from 170 to 600 m a.s.l. (91 stations), which is perfectly relevant for intensively used agricultural land in general, our findings are widely applicable in respect to soil erosion risk from agricultural land use. In order to capture an effect of altitude on both Ra values and Ra differences caused by different variants of ERR specification, the three altitude zones are shown separately in Fig. 1.

Median and mean of Ra based on VAR_AND across altitude zones is about 36 or 30% lower than from Ra VAR_OR. The difference gradually increases with an altitude, while the smallest one (27%) was identified for mean values for lower altitude below 300 m a.s.l. and the highest one (40%) refers to median values for higher altitude above 600 m a.s.l. (mean and average values are given in numbers in Fig. 1). It corresponds to findings of *Janeček et al. (2006)* who used 1-min rainfall data from 13 ombrographs for a 40-year period. They in detail analysed Ra_{avg} which, when derived by VAR_OR was 66, while when derived from VAR_AND was only 45. *Dostál et al. (2006)* employed VAR_OR with resulting Ra_{avg} of 72.6. The difference in our Ra_{avg} results of VAR_OR across the altitude ranges is almost negligible as well as in comparison with results of *Dostál et al. (2006)* where is given by slightly different input data it terms of spatial density and evaluated period.

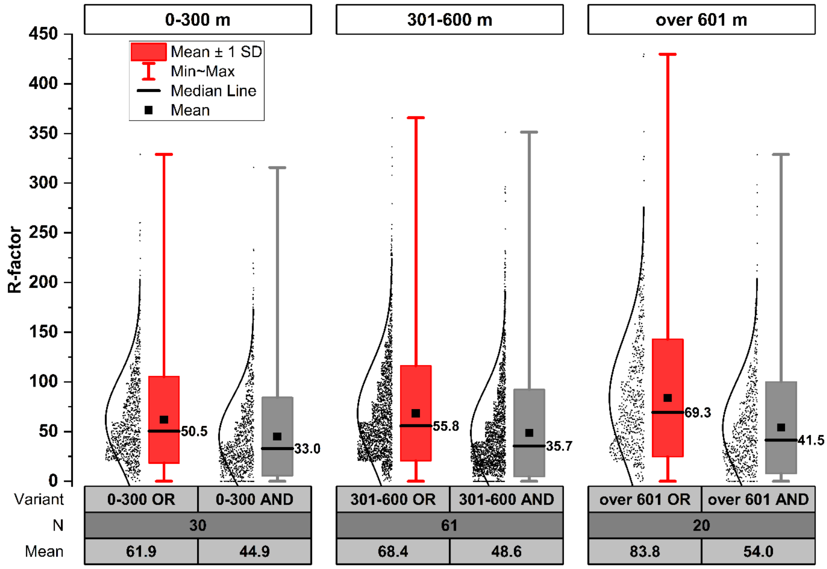

Fig. 1. Comparison of annual R factor values (Ra) for both tested variants VAR_OR and VAR_AND.

Detailed long-term (1991 to 2021) results of Ra values for all stations for both variants are graphically shown in Figs. 2 and 3. By comparison of those two figures the difference of Ra based on both variants (VAR_AND, VAR_OR) can be seen for individual years and stations. These differences are then visually captured in Fig. 4. It can be seen in general that the bigger Ra values are the bigger are the differences. In absolute values it makes sense, but for drawing a conclusion it is reasonable to work with percentage expression (see Figs. 5 and 6). There is neither correlation between relative and absolute Ra percentage difference, nor between relative Ra differences and altitude (Fig. 5). A long-term trend in relative Ra differences (1991–2021) was not detected (Fig. 6).

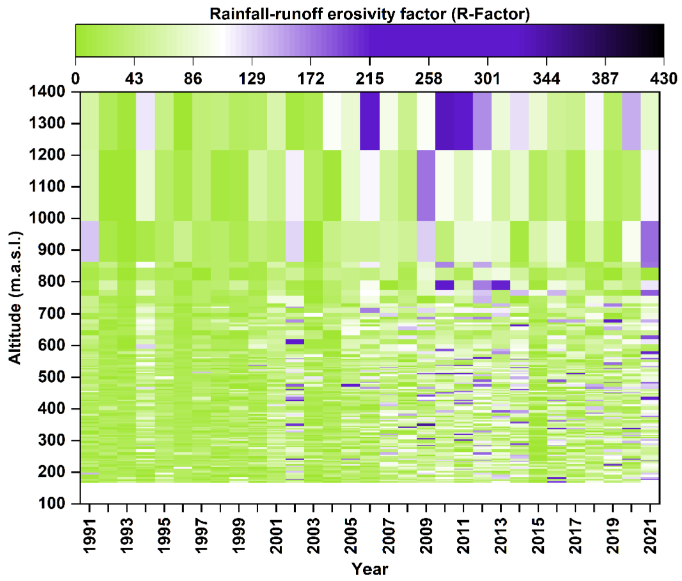

Fig. 2. Ra values for individual stations for VAR_AND.

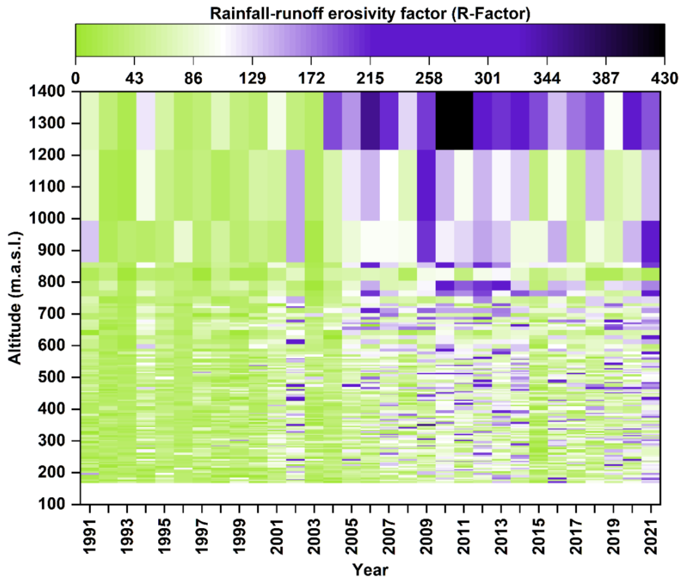

Fig. 3. Ra values for individual stations for VAR_OR.

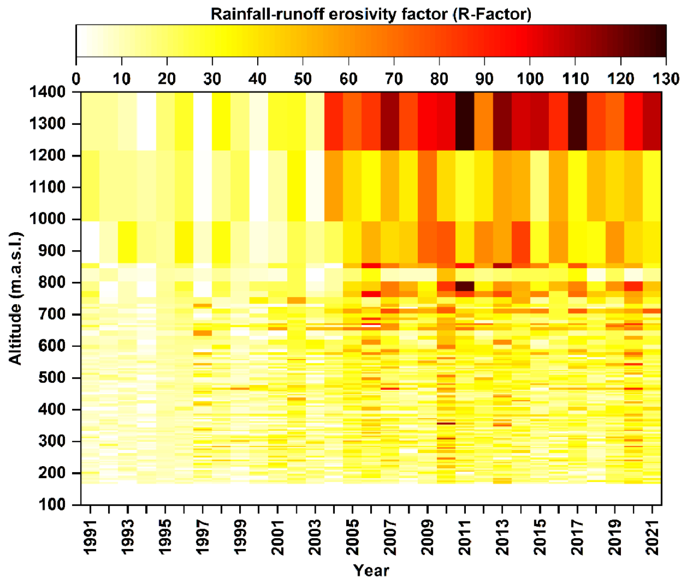

Fig. 4. Absolute Ra differences between VAR_OR and VAR_AND.

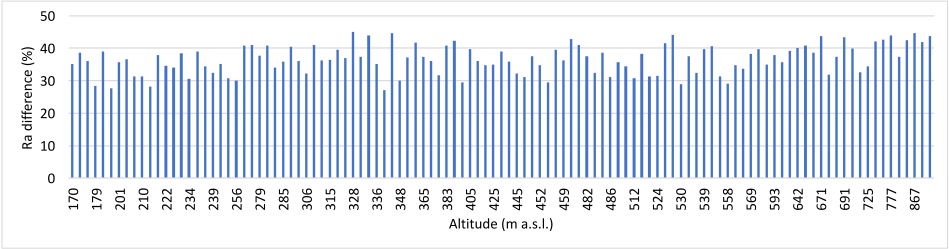

Fig. 5. Relative Ra difference between VAR_OR and VAR_AND, average values across altitude.

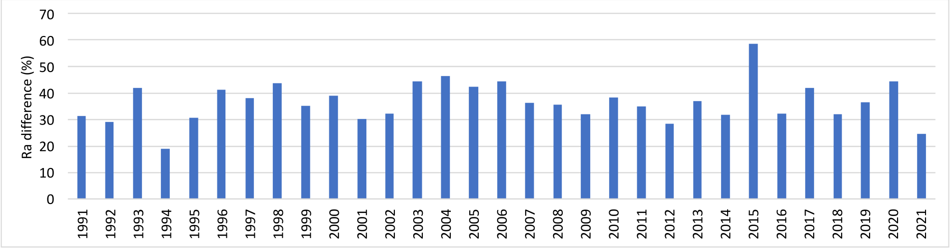

Fig 6. Relative Ra difference between VAR_OR and VAR_AND, average values for 1991–2021.

In order to enable homogenization of the R factor delivered by various studies employing either VAR_OR or VAR_AND for ERR specification and thus their further unbiased application in soil protection, we provide conversion values for $\mathrm{Ra}_{\mathrm{avgVAR\_AND}}$ to $\mathrm{Ra}_{\mathrm{avgVAR\_OR}}$. The conversion values are applicable on the regression equations (Eqs. (6) and (7)) describing a relationship between those two methods or variants with high statistical significance ($r = 0.9768^{**}$, $\alpha = 0.001$).

$$\mathrm{Ra}_{\mathrm{avgVAR\_OR}} = 1.2771 \times \mathrm{Ra}_{\mathrm{avgVAR\_AND}} + 7.4664\,, \tag{6}$$
$$\mathrm{Ra}_{\mathrm{avgVAR\_AND}} = 0.816 \times \mathrm{Ra}_{\mathrm{avgVAR\_OR}} - 10.401\,. \tag{7}$$

When comparing VAR_OR and VAR_AND over the climatic period of 1990–2021 the results also suggest a gradual increase of Ra values regardless to applied ERR specification variant. This tendency is already obvious from Figs. 2 and 3. Figure 7 then brings the evidence of statistical trend. $\mathrm{Ra}_{\mathrm{avg}}$ values for both tested variants VAR_OR and VAR_AND, in average significantly increase over the climatic period ($r = 0.7509^{**}$ or 0.6863^{**}, $\alpha = 0.001$, respectively). This corresponds to the increasing trend of occurrence of abiotic threats in the region in recent decades, such as such as heavy rains events, intense drought, heat waves and their symbiotic effects as described by *Středová et al. (2020)* and *Vido and Nalevanková (2021)*. Although *Středová and Středa (2015); Lukasová et al. (2020)* and *Středová*

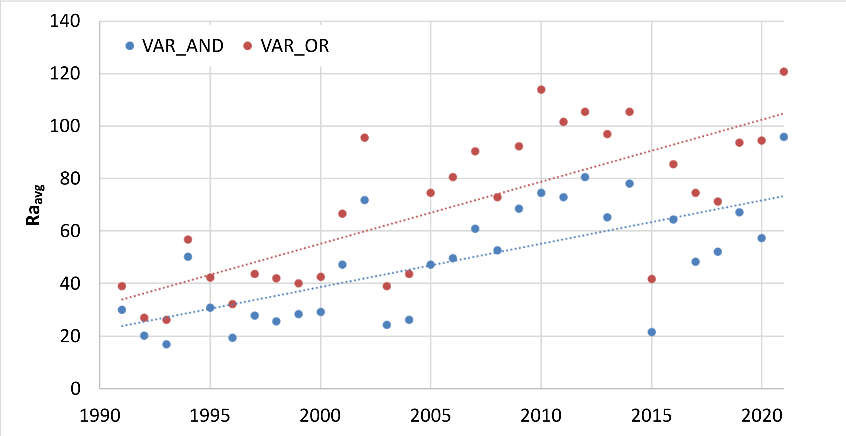

Fig. 7. Course of $\mathrm{Ra}_{\mathrm{avg}}$ values (average for whole area of interest) based on both tested variants of EER specification.

et al. (2013) reported different abiotic climate change impacts across altitude in the region, an increased R factor was identified across all altitudes (Fig. 7). This fact calls for updating its values in order to capture ongoing climate change impacts on soil erosion risks.

Figures 2 to 4 show that significant changes of Ra occur from about 2000 onwards. Similarly marked changes in the R-factor are found from about 800 m a.s.l. onwards. It of course has an effect on headwater function of mountain ecosystems, siltation of water management structures and reservoirs, etc. As the forests perform various ecological functions, while in mountainous areas and extreme habitats the anti-erosion one has the highest importance (*Sitko et al., 2011*), our results provide background material for modelling erosion from mountain forest calamity areas caused by intense rainfall. Increased R factor together with extensive deforestation of mountainous areas of the Czech Republic and Slovakia after wind calamities and the subsequent infestation of bark beetles has raised the risk of water erosion (*Mezei et al. 2017; Bartík et al. 2016, 2019*). The processing of calamities and the impact of mechanisms carrying out logging and transport works induces damage and erosion of forest soils by logging and transport machinery. Sedimentation not only reduces the storage volume of the reservoir, but also leads to other negative consequences in the form of eutrophication or general deterioration of water quality (*Šach et al. 2018* and others).

4. Conclusions

- Due du climate change impacts water erosion is becoming one of the most dangerous degradation processes for soils, threatening agricultural land globally. In Europe, soil protection standards have been adopted as a complex system of good agricultural and environmental conditions (GAEC). These are based on, among other things, processed data-driven information with high spatial accuracy. In context of climate change soil protection measures need to have a strong focus on increasing soil erosion risks as our results suggest a gradual increase of Ra values regardless of applied ERR variant.
- Numerous studies on water erosion provide already worldwide robust datasets of the soil erosivity factor, but there is a need for further region-

alization and validation of methods under climate change conditions. For example, methodological discrepancies in erosive efficient rains (EER) specification used by individual surveys limit homogeneity of obtained data and thus their applicability in soil protection.

- Our study contributed to regionalized validation and trend identification of the annual rain erosivity factor (Ra) through two specified EERs specifications where VAR_AND constitute 64% of median and 70% of mean R factor for ERRs defined by VAR_OR.
- In order to derive a complex view on R factor all constituent studies must be carefully scrutinized in terms of employed methods. Revealed and statistically evaluated relationships between different methodological approaches thus represent an useful tool enabling conversion from one method to another. Conversion factors with high statistical significance for two applied EER methods is provided therefore additionally in our study.

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