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Environmental factors affecting splash erosion in the mountain area (the Western Polish Carpathians)

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Abstract: The aim of this study was to examine the effects of various environmental factors on splash erosion based on the funnel method under natural conditions. The relationship between splash and wash erosion were also studied. The intermediate timescale study (2012–2016, from May to October) was conducted in the Western Polish Carpathians where Inceptisols predominate. The splash erosion rate (kg m^{-2}) was variable and showed a strong correlation with environmental factors, including rainfall parameters, land use (black fallow, meadow), slope gradient (0°, 11°), and also the particle size of soil and usage time (organic matter content, OM). The splash erosion rate on the slope with black fallow was 95 times higher than in the meadow and up to 20 times higher than in flat area. The average downslope splash erosion was 75% higher than the upslope splash erosion, and the soil particles were detached to maximum heights of 50 cm (downslope). There was a positive correlation between splash erosion and wash and a negative correlation between splash erosion and OM.

Key words: splash erosion, environmental factors, wash, Carpathians, Poland

Introduction

Splash erosion involves the detachment of soil particles as a result of raindrops (Poesen 2018) and is the first stage of soil erosion by water (Fernández-Raga et al. 2010, 2017). In addition, it is one of the most important factors affecting the denudation system of river catchments through destruction of soil structure and reduction of soil permeability (Ma et al. 2014, Liu et al. 2015). Furthermore, detached soil particles by raindrops can be transported to river channel throughout the road networks or/and rills system (Affek et al. 2017, Bryndal et al. 2017, Kijowska-Strugała et al. 2017, Kroczak, Bryndal 2017).

Numerous studies show different aspects of splash erosion, which depend on many factors such as rainfall parameters (e.g. intensity, size and velocity of raindrop, kinetic energy) (Renard et al. 1997, Ghahramani et al. 2012, Święchowicz 2012b, Liu et al. 2015, Mahmoodabadi, Sajjadi 2016, Beczek et al. 2018, Święchowicz 2018), wind (Marzen et al. 2017), topography (Saedi et al. 2016), soil properties (Ryżak et al. 2015), and land use and land cover (LULC) (Wainwright 1996, Szpikowski 2001, Ghahramani et al. 2011, Moghadam et al. 2015, Yao et al. 2018). The soil management practices and soil particle size are also important (Sharma et al. 1995, Moghadam et al. 2015). However, there is still a need to analyze the impact of many different environmental factors on splash erosion under different environmental conditions (Mahmoodabadi, Sajjadi 2016, Li et al. 2018a, Li et al. 2018b). This is important for the development of soil erosion models in various areas, especially mountainous ones.

In the Western Polish Carpathians, splash erosion studies were conducted, among others by Gerlach (1976a, b), Chmielowiec (1977), Froehlich, Słupik (1980), Śmietana (1987), Święchowicz (2012a, b), Kijowska-Strugała, Kiszka (2014). Święchowicz (2012b), in the lowest marginal zone of the Carpathian Foothills (the Dworski Potok Stream catchment) with slope with loess-like formation, showed for the first time, functional relationships between precipitation parameters (rainfall amount, rainfall erosivity index, kinetic energy, maximum 30-minute intensity) and splash erosion in the single events during the 3-year study period (2007–2009). Several years of splash erosion studies on Inceptisoil in Polish Carpathians have not been conducted yet.

In the Western Polish Carpathians after transformation from centrally planned to free market economy in 1989, most cultivated land was transformed to grassland and forest, and soil erosion decreased due to these land use and land cover changes (Kozak 2010, Bucała-Hrabia 2017, Kijowska-Strugała 2019). Nevertheless, in Carpathians the negative effects associated with soil erosion are still being observed (Gil 2009, Święchowicz 2010, 2012b, 2017, 2018). In particular, agricultural fields are especially susceptible to splash erosion because they are bare during several months of the year (Kijowska-Strugała et al. 2018). Many studies showed that erosion is the highest on bare soil (Gil 1976, Thornes 1990, Ghahramani et al. 2011, Święchowicz 2018)

Many publications have also focused on trajectories of material movement during splash erosion (e.g. Gerlach 1976a, Froehlich, Słupik 1980, Van Dijk et al. 2003, Saedi et al. 2016, Fu et al. 2017), but the problem of particle size distribution versus different directions of movement remains less recognized (Legout et al. 2005, Wei et al. 2015, Sadeghi et al. 2017). This type of research has led to a significant understanding of the basic mechanisms of detaching soil particles during rainfall and can be used to develop models of soil erosion with different particle sizes in relation to the transport of particles.

It is also important that a number of correlations between environmental factors (e.g. rainfall parameter, slope gradient, wind, soil properties) and splash erosion have been found under laboratory conditions (e.g. Legout et al. 2005, Marzen et al. 2015, Saedi et al. 2016). However, many studies claim that the results of laboratory and theoretical studies should be verified by field measurements, under natural precipitation conditions (Van Dijk et al. 2003, Nanko et al. 2008).

The results of this study supplement the knowledge about splash erosion dynamics in the mid-mountain areas and could be important for the development of rainfall erosion models and be applied in soil conservation planning, especially in the Western Polish Carpathians. In the literature, there is also a lack of studies on the impact of the time of use of the plots on the splash erosion. Święchowicz (2012b) paid attention to the impact of time of conducting research (2007–2009) on splash erosion in the one plot with black fallow in the Dworski Potok stream catchment (with loess-like formation). In the Bystrzanka catchment, the experimental study was carried out in few plots simultaneously (with different time of the plots – used as black fallow). In the Western Polish Carpathians, this type of experimental research, under natural precipitation conditions, with few plots has not been conducted yet. This study reports about an experiment consisting of changing land use, from a meadow to a black fallow, additionally demonstrating the impact of the plot usage time on splash erosion changes. The erosion processes are different in areas with permanent vegetation compared with black fallow due to the organic matter content and the size of soil aggregates (Ekwue 1991, Cerdan et al. 2010). The meadow areas are characterized by a high spatial variation in infiltration capacity (Cammeraat 2002). The literature has documented the negative impact of intensification of agricultural activities on erosion processes (Brandolini et al. 2018, Perović et al. 2018). One example is the transition from meadows to cultivated land, which increases splash and risk of soil erosion (Martínez-Casasnovas, Sanchez-Bosch 2000, Święchowicz 2012b).

The objectives of this study are to examine:

- the effect of different environmental factors including rainfall parameters, land use, slope gradient and also the particle size of soil and usage time (organic matter content, OM) on splash erosion mass (g) and rate (kg m^{-2}) over intermediate timescale (2012–2016) in the Western Polish Carpathians (in the Bystrzanka catchment),
- the effect of soil particle size and distribution on splash erosion,
- the impact of the plot usage time on splash erosion,
- the relationship between splash erosion and wash erosion.

The wash and splash erosion were examined separately to show the interaction between those two processes. Previous studies showed different proportions between splash erosion and wash under different environmental conditions, mainly due to soil properties, rainfall parameters, and the specifics of the study area (Szpikowski 2001, Van Dijk et al. 2003, Święchowicz 2012b, Mahmoodabadi, Sajjadi 2016). Święchowicz (2012b) showed that the occurrence of wash and linear erosion did not occur during every splash erosion event. The recognition of splash and wash under natural rainfall conditions in the Western Polish Carpathians will improve the understanding of sediment production and redistribution processes.

Study area and methods

Monitoring of splash and wash erosion was conducted from May to October (season without snow cover) in 2012–2016 on five experimental plots for each process (A, B, C, D, E – splash plots, L2, L4, L8, L16, L32 – surface runoff and wash plots) located in the

Bystrzanka catchment (49°38'04" N, 21°07'08" E) in the Western Polish Carpathians (Fig. 1). Slopes with gradients of 9–11° are predominant, and the study area is characterized by a warm, humid continental climate: the Cfb type according to Köppen's (1931) classification. The average annual precipitation over 1968–2016 at the Research Station in Szymbark (Institute of Geography and Spatial Organization Polish Academy of Sciences), located within approximately 30 m from the experimental plots, was 837 mm. The maximum and average velocities of rain drops in 2009 (May, June, July, September) during intensive precipitation were 11.3 m s^{-1} and 7.3 m s^{-1}, respectively, and the average maximum rain drop diameters were 7.1 mm (during heavy downpours) and 2.6 mm (during continuous rainfall) (laser distrometer OTT Parsivel, for rainfall intensities of 0.001 to 1200 mm h^{-1}, archival materials of the Research Station in Szymbark, 2009). In the analyzed period, the average precipitation was 833 mm, with the range from 666 mm (2012) to 1098 mm (2014). A very wet year was 2014 and 2016 was humid, 2012 was dry, and 2013

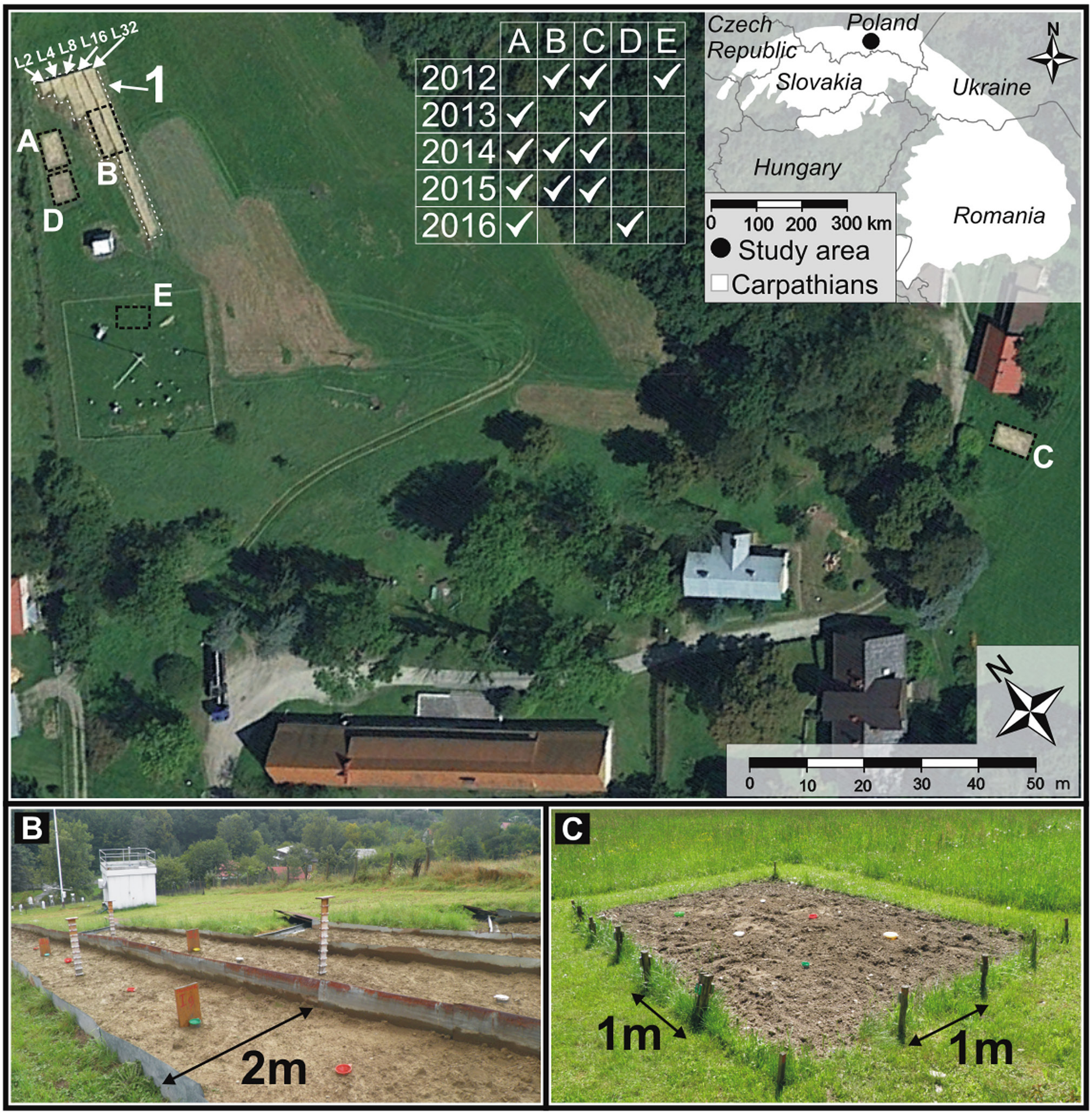

Fig. 1. Location of the experimental plots in the Bystrzanka catchment (the Western Polish Carpathians) (A, B, C, D, 1) with time use of plots

A, B, D – plots with black fallow (11°), C – plots with black fallow (0°), E – plot with meadow (11°), 1 – surface runoff and wash plots and 2015 were average in terms of total precipitation. The maximum 10-minute rainfall during the study period was 11.2 mm, and the mean duration of rainfall events was 285 minutes.

The plots were located on the Taborówka slope, in the Magura nappe. The underlying rocks consist of clay shales intercalated with sandstone (Inoceramian beds) (Świdziński 1973). The soil is classified as an Inceptisol (USDA classification, acc. Soil Survey Division Staff 2017). This type of soil predominates in the Western Polish Carpathians (Skiba, Drewnik 2003). On the study slope, soils are deep and range from 1.5 to 2.5 m, the total porosity of the soil on the agricultural foothill slope is 41–51% (Adamczyk et al. 1973), and the soil infiltration capacity ranges from 0.1 to 11.4 mm min^{-1} (Słupik 1973). Splash erosion was measured on plots with black fallow and meadow. Areas with meadow are one of the dominant types of LULC in the Western Polish Carpathians in recent years (Kijowska-Strugała, Demczuk 2015, Bucała-Hrabia 2017, Kijowska-Strugała et al. 2018). A slope with a gradient of 11° and a flat surface were tested (Table 1). According to the USDA Textural Soil Classification (Soil Survey Division Staff 2017), silt loam was the dominant soil texture on the experimental plots, with average silt contributions of 54% on the slope (ranging from 49% to 59%) and 46% on the flat area (Table 2). On the flat area, the percentage of sand was higher than on the slope (Table 2).

A total of 91 splash events were recorded during the 5-year period. Measurements of splash erosion were made each time after the occurrence of precipitation. The procedure proposed by Święchowicz (2012b) was used. The mass (g) of detached sediment were measured using the funnel method using funnels of varying diameters (75, 110 and 170 mm), which is a common measurement technique (e.g. Święchowicz 2012b, Brant et al. 2017). Six splash funnels were placed in each experimental plot (two funnels of each diameter). Different funnel diameters were used to show the importance of funnels size on the mass of detached material. Validation was made based on the formula proposed by Van Dijk et al. (2002). For the first time in Poland this formula was used by Rejman (2006) and in the Western Polish Carpathians by Święchowicz (2012b). This enabled the splash erosion values released from the diameter of the funnels (Święchowicz 2012b, 2018).

The soil plots were kept bare by mechanical removal of plants (except plots E). The splash funnels were placed a few millimeters above the ground, which prevented delivery of soil from runoff. This method was consistent with the procedure used at the AMU Geoecological Station in Storkowo

Table 1. Description of the experimental plots located in the Bystrzanka catchment (the Western Polish Carpathians)

Plot	LULC	Size [length × with] [m]	gradient [°]	Operated time [years]	OM [%]
		Splash plots			
A	black fallow	6 × 4	11	2013–2016	3.28
B	black fallow	16 × 4	11	2012–2016	2.05
C	black fallow	6 × 4	0	2012–2016	2.69
D	black fallow	6 × 4	11	2016	4.05
E	meadow	6 × 4	11	2012–2013	4.41
		Wash plots			
L2	black fallow	2 × 2	11	2009–2016	2.03
L4	black fallow	4 × 2	11	2009–2016	2.07
L8	black fallow	8 × 2	11	2009–2016	2.05
L16	black fallow	16 × 2	11	2009–2016	2.03
L32	black fallow	32 × 2	11	2009–2016	2.05

Table 2. Soil particle size [mm] in the experimental plots (A, B, C, D) and splash particle size distribution (downslope and upslope) below and above 20 cm height

Particle size [mm]	Experimental plots				Downslope splash		Upslope splash	
					Height [cm]			
	A	B	C	D	<20	>20	<20	>20
					[%]			
Gravel (>2.00)	4	2	3	2	0	0	0	0
Sand (2.00–0.05)	33	41	45	31	44	59	46	56
Silt (0.05–0.002)	54	49	46	59	50	36	48	38
Clay (<0.002)	9	7	7	9	6	5	6	6

(Szpikowski 2001). In the Western Polish Carpathians this method was used by e.g. Święchowicz 2012b. To determine the dominant direction (downslope and upslope) of material detachment in the study area, boards with a height of 70 cm were installed in 2012 and 2013. Additionally, the vertical splash range was defined using a board with a height of 100 cm, width of 15 cm, and thickness of 2 cm (divided with wooden slats every 10 cm). These tools were covered by a roof protecting the collected material from washing down. This method was used for the first time in the Western Polish Carpathians by Gerlach (1976a). Splash rate was calculated as the mass of detached material per unit area (kg m^{-2}). Furthermore, the mass of soil erosion was divided by the duration of events (g m^{-2} min^{-1}). The splash erosion were calculated after each rainfall event. The material was filtered, dried at 105°C and weighed with an accuracy of up to 0.0001 g.

Precipitation parameters (D_i – rainfall duration (min), P_{10} – 10-minute rainfall intensity (mm 10 min^{-1}), P_1 – 1-minute rainfall intensity (mm min^{-1}), I_{30} – 30-minute maximum rainfall intensity (mm ha^{-1}), EI_{30} – 30-minute rainfall erosivity (MJ mm ha^{-1} h^{-1}) were obtained on the basis of measurements by a tipping bucket rain gauge with 1 mm resolution and an automatic rain gauge (Vaisala MILOS 500) with a resolution of 0.2 mm located near the plots at the Research Station in Szymbark.

The erosivity index for individual rainfall events was calculated (Wischmeier, Smith 1978), defined as the product of total energy of precipitation and maximum intensity within 30 minutes:

$$EI_{30} = E_{kin} I_{30} \tag{1}$$

where:
- EI_{30} – 30-minute rainfall erosivity index (MJ mm ha^{-1} h^{-1}),
- E_{kin} – kinetic energy per area unit (MJ ha^{-1}),
- I_{30} – maximum 30-minute rainfall intensity (mm h^{-1}).

The rainfall kinetic energy was calculated according to the equation developed by Brown and Foster (1987):

$$E_{kin} = \sum_{i=1}^{n} 0.29[1-0.72\exp(-0.05I_i)]\Delta P_i \tag{2}$$

where:
- I_i – rainfall intensity in the i-th range (mm h^{-1}),
- ΔP_i – total rainfall in the i-th range (mm).

To determine the distance of soil displaced due to the splash downslope side D (m) and upslope side G (m), the model proposed by Poesen and Savat (1981) was used, which assumes vertical rainfall and windless conditions:

$$D = 0.019\ (D_{50})^{-0.220} + 0.301\ \sin\alpha \tag{3}$$

$$G = 0.019\ (D_{50})^{-0.220} - 0.301\ \sin\alpha \tag{4}$$

where:
- D_{50} – median of particle diameter (m),
- α – slope gradient (°).

The D_{50} (i.e. the median) is defined above as the diameter where half of the population lies below this value. The model was verified in the field for particle sizes ranging from 0.002 to 1 mm and slope gradients ranging from 9° to 14°. The applied model did not include wind because no study of the effects of wind speed and direction on splash erosion was conducted in the Western Polish Carpathians.

Laser diffraction (Fritsch Analysette 22 diffractometer) was used to determine the soil particle size in the experimental plots and the detached material. Based on the USDA classification (Soil Survey Division Staff 2017), four basic fractions were separated: gravel (75.0–2.0 mm), sand (2.0–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm).

The launch of the experimental plots at various times made it possible to examine the impact of the usage times of the plots on splash erosion rate. Plots B and A (black fallow) were created in 2009 and 2013, respectively, and plot D (black fallow) was created in 2016 (meadow converted to black fallow) (Fig. 1). The results from plot D were compared with those from plot A, and those from plot A were compared with plot B. Total carbon (TC) in the samples taken from the experimental plots was determined by combustion using a Thermo Scientific FLASH 2000 CHNS Organic Elementary Analyzer. In the studied area, TC corresponds to organic carbon (OC) due to the absence of carbonate in the soil. This approach was used in the Carpathians by Drewnik et al. (2016). Organic matter (OM) content was calculated by multiplying the OC by a conventional factor of 1.724 (Waksman, Stevens 1930).

The surface runoff and wash on plots with black fallow are measured since 2009. In this study, surface runoff and wash data from the period 2012–2016 were used. To investigate the relationship between splash erosion and wash, the study was carried out on 5 plots with the same width (2 m) and different plot lengths (L2, L4, L8, L16 and L32 m) (Table 1). In addition, the impact of plot length on wash and surface runoff during various rainfall depth, as well as the impact of rainfall parameters (the same as in the case of splash erosion), were analyzed. Plots were fenced by a band of galvanized steel, finished gutter and a calibrated tank, where the water and sediment were collected during rainfall events. The mass of the sediment was converted into a dry mass of sediment according to the index of 1.4 g cm^{-3}. This value was determined experimentally in the same area by Gil (1976), who used the dry-weight method.

To identify trends, correlations, and levels of statistical significance between the parameters, the Statistica program version 9.0 was used. The U Mann-Whitney test and Spearman's correlation were used. The impact of precipitation parameters on splash erosion was calculated based on the Beta factor. The statistical analysis did not include the plot with meadow (plot E) due to the low values and small differences of splash erosion and the short duration of the measurements.

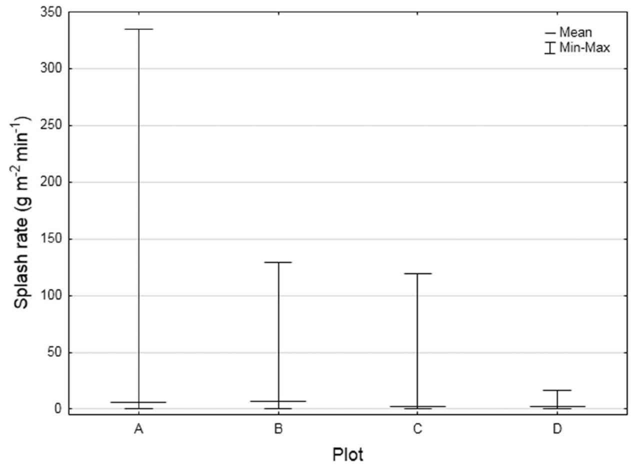

Fig. 2. Splash erosion (g m^{-2} min^{-1}) on experimental plots (A, B, C, D) during 2012–2016 (from May to October)

Results

Mass and rate of soil splash

In June and July, the highest number of splash events was noticed (with 27 and 23, respectively), and the lowest was in October, with only 7 events. The lowest total precipitation with splash was 1.7 mm (June 2013). Splash erosion rate (g m^{-2} min^{-1}) in each experimental plot showed high variation (Fig. 2). The splash mass (g) variation coefficient ranged from 68% (plot D) to 119% (plot C). The highest splash masses were recorded in plots A and B, with black fallow and a gradient of 11° (Fig. 2). The average rates for these plots were similar: 5.31 and 6.63 g m^{-2} min^{-1}, respectively. The lowest soil splash rates (average 0.008 g m^{-2} min^{-1}) were recorded in plot E, with meadow and a gradient of 11°. The maximum splash rates were recorded during 30-minute rainfall erosivity index above 200 MJ mm ha^{-1} h^{-1} (plot A: 334.61, B: 128.78, C: 119.57, D: 16.35, and E: 0.076 g m^{-2} min^{-1}). The statistical analysis using the non-parametric U Mann-Whitney test revealed

Table 3. Splash erosion rate [kg m^{-2}] differences in experimental plots (U Mann-Whitney test, statistically significant *p* marked in bold)

Plots	Rank sum 1	Rank sum 2	U	Z	*p*	N 1	N 2
A–B	4891	3887	1965	−0.751	0.057	76	57
A–C	6385	4493	1937	2.95	**0.000**	76	74
A–D	3600	771	618	0.278	**0.044**	76	17
B–C	4281	3847	1291	3.385	**0.000**	57	74

A, B, C, D – experimental plots: descriptions in the text and Table 1.

Table 4. Parameters a and b of the exponential function for the relationship between splash erosion [g] and [g m^{-2} min^{-1}] and splash funnel diameter [mm] in different plots in the period 2012–2016

Plot	Number of events	Splash erosion mass [g]				Splash erosion rate [g m^{-2} min^{-1}]			
		a	b	R^2	equation	a	b	R^2	equation
A	76	0.0547	1.8375	0.99	power law	2663.5	-0.404	0.75	power law
B	57	4.2063	0.7537	0.87	power law	11732	-0.756	0.95	power law
C	74	0.8373	1.0361	0.97	power law	1272.8	-0.408	0.99	power law
D	17	0.3756	0.9084	0.98	power law	2249.6	-0.904	0.99	power law

Table 5. Splash erosion rate [kg m^{-2}] differences in different funnels diameter in experimental plots (U Mann-Whitney test result, statistically significant *p* marked in bold)

Funnel	A110	A175	B75	B110	B175	C75	C110	C175	D75	D110	D175
A75	0.601	0.677	0.464	0.097	0.081	**0.000**	**0.000**	**0.000**	0.220	**0.036**	**0.000**
A110		0.879	0.763	0.200	0.199	**0.000**	**0.000**	**0.000**	0.386	0.066	**0.002**
A175			0.767	0.241	0.231	**0.000**	**0.000**	**0.000**	0.471	0.070	**0.001**
B75				0.373	0.301	**0.000**	**0.001**	**0.000**			
B110					0.818	**0.001**	**0.006**	**0.000**			
B175						0.003	0.013	0.001			

A, B, C, D – experimental plots, 75, 110, 175 – funnel diameter [mm].

statistically significant differences in the amount of detached soil in the respective plots (Table 3). The obtained splash differences were not statistically significant in plots A and B.

During each rainfall event, the greatest mass of splash (g) was noticed in funnels with the diameter of 175 mm, and the least amount was noticed in funnels with the diameter of 75 mm, but the soil splash rate (kg m^{-2}) increased as the diameter of the funnels decreased. This is due to the distribution of the splash mass, decreasing exponentially with distance from the point of impact of the rain drop, and the related relationship between the splash surface area and the funnel surface area. Thus, the measured splash mass increased with the diameter of the funnel, whereas it decreased on the surface unit. Differences in the mass of soil detached at different experimental plots were observed in various periods of research. The dependence of the splash erosion and the funnels diameters is described by the power law equation y=axb (x – funnels diameter, y – splash erosion). The *a* and *b* parameter values for each research plot are presented in Table 4. The statistical analysis showed significant differences between funnel diameters in plots A and C, as well as B and C (Table 5). In addition, significant differences were noted between selected funnels in plots A and D, with the same LULC and gradient but different usage times. The differences between funnels in plots A and B were not statistically significant (Table 5).

It was found that, on a slope gradient of 11°, soil particles are detached to a maximum height of 50 cm, mainly during rainfalls with high intensity and high total precipitation. Significantly lower percentage of soil was detached in the upslope (23% of the detached soil on average) than in the downslope direction (77%) (Fig. 3A). The splash below 10 cm height was the largest, representing an average of 75% of soil deposited in the downslope and upslope directions (Fig. 3A). There was a difference in splash direction above 20 cm: downslope splash erosion mass (g) was 70% higher than upslope splash (Fig. 3A). The particle sizes of the detached material in different directions (downslope and upslope) and at different heights were analyzed. The silt content in splash erosion was dominant in both the downslope and upslope directions (62% and 61%, respectively) (Fig. 3B). Below 20 cm height, the contribution of silt in both the downslope and upslope directions was the highest (50% and 48%, respectively). Above 20 cm (downslope and upslope), sand was predominant (59% and 56%, respectively). The clay contents in

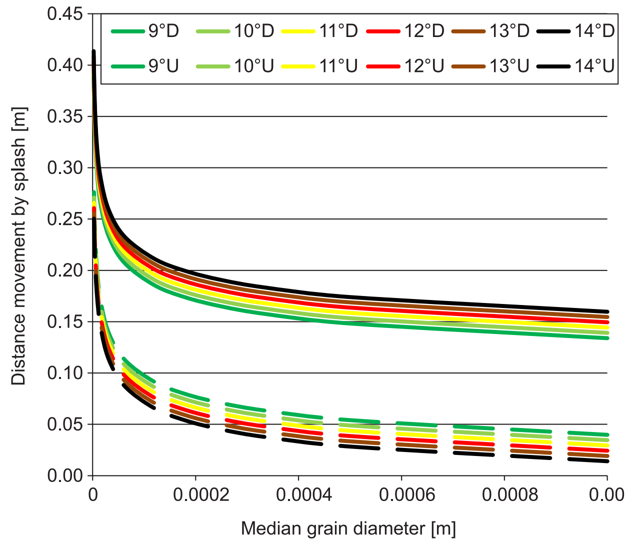

Fig. 4. Nomogram for calculate of soil particle displacement by splash in downslope (D) and upslope (U) in the Bystrzanka catchment (gradient 9–14°), based on Poesen and Savat's empirical model (1981)

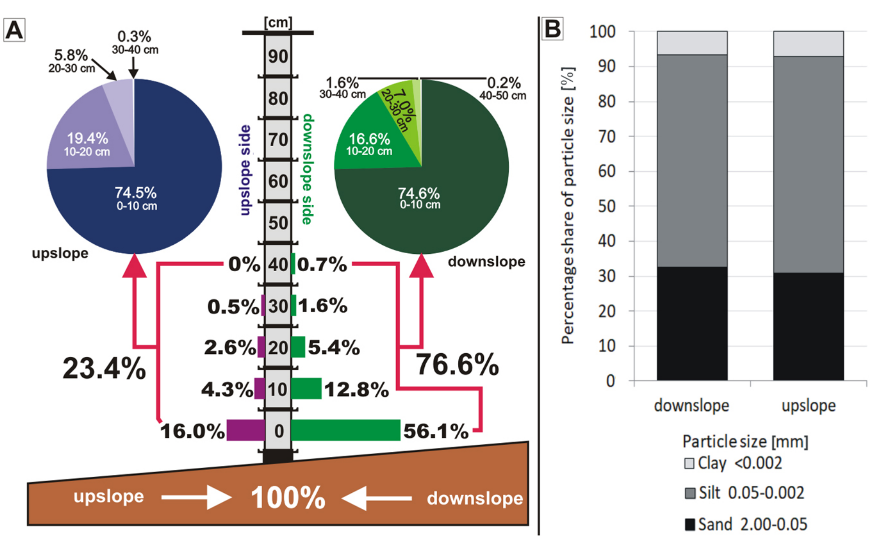

Fig. 3. Splash erosion mass (g) in downslope and upslope on the slope (11° gradient) with black fallow (A) and particle size distribution (B)

both the upslope and downslope directions (below and above 20 cm) were similar: 5% and 6% (Table 2). The analysis showed that an increase in soil particle size increased the average splash erosion.

Based on the nomogram (constructed on the basis of Equations 3 and 4, Fig. 4), at a gradient of 11°, the detached soil particles were moved up to 40 cm downslope and up to 28 cm upslope. The difference in the distance of movement of the soil was approximately 12 cm.

Factors controlling splash erosion

The lowest rainfall with splash erosion during the five year period was 1.7 mm. The calculated Spearman correlation coefficient shows a significant relationship between splash rate (kg $m^{-2)}$ and rainfall parameters (D, P_{10}, P_1, P, I_{30}, EI_{30}) (Table 6). The exception was the duration of precipitation (D_i), which did not significantly influence the splash erosion on plots A and D. Rainfall erosivity (EI_{30}) during the analyzed period ranged from 1.9 to 604.5 MJ mm ha^{-1} $h^{-1.}$ The largest splash erosion rate (kg m^{-2}) was found during the events of the EI_{30} above 50 MJ mm ha^{-1} $h^{-1.}$ Those events accounted for 40% of all noted rainfall events, and the splash erosion ranged from 53% (plot C) to 70% (plot D) of the total splash mass. The splash erosion rate was different during varied EI_{30}. The smallest differences of splash erosion rate was noticed on plot E. Additionally, splash erosion varied during humid and dry years due to the differentiation of the total precipitation. In humid years, during rainfall events with EI_{30} above 50 MJ mm ha^{-1} $h^{-1,}$ the splash erosion mass ranged from 68% (2016) to 83% (2014) of the total splash erosion mass, in the dry year, it averaged 17% (2012). The highest correlation between rainfall EI_{30} and splash erosion rate (kg m^{-2}) was recorded in plot D (Fig. 5A). In the study area, taking into account the EI_{30}, calculated that 90% of events were recorded after exceeding the value of 7 MJ mm ha^{-1} h^{-1}. In addition, 10% of the events occurred after exceeding the value of 196 MJ mm ha^{-1} h^{-1}.

The calculated Beta index, which assesses the relative contribution of each independent variable (D, P_{10}, P_1, P, I_{30}, EI_{30}) to predict the dependent variable (average splash erosion in the period 2012–2016), showed that the total rainfall (P) and the rainfall intensity (P_1, I_{30}, EI_{30}) influence splash in particular experimental plots to the greatest extent, and the duration of precipitation (D_i) influences splash to the least extent. The correlation between the total precipitation and splash erosion rate (kg m^{-2}) in black fallow was best described by power law equations. The highest correlation was recorded on plot B (R^2= 0.34, p<0.001) (Fig. 5B).

High variation of splash erosion depending on LULC and slope gradient was noted on the experimental plots. The splash erosion in the meadow was only 1.4% of the splash erosion on black fallow at the same gradient (11°) and 5.3% of the splash erosion on the flat plot with black fallow. The splash on plot C (flat surface) was lower than on plots A and B, representing 44% to 58% of the values obtained on the slope (plots A and B with the same land use). The differences obtained in the plots with a gradient of 11° (A, B) and in the flat plot (C) were statistically significant, both in terms of the averages and in the

Table 6. Summary of Spearman's correlation results (statistically significant p marked in bold) of environmental factors affecting differences in the splash erosion

Splash	D_i	P_{10}	P_1	P	I_{30}	EI_{30}
			A (N=76)			
AS	0.477	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
MS	0.550	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
MiS	0.311	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
			B (N=57)			
AS	**0.000**	**0.000**	**0.000**	0.464	0.106	**0.004**
MS	**0.000**	**0.000**	**0.000**	0.404	0.134	**0.01**
MiS	**0.000**	**0.000**	**0.000**	0.389	0.077	**0.001**
			C (N=74)			
AS	**0.000**	**0.000**	**0.000**	0.463	**0.006**	**0.000**
MS	**0.000**	**0.000**	**0.000**	0.442	**0.003**	**0.000**
MiS	**0.000**	**0.000**	**0.000**	0.664	**0.010**	**0.000**
			D (N=17)			
AS	0.897	**0.021**	**0.034**	**0.014**	**0.015**	**0.017**
MS	0.871	**0.029**	**0.041**	**0.018**	**0.036**	**0.046**
MiS	0.799	0.051	0.092	**0.031**	**0.038**	**0.029**

D_i – rainfall duration [min], P_{10} – 10-minute rainfall intensity [mm 10 min^{-1}], P_1 – 1-minute rainfall intensity [mm min^{-1}], I_{30} – 30-minute maximum rainfall intensity [mm h^{-1}], EI_{30} – rainfall erosivity [MJ mm ha^{-1} h^{-1}], AS – mean splash [kg m^{-2}], MS – maximum splash [kg m^{-2}], MiS – minimum splash [kg m^{-2}].

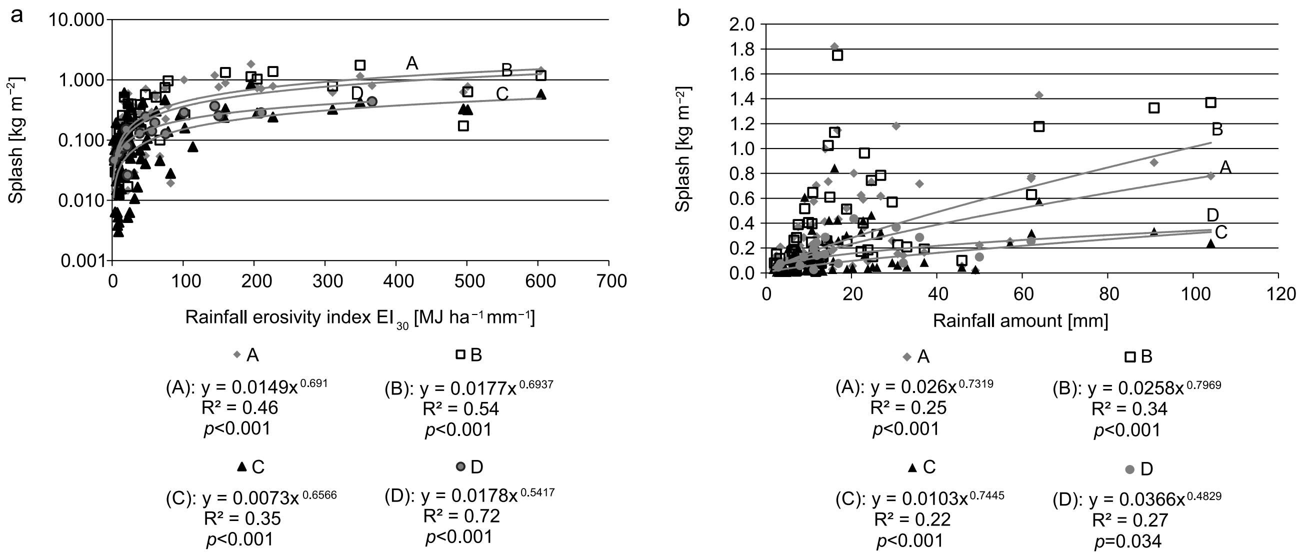

Fig. 5. Correlation between rainfall erosivity index EI_{30} (a), rainfall amount (b) and splash rate [kg m^{-2}] on the plots A, B, C and D with black fallow

case of individual funnels (Table 5). The correlation between splash erosion rate (kg m^{-2}) on the slope (plot B) and flat area (C) was described by a power law equation (R^2=0.77, p<0.001). A higher correlation (R^2=0.84, p<0.001) was noted between plots C and A, with a slightly shorter usage time than plot B. Thus, the average splash erosion rate (kg m^{-2}) on the slope (SEs) in relation to the flat plot (SEf) can be expressed by the following formula:

$$SEs = 1.3287 \cdot (SEf^{0.7126}). \qquad (5)$$

In addition, the comparison of results from plot A (started in 2013) with D (started in 2016) and of A with B (started in 2009) showed the impact of the usage times of the plots on the splash erosion rate (kg m^{-2}). In plot D, the splash erosion rate in the first year of operation was an average of 37% of the value (kg m^{-2}) of plot A. The maximum splash erosion rate on plot D was 61%, and the minimum was 14% relative to the splash erosion rate on plot A. The correlation was statistically significant (R^2=0.82, p<0.001). The statistical analysis using the non-parametric U Mann-Whitney test revealed statistically significant differences in the average amount of detached soil in plots A and D (Table 3). With time, the difference in splash erosion rate decreased between plots of different usage times and the same gradient (plots: A and B). In the first year, the difference was 63%, after two and three years, they were 15% and 3%, respectively. The decrease in differences was influenced by the gradual decomposition of OM. The highest content of OM was noticed on plot E with meadow: 4.41% (Table 1). On plot D (started in 2016), the OM content was lower by only 8% relative to plot E. In the second year of using plot A as black fallow, the OM content was 3.28%. This value was 37% higher than the OM in plot B, where the OM was the lowest (2.05%, Table 1). OM was negatively related to splash erosion.

Surface runoff and wash

The course of the runoff and wash was characterized by different frequencies and dynamics. The surface runoff and wash were recorded most frequently in the very humid year (2014), there were 27 cases overall. In total, there were 86 runoff and 70 wash events recorded over the study period: 5 and 21 fewer events than with splash erosion, respectively. Not all of the surface runoff events triggered the wash.

The runoff coefficient (mm) decreased with the length of the plot and reached values 3 times higher on the shortest plot (L2: 2 m long) compared with the longest plot (L32: 32 m long) (Table 7). The runoff coefficient was the highest in the shortest plot (in 95% of the events). The highest values of the total runoff coefficient were recorded in 2014, ranging from 68 mm (L32) to 239 mm (L2). In most cases, the surface runoff in the experimental plots occurred under unsaturated conditions. Surface runoff is a process of initiating wash, although a total of 16 cases of surface runoff without sediment were found. The wash rate (kg m^{-2}) increased up to the plot length of 16 m (Table 7), with the highest average values of wash rate during one event (0.62 kg m^{-2}). Overall, during the entire research period, an average of 65 kg of material was eroded from a 1 m^2 area of plot. The impact of the surface runoff on wash rate in the study period was characterized by a linear function. The analysis showed that the highest correlation coefficient between runoff and wash rate was observed

Table 7. Mean surface runoff [dm^3] and wash [kg] on the experimental plots with black fallow in 2012–2016 and correlation between mean runoff, mean wash and precipitation parameters

Parameter			Length of experimental plots [m]				
			2	4	8	16	32
			Runoff				
Mean number of events			17	17	17	17	17
Mean runoff [dm^3]			456.1	835.0	1520.0	2101.2	2396.0
Mean runoff coefficient [mm]			114.0	104.5	95.0	65.7	37.4
			Wash				
Mean number of events			12	13	14	14	14
Mean erosion from plots [kg]			27.3	67.3	188.3	419.4	713.1
Mean erosion from 1 m^2 [kg m^{-2}]			6.8	8.4	11.8	13.1	11.1
Parameter		D_i	P_{10}	P_1	P	I_{30}	EI_{30}
Mean runoff	R^2	0.03	0.14	0.06	0.43	0.11	0.26
	p	0.180	0.005	0.072	<0.001	0.012	<0.001
	regression equation*	l	l	l	l	log	l
Mean wash	R^2	0.04	0.27	0.17	0.24	0.03	0.44
	p	0.136	<0.001	0.002	0.001	0.234	<0.001
	regression equation*	pl	log	log	pl	pl	l

*l – linear equation, log – logarithmic equation, pl – power law equation

in the shortest plots SN2 and SN16 (R^2=0.51 and R^2=0.52, respectively p<0.001). The investigated relation between average runoff from all plots and rainfall parameters showed that it was most correlated with P and EI_{30} (R^2=0.43 and R^2=0.26, respectively p<0.001), and the average wash rate from all plots was most correlated with P_{10}, P and EI_{30} (R^2=0.27, R^2=0.24 and R^2=0.44, respectively, p<0.001) (Table 7). The splash erosion rate (kg m^{-2}) average was 65% of the material eroded from the plots by runoff.

Discussion

The study of splash erosion under natural conditions in mid-mountain areas is important for the widely discussed problems of soil management and land degradation. Based on five years of measurement on experimental plots in the Bystrzanka catchment with Inceptisols (USDA classification, Soil Survey Division Staff 2017), general trends in the course of splash erosion have been determined. Two classes of land use have been distinguished: black fallow and meadow. Agricultural lands with black fallow are only present for several months of the year. However, as shown in the results, they can significantly affect splash erosion and wash in mountain areas. Additionally, according to Gyssels et al. (2005), areas with black fallow are the most erosive. As a result of changes in LULC in the Western Polish Carpathians, the areas of meadow increased (Kijowska-Strugała et al. 2018). This resulted in decreases in the splash erosion and wash on the slope. In the study area, the splash erosion rate on black fallow (slope gradient 11°) during single rainfall events ranged from 0.00 to 334.7 g m^{-2} min^{-1}, and that on meadow ranged from 0.00 to 0.01 g m^{-2} min^{-1}. The splash on black fallow averaged approximately 99% higher than on the plots with meadow (at the same gradient). The research of Rejman et al. (1990), conducted under conditions of changing vegetative phases of plants in Belgium, showed linear relationships between plant coverage and individual splash (lower splash sizes were reported with increasing biomass). According to Ma et al. (2014), crops (corn, soybean, millet, winter wheat) significantly reduce splash erosion by an average of 68% compared with splash erosion on black fallow. In addition, Bochet et al. (2002) found that the intensity of detachment of soil particles increases with the distance from a single plant. The smallest splash was recorded directly under the plant. According to Terry and Shakesby (1993), the black fallow can also be more compacted and crusted than soil with plant cover because raindrops can increase the soil bulk density.

Additionally, slope gradient is an important factor in controlling splash erosion. The splash rate (kg m^{-2}) on black fallow slope was 49% higher than on the flat area. This result is compatible with previous research. Parlak and Parlak (2010) found that splash erosion on a slope with a gradient of 4° was 36% lower than on a steeper slope (8°). Splash erosion is therefore positively correlated with slope gradient (Mahmoodabadi, Sajjadi 2016), and more detached particles are transported downslope than upslope (Saedi et al. 2016). In the study area, the average downslope splash mass was 75% higher than the upslope splash. Similar results were obtained in the laboratory by Liu et al. (2015). Differences were due to the force of gravity, the greater impact of the raindrop mass in the downslope direction, and the lower angle of particle splash in the downslope direction (Sadeghi et al. 2017).

In the study area, soil particles were displaced to a maximum height of 50 cm. Based on pictures from a high-speed camera, Ryżak et al. (2015) observed vertical heights of 150 cm for soil from southeast Poland. In the study area, the splash up to 10 cm was the most frequent (75% in both the downslope and upslope directions). However, above 10 cm, the downslope splash was higher than the upslope splash. There was also a differentiation of particle size: up to 20 cm, the contribution of silt was the highest, and sand was predominant above 20 cm. The clay content was lower in both the upslope and downslope directions. According to Bradford and Huang (1992), the lower content of clay in comparison with silt and sand is due to cohesion forces. The studies of particle size during various rainfall events showed some dependencies. Comparison of precipitation with different intensities (8 mm 10 min^{-1} and 0.8 mm 10 min^{-1}) indicated a smaller proportion of sand during heavy rainfall than during lower-intensity rainfall. The silt content was the highest during heavy rainfall both in the upslope and downslope directions (55% and 47%, respectively). However, during low intensity rainfall, the sand particles was slightly higher than silt in both the upslope and downslope directions (47% and 53%, respectively). According to Qinjuan et al. (2008) silt particles can develop soil crust, and consequently silt particles can be less detached than other particles. Rainfall intensity had a significant impact on splash erosion in all experimental plots. According to Mermut et al. (1997), the higher rainfall intensity promoted the breaking up of soil aggregates. In the study area, the lowest value of the EI_{30} during which splash erosion was recorded was 1.9 MJ mm ha^{-1} h$^{-1.}$ There was a positive relationship between EI_{30} and splash erosion rate (kg m^{-2}). Święchowicz (2012b) in slope with loess-like formation in the Carpathian Foothills showed that every potentially erosive rain initiated splash erosion and calculated threshold value for the splash erosion in relation to the humidity of the year and the condition of land surface. In the Dworski Potok stream catchment, during the period 2007–2009, 90% of the soil particles was displacement during rainfall exceeding 2.8 MJ mm ha^{-1} h^{-1} (Święchowicz 2012b). This value was lower than in the study area.

Based on the nomogram, in the study area the soil particles were detached at distances 40 cm downslope and 28 cm upslope . The model distances are longer than the average values given by Rejman (2006) (9 cm, ranging from 5 to 42 cm, Nałęczowski Plateau with loess, Poland) and by Szpikowski (2010) (14 cm downslope and 10 cm upslope, slope gradient 4°, Western Pomerania, Poland). The differences result mainly from the methodology, slope gradient and soil type. According to Legout et al. (2005) the distance of movement of the soil depends on the stability of soil aggregates and wind. The similar value was noted by Święchowicz (2012b) in the Carpathian Foothills, the soil particles were detached at distances up to 48 cm. Agricultural practices are also important. Rejman (2006) found that the splash distance is 1.8 times longer on soils without agricultural practices than on cultivated soils. According to Fu et al. (2017), the splash mass decreases as distance increases. On a horizontal surface, distances are impacted by runoff and wind. Soil particles can be displaced at longer distances during runoff and wind events than during rainfall events without runoff and wind (Marzen et al. 2015, Schmidt et al. 2017). According to Barai et al. (2018), particles of soil (clay loam) can be displaced at a distance of 110 cm (downslope) and 76 cm (upslope) with a rainfall of 1.3 mm min^{-1} and a slope gradient of 6°.

The usage times of plots and the content of OM had a great importance for splash erosion in the study area. The highest differences in splash were noticed in the first year of plot operation (63%). The use of the plots as a black fallow in subsequent years resulted in a reduction of differences, mainly through the decreased content of OM and soil aggregate size. Large soil aggregates and high content of OM protect soil, resulting in lower splash erosion (Moghadam et al. 2015, Mahmoodabadi, Sajjadi 2016, Saedi et al. 2016). Caron et al. (1996) found that OM reduced water entry rate and slaking. In the study area, the highest content of OM was on plots with meadows (4.41%) due to high vegetation cover, and the lowest content of OM was in plot B (black fallow, 2.05%), with the longest study period.

Surface runoff and wash are important in mountain areas. In the study area, plot length was essential for the runoff coefficient, and the highest values were recorded on the shortest plot (2 m). In the study area, there was a linear correlation ($R^2=0.43$, $p<0.001$) between total rainfall (P) and surface runoff and a power law correlation ($R^2=0.24$, $p<0.001$) between rainfall and wash during the analyzed period. The study conducted by Święchowicz (2012b) in the Carpathian Foothills showed a linear or power law correlation between wash and rainfall amount (mm) ($R^2=0.59$ in 2009) and higher correlation between wash and EI_{30} ($R^2=0.98$ in 2009). According to Bochenek and Gil (2010), an increase in precipitation of more than 40 mm per day resulted in a decrease in the differentiation of the wash in plots of different lengths. A detailed analysis in 2012–2016 showed that the decrease of wash at very high intensities of precipitation could be a result of compaction of soil particles caused by the impact of high rain energy. In the study area, there was a statistically significant correlation between splash erosion (SE) and wash (De) ($R^2=0.54$, $p<0.001$), explained by a power law equation ($De=0.7533\ SE^{1.947}$). The annual loads of splash were 35% lower than wash. According to Mahmoodabadi and Sajjadi (2016), wash was much higher than splash erosion at all analyzed rainfall intensities. Defersha and Melesse (2012) noted that duration and rainfall intensity had a significant impact on wash. In the study area, the ratio of wash to splash erosion was not so obvious when analyzing individual rainfall events. Usually, the splash erosion was higher than wash, especially during rainfall events of short duration. However, during long-term rainfall events with high intensity rainfall at the beginning, wash was up to 24 times higher than splash erosion. During such events, a network of rills was created, which was deepened in subsequent phases of rainfall. These results also confirm laboratory analyses showing that the ratio of wash and splash increased with increasing rainfall intensity on slopes with gradients of more than 10° (Mahmoodabadi, Sajjadi 2016). Splash erosion in the analyzed period was noted at a rainfall event with a sum of 1.7 mm (1.2 mm 10 min^{-1}). According to Gil (2009) surface runoff was noted at a rainfall with a sum of 1.0 mm and soil wash with a sum 4.6 mm This values was calculated based on a 30-year study in the Carpathian Mountains.

Conclusions

The intermediate timescale study conducted on slopes under natural rainfall conditions showed that considerable splash erosion occurred in the Bystrzanka catchment in the Western Polish Carpathians. Splash erosion was very diverse and determined by many environmental factors. The analysis showed strong correlation with rainfall parameters, land use, gradient, particle size and usage time (OM content). The highest splash erosion was noticed on slopes without vegetation (black fallow) with low organic matter content. The lowest total precipitation with splash was 1.7 mm and 90% of splash erosion events were recorded after exceeding the value of 7 MJ mm ha^{-1} h^{-1}. The splash erosion on the slope with black fallow was 95 times higher than in the meadow and up to 20 times higher than in flat areas. The average downslope splash erosion rate was 75% higher than the upslope splash, and the soil particles were detached to maximum heights of 50 cm (downslope). In the study area, most of the splash occurred below 10 cm, the silt fraction dominated up to 20 cm, and the sand fraction dominated above 20 cm. There was a positive correlation between splash erosion and wash, and the usage time of plots had a significant impact of splash erosion. With time, the difference between splash erosion decreases in plots of different usage times and the same gradient, mainly due to the content of organic matter and tillage practices.

This study is necessary to understand the basic regularities of splash erosion, and it supplements the knowledge of the splash and wash erosion dynamics under natural conditions. Moreover, the results may be valuable for the development of rainfall erosion models and strategies for controlling water erosion, especially in mid-mountain areas.

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Author's contribution

Małgorzata Kijowska-Strugała: 70% , Krzysztof Kiszka: 30%.

References

Adamczyk B., Maciaszek W., Januszek K., 1973. Gleby gromady Szymbark i jej wartość użytkowa. Dokumentacja Geograficzna 1: 16–66.

Affek A.N., Zachwatowicz M., Sosnowska A., Gerlée A., Kiszka K., 2017. Impacts of modern mechanised skidding on the natural and cultural heritage of the Polish Carpathian Mountains. Forest Ecology and Management 405: 391–403. DOI: https://doi.org/10.1016/j.foreco.2017.09.047.

Barai V.N., Satpute G.U., Atre A.A., 2018. Effect of Rainfall Intensity on Directional Splash Erosion in Clay Loam Soil under Simulated Condition. International Journal of Bio-Resource & Stress Management 9(1):13–16. DOI: https://doi.org/10.23910/ijbsm/2018.9.1.3c0115

Beczek M., Ryżak M., Lamorski K., Sochan A., Mazur R., Bieganowski A., 2018. Application of X-ray computed microtomography to soil craters formed by raindrop splash. Geomorphology 303: 357–361. DOI: https://doi.org/10.1016/j.geomorph.2017.12.019.

Bochenek W., Gil E., 2010. Zróżnicowanie spływu powierzchniowego i spłukiwania gleby na poletkach doświadczalnych o różnej długości (Szymbark, Beskid Niski). Prace i Studia Geograficzne 45: 265–278.

Bochet E., Poesen J., Rubio J.L., 2002. Influence of plant morphology on splash erosion in a Mediterranean matorral. Zeitschrift für Geomorphologie 46(2): 223–243. DOI: https://doi.org/10.1127/zfg/46/2002/223.

Bradford J.M., Huang C.H., 1992. Mechanisms of crust formation: physical components. In: M.E. Summer, B.A. Stewart (eds), Soil Crusting: Chemical and Physical Processes. Lewis Publishing, Boca Raton.

Brandolini P., Pepe G., Capolongo D., Cappadonia C., Cevasco A., Conoscenti C., Marsico A., Vergari F., Del Monte M., 2018. Hillslope degradation in representative Italian areas: Just soil erosion risk or opportunity for development? Land Degradation & Development 29(9): 3050–3068. DOI: https://doi.org/10.1002/ldr.2999.

Brant V., Kroulik M., Pivec J., Zabransky P., Hakl J., Holec J., Kviz Z., Prochazka L., 2017. Splash Erosion in Maize Crops under Conservation Management in Combination with Shallow Strip-tillage before Sowing. Soil and Water Research 12(2): 106–116. DOI: https://doi.org/10.17221/147/2015-SWR.

Brown L.C., Foster G.R., 1987. Storm erosivity using idealized intensity distributions. Transactions of the ASAE 30(2): 379–386. DOI: https://doi.org/10.13031/2013.31957.

Bryndal T., Franczak P., Kroczak R., Cabaj W., Kołodziej A., 2017. The impact of extreme rainfall and flash floods on the flood risk management process and geomorphological changes in small Carpathian catchments: a case study of the Kasiniczanka river (Outer Carpathians, Poland). Natural Hazards 88(1): 95–120. DOI: https://doi.org/10.1007/s11069-017-2858-7.

Bucała-Hrabia A., 2017. Long-term impact of socio-economic changes on agricultural land use in the Polish Carpathians. Land Use Policy 64: 391–404. DOI: https://doi.org/10.1016/j.landusepol.2017.03.013.

Cammeraat L.H., 2002. A review of two strongly contrasting geomorphological systems within the context of scale. Earth Surface Processes and Landforms 27(11): 1201–1222. DOI: https://doi.org/10.1002/esp.421.

Caron J., Espindola C.R., Angers D.A., 1996. Soil structural stability during rapid wetting: influence of land use on some aggregate properties. Soil Science Socciety of America Journal 60(3): 901–908.

Cerdan O., Govers G., Le Bissonnais Y., Van Oost K., Poesen J., Saby N., Gabin A., Vacc A., Quinton J., Auerswald K., Kiks A., Kwaad J.P.M., Raclot D., Ionita I., Rejman J., Rousseva S., Muxart T., Roxo M.J., Dostal T., 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology 122(1–2): 167–177. DOI: https://doi.org/10.1016/j.geomorph.2010.06.011.

Chmielowiec S., 1977. Bombardująca działalność kropel deszczu i jej rola w modelowaniu stoków Pogórza. MS, Instytut Geografii Uniwersytetu Jagiellońskiego.

Defersha M.B., Melesse A.M., 2012. Effect of rainfall intensity, slope and antecedent moisture content on sediment concentration and sediment enrichment ratio. Catena 90: 47–52. DOI: https://doi.org/10.1016/j.catena.2011.11.002.

Drewnik M., Musielok Ł., Stolarczyk M., Mitka J., Gus M., 2016 Effects of exposure and vegetation type on organic matter stock in the soils of subalpine meadows in the Eastern Carpathians. Catena 147: 167–176. DOI: https://doi.org/10.1016/j.catena.2016.07.014.

Ekwue E.I., 1991. The effects of soil organic matter content, rainfall duration and aggregate size on soil detachment. Soil Technology 4(3): 197–207. DOI: https://doi.org/10.1016/0933-3630(91)90001-4.

Fernández-Raga M., Fraile R., Keizer J.J., Tiejiero M.E.V., Castro A., Palencia C., Calvo A.I., Koenders J., Marques R., 2010. The kinetic energy of rain measured with an optical disdrometer: an application to splash erosion. Atmospheric Research 96: 225–240. DOI: https://doi.org/10.1016/j.atmosres.2009.07.013.

Fernández-Raga M., Palencia C., Keesstra S., Jordán A., Fraile R., Angulo-Martínez M., Cerdà A., 2017. Splash erosion: A review with unanswered questions. Earth-Science Reviews 171: 463–477. DOI: https://doi.org/10.1016/j.earscirev.2017.06.009

Froehlich W., Słupik J., 1980. Importance of splash in erosion process within a small flysch catchment basin. Studia Geomorphologica Carpatho-Balcanica 14: 77–112.

Fu Y., Li G.L., Zheng T.H., Li B.Q., Zhang T., 2017. Splash detachment and transport of loess aggregate fragments by raindrop action. Catena 150: 154–160. DOI: https://doi.org/10.1016/j.catena.2016.11.021.

Gerlach T., 1976a. Bombardująca działalność kropel deszczu i jej znaczenie w przemieszczaniu gleby na stokach. Studia Geomorphologica Carpatho-Balcanica 10: 125–137.

Gerlach T., 1976b. Współczesny rozwój stoków w polskich Karpatach fliszowych. Prace Geograficzne PAN, 122: 1–116.

Ghahramani A., Ishikawa Y., Gomi T., Shirak K., Miyata S., 2011. Effect of ground cover on splash and sheetwash erosion over a steep forested hillslope: A plot-scale study. Catena 85(1): 34–47. DOI: https://doi.org/10.1016/j.catena.2010.11.005.

Ghahramani A., Yoshiharu I., Mudd S.M., 2012. Field experiments constraining the probability distribution of particle travel distances during natural rainstorms on different slope gradients. Earth Surface Processes and Landforms 37(5): 473–485. DOI: https://doi.org/10.1002/esp.2253.

Gil E., 1976. Spłukiwanie gleby na stokach fliszowych w rejonie Szymbarku (Slopewash on flysch slopes in the region of Szymbark). Dokumentacja Geograficzna 2: 1–163.

Gil E., 2009. Extreme values of soil downwash on cultivated slopes in the Polish Flysch Carpathians. In: W. Bochenek, M. Kijowska (eds), The operation of the natural environment during economic transformations in Poland IEMP 191–218.

Gyssels G., Poesen J., Bochet E., Li Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. Progress in Physical Geography 29(2): 189–217. DOI: https://doi.org/10.1191/0309133305pp443ra.

Kijowska-Strugała M., 2019. Sediment variability in a small catchment of the Polish Western Carpathians during transition from centrally planned to free-market economics. Geomorphology 325: 119–129. DOI: https://doi.org/10.1016/j.geomorph.2018.10.008.

Kijowska-Strugała M., Bucała-Hrabia A., Demczuk P., 2018. Long-term impact of land use changes on soil erosion in an agricultural catchment (in the Western Polish Carpathians). Land Degradation & Development 29: 1871–1884. DOI: https://doi.org/10.1002/ldr.2936.

Kijowska-Strugała M., Demczuk P., 2015. Impact of land use changes on soil erosion and deposition in a small Polish Carpathians catchment in last 40 years. Carpathian Journal of Earth and Environmental Sciences 10(2): 261–270.

Kijowska-Strugała M., Kiszka K., 2014. Ocena wielkości rozbryzgu gleby na stoku pogórskim (Karpaty fliszowe, zlewnia Bystrzanki). Annales Universitatis Mariae Curie-Skłodowska Sectio B: Geographia, Geologia, Mineralogia et Petrographia 69(2): 79–95.

Kijowska-Strugała M., Wiejaczka Ł., Gil E., Bochenek W., Kiszka K., 2017. The impact of extreme hydro-meteorological events on the transformation of mountain river channels (Polish Flysch Carpathians). Zeitschrift für Geomorphology 61(1): 75–89. DOI: https://doi.org/10.1127/zfg/2017/0434.

Kozak J., 2010. Forest cover changes and their drivers in the Polish Carpathian Mountains since 1800. In: H. Nagendra, J. Southworth (eds), Reforesting Landscapes. Landscape Series, Springer, Dordrecht 10: 253–273. DOI: https://doi.org/10.1007/978-1-4020-9656-3_11.

Köppen W., 1931. Grundriss der Klimakunde Berlin, Walter de Gruyter.

Kroczak R., Bryndal T., 2017. Use of digital terrain models to generate the surface drainage network functioning during heavy rainfall. Methodological aspects based on the Zalasówka catchment (Ciężkowickie foothills). Przegląd Geograficzny 89(1): 67–85.

Legout C., Leguédois S., Le Bissonnais Y., Malam-Issa O., 2005. Splash distance and size distributions for various soils. Geoderma 124: 279–292. DOI: https://doi.org/10.1016/j.geoderma.2004.05.006.

Li C., Grayson R., Holden J., Li P., 2018a. Erosion in peatlands: Recent research progress and future directions. Earth-Science Reviews 185: 870–886. DOI: https://doi.org/10.1016/j.earscirev.2018.08.005.

Li C., Holden J., Grayson R., 2018b. Effects of rainfall, overland flow and their interactions on peatland interrill erosion processes. Earth Surface Processes and Landforms 43(7): 1451–1464. DOI: https://doi.org/10.1002/esp.4328.

Liu D., She D., Yu S., Shao G., Chen D., 2015. Rainfall intensity and slope gradient effects on sediment losses and splash from a saline-sodic soil under coastal reclamation. Catena 128: 54–62. DOI: https://doi.org/10.1016/j.catena.2015.01.022.

Ma B., Yu X., Ma F., Li Z., Wu F., 2014. Effects of crop canopies on rain splash detachment. Plos One 9(7): e99717. DOI: https://doi.org/10.1371/journal.pone.0099717.

Mahmoodabadi M., Sajjadi S.A., 2016. Effects of rain intensity, slope gradient and particle size distribution on the relative contributions of splash and wash loads to rain-induced erosion. Geomorphology 253: 159–167. DOI: https://doi.org/10.1016/j.geomorph.2015.10.010.

Martínez-Casasnovas J.A., Sánchez-Bosch I., 2000. Impact assessment of changes in land use/conservation practices on soil erosion in the Penedès–Anoia vineyard region (NE Spain). Soil & Tillage Research 57(1–2): 101–106. DOI: https://doi.org/10.1016/S0167-1987(00)00142-2.

Marzen M., Iserloh T., Casper M.C., Ries J.B., 2015. Quantification of particle detachment by rain splash and wind-driven rain splash. Catena 127: 135–141. DOI: https://doi.org/10.1016/j.catena.2014.12.023.

Marzen M., Iserloh T., de Lima J.L., Fister W., Ries J.B., 2017. Impact of severe rain storms on soil erosion: Experimental evaluation of wind-driven rain and its implications for natural hazard management. Science of the Total Environment 590: 502–513. DOI: https://doi.org/10.1016/j.scitotenv.2017.02.190.

Mermut A.R., Luk S.H., Römkens M.J.M., Poesen J.W.A., 1997. Soil loss by splash and wash during rainfall from two loess soils. Geoderma 75(3–4): 203–214. DOI: https://doi.org/10.1016/S0016-7061(96)00091-2.

Moghadam B.K., Jabarifar M., Bagheri M., Shahbazi E., 2015. Effects of land use change on soil splash erosion in the semi-arid region of Iran. Geoderma 241: 210–220. DOI: https://doi.org/10.1016/j.geoderma.2014.11.025.

Nanko K., Mizugaki S., Onda Y., 2008. Estimation of soil splash detachment rates on the forest floor of an unmanaged Japanese cypress plantation based on field measurements of throughfall drop sizes and velocities. Catena 72(3): 348–361. DOI: https://doi.org/10.1016/j.catena.2007.07.002.

Qinjuan C., Qiangguo C., Wenjun M., 2008. Comparative study on rain splash erosion of representative soils in China. Chinese Geographical Science 18(2): 155–161. DOI: https://doi.org/10.1007/s11769-008-0155-9.

Parlak M., Parlak A.Ö., 2010. Measurement of splash erosion in different cover crops. Turkish Journal of Field Crops 15(2): 169–173.

Perović V., Jakšić D., Jaramaz D., Koković N., Čakmak D., Mitrović M., Pavlović P., 2018. Spatio-temporal analysis of land use/land cover change and its effects on soil erosion (Case study in the Oplenac wine-producing area, Serbia). Environmental Monitoring and Assessment 190(11): 675. DOI: https://doi.org/10.1007/s10661-018-7025-4.

Poesen J., 2018. Soil erosion in the Anthropocene: Research needs. Earth Surface Processes and Landforms 43(1): 64–84. DOI: https://doi.org/10.1002/esp.4250.

Poesen J., Savat J., 1981. Detachment and transportation of loose sediments by raindrop splash Part 2: Detachability and transportability measurements. Catena 8: 19–41. DOI: https://doi.org/10.1016/S0341-8162(81)80002-1.

Rejman J., 2006. Wpływ erozji wodnej i uprawowej na przekształcenie gleb i stoków lessowych. Acta Agrophysica 136 (3): 1–91.

Rejman J., Michiels P., Cadron W., Gabriels D., Dębicki R., 1990. Splash detachment on a silt loam soil with and without a plant cover of triticale. Zeszyty Problemowe Postępów Nauk Rolniczych 388: 161–168.

Renard K.G., Foster G.R., Weesies G.A., McCool D.K., Yoder D.C., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE) US Department of Agriculture, Agriculture Handbook, 703.

Ryżak M., Bieganowski A., Polakowski C., 2015. Effect of soil moisture content on the splash phenomenon reproducibility. Plos One 10(3): e0119269. DOI: https://doi.org/10.1371/journal.pone.0119269.

Sadeghi S.H., Harchegani M.K., Asadi H., 2017. Variability of particle size distributions of upward/downward splashed materials in different rainfall intensities and slopes. Geoderma 290: 100–106. DOI: https://doi.org/10.1016/j.geoderma.2016.12.007.

Saedi T., Shorafa M., Gorji M., Khalili Moghadam B., 2016. Indirect and direct effects of soil properties on soil splash erosion rate in calcareous soils of the central Zagross, Iran: A laboratory study. Geoderma 271: 1–9. DOI: https://doi.org/10.1016/j.geoderma.2016.02.008.

Schmidt J., Werner M.V., Schindewolf M., 2017. Wind effects on soil erosion by water—A sensitivity analysis using model simulations on catchment scale. Catena 148: 168–175. DOI: https://doi.org/10.1016/j.catena.2016.03.035.

Sharma P.P., Gupta S.C., Foster G.R., 1995. Raindrop-induced soil detachment and sediment transport from interrill areas. Soil Science Society of America Journal 59: 727–734. DOI: https://doi.org/10.2136/sssaj1995.03615995005900030014x.

Skiba S., Drewnik M., 2003. Mapa gleb obszaru Karpat w granicach Polski. Roczniki Bieszczadzkie 11: 15–20.

Słupik J., 1973. Zróżnicowanie spływu powierzchniowego na fliszowych stokach górskich. Dokumentacja Geograficzna 2: 1–118.

Soil Science Division Staff. 2017. Soil survey manual. C.Ditzler, K.Scheffe, H.C.Monger (eds), USDA Handbook 18, Government Printing Office, Washington, D.C.

Szpikowski J., 2001. Wzajemne relacje rozbryzgu i spłukiwania jako przejaw zmienności erozji wodnej gleb na stokach o zróżnicowanym użytkowaniu rolniczym (Zlewnia Chwalimskiego Potoku, Górna Parsęta). Folia Universitatis Agriculturae Stetinensis 217(87): 221–226.

Szpikowski J., 2010. Uwarunkowania i wielkość rozbryzgu gleby na podstawie pomiarów na powierzchniach testowych w zlewni Chwalimskiego Potoku (Pomorze Zachodnie). Prace i Studia Geograficzne 45: 181–195.

Śmietana M., 1987. Zróżnicowanie rozbryzgu gleby na użytkowanych rolniczo stokach fliszowych. Studia Geomorphologica Carpatho-Balcanica 21: 161–182.

Świdziński H., 1973. Z badań geologicznych w Karpatach, Prace Geologiczne 80: 11–62.

Święchowicz J., 2010. Ekstremalne spłukiwanie i erozja linijna na stokach użytkowanych rolniczo w polskich Karpatach fliszowych. In: E. Smolska, J. Rodzik (red.), Procesy erozyjne na stokach użytkowanych rolniczo (metody badań, dynamika i skutki). Prace i Studia Geograficzne Uniwersytetu Warszawskiego 45: 29–48.

Święchowicz J., 2012a. Water erosion on agricultural foothill slopes (Carpathian Foothills, Poland). Zeitschrift für Geomorphology 56(3): 21–35. DOI: https://doi.org/10.1127/0372-8854/2012/S-00102.

Święchowicz J., 2012b. Wartości progowe parametrów opadów deszczu inicjujących procesy erozyjne w zlewniach użytkowanych rolniczo. Instytut Geografii i Gospodarki Przestrzennej UJ, Kraków.

Święchowicz J., 2017. Assessment of natural and anthropogenic conditions for soil erosion by water in agricultural catchment in Poland. Geographia Cassoviensis 11(1): 89–105.

Święchowicz J., 2018. The assessment of influence of soil erosion by water in the transformation of agricultural slopes of the Wiśnicz Foothills. Landform Analysis 36: 85–95. DOI: 10.12657/landfana.036.008.

Terry J.P., Shakesby R.A., 1993. Soil hydrophobicity effects on rainsplash: simulated rainfall and photographic evidence. Earth Surface Processes and Landforms 18(6): 519–525. DOI: https://doi.org/10.1002/esp.3290180605.

Thornes, J.B., 1990. Vegetation and erosion: processes and environments . Chichester: Wiley.

Van Dijk A.I.J.M., 2002. Exponential distribution theory and the interpretation of splash detachment and transport experiments. Soil Science Society of America Journal 66: 1466–1474. DOI: https://doi.org/10.2136/sssaj2002.1466.

Van Dijk A.I.J.M., Bruijnzeel L.A., Eism E.H., 2003. A methodology to study rain splash and wash processes under natural rainfall. Hydrological Processes 17(1): 153–167. DOI: https://doi.org/10.1002/hyp.1154.

Wainwright J., 1996. Infiltration, runoff and erosion characteristics of agricultural land in extreme storm events, SE France. Catena 26: 27–47. DOI: https://doi.org/10.1016/0341-8162(95)00033-X.

Waksman S.A., Stevens K.R. 1930. A critical study of the methods for determining the nature and abundance of soil organic matter. Soil Science 30: 97–116.

Wei Y., Wu X., Cai C., 2015. Splash erosion of clay–sand mixtures and its relationship with soil physical properties: The effects of particle size distribution on soil structure. Catena 135: 254–262. DOI: https://doi.org/10.1016/j.catena.2015.08.003.

Wischmeier W.H., Smith D.D., 1978. Predicting rainfall erosion losses – a guide to conservation planning. US Department of Agriculture. Agriculture Handbook No. 537. USDA, Washington.

Yao J.J., Cheng J.H., Zhou Z.D., Sun L., Zhang H.J., 2018. Effects of herbaceous vegetation coverage and rainfall intensity on splash characteristics in northern China. Catena 167: 411–421. DOI: https://doi.org/10.1016/j.catena.2018.05.019.