PRACE GEOGRAFICZNE, zeszyt 103
Instytut Geografii UJ
Kraków 1998

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DEFINING CONDITIONS FOR AEOLIAN CIRCULATION OF MATTER AS POLLUTION CARRIER IN THE MARGINAL ZONE OF THE CARPATHIAN FOOTHILLS

Abstract: Analysis of the diversity of conditions of the aeolian circulation of pollutants transported by mineral and organic particles and snow was carried out over the Carpathian Foothills marginal zone between the Raba and Uszwica Rivers. It was based on the results of studies applying to the conditions, effects and course of airborne deflation, transport and deposition of the above mentioned types of material and on the characteristics of selected elements of the local environment.

Displacement of mineral and organic material and snow by wind may occur in various parts of the area and at different seasons of the year, depending on land use, inclination and exposure, changes of wind directions and velocities, and the condition of the soil. Only the transport of suspended mineral dust and organic matter from forests occurs all year long and at all wind velocities. Organic matter from meadows is involved in the airborne transport only during the snowless season and from fields only during the vegetation season. Displacement of mineral particles and snow in the near-ground layers of the air requires the wind velocity to reach ≥5 m s^{-1}. Mineral material from the fields is supplied from ploughed land only during the postvegetation period .

To classify the periods of potential occurrence of aeolian processes, the number of occurrences of windward and leeward orientation of areas with different use and exposure was analyzed. Comparison of their durations led to the designation of areas with conditions particularly favourable to deflation, deposition or equally-favourable to both processes.

Areas with conditions favourable to the removal or accumulation of material occupy a similar surface but they seldom form concentrated clusters. This is a result of the limited range of matter circulation, which mainly takes place within areas located between the valleys. For this reason also, matter exchange between the marginal zone of the Foothills and the adjacent territories is limited.

1. Problem outline

Pollution problems mainly concern areas exposed to strong, human-activity-related pressure. The densely populated borderline part of the Carpathian Foothills, which has historically been intensively used for agricultural purposes, can be classified as this area type (Wielowiejski, 1979). Local, transportation-related and agricultural pollution is further increased by long-range industrial emissions from the large urban agglomerations and industrial complexes of Upper Silesia and Cracow (on the west side) and Tarnów (on the east side).

A large part of particulate and gaseous pollutants are directly discharged to the atmosphere and transported by air. Wind has a direct influence on the removal, transport and delivery of pollutants. Pollution from distant sources is transported at high altitudes by air molecules, and less frequently by suspended particulate matter, over hundreds and even thousands of kilometers (Wojtanowicz, 1972). Local-scale pollutant transport takes place in near-ground layers of the air, often by means of wind-driven mineral-, organic- and snow particles.

Studies on the course and consequences of aeolian matter circulation were carried out in 1994-1995 in the surroundings of the Research Centre of the Institute of Geography (Jagiellonian University) in Łazy, in 1994-1995. They included measurements of the amount of windblown and deposited mineral and organic material and observations of results of nival-aeolian processes, carried out during winds of different velocities and on land used in various ways. They demonstrated a tremendous diversity of effects depending on the anemological conditions, the condition of the ground, relief and land use patterns (Izmaiłow, 1995). The results of the studies performed allow area types to be differentiated according to the varying degrees in which they favour the removal or accumulation of pollutants as a result of wind activity. The objective of this study was to attempt such a typological classification of the borderline areas of the Carpathian Foothills between the Raba and Uszwica Rivers.

2. Characteristics of the natural environment

2.1. Relief, vegetation and landuse

The analyzed area is surrounded by three steep, 30-90 m high geomorphological escarpments. They are set on the north side - the face of a flysh overthrust - and the west and east sides - steep slope undercuts of the Raba and Uszwica River valleys. The southern boundary of this area stretches parallel, south from the water-divide of Łapczycki Stream and Stara Rzeka River catchments.

There are two hypsometric levels within the investigated area. The higher one is located in the southern and north-eastern part of the area. It is built of resistant sandstones of the Silesian and sub-Silesian tectonic nappe (Olewicz, 1973). It is delineated by the hilltop level with fragments of the foothill planation surface (Starkel, 1972) at an altitude of 320-340 m. a.s.l. (80-110 m above the valley floors) and with culminations over 360 m.a.s.l. (Fig. 1). Their steep slopes fall along the Stara Rzeka

Fig. 1. Main elements of the relief forms in the marginal zone of the Carpathian Fothills between the Raba and Uszwica Rivers: 1 - summit planes, 2 - lower watershed planes, 3 - erosional levels, 4 - summits, 5 - slopes, 6 - valley floors.

Ryc. 1. Główne elementy rzeźby progowej części Pogórza Karpackiego między Rabą a Uszwicą: 1 - spłaszczenia wierzchowinowe, 2 - spłaszczenia niższych garbów wododzielnych, 3 - poziomy erozyjne, 4 - grzbiety, 5 - stoki, 6 - dna dolin.

River towards the lower, northern part of the Foothills. This part is built of less resistant rocks of the sub-Silesian tectonic nappe and Miocene formations (Olewicz, 1973). The lower step of the Foothills is formed by wide watershed summit planes at 280-300 m.a.s.l (50-60 m above the valley plains).

The course of the main elements of the relief is dominated by directions close to parallel, due to the tectonic substratum conditions. The WSW-ENE or WNW-ESE orientation's correlation with the tectonic units pattern is clearly discernible in the course of the flysh escarpments of the Foothills and of the numerous tributaries of the Raba and Uszwica Rivers. The W-E orientation's correlation with the axis of the upfold is marked with an extension of the summit planes and watershed hummocks. It is also discernible in the pattern of valleys in the northern parts of the area. The course of the Raba and Uszwica River valleys, the course of the northern section of the Stara Rzeka River and the numerous cuttings through the main foothill escarpment (oriented from SSW-NNE) are correlated with the general land gradient declining towards the north.

The river valley plains are 50 to 250 m wide. They are flat, accumulative and wet. Erosion flattening areas are easily discernible in their longitudinal profiles. Valleys formed on the borderlines between tectonic units and rocks of different resistance have asymmetric slopes. In most of the area slope inclinations are small (4°-9°). Slopes exposed N and NW are steeper (<45°-77°).

The Quaternary covers in the northern part of the foothill area are dominated by loess-like deposits. In the southern parts of the area they occur along with flysh rock weathering mantle (loam, dust and debris) having a broader range of occurrence. They cover the summits and slopes with a layer of several to a dozen or so meters. These deposits are also an element of the colluvia in landslide areas and at the foot of slopes. After washing they form dusty prolluvia in the dry valley plains.

All the above mentioned deposits have a similar, rather uniform mechanical composition (Skiba, 1992). They are dominated by a dusty fraction (50-60%) with the majority of grain sizes between 0.05-0.02 mm. There is also a significant amount of colloid loess <0.002 mm (8-19%). This allows the described deposits to be classified as dusts and loamy clays. The high loam content prevents the infiltration of precipitation water and causes long lasting and often excessive wetting of the covers, and, in lower positions, even periodic stagnation of water. In a dry state it is responsible for the coherence of these deposits.

In terms of land use, the largest area (51%) is occupied by agricultural farmland. Grasslands account for 19%. The remaining area (30%) is occupied by forests and tree stands. The largest forest ranges are preserved in the southern parts of the area, on summits, slopes and in the upper sections of valleys in the higher zone of the Foothills. Grasslands are almost exclusively connected with the river valley plains.

2.2. Selected features of the climate

The aeolian circulation of pollutants depends on the anemological conditions and the physical state of the soil surface. These parameters are both strictly dependent on the course of temperatures, precipitation and snow cover occurrence. The above listed elements of the climate are characterized based on measurement data recorded over 1989-1995 at the meteorological post of the Institute of Geography in Łazy.

2.2.1. Wind

The average annual wind frequency was 87.2% (over the entire period investigated). The windiest months (90.4-92.3%) were February and March, and the lowest frequencies (82.4-84.0%) were observed in July and August. The lowest number of calms (7.7-9.6%) was recorded in February and March and the highest (16.0-17.6%) in July and August.

On an annual scale, the dominant wind directions were W, SW and WSW (11.0-18.0%) (Fig. 2), and the less frequent directions were ESE, ENE, NNE, SSE, NNW and N (1.7-2.9%). The total percentage of winds from the three main directions changed during the year from 29.0% in May to 56.8% in January. Over most of the months, the dominant wind direction was W (maximum frequency 23.8% in September). Only in February, October and December did SW winds have a higher frequency (15.4-19.8%). The frequency of all wind directions demonstrated seasonal variability, reaching maximum values during different months and seasons of the year.

Over the year, days with weak winds (>0-4 m s^{-1}) were dominant (an average of 226.9 days), followed by 129.4 days with moderate winds (5-9 m s^{-1}) and only 6.2 days with strong winds (10-14 m s^{-1}) and 0.5 day with very strong winds (≥15 m s^{-1}). There was an average of two calm air days per year, most frequently in December and January. Windless days did not occur in March, April, June or September. Also the number of days with a particular wind velocity changed over the year (Fig. 3). Days with weak winds were most numerous in July and August and least frequent between December and February. The annual pattern of days with higher velocity winds exhibited reverse structure. Most of the days with moderate winds were recorded between December and March, and the lowest numbers in July and August. Days with strong winds (dominant in December, January and March) did not occur in May, July and September. Very strong winds occurred during the months of March and December only.

The average maximum wind velocities ranged from 5 m s^{-1} in August to 10.3-10.8 m s^{-1} in December, January and March (Fig. 4). The absolute maximum wind velocity was reached in December (19.0 m s^{-1}) and March (17.0 m s^{-1}). In February and from May to September wind velocity did not exceed 9-10 m s^{-1}.

There is a discernible correlation between wind velocity, direction and frequency. Only the weakest winds blew all directions all year long. The dominant direction of moderate winds was W (and less frequently NNE, ENE and NNW). Winds oriented WNW, W and WSW (with W dominating) most frequently reached high velocities (≥10-15 m s^{-1}). NE, NNW, N, ENE and ESE rarely reached this range of velocities. Such a wind velocity was never observed in the case of NNE winds. Very strong winds were exclusively connected with SSW, W, SW and WSW directions.

Fig. 2. Average monthly frequencies of wind directions in several ranges of velocity over 1989-1995.

Ryc. 2. Średnia miesięczna częstość kierunków wiatru w różnych przedziałach prędkości w latach 1989-1995.

Fig. 3. Average monthly number of days with winds of various velocities in 1989-1995.

Ryc. 3. Średnia miesięczna liczba dni z wiatrem o różnej prędkości w latach 1989-1995.

Fig. 4. Maximum monthly wind velocities in 1989-1995.

Ryc. 4. Maksymalne miesięczne prędkości wiatru w latach 1989-1995.

2.2.2. Precipitation and snow cover

The average annual number of days with precipitation was 191.4. Their annual distribution was regular (from 12.8 days in September to 18.4 days in March) (Fig. 5). The total precipitation levels were more variable in time. For a total precipitation level of 624 mm, the majority occurred between April and September and the least between November and January.

Snow cover, beginning in the period from the middle of November to the beginning of December, lasted until the period to the middle of March - middle of April. It was not permanent. Usually it remained over an average period of 51.1 days per annum. Of this time period, it was continuous for 35.6 days and formed snow patches for 15.5 days. Most of the days with snow cover were recorded from December to January (and the less in April) (Fig. 6). The average thickness of snow cover was small, ranging from 1.5 cm in November to 5.6 cm in February (also reaching a maximum thickness of 10.8 cm during this month). The absolute maximum thickness of the snow cover over the observation period was 32 cm.

During the snowless season, the ground was frozen for 13.2 days (from October to April). Most of such days were observed between December and February (Fig. 6). During thaws and precipitation periods the soil surface was wet (23 days) or damp (169

Fig. 5. Average monthly distribution of atmospheric precipitation in 1989-1995.

Ryc. 5. Rozkład średnich miesięcznych sum opadów w latach 1989-1995.

Fig. 6. Average monthly number of days with different soil conditions in 1989-1995.

Ryc. 6. Średnia miesięczna liczba dni z różnym stanem gruntu w latach 1989-1995.

days). The highest number of days with wet ground occurred in the period from November to January (damp ground dominated in March and from September to November). Respectively, the numbers of such days were the lowest in July and August and from December to February. Of the 108 days with dry ground, most of them were observed from May to August and the less from November to February.

3. Conditions and zones of deflation and aeolian deposition

The above description of selected elements of the geographical environment indicates that the conditions for wind-driven pollutant circulation are variable in space and time. The spatial variability is influenced by relief (altitude, slope, exposure), features of the surface deposits (mechanical composition, permeability, absorbability, compactness), land use patterns and the types of plant communities. The time variability is linked with the seasonal variability of wind directions and velocities, as well as the variability of ground cover and condition (depending on the amount of precipitation and the occurrence or lack of snow cover).

Additionally, previous studies (Izmaiłow, 1995) demonstrated that the wind transport of mineral, organic and snow particles does not occur in the same areas and times of the year. Therefore, the specific circulation conditions for all the materials listed (involved in the transport of pollutants) shall be researched separately.

3.1. Mineral matter

Deflation of mineral matter may only occur in loose, small sized and dry (up to 2.5% moisture content) deposits, with no fixing vegetation cover. The process occurs through a thin layer of dry and fluffy snow. The minimum wind velocity needed to put the locally occurring dust sediments in motion is 5 m s^{-1}. The intensity of this process increases with wind velocity.

Investigation of the deflation conditions allows the areas and occurrence periods to be determined. Deflation does not occur in forests and is only occasionally observed in grass-covered areas, where it is limited to molehill blowing. It occurs as a surface phenomenon only on ploughed fields after the vegetation season (October-April).

The current condition of the ground surface allows deflation to occur over 76.1 days per annum only (at wind velocity ≥5 m s^{-1}). Over this time period, the ground is dry for 13.1 days, covered with dry snow for 12.6 days, and damp for 50.4 days. Most of the days with dry ground were recorded in April and October, when strong winds are rare and there are no very strong winds at all (their activity is strongly linked with airborne processes). The period of highest velocity winds (from December to March) is also the period with the lowest number of dry-ground days (and the highest number of snow cover and damp ground days). Among winds exceeding 5 m s^{-1} the dominant directions during this period are W, SW, WSW (Fig. 7). Winds oriented NNE, NNW, N and ENE are the least frequent.

The variability of wind direction impacts the changes in the distribution and size of the deflation surfaces over the year. Deflation mainly occurs in upper parts of the windward slopes and on the summits (Gerlach, Koszarski, 1968; Jahn, 1969; Janiga, 1971). As compared to these areas, deflation is 9-19 times weaker in the valley plains (Izmaiłow, 1995) because of lower wind velocities and the presence of loess-like particles in the ground. Also the deposition is 6-7 times lower as compared to the upper sections of the leeward slopes, which are considered to be the main areas of mineral deposition (Gerlach, Koszarski, 1968; Jahn, 1969;

Fig. 7. Average frequency of directions of ≥5 m s^{-1} winds during the postvegetation period (X-IV).

Ryc. 7. Średnia częstość kierunków wiatru o prędkości ≥5 m s^{-1} w okresie powegetacyjnym (X-IV).

Wojtanowicz, 1972). In reality the surface on which mineral materials are deposited is much wider, and its location does not only depend on the exposure of the slopes but particularly on their longitudinal profile and land use pattern.

The transport of coarser material by rolling and saltation occurs at ground level up to a height of 35 cm (Izmaiłow, 1995). The transport distance thus depends on the length of vegetation-free stretches of ground. On ploughed fields only, such material can be transported over long distances along slopes or valley plains and across water divides, and then deposited on the leeward side (in wind shadow). Deposition of the rolled and salted material does not necessarily require a decrease in wind velocity. At wind velocities exceeding the critical value, the majority of this material is stopped on the windward side, at the foot of slopes and on vegetated areas. Meadows and forests are the main mineral material deposition areas. The deposition processes are most intense in their fringe zones, directly adjacent to ploughed fields, as the transport of material ceases within 0.5 m from the deflation zone (which equals the particles' saltation length). Only the finest material (carried in suspended form) is transported over longer distances and deposited over wider areas. The domination of deflation or deposition thus depends on the land use patterns and orientation in relation to wind direction.

With respect to the domination of windward slope orientation of different exposures (perpendicular to wind direction with a 90° deviation both ways) over the leeward orientation, slopes were identified on which deflation periods last longer than deposition-favourable conditions (Fig. 8). These are low-angle slopes exposed SW, SSW, WSW, S, W, WNW, NW, NNW and SSE (86.0-56.5% of all cases with active wind). N-oriented slopes have a uniform distribution of windward (48.8%) and leeward (51.2%) exposures. Other slopes (ENE, NNE, NE, E and ESE) are more frequently in wind shade (77.3-70.5%) than in a windward situation. If land use patterns allow the material to be transported from windward slopes and water-divides, deposition may dominate in their upper zones (even on ploughed fields). If the supply of material is limited, deflation will be the main process taking place over the entire length of the slopes

Fig. 8. Percentage contributions of windward and leeward situation of particular slope exposures during ≥5 m s^{-1} winds (postvegetation period).

Ryc. 8. Procentowy udział sytuacji dowietrznych i zawietrznych na stokach o różnych ekspozycjach w stosunku do wiatrów o prędkości ≥5 m s^{-1} w okresie powegetacyjnym.

and over the cultivated fields. Forest and grass-covered areas, regardless of slope exposure, are subject to material deposition only (similarly to the foot of steep slopes, where only deflation may occur). Flat summit planes and watershed hills are subject to deflation, regardless of wind direction.

The transport of material in the valley plains mostly occurs in valleys oriented W-E, NE-SW and ENE-WSW (29.5-17.3%). Valleys oriented SSE-NNW and NNE-SSW are the best wind-protected areas (active wind blowing along their axis for 4.5-5.6% of the overall active wind time).

The finest material, transported in suspension through the higher layers of air, is deposited beyond the source area. There are simultaneous processes of the elevation of mineral particles and the fallout of long-distance transported dusts. Even weak winds are sufficient for this type of transport. Therefore winds from all directions may be involved in this type of circulation. Sedimentation of suspension-transported dusts, although observed during strong (Cegła, 1972; Manecki et al., 1978) and moderate (Wojtanowicz, 1972; Pye, 1984) winds, most frequently occurs when the wind velocity decreases to 3-4 m s^{-1} (Paduszyński, 1954; Duchniewski, 1961; Maruszczak, 1967; Różycki, 1967). Another reason suspended dust sedimentation takes place are intense rainfalls (Scriven, Fisher, 1975; Davenport, Peters, 1978; Bruins, Yallon, 1979).

Theoretically, conditions for suspended dust deposition occur all year long, although they are the most conducive in spring and summer. During these seasons the recorded monthly averages of high intensity rainfalls were the highest. Also during this time of the year there is a maximum frequency of weak winds. The lowest numbers of days with weak winds are recorded between December and February (this is also the time of the most frequent calms). The lowest precipitation totals also occur in this part of the year.

Dust deposition may occur over the entire area, regardless of the land use pattern. The highest intensity of deposition occurs at the fringes of various plant communities (Gerasimov, 1973; Yallon, Dan, 1974; Catt, 1978; Weise, 1983; Pye, 1984). Deposition occurs regardless of the land exposure, although higher values are most frequently observed on leeward slopes (Simonson, Hutton, 1954; Tavernier, 1954; Lewis, 1960; Różycki, 1967; Vanmaercke, Gottigny, 1981; Weise, 1983). Only in the case of high suspended matter concentration and low transport a higher deposition is recorded on the windward side of elevations (Gullentops, Paulissen, 1981; Goosens, Offer, 1993).

Fig. 9. Average annual frequency of >0-4 m s^{-1} wind directions.

Ryc. 9. Średnia częstość kierunków wiatru o prędkości >0-4 m s^{-1} w ciągu roku.

Fig. 10. Annual percentage contributions of windward and leeward situation of particular slope exposures during >0-4 m s^{-1} winds

Ryc. 10. Procentowy udział sytuacji dowietrznych i zawietrznych na stokach o różnych ekspozycjach w stosunku do wiatrów o prędkości >0-4 m s^{-1} w ciągu roku.

Regarding the dominant weak winds (SW, W and WSW) (Fig. 9) leeward exposure most frequently applies to ENE, E, ESE, NE, NNE and SE slopes (66.9-51.9%). The remaining ones are in wind shadow during 47.0-26.2% of the weak wind periods (Fig. 10). The watershed areas, because of high wind velocity, probably retain smaller amounts of dust. The best conditions for dust deposition occur in valley plain areas oriented SSE-NNW, SSW-NNE, ESE-WNW and S-N, which are most frequently shielded from the wind (93.3-90.3%). Such conditions are the least frequent in SW-NE oriented valleys (78.5%). As compared to the amount of material from low transport, the amount of precipitated suspended dust is minimal.

3.2. Organic matter

The rate and seasonal variability of organic matter circulation mainly depend on the type of plant communities and their annual development cycle. They are less correlated with wind velocities because the transport of organic particles may also occur during weak winds.

Most of the identifiable macroscopic fragments of plants transported by the wind originate in woods and afforested areas. These are mainly leaves and smaller amounts of bark, branches and seeds. They are transported over long distances from their source areas. This type of material is deflated from forest areas all year long, but mainly in the autumn. Its amount is three times higher than the amount of material originating from open areas. Forests create adequate conditions for a quantitative domination of material outflow over inflow.

Grass- or crop-covered areas generate a small amount of leaves, stems, rootstock, flowers and seeds. The range of low altitude transport is small and rarely expands beyond the borderlines of the source plant community. Additionally the material outflow is limited in time. In the case of cultivated fields it is restricted to the vegetation season (May-September) and in grasslands to the snowless season (May-October). Over the remaining periods of the year, both these types of areas become receptors of material transported from the forests. Whether a given areas has dominant organic matter outflow or inflow conditions depends on the windward or leeward position with respect to the forest areas.

Both during the vegetation season and the entire snowless season, W, SW and WSW winds are dominant (Fig. 11). The least frequent winds at this time are ENE, ESE, SSE and NNE. As material outflow from the slopes deviated by ≤90° from the wind direction during the entire snowless period, material removal dominates over deposition (Fig. 12) on W, SW, WNW, NW, WSW, SSW, S, NNW and N exposed slopes (76.8%-58.6%). On these slopes, the dominant favourable conditions for organic matter outflow do not only apply to forests, but also to meadows and ploughed fields without forest shielding. ESE, ENE, E, NE, NNE, SE and SSE exposed slopes are on the leeward side during most of the winds (69.3-51.5%). This favours the accumulation of wind-driven material from the outside rather than outflow. This applies to all types of plant communities occurring in the upper sections of these slopes. Their lower sections, only reached by plant pollens, are typically deflation areas (30.7-48.5%).

During the snowless season, material transport in the valley plains occurs in both cases of winds blowing from opposite directions (along the axis of the valley). Appropriate conditions for such processes most frequently occur in W-E oriented valleys (26.2%), and less frequently in SSW-NNE, NNW-SSE and S-N oriented valleys (6.1-8.1%). N-W-

Fig. 11. Average frequency of wind directions during the snowless season (V-X).

Ryc. 11. Średnia częstość kierunków wiatru w okresie bezśnieżnym (V-X).

Fig. 12. Percentage contributions of windward and leeward situation of particular slope exposures during the snowless season (V-X).

Ryc. 12. Procentowy udział sytuacji dowietrznych i zawietrznych na stokach o różnych ekspozycjach w okresie bezśnieżnym (V-X).

Fig. 13. Average frequency of wind directions during the snow cover season (XI-IV).

Ryc. 13. Średnia częstość kierunków wiatru w okresie występowania pokrywy śnieżnej (XI-IV).

Fig. 14. Percentage contributions of windward and leeward situation of particular slope exposures during the snow cover season (XI-IV).

Ryc. 14. Procentowy udział sytuacji dowietrznych i zawietrznych na stokach o różnych ekspozycjach w okresie występowania pokrywy śnieżnej (XI-IV).

SSW-oriented valleys are dominant and they determine the main direction of matter transport. Thanks to this, areas located E-NNE from forests receive more material than areas on the opposite side. A similar situation occurs on the summits, although some of the processes occurring there are much more intense because of land exposure to winds.

Only small deviations from the above described situation occur during the snow cover period. WSW and WSW winds are still dominant (Fig. 13), with a minimum percentage of ESE, NNW, ENE, N and NNE directions. The domination of windward situation is recorded on slopes having the same exposure (as described for the previous period analyzed) (Fig. 14). The dominant process is organic matter removal from forests and deposition on the remaining area. The deposition zone mainly covers sections of ENE, NE, E, NNE, ESE, SE, N and SSE slopes, regardless of their use. Forests located in their lower parts are within the deflation range during 49.1-23.4% of the winds. In valley plains, the most frequent material deflation from forests occurs in those oriented W-E, SW-NE, WSW-ENE (20,7-13.7%). It is less frequent in the remaining valleys (9.0-4.7%). Deposition of material most frequently takes place on the S-SW-W-NW side of the forests (4.7-18.0%) rather than on the opposite side.

3.3. Snow cover

Snow deflation and transport were observed during winds exceeding 5 m s^{-1}. The snow transported was dry and weakly bound to the ground. Favourable conditions for this type of transport are present during 12.6 days per annum on average. The highest number of days with dry snow cover and winds ≥5 m s^{-1} was recorded between December and February (2.9-3.7 days per month). All the local winds reach a velocity necessary to displace snow but their frequency varies. They are dominated by W, WSW and SW winds (Fig. 15) which also reach the highest velocities of ≥ 15 m s^{-1}. Winds oriented NNE, ENE, N, NNW and ENE are the least important.

Wind directions not only determine the snow transport route but are also decisive for the distribution of snow deflation and deposition areas, depending on the exposure of various landforms. The most intense snow deflation phenomena were observed on watershed planes and windward slopes. They were less intense along the slopes and the weakest along valleys whose orientation was parallel to the wind direction. Snow is mainly deposited in the upper sections of the leeward slopes. Transport phenomena do not occur in their lower parts or in the valley plains located at the foot of the slopes. Snow also accumulates on the windward side, at the base of steep sections of slopes and in front of forest areas. Forest ranges as such are not subject to deflation or aeolian deposition of snow.

Fig. 15. Average frequency of ≥5 m s^{-1} wind directions during the snow cover season (XI-IV).

Ryc. 15. Średnia częstość kierunków wiatru o prędkości ≥5 m s^{-1} w okresie występowania pokrywy śnieżnej (XI-IV).

Fig. 16. Percentage contributions of windward and leeward situation of particular slope exposures during the snow cover and ≥5 m s^{-1} wind season.

Ryc. 16. Procentowy udział sytuacji dowietrznych i zawietrznych na stokach o różnych ekspozycjach w okresie występowania pokrywy śnieżnej i wiatrów o prędkości ≥5 m s^{-1}.

Only the watershed areas are subject to dominant deflation, regardless of wind direction. Changes in wind direction make all the slopes alternate in roles of dominant snow deflation or accumulation zones. Taking into account the frequency of particular wind directions and the fact that deflation phenomena not only apply to slopes perpendicular to the wind but also to those whose deviation does not exceed 90°, slopes with dominant windward and leeward situation were identified (Fig. 16). Slopes exposed SW, WSW, SSW, W and S are the most frequently exposed to deflation (86.8-80.9% of all cases of active winds). The domination of windward exposure frequency over leeward exposure (77.4-55.8%) is also a feature of the WNW, NW, NNW and SSE slopes. N-exposed slopes are evenly windward (49.1%) and leeward-exposed (50.9%). The remaining slopes (ENE, NE, NNE, E, ESE and SE) are most frequently leeward (78.5-56.8%). Thus, conditions in their upper parts are more frequently favourable to snow accumulation than deflation. The lower parts of these slopes are usually out of reach of the transported snow and favour deflation (49.1-21.5%).

Conditions favourable to snow movement in the valley plains are even less frequent. They occur only when the wind blows along the valley axis. According to the patterns of wind direction frequencies, snow transport may take place in valleys oriented W-E, SW-NE and WSW-ENE (30.0-17.9%). Conditions in other forms of valleys (SE-NW, ESE-WNW, N-S, NE-SSW and NNW-SSE) are less favourable (9.8-4.6%). Because of the low wind velocities in local depressions, snow transport takes place over a short distance (it is local and does not reach beyond the limits of these land forms).

4. Types of areas with different conditions for aeolian matter circulation

The conditions for aeolian matter circulation depend on the land's slope and exposure in relation to the dominant active wind direction and land use patterns. They determine the length of the time period favourable to the deflation or accumulation of material. Comparing the durations of these periods in various places allows areas to be identified which are favourable mostly to deflation or to deposition, or to a balance between or absence of these processes.

Summit planes and ridges have specific conditions for mineral and organic matter or snow removal. Valley plains are areas of closed matter circulation. Slopes inclined over 55°, regardless of their exposure, favour deflation of mineral and organic matter only. They do not take part in snow circulation. Less steep slopes, depending on their exposure, may be classified in four groups (in terms of the conditions for wind-driven matter circulation phenomena):

1. S, SSW, SW, WSW, W, WNW, NW and NNW slopes allow deflation of all types of matter all year long.
2. SSE-exposed slopes ensure a longer period of conditions favourable to mineral matter and snow deflation, rather than deposition. The opposite situation occurs in the case of organic matter, which can be deposited all year long.

Fig. 17. Distribution of area types with different conditions of aeolian matter circulation (explanation in the text).

Ryc. 17. Rozmieszczenie typów obszarów o różnych warunkach eolicznego obiegu materii (objaśnienia w tekście).

3. N-exposed slopes guarantee deflation of organic matter in the summer and its deposition in the winter. Also mineral matter and snow are accumulated more often than removed.
4. NNE, NE, ENE, E, ESE and SE slopes favour deposition of all types of matter all year long.

The morphological conditions of the airborne processes presented above are further modified by vegetation cover. Forest plant communities are areas which only allow deposition of mineral matter. Snow transport does not take place and the amount of organic matter removed exceeds the supply. Also in grassland areas the main process is mineral matter deposition. The circulation of organic matter and snow depends, is in the case of ploughed fields, on their position relative to other plant communities and the deflation and deposition rates in each of them. Conditions on ploughed fields are more favourable for deflation than the supply of mineral matter.

Taking into account the forementioned presented influences of relief and vegetation cover on the type of wind-driven phenomena, ten types of areas were identified with different conditions for aeolian matter and pollutant circulation:

Type I - conditions favourable to the deflation of all types of matter. It includes ploughed land on summits and moderate slopes exposed S, SSW, SW, WSW, W, WNW, NW and NNW without forest shield on the windward side.

Type II - conditions favourable to the deflation of mineral and organic matter with no snow transport. It includes open steep slopes over 55°, regardless of their exposure.

Type III - conditions favourable to the deflation of mineral matter and lack of organic matter or snow exchange with the adjacent areas. It includes ploughed land in valley plain areas.

Type IV - conditions favourable to the deflation of mineral matter and snow and to the deposition of organic matter. It includes ploughed lands on summits and low-angle slopes exposed S, SSW, SW, WSW, WNW, NW, NNW and N, located leeward from forests and also on SSE slopes.

Type V - conditions favourable to the deflation of organic matter and snow and to the deposition of mineral matter. It includes meadows on the summits and low-angle slopes exposed S, SSW, SW, WSW, W, WNW, NW and NNW.

Type VI - conditions favourable to the deflation of organic matter, the deposition of mineral matter and a lack of snow displacement. It includes forests in the valley plains, on the summits and low-angle slopes exposed S, SSW, SW, WSW, W, NNW, NW, NNW, N, NNE, NE, ENE, E, ESE and SE. They are located leeward from meadows and ploughed fields.

Type VII - conditions favourable to the deflation of organic matter and the deposition of mineral matter and snow. It includes meadows on N-exposed low-angle slopes.

Type VIII - a lack of exchange of snow and organic matter with the adjacent areas and conditions favourable to the deposition of mineral matter. It includes meadows in valley plains.

Type IX - conditions favourable to the deposition of mineral and organic matter, a lack of snow displacement. It includes forests on slopes exposed SSE, NNE, NE, ENE, E, ESE and SE, located leeward from forests.

Type X - conditions favourable to the deposition of all types of matter. It includes ploughed land on N-exposed low-angle slopes and ploughed land and meadows on slopes exposed NNE, NE, ENE, E, ESE and SE. It also covers areas at the foot of open, steep slopes inclined over 55°, regardless of their exposure.

The types of areas specified can be grouped into three sets: mineral and organic material or snow removal or the lack of such phenomena (I-III), diversity of the directions of displacements applied to the particular types of material (IV-VII), deposition of mineral and organic matter and snow or the lack of changes in their distribution (VIII-X).

In terms of the area occupied, these three groups are similar. Types I and VI are dominant. Type I areas occur in the western, northern and eastern parts of the lower step of the foothill marginal zone. Type VI areas are concentrated in the southern parts, within the higher morphological step. The other types of areas are scattered in small fragments over the entire area of the Foothills.

5. Conclusions

The tremendous diversity of the marginal zone of the Carpathian Foothills between the Raba and Uszwica Rivers in terms of aeolian matter circulation reflects the varied structure of relief and dissection density, land use patterns and seasonal variability of wind directions. The type of vegetation cover plays a key role in determining the type of transported matter. Forest communities attenuate the impacts of relief on the course of aeolian transport processes. The diversity of deflation and deposition-specific conditions related to exposure and land inclinations becomes discernible at the level of particular plant communities.

Zones of dominant conditions favorable to deflation and deposition occupy similar areas. The circulation of matter between these zones (in terms of near-ground and low altitude transport) is limited in space and most frequently does not reach beyond the valley plains. Therefore, one may conclude that the aeolian exchange of mineral and organic matter and snow between the analyzed area and the adjacent lands is also restricted. It is limited by the steepness of the foothill escarpment and of the Uszwica and Raba River valley slopes. Such an exchange only occurs through circulation of suspended mineral and organic dusts.

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Zróżnicowanie warunków eolicznego obiegu materii jako nośnika zanieczyszczeń w progowej części Pogórza Karpackiego między Rabą a Uszwicą

Streszczenie

Analizę zróżnicowania warunków eolicznego obiegu zanieczyszczeń, przenoszonych za pośrednictwem cząstek mineralnych, organicznych i śniegu, przeprowadzono dla progowej części Pogórza Karpackiego między Rabą a Uszwicą. Dokonano jej na podstawie wyników badań dotyczących warunków przebiegu i efektów deflacji, transportu i depozycji eolicznej wymienionych wyżej rodzajów materiału oraz charakterystyki wybranych elementów środowiska omawianego obszaru.

Przemieszczanie materiału mineralnego, organicznego i śniegu przez wiatr może zachodzić w różnych częściach obszaru i w różnych okresach, w zależności od użytkowania, nachylenia i ekspozycji terenu, zmienności kierunków i prędkości wiatru oraz stanu gruntu. Jedynie przenoszenie pyłów mineralnych w suspensji i materiału organicznego, pochodzącego z lasów, zachodzi w ciągu całego roku, przy wiatrach o dowolnej prędkości. Materiał organiczny z łąk bierze udział w transporcie eolicznym tylko w okresie bezśnieżnym (V-X) a z pól - wyłącznie w okresie wegetacyjnym (V-IX). Przemieszczanie zarówno cząstek mineralnych, jak i śniegu w przygruntowych warstwach powietrza wymaga wiatru o prędkości ≥ 5 m s^{-1}. Materiał mineralny jest dostarczany z pól ornych wyłącznie w okresie powegetacyjnym (X-IV).

Dla wyróżnienia okresów potencjalnego występowania procesów eolicznych analizowano ilość sytuacji dowietrznego i zawietrznego położenia terenów o różnym użytkowaniu i ekspozycji. Porównując długość ich trwania, wyróżniono obszary

o warunkach sprzyjających deflacji, depozycji lub równowadze obu procesów. W ten sposób wyróżniono dziesięć typów obszarów, które można połączyć w trzy grupy:

1. Obszary typu I, II i III warunkują wywiewanie wszystkich albo części analizowanych rodzajów materiału, najczęściej - mineralnego, najrzadziej - śniegu. Należą do nich wszystkie strome (>55°), bezleśne stoki oraz pola orne w dnach dolin, na wierzchowinach i spłaszczeniach wododzielnych oraz na słabo nachylonych stokach o ekspozycji: S, SSW, SW, WSW, W, WNW, NW, NNW, nie osłoniętych lasem od strony dowietrznej.
2. Obszary typu IV, V, VI i VII sprzyjają zróżnicowanym procesom w odniesieniu do poszczególnych rodzajów przemieszczanego materiału. Najczęściej warunkują one ubytek materiału organicznego albo depozycję materiału mineralnego. Obejmują one swym zasięgiem zbiorowiska leśne na spłaszczeniach wierzchowinowych i wododzielnych oraz wszystkie słabo nachylone stoki, poza stokami SSE, nie znajdujące swojej kontynuacji po stronie dowietrznej. W ich skład wchodzą także grunty orne i łąki na wierzchowinach, słabo nachylonych stokach SSE, S, SSW, SW, WSW, W, WNW, NW, NNW i N, osłonięte lasami od strony dowietrznej.
3. Obszary typu VIII, IX i X warunkują głównie osadzanie wszystkich rodzajów materiału lub brak zmian w rozmieszczeniu niektórych z nich. Najczęściej sprzyjają one depozycji materiału mineralnego, najrzadziej - śniegu. Do takich obszarów należą podnóża wszystkich nie zalesionych stromych (>55°) stoków, lasy na stokach NNE, NE, ENE, E, ESE, SE, SSE, znajdujące swoje przedłużenie na stokach przeciwległych, łąki w dnach dolin i na stokach NNE, NE, ENE, E, ESE, SE oraz pola orne na stokach o tych samych ekspozycjach oraz N.

Obszary o warunkach sprzyjających głównie usuwaniu lub gromadzeniu materiału zajmują podobną powierzchnię ale rzadko tworzą zwarte kompleksy. Jest to wynikiem ograniczonego zasięgu obiegu materii, który odbywa się najczęściej tylko w obrębie międzydolinnych części obszaru. Z tego względu również wymiana materii między progową częścią Pogórza a położonymi poza nią, sąsiednimi obszarami jest utrudniona.