Mapping of Erosion by Wind with RS Data and GIS (case study of Dedoplistskaro Municipality, Georgia)

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Abstract

Wind erosion plays a significant role in the degradation of agricultural land. When formulating strategies for mitigating wind erosion, it is crucial to possess precise quantitative data pertaining to the possible soil loss. Various types of equations and models are developed for this objective. This article used the WEQ to quantify the mean annual soil loss resulting from wind erosion on agricultural soils within the Dedoplistskaro Municipality in Eastern Georgia. The area of eastern Georgia experiences a higher degree of wind erosion because of its specific meteorological characteristics. The agricultural soils in the study area have been identified based on the land use classification provided by the ESA in 2021. The climate data for the research area has been obtained from the GWA and MODIS open-access satellite images. The WSD was used as the primary data source for the computation of the soil erodibility index. To evaluate the impact of vegetation cover, the LAI was chosen, which was derived from the yearly average NDVI data acquired using Sentinel 2. The width of open plots was determined by applying satellite-based Land Use and Land Cover (LULC) open access data as well as data acquired from the Ministry of Agriculture and Environmental Protection of Georgia. This data specifically pertains to windbreaks and plots that were occupied by perennial crops. The mathematical computations were executed via the web platforms GEE and ArcMap 10.8. Subsequently, a raster file depicting the probable soil loss resulting from wind erosion on the agrarian soils within the Dedoplistskaro municipality was obtained.

Keywords: Wind, Erosion, WEQ, RS, GIS, Georgia

Introduction

Agricultural soil plays an important role in food production and agricultural development. Agricultural soil, including arable land, perennial crops, and pastures, is used for agricultural purposes. The physical and chemical features of agricultural soil determine its suitability for different crops. These soils are usually rich in organic matter, nutrients, and beneficial microorganisms that promote plant growth. Agricultural soil fertility is critical for maintaining high yields and ensuring a continuous food supply.

The use and protection of agricultural soil include various measures aimed at optimizing its productivity and sustainability. These measures include tillage, irrigation, crop rotation, nutrient application, and erosion control.

Erosion (water and wind), nutrient depletion, and thus soil degradation are common challenges for intensive agriculture. For example, 42 million hectares of European soils suffer from erosion by wind (Klik, 2004). The implementation of erosion control measures such as contour ploughing, terracing, and windbreaks can help prevent soil erosion and preserve valuable topsoil.

In Georgia, agricultural soil plays a crucial role in supporting the agricultural sector and rural communities. With diverse landscapes and climate zones, Georgia has a wide range of agricultural soils that are vital for food production and economic development. However, as in many regions of the world, erosion by wind remains one of the main challenges in Georgia, which, among other factors, may affect the productivity and sustainability of agricultural soils. Erosion by wind occurs when strong winds carry topsoil particles away, causing loss of important nutrients and organic matter and deterioration of the soil structure. Erosion by wind is particularly common in areas with little rainfall and dry climates, where soil moisture is limited, and vegetation is poor.

The lowlands of eastern Georgia are particularly affected by erosion by wind, which has a semiarid and continental climate characterized by hot summers and little precipitation. The combination of dry conditions, open plains, and exposed soil surfaces increases the risk of erosion by wind. In addition, the spread of certain agricultural practices, such as extensive cultivation, overgrazing, and inadequate soil conservation measures, further increases the vulnerability of agricultural soils to erosion by wind (Ministry of Agriculture of the USSR of Georgia, 1981).

A total of 21.1% of the arable land in Eastern Georgia is damaged by wind. Quantitatively, this number is 102.5 thousand hectares throughout the country (Gogichaishvili, 2019). According to previous studies, this number is quite high. According to data from the 1970s, 172,000 hectares of arable land in eastern Georgia suffer from erosion by wind. The outer Kakheti Plateau, Sagarejo, Gurjaani, and Sighnaghi Municipalities, and Dedoplistskaro municipality are the most affected by wind (Ministry of Agriculture of the USSR of Georgia, 1973).

Recognizing the importance of erosion by wind as a threat to agricultural soils, there are efforts in Georgia (The parliament of Georgia, 2023) to implement soil conservation measures and reduce its impact. These measures include the adoption of conservation agricultural practices, such as minimum tillage and contour ploughing, to reduce the risk of soil disturbance and erosion. Agrosilvopastoralism and the cultivation of windbreaks contribute to the formation of vegetative barriers that protect fields from strong winds and prevent soil erosion. Appropriate land management techniques such as crop rotation, contour farming, and terracing are also encouraged to reduce erosion by wind and maintain soil health.

In addition, awareness campaigns and educational programs are being implemented among farmers and landowners to promote sustainable soil management practices. These initiatives aim to promote the importance of soil conservation, the risks associated with erosion by wind, and the adoption of erosion control measures.

It is crucial for the government of Georgia, agricultural organizations, and interested parties to cooperate in the development of comprehensive soil conservation strategies. This includes conducting research on the development and impact of erosion by wind, implementing monitoring systems, and providing support and incentives to farmers to implement sustainable land management practices. For example, we can cite the Resolution of the Government of Georgia (No. 146, March 24, 2022) on the approval of the rules for restoration, planting, maintenance, protection, and supervision of windbreaks (Government of Georgia, 2023).

These models, accompanied by field and laboratory studies (Zou et al., 2015), are actively used in research on erosion caused by wind. These models serve different levels of research, and such research helps those responsible for monitoring and predicting the development of appropriate conservation policies. Erosion by wind models varies in complexity (Tatarko et al., 2013) depending on the number of variables included in the model. Therefore, the selection of the model depends on the objectives of the research and the scale of the obtained result (local, regional, or global). It is also important to have the data available to calculate the variables needed for the model. All erosion models have limitations that lead to some level of inaccuracy in the results obtained. At the initial stage of modelling development, these inaccuracies were much greater; however, the demand for quantitative data was so great that their use did not stop, and over time, along with the refinement of models, the inaccuracies were eliminated. Developments in the implementation of geophysical models in geoinformation systems (GIS) have made the process of erosion by wind modelling more flexible (Rousseva et al., 2016)

A quantitative assessment of the risks of erosion by wind is important for the proper implementation of these measures. The first established erosion by wind prediction model was the erosion by wind equation (WEQ) (Woodruff & Siddoway, 1965), which calculates the potential soil loss in the study area through factors affecting the development of erosion by wind (climatic, soil erodibility, topography, vegetation). This research aimed to calculate the soil loss due to erosion by wind on the agricultural soils of Dedoplistskaro Municipality. To achieve the set goal, we must implement the following tasks:

a) Modelling of the main factors affecting erosion by wind in the study region (climate, soil erodibility, topography, vegetation cover, bare plot length) using open data satellite images and GIS analysis.

b) Calculation of the possible loss of soil caused by erosion by wind by collecting the data obtained from the research area and by corresponding arithmetical calculations.

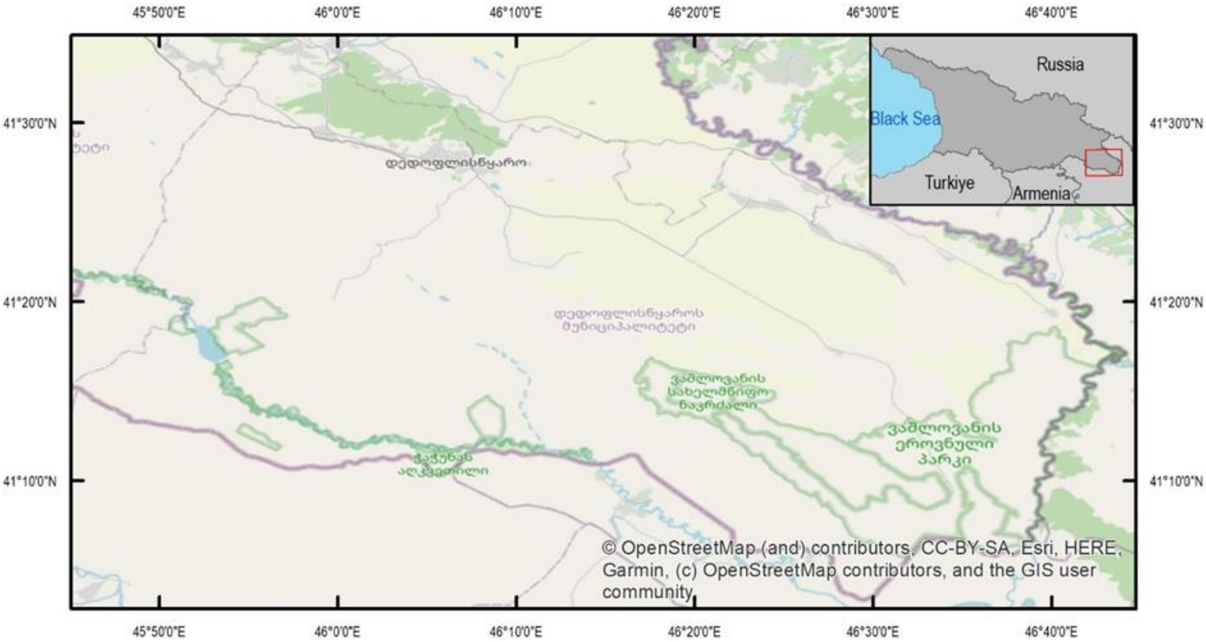


Figure 1. Study area – Dedoplistskaro Municipality

Methods and Materials

Study Area

Dedoplistskaro municipality is in the extreme southeastern part of the country (Fig. 1). The municipality is the second largest in the country by area (2532 sq. km). The study area is the only place in Georgia where a semidesert landscape has developed. Therefore, the hydrographic network of the study area is poor. In addition to the two main rivers (Alazani and Iori), there are mainly periodic rivers. There are 4 main climate types in the study area (Climate Types, 2018): a moderate warm steppe climate with hot summers and precipitation with two minimums per year, a transitional climate from moderate warm steppe to moderate humid climate, a moderate humid climate with moderately cold winters and hot summers and a moderate humid climate with moderately cold winters and prolonged warm summers. The study area is characterized by a wide distribution of fertile soils. According to Figure 2, these are *Kastanozems, Leptosols, Vertisols,* and *Solontz. Kastanozems*, which are brown or grayish in colour, are common in the dry steppes of Georgia. The Vertisols in the study area are relatively younger and belong to the Upper Tertiary and Quaternary Ages (Matchavariani & Kapanadze, 2019).

Considering the abovementioned natural factors, the study area is particularly vulnerable to droughts (Tatishvili et al., 2022). Studies based on data from the Dedoplistskaro meteorological station have confirmed that rainfall erosivity has increased in recent decades under the influence of climate change (Tsitsagi et al., 2018).

Methods

The erosion by wind equation (WEQ) is an empirical model used to estimate erosion by wind and sediment transport potential.

The WEQ is calculated by the following equation:

$$E = f\,(C * \mathcal{I} * K * L * V) \qquad (1)$$

where E is the estimated mean annual soil loss (t ha -1 yr -1); C is a climatic factor, which is calculated based on the mean annual wind velocity and soil moisture; I is the soil erodibility index (t ha -1 yr -1), which quantitatively determines the sensitivity of the soil to erosion by wind; K is the surface roughness factor; L is the unsheltered distance along the prevailing wind (m); and V is the vegetation cover factor, which represents the proportion of the land surface protected by plants. f is a mathematical notation of the functional relationship between erosion by wind and other variables.

All the data were processed in ArcMap 10.8.1, and the corresponding raster layers were created based on equation 2.

$$E = 0.0015 * r2.718^{\frac{V}{4500}} * \left(I^{1.87} * K^2 * \left(\frac{C}{100}\right)^{1.3}\right) * L^{0.3} \qquad (2)$$

The climatic (C) factor. Studies have shown that the movement of soil particles is directly related to the wind velocity and effective moisture, which in turn depends on the temperature and precipitation. Areas with higher wind velocities and durations are more prone to erosion by wind. Higher values indicate greater potential for erosion by wind. The C factor is determined by the following equation:

$$C = \frac{386u^3}{(\mathrm{PE})^2} \qquad (3)$$

where u is the mean annual wind velocity (m/s). (PE) is the precipitation-effectiveness index of Thornthwite (1936), and 386 is a constant used to adjust local values to the common base. Later, Thorn White introduced the concept of potential evapotranspiration (PET) (Allaby, 2023).

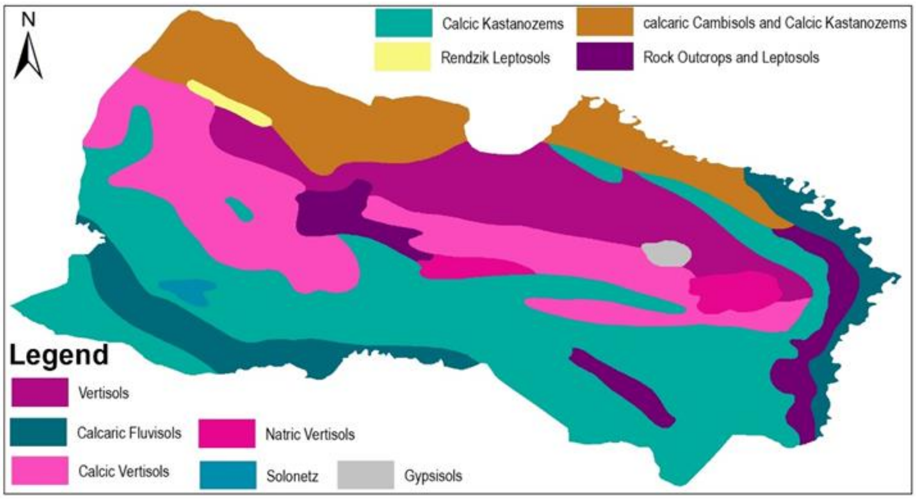


Figure 2. Soils in the study area (Soils, 2018)

In the present study, when determining the C factor, we used the Global Wind Atlas (GWA 3.0) (DTU, 2023) as a source of data on the mean annual wind velocity (Fig. 3A). GWA is a free web-based application. PET data (Fig. 3B) were obtained by processing the MODIS images (Running, 2017). The MOD16A2 V.6 product is an 8-day composite dataset with 500 m pixel resolution. We used 20-year average values of MODIS-based PET data. After equalizing the pixel resolution of the raster file obtained from the wind atlas and the MODIS raster file, both raster layers were placed in equation (2) through ArcMap's Raster Calculator, and finally, we obtained a new raster layer representing the C factor (Fig. 5A).

The soil erodibility index ($\mathcal{J}$) is related to the percentage of nonerodible surface soil aggregates larger than 0.84 mm in diameter (Chepil, 1942). It considers soil properties such as texture and organic matter content. Clay soils are generally more prone to erosion than sandy soils. Soils rich in organic matter and with good structure are more resistant to erosion by wind.

The $\mathcal{J}$ factor is calculated by the following equation (Mandakh et al., 2016):

$$\mathcal{J} = \frac{0.31S_A+0.17S_i+0.33\frac{S_A}{CL}-2.59OM-0.95CaCO_3}{100} \qquad (4)$$

where S_A is the sand content (%), Si is the silt content (%), CL is the clay content (%), OM is the organic matter (%), and $CaCO_3$ is the calcium carbonate content (%). As a rule, the abovementioned data were obtained through field and laboratory studies. The present study is regional in scope, and in this case, fine-scale data can be used. Data on the above soil characteristics were obtained from the World Soil Database (FAO, 2023). The abovementioned database is a global inventory of soils that provides information on the morphological, chemical, and physical properties of soils with a resolution of 1 km. The database did not contain information on organic matter content but instead provided information on soil organic carbon. Using formula 4, we calculated the content of organic matter in the soils of the study area.

$$OM = SOC * 1.72 \quad (5)$$

where SOC is the soil organic carbon content (%). The layer obtained from the mentioned database was placed in equation (4) through the ArcMap raster calculator, and finally, we obtained a new raster layer representing the $\mathcal{J}$ factor (Fig. 5B).

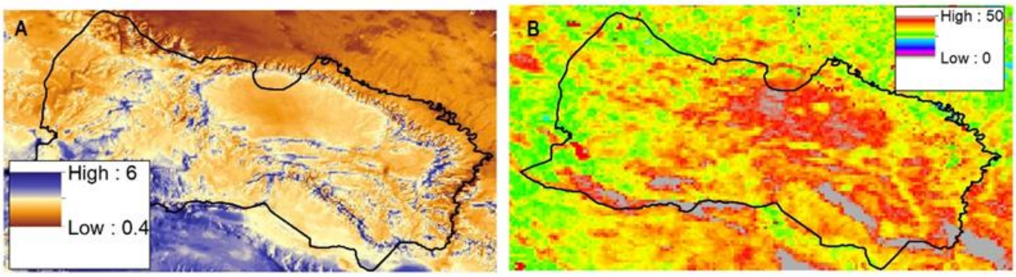


Figure 3. A – Mean annual wind velocity based on Wind Atlas; B – PET based on MODIS

The roughness factor (K) describes the effect of soil surface roughness on erosion by wind. Steep slopes are known to be more prone to erosion than gentle slopes. Calculating the same K factor for terrain influence is a rather complicated procedure. In large-scale studies, when the study area is small, it is possible and mandatory to conduct appropriate measurements. In regional studies, K is considered constant and assigned a value of 1.

For the length of the unsheltered plot, the same L factor represents the distance along the prevailing erosion by the wind direction. Windbreaks, forests, and buildings are perceived as protective barriers. To calculate the L factor, we used the ESA land use map (Zanaga et al., 2021) and aerial images.

Studies have shown that the protective function of trees of medium height extends to 20 metres, that of buildings extends to 10 metres, that of orchards extends to 5 metres, and that of vineyards extends to 1.7 metres. Through the land use layer, vineyard cadastre, and orthophotos, the distribution areas of each of the abovementioned classes (trees, orchard, cultivation, vineyard) were determined, and after placing the abovementioned distance buffer, we obtained a new polygon, which we assigned a value of 1. In the remaining area, according to the prevailing wind direction (on the Kartli Plain from west to east, on the Kvemo Kartli Plain from the east, on the Iori Plateau from the west, and on the Alazni Plain from the southeast), the length of the plots was measured. The prevailing wind direction in the study area is western. We received data about windbreaks from the Agency for Sustainable Land Management and Land Use (Land Agency).

The vegetation factor (V) quantifies the effectiveness of vegetation in reducing erosion by wind. A higher vegetation cover results in a lower wind velocity at the surface, thereby reducing the wind erosion potential. Research has shown a correlation between the normalized difference vegetation index (NDVI) and wind velocity (Mao et al., 2013). Based on past studies (Mandakh et al., 2016; Carlson & Ripley, 1997), we used the leaf area index (LAI) to calculate this factor, which was calculated according to the following equation:

$$LAI=2.745*NDVI-0.201 \quad (6)$$

$$NDVI=((NIR-R)/(NIR+R)) \quad (7)$$

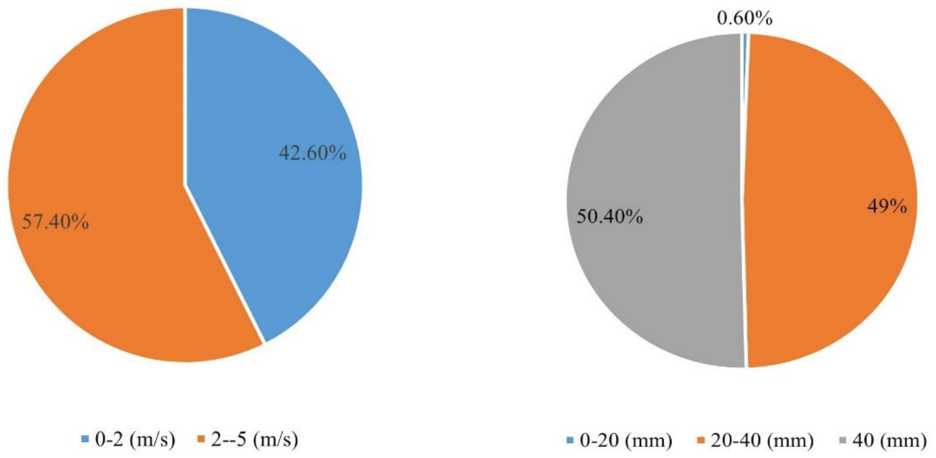
where NIR is the near-infrared band and R is the red band of the electromagnetic spectrum. To calculate the NDVI, we used Sentinel-2 10-m resolution satellite images from April-October 2022 (the growing season). Using the appropriate algorithm in the Google Earth Engine (GEE), we calculated the average values of the mentioned images, and by substituting them into equation (6), we obtained the LAI.

Finally, we used WGS84 and UTM38 for all the data. After changing the projection, the raster files representing all the factors were placed in equation (2), and using the ArcMap Raster Calculator, we obtained the final raster image. Each pixel in this image contains information about the estimated soil loss due to erosion by wind.

Papers reporting something other than experiments, such as a new method or technology, typically have different sections in their body, but they include the same Introduction and Conclusion sections as described here.

Results

As mentioned above, climatic factors are crucial in the assessment of erosion by wind. In this case, the wind velocity is the main influencing factor. As Fig. 4a shows, 42% of the study area has an average annual wind velocity of 0-2 m/s, and more than half of the area is in the zone with an average annual wind velocity of 2-5 m/s.



(**a**) (**b**)

Figure 4. Distribution of territory (percent) based on wind velocity (a) and PET (b)

The second least important climatic factor is soil moisture, which in turn is determined by precipitation and air temperature regimes. According to the MODIS PET data, the values in half of the study area are greater than 40 mm (Fig. 5b), and in the other half, they are 20-40 mm. Only a small part of the territory is within 0-20 mm. Considering both abovementioned factors, the C factor values (Fig. 5A) were spatially distributed in such a way that high values were recorded in the eastern and southwestern parts of the municipality. Relatively low values of the C factor are recorded in areas where there is mostly agricultural land.

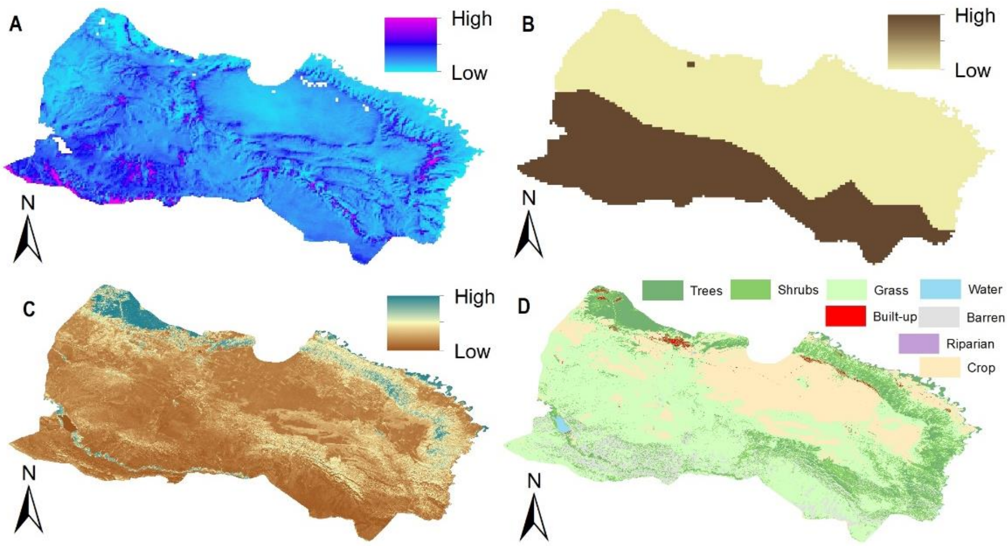


Figure 5. A – C factor; B – $\mathcal{J}$ factor; C - V factor; D – LULC in the study area

The results obtained by processing the global data showed that 2 values of the $\mathcal{J}$ factor were present in the study area. According to Figure 5B, the research area is almost equally divided. A relatively low value of factor I is recorded in the northern part, and a relatively high value is recorded in the southern part.

Table 1. Physical and chemical characteristics of the soil in the study area

ID	*Depth (cm)*	*Texture*	*Sand (%)*	*Silt (%)*	*Clay (%)*	*SOC (%)*	*$CaCo_3$ (%)*
28044	0-20	Clay loam	33	31	36	1.93	0
28045	0-20	Clay loam	33	31	36	1.93	0
28046	0-20	Sandy clay loam	61	19	20	0.744	0

The results obtained by processing the global data showed that there are three types of soil in the study area. The table shows the soil ID in the global database, the depth, and the physical and chemical characteristics of each type. As shown in Table 1, ID 28044 and 28045 are characterized by a clay loam texture, while 28046 is a sandy clay loam. Accordingly, in the case of the first two soils, the percentage of clay is 36%, and in the third, it is only 20%. An important variable in determining soil erodibility is organic carbon, the content of which, in the case of ID 28046, is almost 2 times less than that of the other two variables. By placing the mentioned data in the formula, we have 2 values of the $\mathcal{J}$ factor. According to Figure 5B, the research area is almost equally divided. A relatively low value of the $\mathcal{J}$ factor is recorded in the northern part, and a relatively high value is recorded in the southern part.

The creation of protective barriers is crucial for controlling erosion by wind, especially in areas occupied by annual crops. Considering the protective barriers in the study area, the width of the unsheltered plots in the direction of the prevailing wind was determined. Figure 6a shows that the width of the unsheltered plots between the protective barriers is especially large in the central and southwestern parts of the study area. According to Figure 6b, 62% of the arable lands in the research area are unheated plots, the width of which is more than 500 meters in the direction of the prevailing wind, and 20% of the plots are within the range of 100-300 meters.

Vegetation cover has a decisive role in the process of erosion by wind. Plant height and leaf area reduce wind velocity, preventing soil particles from being blown up. In Dedoplistsakro municipality, high LAI values (2 or more) are associated with areas covered by forest (Figure). Riparian vegetation in the Alazni and Iori floodplains is associated with medium LAI values (1-2), while arable land has low LAI values (0-1).

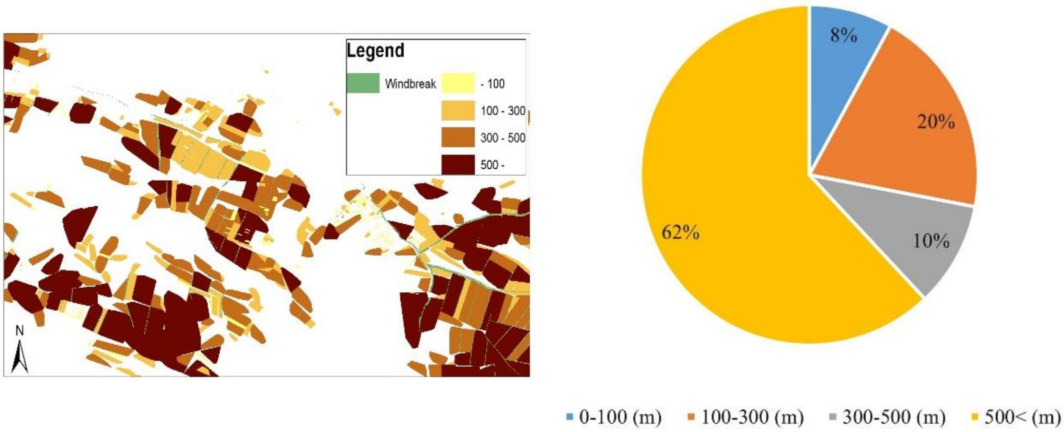


Figure 6. a-Unsheltered land width (m), b-spatial distribution (percent) of unsheltered land plots

The functional relationship of the geophysical variables discussed above showed that the maximum values of annual soil loss in the study area are fixed in the southwestern part of the municipality (Fig. 7), while relatively low values are fixed in the main part of the study area.

Discussions

The purpose of this study was to quantify the average annual soil loss on the agrarian soils of Dedoplistskaro municipality. The analysis of the main factors of erosion by wind mechanisms revealed that the study area is relatively vulnerable to erosion by wind. This result is confirmed by the resolution of the Government of Georgia, where the country's municipalities are divided into categories according to the average annual wind velocity. The Dedoplistskaro municipality belongs to the first category. In this case, one circumstance is worth noting, namely, the first category of municipalities according to the government's decree were assigned to those where the average annual wind velocity was 9.9 m/s.

According to the data used in our research (GWA), a maximum average annual wind velocity of 5 m/s was recorded in the research area. The reason for this difference may be as follows. The data mentioned in the resolution of the Government of Georgia (Government of Georgia, 2023) are based on data from past observations. On the other hand, the results of past research indicate that the average annual wind speed in the research area is within 0-4 m/s (Soils, 2018). Currently, wind velocity is not measured at most meteorological stations in the country. Therefore, global data were selected for the study. Here, we assume that the improvement of the observation network in the country will confirm that the global mean annual wind data in the study region are underestimated.

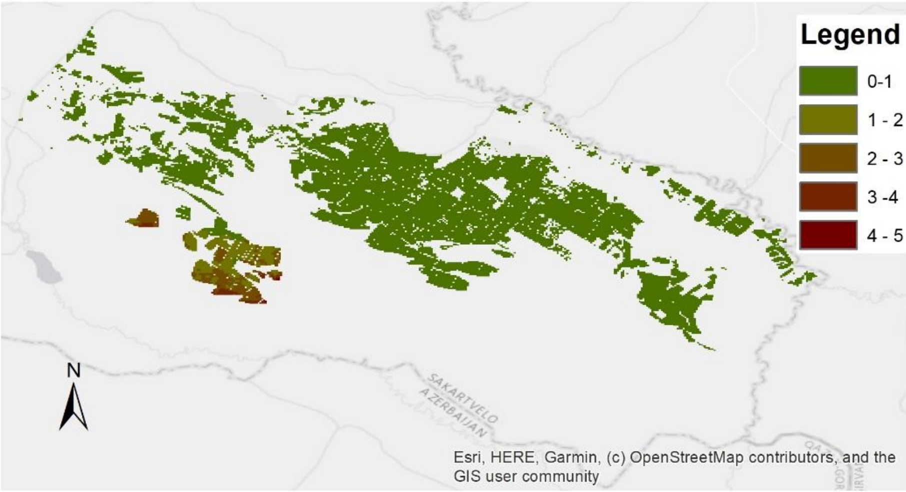


Figure 7. Average annual soil loss in the study area (t ha -1 yr -1)

The intermittency of the Dedoplistskaro meteorological station data prompted us to use MODIS open-access data. In this case, the high values of PET (30-48 mm) in the study area are due to local climatic conditions. The study area is characterized by high temperatures (especially in summer) and a low amount of precipitation (this is where the dry pole of the country is located). Such a ratio of temperatures and precipitation determines the high values of PET. Other studies also prove that there has been an increase in temperature in recent decades, especially in eastern Georgia (Elizbarashvili et al., 2017). For more concreteness, studies have shown that the study area has the highest average annual amplitude of ground surface temperature in the country (Tavartkiladze & Kikava, 2021).

These conditions, in turn, affect soil depletion, and the depleted and dried soil surface is easily split by the wind. According to global data, three soil types are represented in the study area. Based on their physical and chemical features, clay loam soils are characterized by lower erosivity than sandy clay loam soils.

The Dedoplistsakaro municipality is the main region of grain crops in Georgia. Accordingly, a large area of the municipality is occupied by arable land. These lands are completely free of vegetation in early spring and late autumn when strong winds are characteristic of the region. Of course, there are windbreaks in the research area (unpublished data from the Land Agency - 1550 ha); however, their condition and functionality are separate topics of discussion. Therefore, it is logical that the width of the unsheltered plots in the study area is quite large. As repeatedly mentioned, the study area is a region of intensive agrarian practices, and there are few forested areas to which to connect; additionally, the study area is mainly in river floodplains and protected areas. Trees and plants on agrarian soils are the aforementioned windbreaks.

Conclusion

In eastern Georgia, in the municipality of Dedoflitskaro, during the assessment of erosion by wind, it was revealed that the study area is quite vulnerable. The main difficulty in the study was the availability of data needed for model parameters, so the study is based on open-access data, including GWA, MODIs, ESA LULC, and WSD. High-accuracy data are also used in the study; for example, windbreaks in the study area are recorded in the field via GPS planning. The combined results showed that although the average annual wind speed (0-4 m/s) is recorded in the research area, low soil moisture, lack of vegetation, and large width of uncovered plots create favourable conditions for the activation of erosion by wind.

In the future, it is recommended to include relatively high-resolution data, especially for soils, to obtain more detailed and valid results.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

M.T. developed the theory and performed the computations. L.M. aided in interpreting the results and worked on the manuscript. A.T. and L.M. contributed to the design and implementation of the research, to the analysis of the results, and to the writing of the manuscript. All authors discussed the results and commented on the manuscript.

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