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Article

The influence of slope exposure on the yield characteristics of winter wheat and spring barley in the Oka River basin, Russia

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Abstract: We studied the relationship of the yield of winter wheat and spring barley with slope exposure components in the west of the Oka River basin. The size of the study area was 250 km by 360 km. The yield characteristics included the maximal yield obtained when applying the optimal dose of fertilizers, the yield without applying fertilizers (control) and the maximal addition to yield, that is, their difference. The addition is shown to be most sensitive to climatic factors. For wheat, the addition increased on the warmer south-western slopes, and for barley—on the wetter north-eastern slopes. The high sensitivity of the addition for barley to moisture is shown using it comparison with climatic water deficit. To compare slopes by the energy of incident solar radiation, we used the slope insolation in energy units. Although the difference in energy between the south-west and north-east slopes was only 2.2%, wheat addition on these slopes varied by more than a factor of two. The reasons for this are discussed. The results obtained show that when choosing locations for crop areas, it is advisable to take into account the exposure of the slopes.

Keywords: slope exposure; solar irradiation; winter wheat; spring barley; water deficit; incident solar energy

1. Introduction

The effectiveness of using fertilizers for growing crops depends on agricultural practices, climate, soils and topography. The influence of environmental factors has been studied in many works (e.g., Alvarez and Grigera [1]; Lobell and Field [2]; Ferrara et al. [3]). The use of a limited number of topographic attributes, such as elevation, exposure, steepness, and soil moisture index, resulted in crop yields appearing weakly related to environmental factors, typically explaining 15%–35% of the variance in yields [4]. Data from hundreds of observation points were used to increase the statistical significance of the results. However, using heat- and light-related slope characteristics together with climate characteristics provided stronger relationships, explaining 74% of winter wheat yield in a 2.5° by 3.6° study area located in the western Oka River basin in European Russia [5,6].

An increase in temperature to a certain point may not be accompanied by a significant change in yield, but further increases in temperature can lead to a sharp decrease in yields [7,8]. Temperature thresholds are thus expected in hot regions, making it difficult to use historical time series data where such high temperatures were rare in previous years.

At the local scale, the important role of topography was often discovered. However, these attempts have been ad hoc and based on non-quantitative descriptions of relative position in the landscape [9,10] or very few quantitative characteristics of the terrain [3,9,10,11–13]—but in the topography [5,6,14] is taken into account well), the influence of topography on the distribution of moisture was often taken into account, but not on the distribution of heat and light. The partial nature of studies on a local scale was expressed, for example, in the fact that in mountain fields in Italy a close negative relationship (R^2 = 0.8) of winter wheat yield with slope steepness was found [3], or the results were related to individual fields in USA [11]. The role of topography as a distributor of heat and light has often been ignored. Jankauskas et al. [15] found a close relationship caused by water erosion (R^2 = 0.79) between the yield of winter barley and the steepness of steep (3°–15°) slopes of upland fields in Lithuania, although such slopes are sometimes recommended to be excluded from agricultural land use [13].

Studies conducted at a regional scale often use simulation models such as CERES (Crop Environment Resource Synthesis) [16,17] or EPIC (Erosion/Productivity Impact Calculator) [18], which require detailed knowledge of weather, soil conditions and the specifics of crops during the growing season, but these models ignore topography. However, topography creates terrain anisotropy [19], redistributing climatic heat and light, which are important for agricultural plants. Therefore, along with process-based (simulation) models, inventory-based (statistical) models are also used, which statistically compare crop yields with environmental factors [20] and use the patterns found to identify leading relationships and construct predictive maps. There are reviews of statistical models and their applications in agriculture [21,22].

To account for heat and light, radiation balance measurements are used, which are often related to night-time air temperature, sometimes leading to some misunderstandings in interpretation [23]. The radiation balance interpolated between measurement points does not always correctly reflect the differences between northern and southern slopes. To describe the redistribution of heat and light, slope exposure components are used, such as the "northerness" of slopes $\cos A_0$ and the "easterness" of slopes $\sin A_0$, since the exposure A_0 is a circular variable and it is incorrect to use it in statistical comparisons [19]. However, the earth's surface receives different amounts of solar energy on slopes of the same aspect but of different steepness, which is taken into account in a non-circular variable known as slope insolation [24]. This variable allows you to compare slopes by the energy (in W/m^2) of solar radiation received on them.

In this work, for simplicity, we limit ourselves to considering the effect on yield of only insolation and exposure components that modify the light and thermal regimes of slopes, comparing them in terms of energy. Results are conducted for winter wheat and spring barley at a regional scale for a 2.5° by 3.6° study area located in the western Oka River basin in Russia. Here, as throughout Russia, field experiments have been carried out over the past 50 years with the application of different doses of fertilizers [25].

The purpose of the work is a statistical comparison on a regional scale of the yield characteristics of winter wheat and spring barley in the west of the Oka River basin with insolation and exposure components on slopes of different exposures to identify places with favorable conditions for plant development.

2. Materials and methods

Samples for yield indicators of winter wheat *Triticum aestivum* L. (41 plots of size 50 × 50 m^2, sample A41) and spring barley (49 plots of the same size, sample B49) in the west of Oka River basin were formed from the "Agrogeos" database [25], which collected data over the last 50 years from tens of thousands of experimental plots (all over Russia), where crops were grown using a single method with different doses of NPK fertilizers. The location of plots A41 and B49 is shown in **Figure 1**.

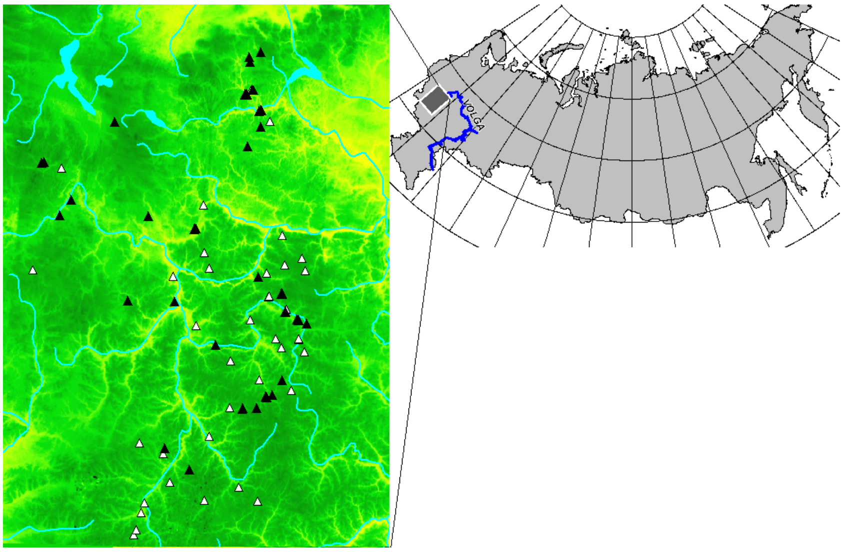

Figure 1. Location of winter wheat (black triangles) and spring barley (white triangles) plots against the background of the elevation map (darker means greater elevation). The study area size is 2.5° by 3.6° (~250 km by 360 km).

In the north of the study area there are soddy-podzolic soils, in the middle part—gray forest soils, in the south—thin chernozems. The terrain is quite flat; in the study area the elevation varies from 104 to 308 m.

The yield characteristics we used included, averaged over the years: (1) the yield without fertilizing, that is, the control (*K*), (2) the maximal yield (*Ox*), obtained when applying the optimal dose of fertilizers, and (3) the maximal addition in yield from fertilizing, that is, the difference *Ox*-*K*. Field experiments were located in the western part of Oka River basin of the size 2.5° in longitude and 3.6° in latitude. The average long-term (1950–2000) annual precipitation for samples A41 and B49 was 641 mm, the average annual temperature was 4.9 °C. The average *Ox* value for winter wheat at observation points A41 was 3.13 t/ha, control *K*—1.96 t/ha (63% of *Ox*); addition *Ox*-*K*—1.17 t/ha (37% of *Ox*). The average *Ox* for spring barley at observation points B49 is 2.75 t/ha, control *K*—1.87 t/ha (68% of *Ox*), addition—0.89 t/ha (32% of *Ox*).

The elevation data is taken from the SRTM30 elevation grid [26] with a resolution of 30″, that is, about 900 m at the equator. In the Oka River basin, the parallels are shorter, so we generated a Digital Elevation Model (DEM) with a resolution of 600 m. Based on it, the exposure components and insolation were calculated. The exposure (A_0) is a circular variable, that is, 0° and 360° are the same thing (northern slopes), therefore it is correct to use non-circular variables: "northerness" $\cos A_0$ and "easterness" $\sin A_0$ of slopes. The degree of expression of the "northerness" and "easterness" is determined by the positive value of the functions $\cos A_0$ and $\sin A_0$ (from 0.001 to 1), the severity of the "southerness" and "westerness" of the slopes is determined by the value of the negative value of $\cos A_0$ and $\sin A_0$ (from −1 to −0.001). Positive values of the exposure component $\cos A_{45}$, where $A_{45} = A_0 + 45°$, correspond to the north-western slopes (negative values correspond to the south-eastern ones), positive values of the $\sin A_{45}$ exposure component correspond to the north-eastern slopes, negative values correspond to the south-western ones. The $\sin A_{45}$ component was proposed quite a long time ago [27] due to the fact that the south-western slopes of the Northern Hemisphere are known to warm up most strongly.

Slope insolation $F(a, b)$ is a non-circular variable. It depends on two angles: the declination of the Sun the horizon, a, and the azimuth of the Sun, b, measured clockwise from the north. The effective azimuth b_0 can be found from statistical comparisons (see the last figure below), and we fixed the declination angle, assuming $a_0 = 35°$ for the study area. Exposure components and slope insolation were calculated from DEM as described in [24].

We also use the annual climatic water deficit *WD* [28], defined as the difference *PET*–*AET*, where *PET* is potential evapotranspiration (maximum possible surface evapotranspiration) and *AET* is actual evapotranspiration. We calculated *PET* according to the method of Thornthwaite [29], *AET*—according to the method [30] (repeated by Brutsaert [31]). More recent versions of the PET calculation methodology are noted by Lutz [28], but they require a larger data set, not available for us.

3. Results

Both maximal yield (*Ox*) and addition (*Ox*-*K*) generally depend on fertilizer applied, control (*K*), and environmental factors. The dependence of *Ox* and *Ox*-*K* on *K* is shown in **Figure 2**.

As can be seen from these graphs, the maximal yield increases linearly with the control. We do not provide linear trends for *Ox*-*K* because this dependence is not significant. Unlike *Ox*, the maximal addition (*Ox*-*K*) is practically independent of *K*. If control depends on the properties of soils and previous crops and soil treatment regimes, then in the study area the addition does not depend on them, since it is practically independent of *K*. Since the addition (*Ox*-*K*) depends less on the history of the fields (previous crops, plowing regimes, etc.), we can expect that it is more clearly related with environmental factors (temperature, solar radiation, precipitation, etc.) than *Ox*. Therefore, we do not study the relationship between *K* and environmental factors.

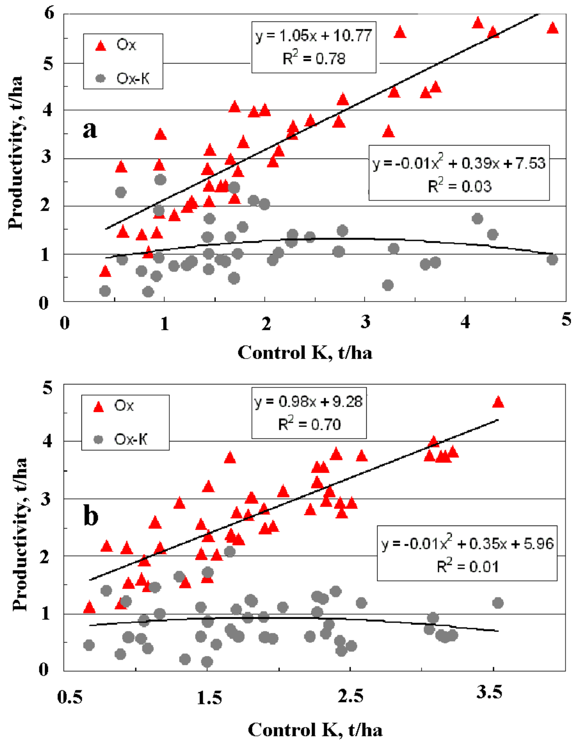

Figure 2. Dependence of maximal yield (*Ox*) and addition (*Ox-K*) on control (*K*) for **(a)** winter wheat; and **(b)** spring barley.

Indeed, on slopes of different exposures, the addition for winter wheat varied in the study area by ±78% of the average (1.17 ± 0.45 t/ha: we estimate the spread by standard deviation), and the maximal yield *Ox* changed by only ±22% (3.13 ± 0.58 t/ha). The control *K* for winter wheat varied by ±33% (1.96 ± 0.32 t/ha). The dependence of yield characteristics on slopes is shown in **Figure 3**.

Figure 3 shows that the highest values of *Ox* and *Ox-K* for winter wheat are achieved on the south-western slopes. The relationship between the addition to winter wheat and the north-eastern component of slope exposure is shown in **Figure 4**.

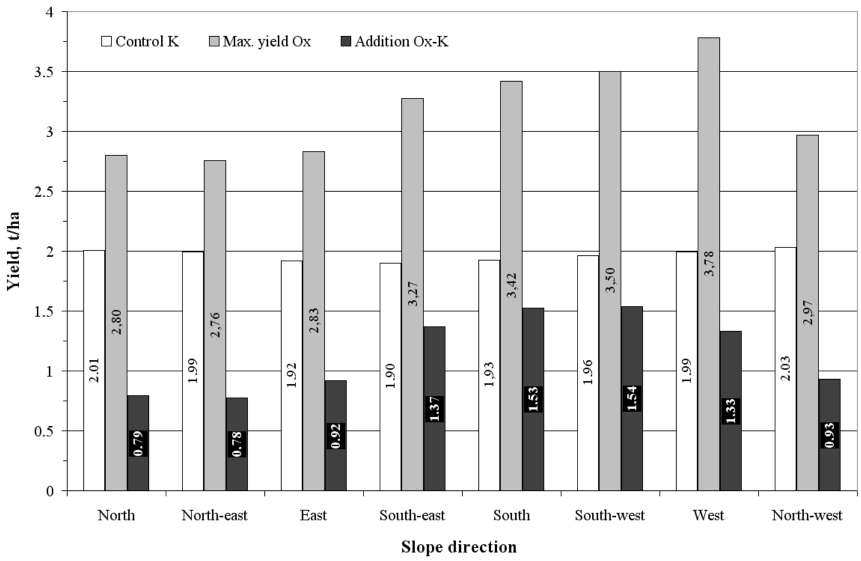

Figure 3. Distribution of winter wheat yield characteristics on slopes of different exposures.

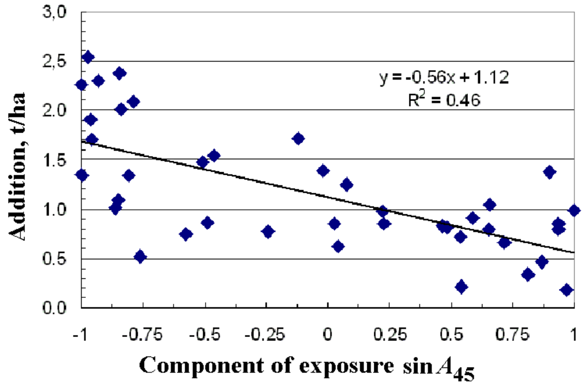

Figure 4. Dependence of the addition to yield for winter wheat on the north-eastern component of slope exposure sinA_{45}.

Values of sinA_{45} close to −1 correspond to the south-western slopes, and close to +1 refer to the north-eastern ones. Thus, 46% of the variance in the addition to winter wheat is explained by the north-eastern component of the slope exposure, and this addition approximately doubles on the warmer south-western slopes, taking the lowest values on the north-eastern slopes.

A somewhat different situation is observed for spring barley, **Figure 5**.

As can be seen from **Figure 5** for spring barley, the maximal yield *Ox* and the addition *Ox-K* have the lowest values on the warmest south-western slopes. Apparently, greater heating of these slopes and the resulting dryness of these slopes suppresses spring barley, reducing its yield, and also reduces the effectiveness of fertilizers, diminishing the addition *Ox-K*.

The relationship between the addition for spring barley and the north-eastern component of slope exposure is shown in **Figure 6**.

If we take all sample points B49, then the linear relationship of *Ox-K* with sinA_{45} is insignificant (R^2 = 0.08). Therefore, we took part of this sample, for which the addition had values above the average (**Figure 6**), equal to 0.885 t/ha.

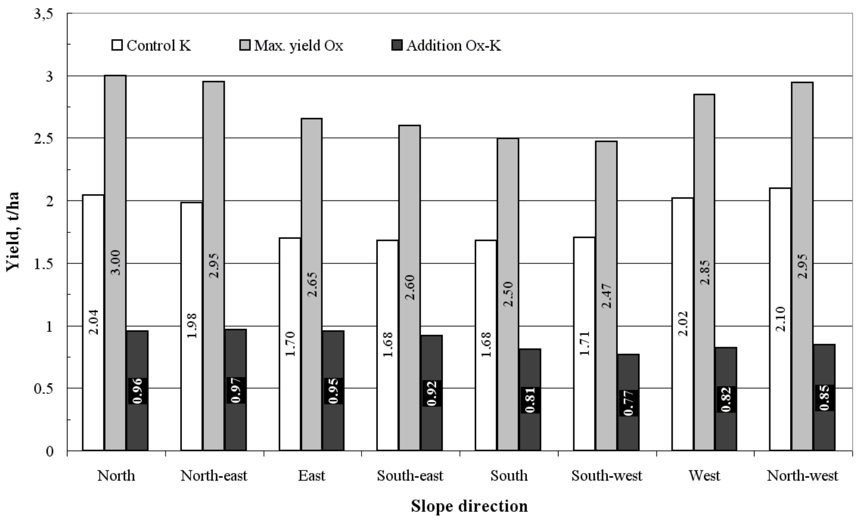

Figure 5. Distribution of spring barley yield characteristics on slopes of different exposures.

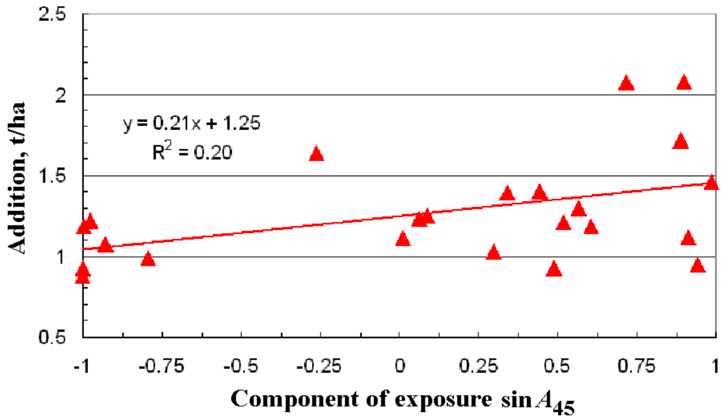

Figure 6. Relationship between the addition *Ox-K* to spring barley yield and the north-eastern component of slope exposure sinA_{45}. From the total *B*49 sample, 23 points with *Ox-K* values greater than average are taken.

To clarify the meaning of this result, consider for spring barley the relationship between the addition *Ox-K* and the climatic water deficit *WD*, **Figure 7**.

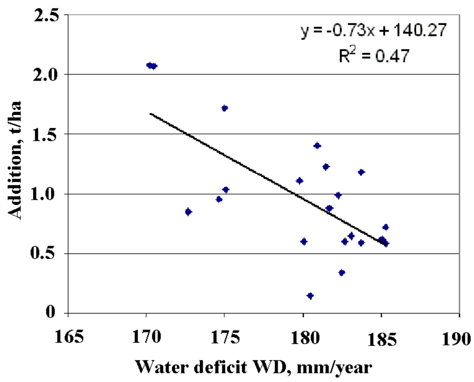

Figure 7. Relationship between addition to spring barley and water deficit *WD*. From the *B*49 sample, 22 points with *WD* values greater than the average were taken.

According to **Figure 7**, the addition *Ox-K* to spring barley decreases with increasing water deficit *WD*, that is, for barley the addition should decrease on better warmed, and therefore drier, south-western slopes. Apparently, the humidity of the north-eastern slopes is more important for the addition to spring barley than the warmth and light of the south-western slopes for the addition to winter wheat (compare **Figures 4** and **6**). In the case of **Figures 6** and **7** we speak about tendencies, not rules.

In turn, the north-eastern component of exposure, sinA_{45}, is closely related to the insolation of slopes from the south-west *F*(35°, 225°), **Figure 8**.

Therefore, it is possible to express the relationship between yield characteristics and exposure components in energy units, which makes it possible to compare the effects of solar radiation on different slopes. The exposure itself (as well as its components) does not allow this. Let us carry out such an assessment to distinguish between the south-western and north-eastern slopes.

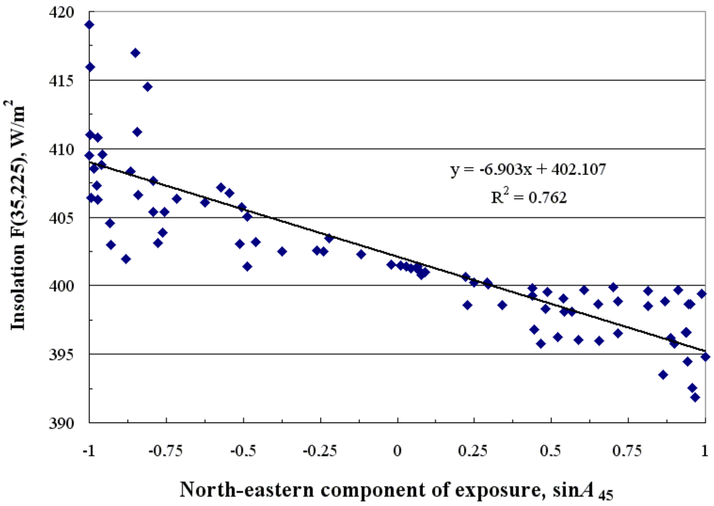

Figure 8. Relationship between insolation from the south-west $F(35°, 225°)$ and the north-eastern exposure component $\sin A_{45}$ for the combined sample *A*41 + *B*49.

The insolation of the earth's surface by the Sun on a clear day with perpendicular incidence of rays is 700 W/m^2, but the sun's rays fall obliquely (declination 35°), which reduces $F(35°, b)$. The average insolation value from the south-west $F(35°, 225°)$ for points with $\sin A_{45} > 0$ lying on the north-eastern slopes is 398.2 W/m^2, and the average value for points with $\sin A_{45} < 0$ lying on the south-western slopes, equal to 407.0 W/m^2. An assessment of the difference between these slopes in energy units is given by the difference between these two values, equal to 8.8 W/m^2. This difference in insolation is a fairly small value, only 2.2% of the average insolation $F(35°, 225°)$ for all slopes, equal to 402.2 W/m^2.

Nevertheless, this small change in insolation gives an increase in the addition to winter wheat yield on the south-western slopes by more than 2 times compared to the north-eastern slopes (**Figure 4**), which is apparently caused by the high sensitivity of wheat to heat and light in the study area. For spring barley, the addition, on the contrary, is greater on the relatively moist north-eastern slopes (**Figure 6**), which is apparently due to the greater sensitivity of barley not to heat and light, but to soil moisture.

The substantiation for the chosen value of the azimuth angle is given in **Figure 9**.

The maximum of correlation coefficient is achieved for azimuth b_0 = 225° (south-western slopes). Using this method, it is possible to find the values of the effective azimuth b_0 for other crops and yield characteristics.

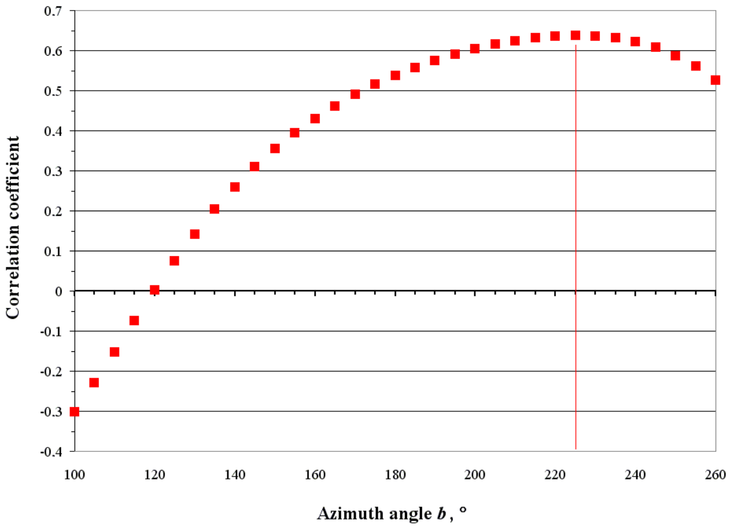

Figure 9. Dependence of the correlation coefficient *r* between the addition to winter wheat yield and the insolation *F*(35°, *b*) for different azimuth angles *b*. The vertical bar shows the value of b_0 corresponding to the maximum of *r*.

4. Discussion

The importance of the north-eastern component of slope exposure [27] in the Northern Hemisphere has been repeatedly noted in the literature, including for the photosynthetic activity of forests in western Carolina, USA [32]. In the study area, this component ($\sin A_{45}$) turned out to be important for the yield characteristics of winter wheat and spring barley. The energy assessment presented above showed that a change in slope insolation of only 2.2% (the difference between the north-eastern and south-western slopes) leads to a difference in the addition to winter wheat yield by more than 2 times, with this addition increasing on the south-western slopes compared to the north-eastern slopes. For winter wheat, this is apparently caused by an increase in heat and light on the south-western slopes.

On the other hand, the north-eastern slopes, due to less heating, are usually wetter. For agricultural plants, this creates an alternative to have greater yields either on the relatively warm south-western slopes or on the relatively wet north-eastern slopes. If the first alternative is implemented for winter wheat in the study area, then the second is implemented for spring barley. We tested the assumption about the important role of moisture by comparing the addition to spring barley yield with the climatic water deficit *WD*. The positive relationship between them indicates the significant role of moisture for spring barley.

Why did a small change of 2.2% in energy lead to a large change in yield characteristics? There are examples in the literature where small changes in environmental factors lead to large changes in the ecosystem. For example, an annual increase in annual temperature of only 0.025 °C on average, small compared to intra-annual temperature variations, over 40 years led to a rise in the boundary between coniferous and deciduous forests by 100 m in the Green Mountains in USA [33]. If forests change over decades in response to changing climatic factors, then differences in the microclimate of different slopes should appear in wheat and barley yields much faster, within a year. As already noted, the most sensitive is the addition to yield, which characterizes the economic effect of applying fertilizers, so special attention is paid to it here.

5. Conclusion

Despite small changes, 2.2% in energy, slope exposure, which modifies heat and light regimes, and subsequently soil moisture in agricultural fields, can be important factor for crop yield characteristics, especially the maximal addition to yield obtained with optimal fertilization. In the study area, this is most manifested in the difference in the addition to winter wheat yield, for which the addition on the south-western slopes is more than twice as high as on the north-eastern slopes. However, the addition to spring barley yield, on the contrary, decreases on the south-western slopes. Apparently, this is due to the relatively high sensitivity of barley to soil moisture, which we showed by comparing this addition with climatic water deficit. The better warmed south-western slopes tend to be drier, therefore, in the study area, for winter wheat, which is more sensitive to heat and light, the addition is higher on the south-western slopes, and for the more moisture-loving spring barley, on the north-eastern slopes. Since even small changes in influential topographic attributes can lead to noticeable changes in yield, it is advisable to take into account the exposure of slopes when choosing locations for crop areas.

Author contributions: Conceptualization, PAS and LSS; methodology, PAS; software, PAS; validation, PAS, LSS and OVR; formal analysis, LSS; investigation, LSS; resources, OVR; data curation, OVR; writing—original draft preparation, PAS; writing—review and editing, PAS; visualization, PAS and LSS; supervision, PAS; project administration, PAS; funding acquisition, OVR. All authors have read and agreed to the published version of the manuscript.

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