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MODELLING PHOTOSYNTHETICALLY ACTIVE RADIATION IN BELARUS

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Abstract

This research considers indirect methods for modelling values of photosynthetically active radiation (PAR) from shortwave radiation data in the Republic of Belarus. The authors performed calculation and modelling in three models. Model 1 (the Ross and Tooming formula) is a universal one and does not take into account the area latitude. The PAR coefficient (qf) here is 52 % of the shortwave radiation. Models 2 and 3 were proposed by the Meteorological Observatory of Moscow State University and applied to the territory of Belarus. One of them was adjusted for Belarus area particularly. The results of calculation by model 2 show that the PAR coefficient (qf) for Belarus is 46–47 % of the shortwave radiation at different times of the year. Thus, PAR ranges from 1500 MJ/m^2 to 1600 MJ/m^2 around Belarus in the vegetation period. The PAR values calculated in the third model range from 1540 MJ/m^2 in Vitebsk and Braslav to 1630 MJ/m^2 in the area of the Polesskaya station. In central Belarus, PAR is 1560–1580 MJ/m^2. The comparison analysis of the modelling results with each other and the results of similar research in the neighboring countries shows advantages and drawbacks of the models under consideration. The calculation results are visualized on the maps created by the authors to show the distribution of photosynthetically active radiation over the territory of Belarus. The spatial distribution of PAR across the territory of Belarus goes in the direction from northwest to southeast.

Keywords: photosynthetically active radiation, shortwave radiation, modelling, spatial distribution of PAR, Belarus.

МОДЕЛИРОВАНИЕ ФОТОСИНТЕТИЧЕСКИ АКТИВНОЙ РАДИАЦИИ В УСЛОВИЯХ РЕСПУБЛИКИ БЕЛАРУСЬ

О. П. Мешик, М. В. Борушко

Реферат

В работе рассматриваются косвенные методики моделирования значений суммарной фотосинтетически активной радиации (ФАР) на основе данных о суммарной коротковолновой радиации в Республике Беларусь. Выполнены расчеты и моделирование по трем моделям. Универсальная модель 1 (формула Росса-Тооминга) не учитывает широту местности. Коэффициент ФАР (q_f) по формуле Росса-Тооминга составляет 52 % от коротковолновой радиации. Модели 2 и 3 предложены специалистами Метеорологической обсерватории Московского государственного университета и применены к территории Республики Беларуси. Одна из них адаптирована авторами именно для территории Беларуси. Результаты расчета по модели 3 показывают, что коэффициент ФАР (q_f) для Беларуси составляет 46–47 % от коротковолновой радиации в разное время года. Таким образом, ФАР колеблется от 1500 МДж/м^2 до 1600 МДж/м^2 по территории Беларуси в течение вегетационного периода. Величины ФАР, рассчитанные по третьей модели, варьируются от 1540 МДж/м^2 в Витебске и Браславе до 1630 МДж/м^2 в районе станции Полесская. В центральной части Беларуси ФАР составляет 1560–1580 МДж/м^2. Сравнительный анализ полученных результатов между собой и с подобными исследованиями в соседних регионах выявил преимущества и недостатки исследуемых моделей. Полученные результаты вычислений визуализированы на картах, построенных авторами с целью наглядной демонстрации распределения суммарной фотосинтетически активной радиации на территории Республики Беларусь. Пространственное распределение фотосинтетически активной радиации по территории Беларуси идет в направлении с северо-запада на юго-восток.

Ключевые слова: фотосинтетически активная радиация, коротковолновая радиация, моделирование, пространственное распределение ФАР, Беларусь.

Introduction

Most biochemical processes in living nature, including photosynthesis, occur thanks to solar radiation. Chlorophyll molecules in plants are activated by quanta not of the entire spectrum of sunlight but only of the blue-violet and orange-red parts which are called photosynthetically active radiation (PAR). Its wavelength ranges from 400 to 700 nm (Figure 1).

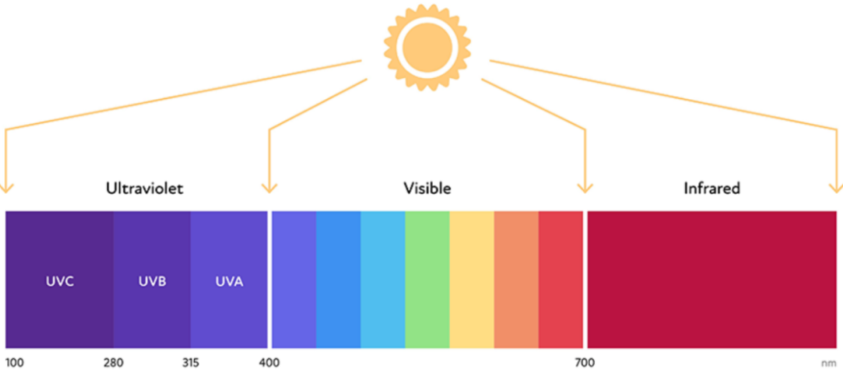

Figure 1 – Sunlight spectrum, PAR

Data on PAR are sought after in agricultural engineering, plant growing, forestry and other industries. It is necessary to know PAR values to study the productivity of vegetation, and therefore to forecast and possibly increase crop yields in different areas by using different agricultural techniques. Organic substances generated during photosynthesis make up 90–95 % of dry plant biomass. Therefore, the main way to increase crop yields is to increase the photosynthetic productivity of plants and the PAR utilization coefficient, for instance, by supplementary lighting of plants in agricultural seedling production [1] or creating optimum conditions for growing plants in greenhouses [2, 3]. Data on direct, diffuse and total radiation are used not only in agriculture, agrometeorology and hydrometeorology but also in industries such as construction, utilities, solar engineering, healthcare, fisheries, peat extraction and refrigeration.

Researchers worldwide are developing empirical PAR models that can satisfactorily predict PAR at different locations [4]. The models are different for different climates. The authors propose to use easily observable meteorological parameters [5–8].

Knowing the inflow of PAR in a certain area allows calculating the value of the potential biomass of plants in the area. A. A. Nichiporovich [9] developed a method to calculate a potential yield. It includes the inflow of PAR and a coefficient of its utilization. His approach has become widespread. The potential yield of absolutely dry mass is determined by the formula

$$У = \frac{\sum Q_p * К}{10^5 * g}, \quad (1)$$

where Y is a biological yield of absolutely dry plant mass, t/ha; $\sum Q_p$ is the amount of PAR during the vegetation period of a crop in a certain area, billion kcal/ha; K is a designed utilization coefficient of PAR, %; g is the amount of energy released when 1 kg dry plant biomass is burnt, kcal/ha; 10^5 is conversion of kg to tons.

Although there are attempts to learn how to measure PAR by instrumental methods [10], for practical purposes it makes sense to model the PAR values in a certain area (farm) based on the data on shortwave solar radiation observed at the nearest actinometric station. In the Republic of Belarus, solar radiation observations are carried out only at three meteorological stations: Minsk, Vasilevichi, and Polesskaya. The database with their actinometric observations is stored in the Republican Hydrometeorological Centre.

Modelling PAR

The sums of shortwave radiation registered at weather stations can be converted into the sum of PAR ($\sum Q_{PAR}$) using the Ross and Tooming formula developed in the 1960s by Estonian scientists with theoretical calculations of the energy in the solar radiation spectrum [11]:

$$\sum Q_{PAR} = 0{,}4225 \sum S + 0{,}582 \sum D, \quad (2)$$

where $\sum S$ is the sum of direct solar radiation, $\sum D$ is the sum of diffuse solar radiation.

Later it became clear that it is more expedient to use a single coefficient q_f to estimate the total PAR instead of two individual ones for direct and diffuse radiation. Moreover, there are difficulties in accessing data on direct and diffuse radiation therefore the method of modelling Q_{PAR} by the total shortwave radiation Q has become widespread [11]:

$$\sum Q_{PAR} = 0{,}52 \sum Q. \quad (3)$$

Since actinometric observation over shortwave radiation in Belarus is performed only at a few meteorological stations and these measurements are not enough to receive better differentiated values of PAR for the rest of the country, it becomes necessary to calculate the values of total Q for the entire territory of the republic [12]. There are various empirical models for calculating solar radiation values based on more easily accessible meteorological parameters, such as cloudiness, sunshine duration, and ambient temperature. In this study, we used the method described in [13] to model monthly amounts of total shortwave radiation in Belarus. Table 1 presents the results of the calculation performed. Figure 2 shows a spatial distribution of yearly sums of total shortwave radiation in Belarus [14].

Table 1 – Total shortwave radiation in Belarus (Q), MJ/m²

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Brest Region													
Brest	73	143	291	431	576	618	610	500	341	206	94	51	3933
Polesskaya	61	133	281	422	567	607	596	483	323	188	79	39	3909
Pruzhany	60	129	277	419	566	609	560	487	326	190	81	38	3782
Vitebsk Region													
Vitebsk	46	116	266	416	573	622	609	487	318	177	67	25	3719
Verhnedvinsk	54	125	277	427	585	633	621	498	328	187	75	32	3840
Lepel	55	125	277	425	580	628	617	496	328	187	76	34	3828
Gomel Region													
Gomel	71	140	288	429	575	618	610	499	389	203	92	49	3912
Vasilevichi	72	141	290	430	574	614	606	497	339	204	93	51	3910
Bragin	76	145	294	432	576	617	610	501	343	208	97	54	3953
Grodno Region													
Grodno	59	129	278	422	573	619	610	494	330	191	80	37	3822
Oshmyany	56	145	277	423	577	623	612	493	327	188	77	35	3833
Lida	57	127	276	421	573	619	610	493	328	189	78	36	3808
Mogilev Region													
Mogilev	57	127	277	422	574	619	609	492	327	188	78	35	3805
Gorki	56	127	278	423	576	622	611	493	327	188	77	35	3814
Minsk Region													
Minsk	58	127	276	420	571	615	607	494	329	190	80	37	3804
Soligorsk	60	129	276	419	566	608	599	487	326	190	81	39	3778
Borisov	57	127	277	423	576	622	611	493	327	188	77	35	3812

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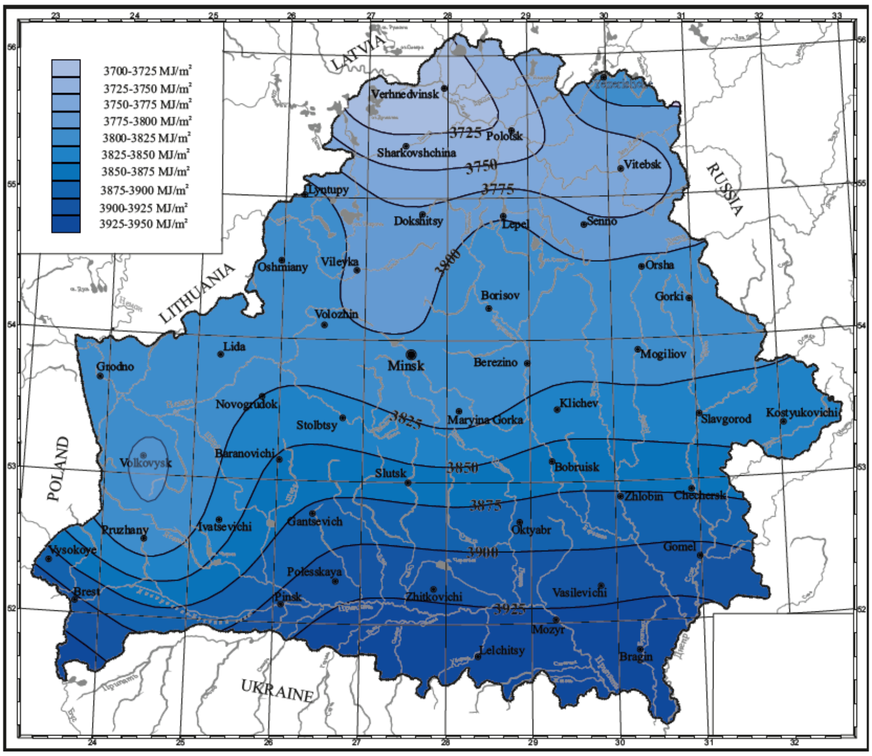

Figure 2 – Total shortwave radiation in Belarus (Q), MJ/m²

Comparison of the calculated values of total shortwave radiation with those measured at the Minsk and Vasilevichi stations shows a sufficiently high convergence in the results [13], which allows us to apply the theoretical model for calculating integral radiation *Q* at any geographic point in Belarus with errors that do not exceed instrumental measurements. A discrepancy of 20–40 MJ/m² per month is observed in the summer months [15, 16]. We consider such a discrepancy in *Q* values to be insignificant for the warm season. The results of modelling the *Q* values are presented in Figure 3 as a map of spatial distribution of the total annual shortwave radiation in the territory of the Republic of Belarus. The modelling considers the total shortwave radiation for the vegetation period with the average daily air temperature of over 5°C, i. e. from April to October.

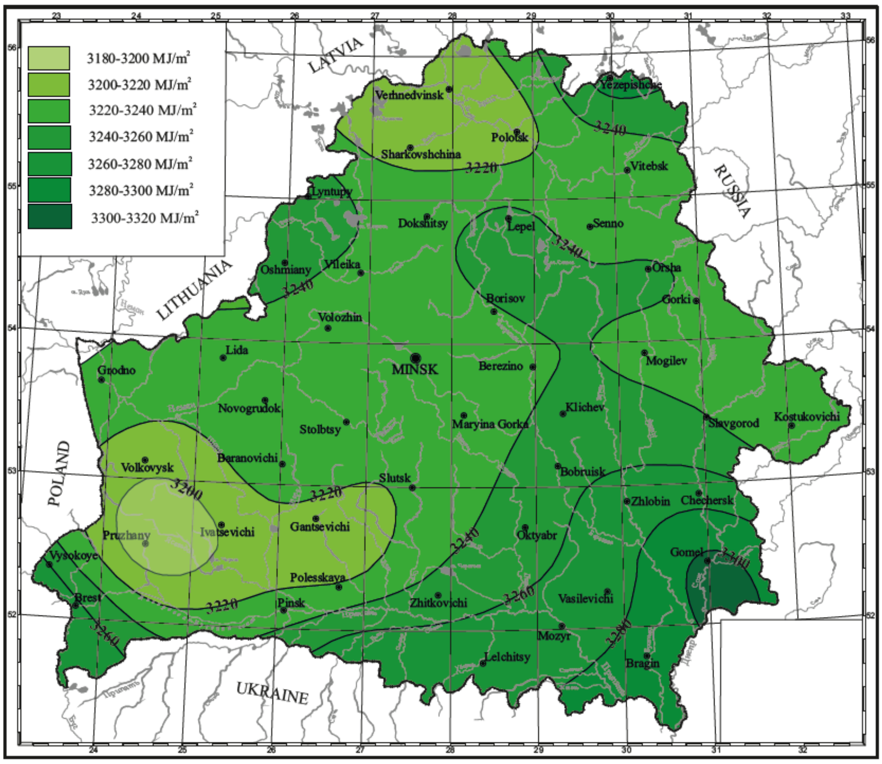

Figure 3 – Total shortwave radiation in April-October, MJ/m²

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Figures 2 and 3 show that the isolines of the total shortwave radiation do not have a strict latitude direction. The radiation grows from the northwest to the southeast. Thus, the values of the total shortwave radiation in the warm season range from 3200 MJ/m^2 in Pruzhany and Verkhnedvinsk to 3320 MJ/m^2 in Gomel.

In this study, calculation of total PAR (Q_{PAR}) was performed with the use of 3 models. All of them are based on total shortwave radiation data. The calculation results of all the three models are presented selectively in Table 2.

Table 2 – PAR values calculated in the models under study, MJ/m^2

	Model 1	Model 2	Model 3
Brest	1706	1551	1589
Vitebsk	1664	1512	1545
Gomel	1702	1547	1584
Grodno	1684	1530	1566
Minsk	1678	1525	1560
Mogilev	1680	1527	1562

The 1st theoretical model ($Q_{PAR} = 0,52Q$) is mentioned above [11]. The modelling results are depictured in Figure 4.

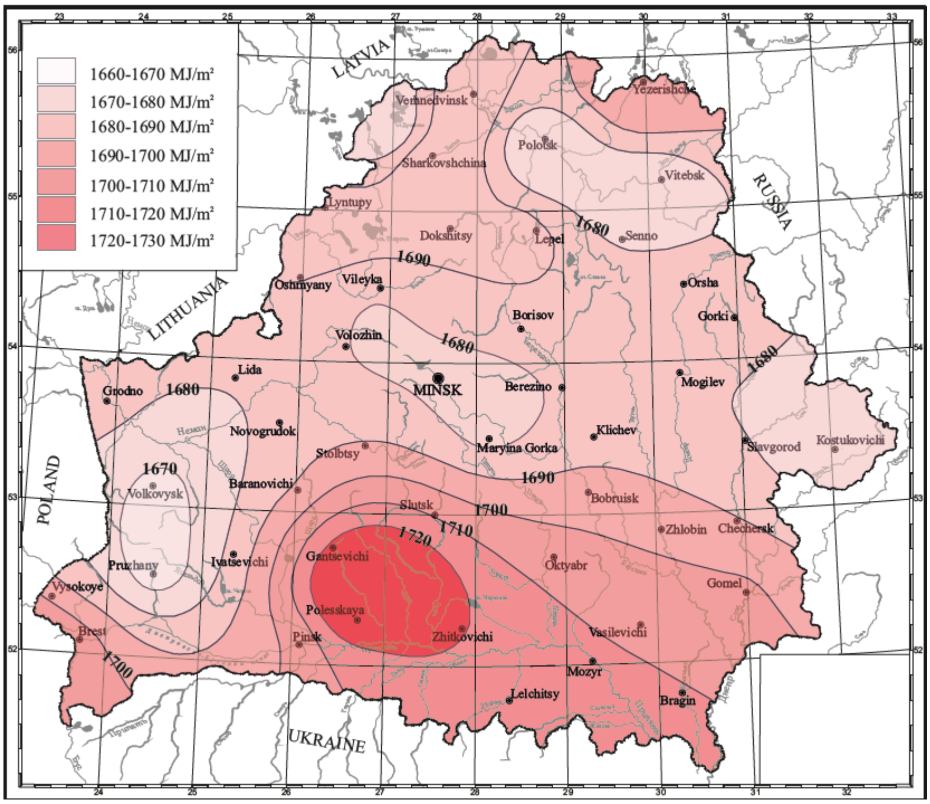

Figure 4 – Total PAR calculated in model 1 (April-October), MJ/m^2

The other two models were developed by the Meteorological Observatory of Moscow State University based on data on total integral radiation [17]. In order to get more accurate values of PAR using the model $Q_{PAR} = q_f Q_{ir}$, the authors propose calculating a more accurate transition coefficient of PAR (q_f) for specific geographic points using the formula [17]:

$$q_f = 0,451 - 0,0217(sinh)^2 + 0,0449sinh, \quad (4)$$

where *h* is the sun elevation at noon.

According to formular 4, the PAR coefficient (q_f) for Belarus is 46–47 % of the shortwave radiation at different times of the year. Thus, PAR ranges from 1500 MJ/m^2 in Volkovysk to 1600 MJ/m^2 at Polesskaya station in the vegetation period (Figure 5). As we can see, the PAR values calculated by the formula $Q_{PAR} = q_f Q_{ir}$ with the transition coefficient $q_f = 0.46$-0.47 adjusted for the territory of Belarus are naturally lower than those calculated by the traditional formula $Q_{PAR} = 0.52Q$. The spatial distribution of the total PAR, modelled by the formula $Q_{PAR} = q_f Q_{ir}$, MJ/m^2, is shown in Figure 5.

The third model applied in this study was also developed by the researchers at the Moscow State University Meteorological Observatory. They propose modelling the total PAR for the warm season of the year using the formula [17]:

$$Q_{PAR} = 0,4424exp(0,1148sinh)Q_{ir}, \quad (5)$$

where *h* is the sun elevation at noon, Q_{ir} is the sum of integral irradiance per day.

The authors claim that the calculation error is 6–8 %, which is even less than the error in measuring PAR instrumentally.

Modelling of PAR with model 3 is presented in Figure 6. The spatial distribution of PAR across the territory of Belarus goes in the same direction from northwest to southeast, which is not surprising, since all the three models (Figures 4–6) are based on the values of total shortwave radiation and correlate with its spatial distribution (Figure 2 and 3). However, the PAR values here are somewhat higher than in model 2 ($Q_{PAR} = q_f Q_{ir}$) where $q_f = 0.46$–0.47 for the territory of Belarus.

The PAR values calculated in the third model (formular 5) range from 1540 MJ/m^2 in Vitebsk and Braslav to 1630 MJ/m^2 in the area of the Polesskaya station. In central Belarus, PAR is 1560–1580 MJ/m^2.

Comparison of the modelling results shows that the PAR values in the first model (formular 3) are somewhat overestimated. The calculation results in models 2 and 3 are more accurate since they take into account the sun elevation, i. e. the latitude of the area. Moreover, comparing the modelling results with similar studies in neighbouring regions [18–20], namely Ukraine, shows that the results of models 2 and 3 are consistent with the data of the study [18–19] where Q_{PAR} in the north of Ukraine (Kovel, Boryspil) on the border with Belarus is 1650–1670 MJ/m^2.

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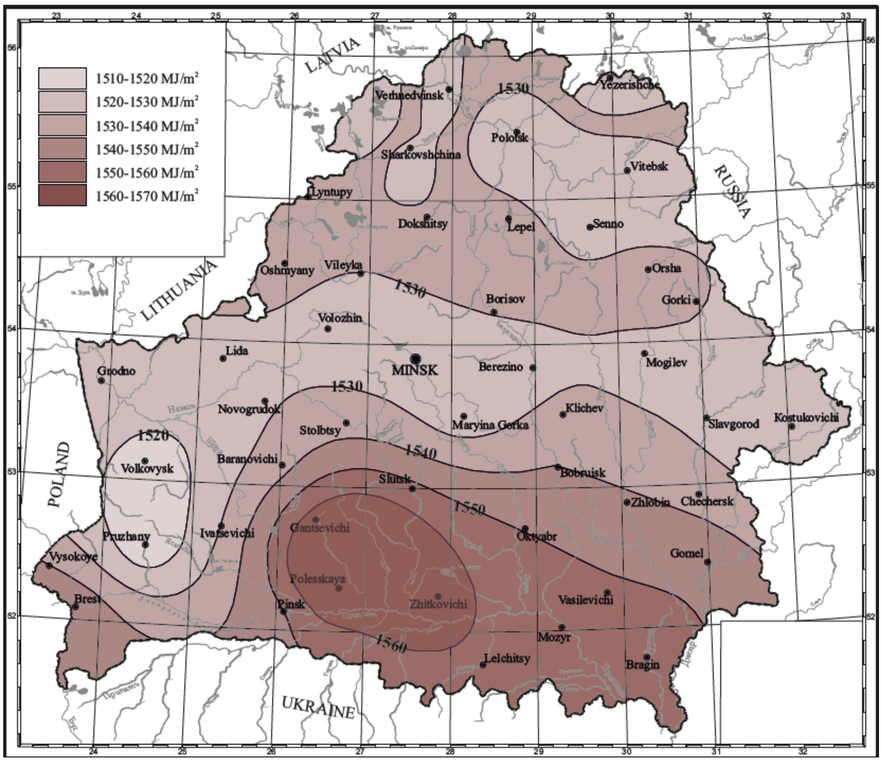

Figure 5 – Total PAR calculated in model 2 (April-October), MJ/m²

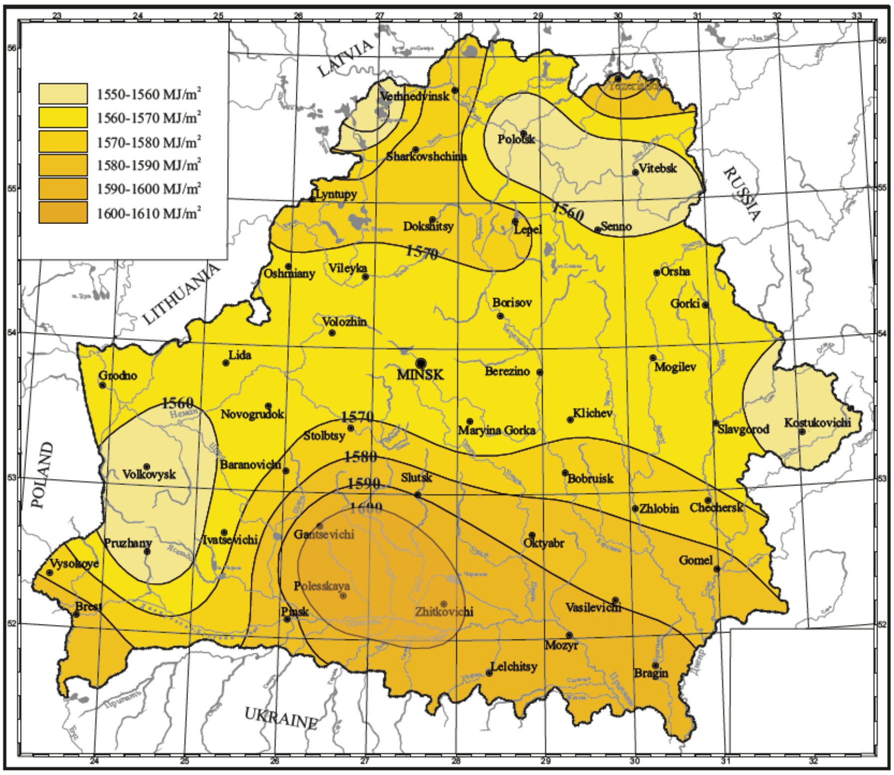

Figure 6 – Total PAR calculated with model 3 (April-October), MJ/m²

Conclusion

There is a need for agrometeorologists to get PAR data to help solve problems in the long-term effective planning of agricultural development of regions. The use of indirect methods for PAR assessment in areas where there are no regular instrumental measurements can be a good alternative to complex instrumental measurements of PAR. Modelling of PAR values based on total shortwave radiation data revealed differences in the calculation results. Comparison of the calculation results with each other and with the research done in the neighbouring regions showed that the PAR values in model 1 are somewhat overestimated while the calculation results in the 2nd and 3rd models are more accurate. The calculation of the total PAR from shortwave radiation data in Belarus in models 2 and 3 is consistent with similar results in other regions of the temperate zone.

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